Face Time

THE EMERGENCE OF THE FACADE AS THE INTEGRATIVE FACTOR IN HOLISTIC BUILDING DESIGN

Conference Proceedings
Volume 2

Facade Tectonics

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FACADE TECTONICS

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9 7 8 1 8 8 2 3 5 2 4 3 2

Contents

Process <> Delivery

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Maintenance <> Lifecycle

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Introduction

NOTHING IN ARCHITECTURE COMBINES ISSUES OF APPEARANCE AND PERFORMANCE LIKE THE BUILDING SKIN

The Facade Tectonics Institute is an international member organization with the mission of carrying out progressive and broad-based research in building facade technology. The intent is to catalyze and foster a deep dialogue of collaborative research activity that bridges the fragmented market segments of the building industry, pairing industry, government, academia, the profession, and ownership.

Facade Tectonics started in 2007 at the USC School of Architecture with considerable efforts in ongoing conferences, research initiatives and publications related to the building envelope. In 2015, we saw the coalescence of these efforts in the formation of the Facade Tectonics Institute. The dialogue we started together in 2007, along with the assets and activities we have accumulated along the way, now have a permanent home at the Institute. However, the Institute is not merely a string of conferences; we are a building facade focused research institute that produces events as educational and collaborative outreach, bridging the fragmentation that characterizes our industry, ultimately bringing together industry, the profession, academia, government, owners, and others. In addition, we are expanding our publication programs, launching new research initiatives, developing educational programs, pursuing research grant opportunities, and forming working groups to address key areas of building facade science and technology at this very moment. In addition to the 2016 World Congress in Los Angeles, we have hosted many smaller regional focus forums such facades' research, the building skin, and precast concrete at USC, lighting and daylighting at UTSA, the future of facades at the AIA National Convention, a façade workshop in Shanghai, and others.

The 2016 Annual Conference and inaugural World Congress focused on issues of facades for both professionals and academics while featuring blind peer reviewed papers with both new research and case studies. It combined the art, science, and technology of the building skin with an unparalleled networking opportunity from the domestic and international building community. As we had reached such a level of enthusiasm and participation that we have outgrown our on-campus facilities; the conference was held in a high-profile venue in downtown Los Angeles, October 10-11th.

The presentations and conference proceedings of the Facade Tectonics Annual Conference is a curated speaker program that includes diverse voices in the creation of advanced building facade systems that showcase new perspectives on the opportunities for innovation in the design and delivery of the building skin. Multiple emergent drivers are forcing a step change in the performance demands on buildings, and most particularly on the facade system. These demands mandate an innovative response to issues ranging from systems and materials to design and delivery strategies. A stellar line-up of authors wrote papers that were sorted into multiple tracks: material<>tectonics, daylight<>control, integration<>adaption, façade<>education, comfort<>skin, process<>delivery, renovation<>preservation, glass<>structure, transparency<>security, layers<>orientation, façade<>future, ventilation<>skin, acoustics<>skin, advanced<>case studies, and maintenance<>lifecycle. Although the discussions and dialogues could not be captured, the papers are contained herein.

Please consider becoming a member of the Façade Tectonics Institute (facadetectonics.org) to get on our mailing list and join the conversation.

Sincerely,

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Daylight <> Control

DISCOMFORT GLARE METRICS

Investigating their accuracy and consistency in daylight glare evaluation by using human subject study data

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ABSTRACT

Daylighting has been widely adopted in buildings to reduce building energy consumptions and to promote occupant productivity and comfort. Many daylighting and discomfort glare metrics and tools have been developed to provide the desired amount of natural light while avoiding excessive visual discomfort. Considerable research has been done to examine how to evaluate glare and how to mitigate the problem for building users from a design standpoint. Confounding the problem is the fact that glare is a subjective phenomenon, and people do not always agree on what constitutes glare. For more accurate glare evaluation, it is critical to make a clear understanding of the existing glare metrics and tools.

This study performs validation studies on five glare metrics including Daylight Glare Probability (DGP) and Daylight Glare Index (DGI) that have been developed specifically for daylight glare issues. A parallel human subject study has been performed to collect subjective discomfort glare evaluations. In addition, high dynamic range (HDR) imaging was used to capture and analyze the glare scenes that were experienced by those human subjects. More than 450 daylight glare scenes and subjective surveys were collected in a closed office setting. The collected data has been processed in hdrscope and Evalglare to obtain glare scores, and the results were compared for statistical analysis of subjective evaluations. The results show only one or none of the five metrics correctly matches to the subject's evaluation for each glare scene. This evaluation comparison study shows that the five glare metrics have significant inconsistency and inaccuracy issues.

KEYWORDS

Daylighting, discomfort glare, shading, occupant comfort, architectural glass, human subject study, Evalglare

INTRODUCTION

Daylighting provides significant benefits in buildings such as energy saving, occupant comfort, and occupant productivity. Different daylighting analysis methodologies and tools have been developed to ensure desired amount of natural light in buildings. Energy simulation tools calculates estimated amount of energy savings from different daylighting strategies. Daylighting and lighting simulation tools allow checking illuminance levels inside a building. Discomfort glare analysis tools and metrics evaluate different levels of visual discomfort in indoor spaces (Konis, 2013; Suk et al., 2013; Hirning et al., 2013 and 2014). Although many people cannot accurately define the causes and types of glare, most people experience it daily inside and outside of buildings. Researchers agree that glare occurs when the eyes have adjusted to a certain general level of brightness, and some annoying, distracting, or blinding light appears within the visual field. It is also well acknowledged that excessive levels of glare source luminance cause discomfort glare regardless of contrast levels. Veiling reflection is also classified as a type of discomfort glare. Glare can be described in one of three main ways: according to the process that created the glare, according to an individual's perceived degree of glare intensity, and according to the results of the glare. Many existing glare metrics including DGP (Daylight Glare Probability), DGI (Daylight Glare Index), UGR (Unified Glare Rating), VCP (Visual Comfort Probability), and CGI (CIE Glare Index) focus on evaluating perceived degree of glare intensity.

BACKGROUND

DGP is the most recent glare metric that was developed to evaluate daylight glare. For determining glare, its formula combines the vertical eye illumination as a glare measure with the central term of existing glare metrics. It also considers the influence of the glare source. Compared with the other existing glare metrics, DGP shows a very strong correlation with the user's response regarding glare perception (Wienold and Christoffersen, 2005). DGI was also developed for daylight glare as it evaluates a large glare source such as high luminance levels of windows (Bellia et al., 2008). UGR, VCP, and CGI were developed to address glare issues caused by electrical light sources. Even though they are not designed for daylight glare, several studies claim potential use of these metrics for daylit spaces (Isoardi et al., 2012). Therefore, all five existing glare metrics were examined in this study.

For automatic glare evaluation of the luminance images captured by High Dynamic Range Imaging (HDRI), the software program Evalglare was developed (Wienold and Christoffersen, 2006). Evalglare identifies potential glare sources based on a threshold value, which can be 1) specified by the user manually as a fixed luminance value; 2) computationally determined based on average luminance in the field of view; or 3) computationally determined based on a user specified task location (Inanici, 2004 and 2005). The threshold value in Evalglare is by default a multiplier "5 times" of the mean total image luminance or the mean task area luminance. Evalglare can be plugged into several daylighting analysis software programs making glare analysis easier, but its use has not been widely adopted yet. Evalglare calculates five glare metrics from an image in either HDR or PIC format in either a 180 degree angular fisheye or a normal perspective image. By typing Evalglare commands in a DOS window or using hdrscope software, it calculates luminance value and location of each pixel of the image, then uses the information to calculate the crucial values such as background mean luminance, glare source luminance, glare source position, solid angle of glare sources, vertical illuminance, and direct vertical illuminance, etc. Based on the information taken from an image, Evalglare provides glare scores and visual representation of potential glare source locations and sizes. The following table shows different glare score ranges of the five glare metrics to categorize different levels of perceived glare from imperceptible glare to intolerable glare. Higher score represent worse discomfort glare issues in DGP, DGI, UGR, and CGI. Unlike the other glare metrics, the higher score represents better visual comfort in VCP, since it is the probability of comfort.

Degree of Perceived Glare	DGP	DGI	UGR	VCP	CGI
Imperceptible	< 0.35	< 18	< 13	80-100	< 13
Perceptible	0.35-0.40	18-24	13-22	60-80	13-22
Disturbing	0.40-0.45	24-31	22-28	40-60	22-28
Intolerable	> 0.45	> 31	> 28	< 40	> 28

Table 1. Degree of Glare in Different Glare Metrics (Jakubiec, 2010)

Based on simulation-only study, Jakubiec and Reinhart claim that DGP shows the most robust results for most daylight situations among the five metrics (Jakubiec and Reinhart, 2010). Their study also found that VCP is not intended to be used for daylight glare calculations, and CGI tends to show much higher glare levels than the other metrics. DGI and UGR can be used for daylight glare evaluation, but they work only when the direct sunlight does not enter (Jakubiec, 2010). Based on human subject study performed in a large open office space, Hirning et al. claim that DGP and DGI were unable to provide accurate evaluations of discomfort glare experienced by the participants (Hirning et al., 2013 and 2014). These previous findings and claims on the application of the existing glare metrics were expected to be verified in this study. Evalglare is one of the most practical tools for calculating daylight glare, but previous research has shown that the existing glare metrics provide inconsistent glare evaluations for a same glare scene, which makes users suspicious of their evaluation accuracies (Suk and Schiler, 2012). The previous study was done entirely without subjective inputs; recent research utilizing extensive human subject study data was performed to find out levels of accuracy and consistency of the five metrics.

METHOD

After reviewing a number of precedents (Luckiesh and Guth, 1949; Hopkinson, 1957; Ngai and Boyce, 2000; Velds, 2002; Osterhaus, 2005; Linney, 2008; Wymelenberg, 2012; Hirning et al, 2013; Konis, 2013), a human subject study methodology was developed to collect accurate and consistent subjective evaluations of discomfort glare caused by daylight. Electrical lighting sources were completely excluded so that the visual discomfort experienced by participants is known to be the sole result of daylight glare, rather than glare contributed from artificial light sources. HDRI was used to capture the visual information that was experienced by human subjects.

HUMAN SUBJECT STUDY AND HIGH DYNAMIC RANGE PHOTOGRAPHY

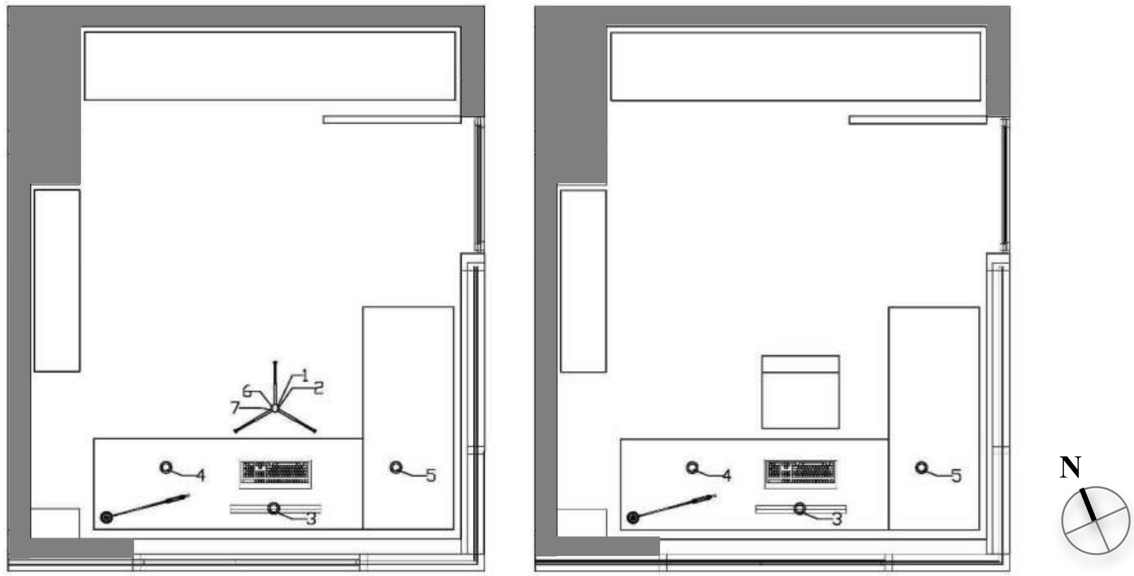
Three male and three female subjects were recruited for the human subject study. No participants with vision-related illness or color blindness were included in the study.

Similar to Hopkinson's (1957) research, a small number of subjects was chosen instead of a large number of random subjects because of the unique characteristics of daylight glare research. Hopkinson's study compared the findings from an experienced group of six people to the findings from fifty random subjects and found that the experienced group provided more consistent glare evaluation data than the random subjects. As the sun and sky conditions constantly change, it is hard to control daylight glare conditions to be identical for a large number of subjects. Therefore, it is ideal to have a small number of subjects and have them all experience many different daylit environments. Testing the same subject multiple times helps to ensure evaluation accuracy and consistency. Further study with an expanded number of subjects should be pursued, expanding on the findings of this study.

The human subject study to assess discomfort glare issues was performed inside a closed office space at the University of Southern California. There is no exterior visual obstruction that is closely located to the office. The room is a corner office with two clear glass windows facing southwest and southeast (Figure 1). Each window has two adjustable blinds: a venetian blind and a roller blind. The corner office condition was selected to allow more natural light inside the space (to be more exposed to the outside) and to avoid the severe contrast issues that can occur in a closed room with small aperture windows. This research setting represents many office buildings with large amount of fenestrations to allow direct view to outside and natural light inside buildings. The allowance of adequate daylight also helped to avoid the necessity of electrical lighting usage. Another advantage of using the corner office condition is that it provides more opportunity to experience potential glare sources. Since the office has front and side windows, it can have potential glare sources from different directions.

The research setting was used for the subjects and HDR photography (Figure 1). The room is 11'-3'' high by 9'-6'' wide by 11'-4'' long. The height of the windows goes from task height (2'-6" A.F.F.) to ceiling. A desk was located adjacent to the windows facing southwest and southeast; a desktop monitor was placed on top of the desk, in front of a southwest-facing window. A total of four illuminance sensors and data loggers were installed: one behind the monitor facing the window, one above the camera facing the window, and sensors on either edge of the desk facing up. Data loggers were provided with thirty-second recording intervals in which to record data from the sensors. The equipment was carefully calibrated and normalized prior to the study.

A glare scene was captured using various exposures by a Nikon Coolpix 4500 camera and angular fisheye lens. More than +-2 full stop exposures from normal exposure were taken to capture the dynamic ranges of human eyes by adjusting shutter speeds only. For the scenes with a direct view of the sun, much wider exposure ranges were taken to capture the extreme ranges of the luminous environment: the sun's disk and interior surfaces. The luminance values on the captured HDR images were also calibrated with field measured luminance values by a Cooke luminance meter. Illuminance sensors (Li-Cor LI-210R) and data loggers recorded the vertical illuminance values arriving into the subject's eyes and horizontal illuminance at the task height. The captured HDR images were then processed in hdrscope and Evalglare to compare DGP, DGI, UGR, VCP, and CGI index scores.



With HDR Photography With Human Subject

Figure 1. Interior glare study research setting: 1) Camera; 2, 3, 4, 5) Li-Cor sensors for vertical illuminance; 4, 5) Li-Cor sensors for horizontal illuminance; 2, 3, 4, 5) HOBO sensors; 6) Tripod; 7) Cooke luminance meter

Each subject was tested under three different lighting conditions. For each, the subjects were asked to perform three different tasks: no task, typing task, and writing task. The room had both venetian blinds and roller blinds on the windows. There were three lighting conditions:

- Fully open: both roller and venetian blinds were fully opened on both front and side windows and could not be adjusted (Figure 2, top).
- Roller blinds only: the subjects were able to separately adjust front and side roller blinds as they preferred. The venetian blinds were fully open and could not be adjusted (Figure 2, middle).
- Venetian blinds only: the subjects were able to separately adjust front and side venetian blinds as they preferred. The roller blinds were fully open and could not be adjusted. Unlike with the roller blinds, venetian blinds can also be set to different angles. This allowed the subjects to introduce more natural light into the room if they wanted higher light levels and to block incoming natural light if they wanted lower light levels (Figure 2, bottom).

After performing each task, the subjects provided subjective evaluations on each glare scene. Visual comfort and visual satisfaction levels were asked in a seven point Likert scale. Also, perceived glare categories such as imperceptible, perceptible, disturbing, and intolerable glare were asked to the subjects. The collected subject's responses to different questions were compared each other to verify consistency of their responses on a same glare scene.

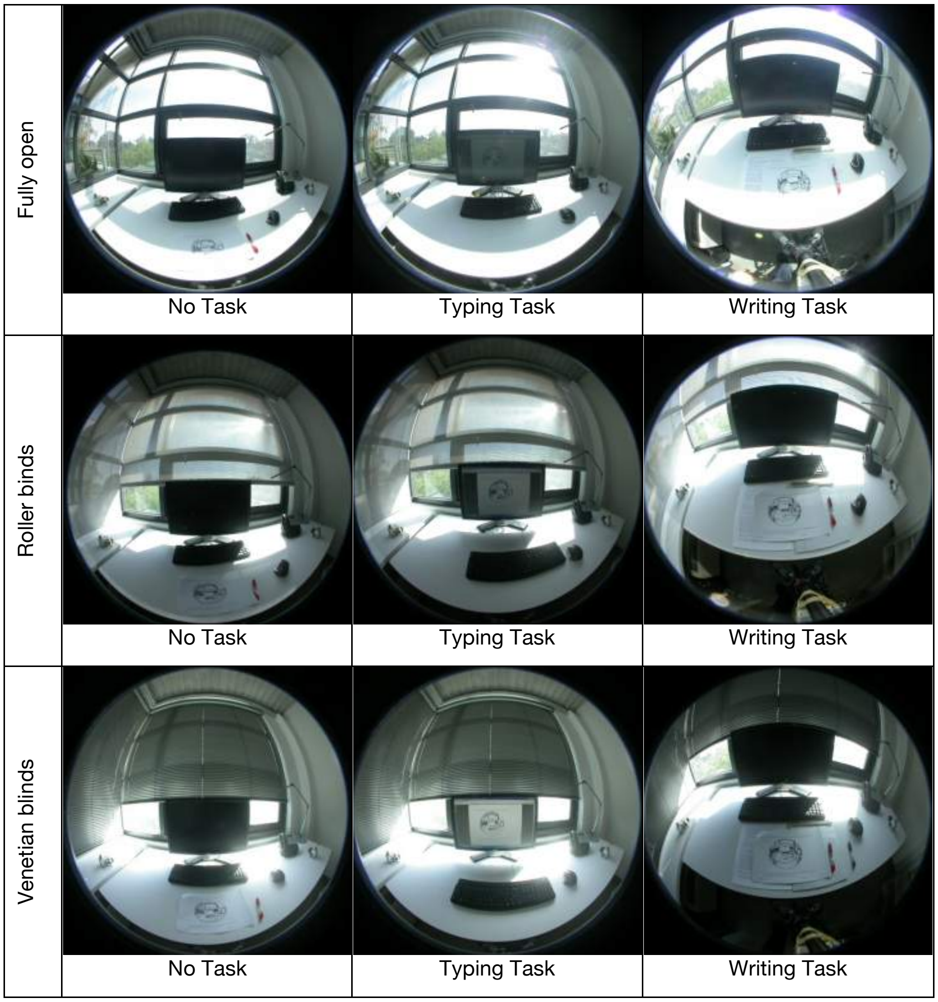


Figure 2. Nine different glare scenes under three different task and lighting types

EVALGALRE SIMULATIONS

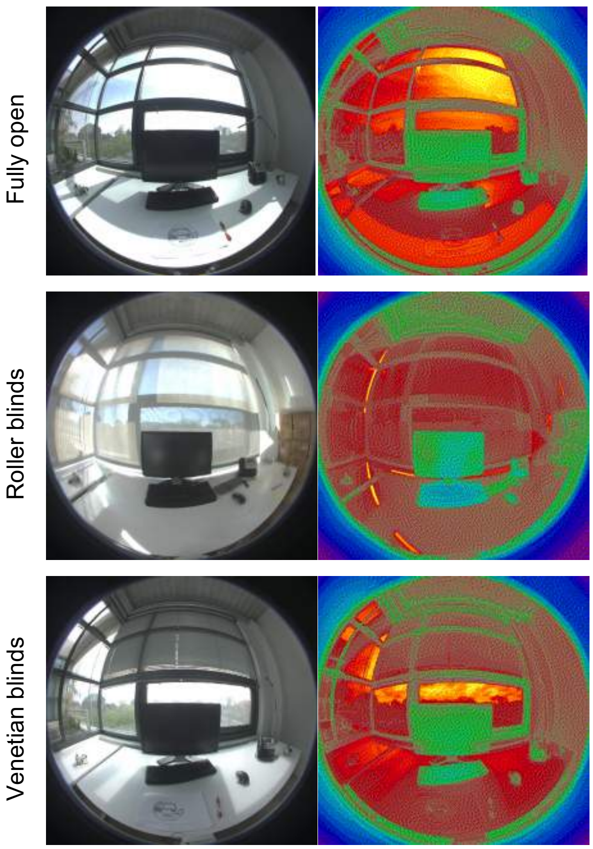
Human subject study was performed inside the office from February 18, 2013, to June 17, 2013. Each subject experienced at least 75 different daylit conditions (25 different conditions per task). Most of the tests were performed under clear sky conditions, but each subject performed at least one test under an overcast sky condition. With the various sky conditions, subjects experienced various levels of discomfort glare, even when the blinds were fully opened.

The collected human subject study data was analyzed using the five existing glare metrics (DGP, DGI, VCP, UGR, and CGI). The captured glare scenes in HDR image format were properly edited in hdrscope. Then, they were processed in Evalglare to obtain glare scores calculated by each metric. Comparison of the calculated glare scores to subjective evaluations was expected to show the accuracy of each glare index's analysis of various daylit conditions. As the existing metrics have an inconsistent evaluation issue on one set of data (Suk and Schiler, 2012), the expanded set was evaluated first to confirm the findings in the previous study and also to see whether or not they would have an inaccuracy issue.

DATA

More than 450 captured glare scenes were analyzed in Evalglare to calculate glare evaluations using the five glare metrics. The glare scores from Evalglare were transferred to the perceived glare degree categories based on the glare score ranges that were developed for each glare index. Then, the glare evaluation results from each glare index were compared to the collected human subject evaluation data to see whether they matched each other or not.

Subjective glare evaluation data was compared to the glare scores calculated by the existing glare metrics to check what glare metrics match best to the subjective evaluation for the no-task glare scene for fully open blinds, roller blinds, and venetian blinds (Figure 3). Subjective evaluation and the glare metrics matching subjective glare evaluations are in bold. The fully open blind scene was evaluated as disturbing glare by a human subject but no glare metric matches it. DGI and UGR underestimate the glare scene while the other metrics apparently overestimate the scene as intolerable glare. This example supports the previous finding that DGI and UGR cannot be used for a glare scene with direct sunlight. DGI's evaluation on this scene is surprising as it reported imperceptible glare even though the sun is visible in the field of view. For the roller blind scene, UGR matches to subjective evaluation, as it evaluates perceptible glare. DGP and DGI underestimate the glare scene while VCP and CGI overestimate it. None of the metrics evaluates the venetian blind scene as imperceptible glare, and all of them overestimate the glare to be perceptible, disturbing, or intolerable compared with the subjective evaluation.



Subjective evaluation: Disturbing glare

- DGP = 0.841 (Intolerable glare)
- DGI = 13.71 (Imperceptible glare)
- UGR = 20.07 (Perceptible glare)
- VCP = 19.12 (Intolerable glare)
- CGI = 29.47 (Intolerable glare)

Subjective evaluation: Perceptible glare

- DGP = 0.26 (Imperceptible glare)
- DGI = 17.66 (Imperceptible glare)
- **UGR = 20.69 (Perceptible glare)**
- VCP = 48.89 (Disturbing glare)
- CGI = 24.62 (Disturbing glare)

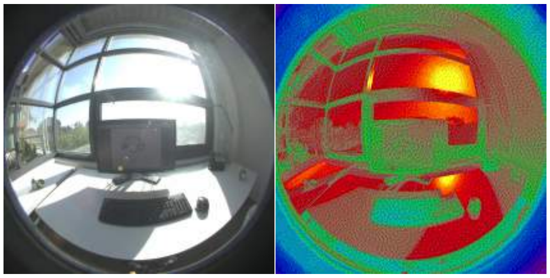
Subjective evaluation: Imperceptible glare

- DGP = 0.352 (Perceptible glare)
- DGI = 21.74 (Perceptible glare)
- UGR = 26.76 (Disturbing glare)
- VCP = 17.60 (Intolerable glare)
- CGI = 32.07 (Intolerable glare)

Figure 3. No-task condition scenes processed in Evalglare, compared accurately to participants' subjective evaluation

Glare evaluations between human subjects and the existing glare metrics were compared for typing task glare scenes (Figure 4). The fully open blind scene shows that DGP, VCP, and CGI evaluate the scene as intolerable glare, which matches what the subject experienced. As shown in this example, the glare metrics show better accuracy and consistency for an extreme glare condition. DGI and UGR still underestimate the scene even though it includes direct sunlight in the field of view. This confirms that DGI and UGR are not suitable to analyze indoor daylit conditions with high potential of direct sunlight (or direct view of the sun). Again, none of the metrics matches the subjective evaluations for the roller blind scene. All of the metrics clearly underestimate the glare source through the roller blind. Also, only UGR matches to the subjective evaluation for the venetian blind scene in its evaluation of the scene to have disturbing glare. DGP reports imperceptible glare, DGI reports perceptible glare, and VCP and CGI report intolerable glare. This example clearly shows inconsistency issue as five glare metrics evaluate from imperceptible to intolerable glare on a same scene.

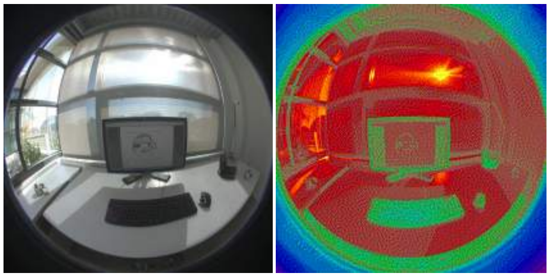
Fully open



Subjective evaluation: Intolerable glare

- **DGP = 0.713 (Intolerable glare)**
- DGI = 18.82 (Perceptible glare)
- UGR = 23.51 (Disturbing glare)
- **VCP = 18.42 (Intolerable glare)**
- **CGI = 32.24 (Intolerable glare)**

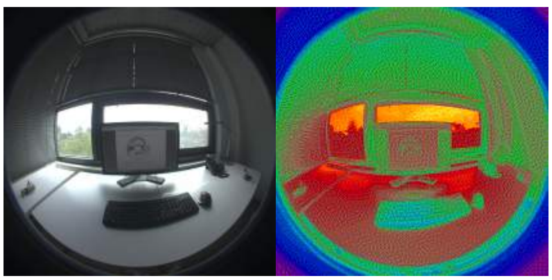
Roller blinds



Subjective evaluation: Disturbing glare

- DGP = 0.257 (Imperceptible glare)
- DGI = 10.78 (Imperceptible glare)
- UGR = 13.86 (Perceptible glare)
- VCP = 72.63 (Perceptible glare)
- CGI = 18.08 (Perceptible glare)

Venetian blinds



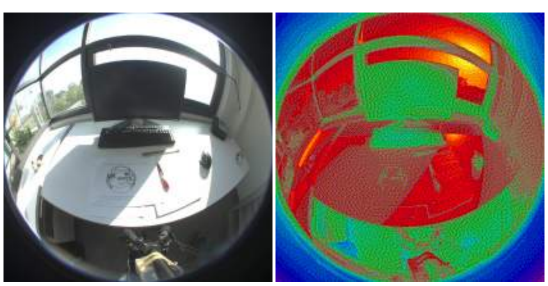
Subjective evaluation: Disturbing glare

- DGP = 0.338 (Imperceptible glare)
- DGI = 22.40 (Perceptible glare)
- **UGR = 27.72 (Disturbing glare)**
- VCP = 15.91 (Intolerable glare)
- CGI = 32.20 (Intolerable glare)

Figure 4. Typing task scenes processed in Evalglare

Three examples were chosen for the writing task condition glare scenes (Figure 5). With direct sunlight in the field of view, the fully open blind scene has no matching glare metric evaluation to intolerable glare. Again, the glare metrics provide a wide range of evaluations from imperceptible to disturbing glare, which is still underestimated compared to human subject's evaluation. Again, DGI makes extremely underestimates this glare scene as imperceptible glare. The roller blind scene was correctly evaluated by UGR only. Similar inconsistent evaluation issue is shown in this example. The venetian blind scene was correctly evaluated by DGP as it reports perceptible glare. The other metrics overestimated the scene as disturbing or intolerable glare.

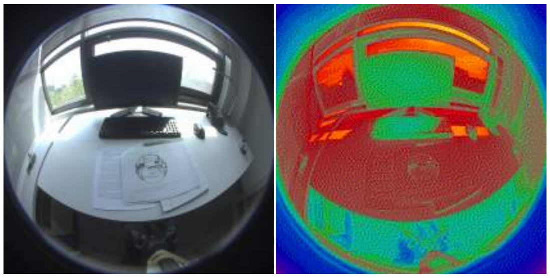
Fully open



Subjective evaluation: Intolerable glare

- DGP = 0.377 (Perceptible glare)
- DGI = 13.85 (Imperceptible glare)
- UGR = 17.53 (Perceptible glare)
- VCP = 59.25 (Disturbing glare)
- CGI = 23.26 (Disturbing glare)

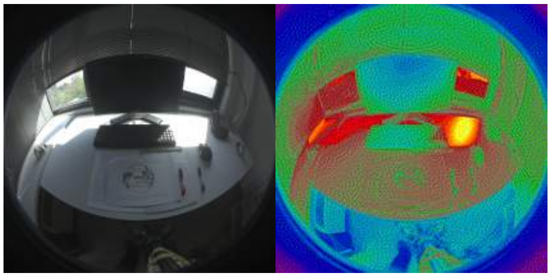
Roller blinds



Subjective evaluation: Perceptible glare

- DGP = 0.308 (Imperceptible glare)
- DGI = 16.71 (Imperceptible glare)
- **UGR = 20.50 (Perceptible glare)**
- VCP = 31.42 (Intolerable glare)
- CGI = 25.64 (Disturbing glare)

Venetian blinds



Subjective evaluation: Perceptible glare

- **DGP = 0.370 (Perceptible glare)**
- DGI = 25.86 (Disturbing glare)
- UGR = 33.13 (Intolerable glare)
- VCP = 4.35 (Intolerable glare)
- CGI = 36.47 (Intolerable glare)

Figure 5. Writing task scenes processed in Evalglare

EXPLANATION

The rest of 450 captured glare scenes show a similar pattern as these examples. At most one of the five metrics correctly matches to the subject's evaluation for each scene. This evaluation comparison study supports the findings that the five glare metrics have vast inconsistency issues. Furthermore, it indicates that the existing glare metrics have significant inaccuracies in their evaluations of glare scenes. Higher accuracy and consistency were observed in extreme glare conditions such as intolerable or imperceptible glare scenes. Based on the analysis of 450 glare scenes, DGP shows the highest accuracy rate at 54.0% and DGI shows the second highest rate at 42.2% of matching evaluation. UGR, VCP, and CGI shows lower evaluation accuracy as 37.8%, 35.8%, and 27.8%. Similar to the findings from the study performed by Jakubiec and Reinhart, the result shows that DGP is the most reliable daylight glare evaluation metric among the currently available metrics even though its accuracy rate is not satisfactory. It is also found that VCP and CGI are inappropriate to analyze discomfort glare caused by natural light as they mostly overestimate glare levels. This is not surprising as they were originally developed for glare issues caused by electrical lighting. As previously noted, DGI and UGR do not work with a glare scene with direct sunlight. This significantly limits their capability and reliability as successful daylighting design cannot be achieved without accurately evaluating excessive sunlight penetrations. Further analysis is required to verify the findings.

CONCLUSION AND FUTURE WORK

More than 450 daylight glare scenes were analyzed by the five existing glare metrics and were compared to subjective surveys in statistical analysis software. The analysis results indicate that DGP shows the best evaluation accuracy among the five metrics when the subjective evaluations are used as the baseline for determining accuracy. Unfortunately, the evaluation accuracy of all the existing glare metrics is too low to be trusted as the highest accuracy level is slightly over 50%. The accuracy levels of VCP and CGI shows that these glare metrics are not appropriate for daylight glare analysis. DGI and UGR show slightly higher accuracy rates than VCP and CGI but they are not capable of analyzing glare scenes with direct sunlight. This makes all four glare metrics except DGP inappropriate for daylight glare analysis. Besides the accuracy issue, the inconsistent evaluation issue found from the previous study arose again throughout this analysis of human subject data. Furthermore, each glare index shows higher or lower evaluation accuracy depending on the glare levels and blind conditions of a scene, indicating inter-index inconsistency. The findings might be applicable only to a closed office with large glazing in a dominantly sunny sky condition. Further study is required to verify the findings in an open office setting or a closed office with small glazing. Further distance from windows to human subject or a field of view parallel to windows should be also tested to verify the findings. Based on the precedents and current study, it is recommended to use DGP for daylight glare analysis. It is also important to thoroughly check luminance distributions and levels in a glare scene so that inaccurate evaluations can be avoided. Overall, these findings can help users of the existing glare metrics to find a better understanding of what they can expect from each of the metrics. And, it will help developing a better daylighting design process which would create visually comfortable daylit environments in buildings.

REFERENCES

Konis, Kyle. “Evaluating daylighting effectiveness and occupant visual comfort in a side-lit open-plan office buildings in San Francisco, California.” Building and Environment 59 (2013): 662-677

Hirning, Michael, Isoardi, Gillian, Coyne S, Cowling, Ian, and Garcia-Hansen, Veronica. “Post occupancy evaluation relating to discomfort glare: A study of green buildings in Brisbane.” Building and Environment 59 (2013): 349-357

Hirning, Michael, Isoardi, Gillian, and Cowling, Ian. “Discomfort glare in open plan green buildings.” Energy and Buildings 70 (2014): 427-440

Wienold, Jan and Christoffersen, Jens. “Towards a New Daylight Glare Rating.” Lux Europa. Berlin, 2005

Bellia, Laura, Arcangelo Cesarano, Giuseppe F. Iuliano, and Gennaro Spada. “Daylight glare: a review of discomfort indexes.”, visual quality and energy efficiency in indoor lighting: Today for tomorrow, International Workshop, Rome, Italy, 31 March 31, 2008.

Isoardi, Gillian, Veronica Garcia-Hansen, and Michael Hirning. “Evaluation of the Luminous Environment in Open-plan Offices with Skylights.” The World Renewable Energy Forum, SOLAR 2012, Denver, Colorado, May 13-17, 2012.

Wienold, Jan and Christoffersen, Jens. “Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras.” Energy and Buildings (2006); Volume 38, Issue 7

Inanici, Mehlika and Galvin, Jim. “Evaluation of High Dynamic Range Photography as a Luminance Mapping Technique.” Lawrence Berkeley National Laboratory 2004. LBNL-57545. http://escholarship.org/uc/item/9h61f5h8 (accessed April 3, 2010)

Inanici, Mehlika. “Per-Pixel Lighting Data Analysis. Lawrence Berkeley National Laboratory 2005.” NBNL-58695. http://escholarship.org/uc/item/688137zg (accessed April 3, 2010).

Suk, Jae Yong and Schiler, Marc, “Investigation of Evalglare Software, Daylight Glare Probability and High Dynamic Range Imaging for Daylight Glare Analysis.” Lighting Research and Technology (2012)

Jakubiec, Alstan and Reinhart, Christoph. “The Use of Glare Metrics in the Design of Daylit Spaces: Recommendations for Practice.” 9th International Radiance Workshop, 2010. http://www.gsd.harvard.edu/research/gsdsquare/Publications/2010RadianceWorkshop_GlareIndices.pdf (accessed April 1, 2011)

Luckiesh, Matthew and Guth, Sylvester K. “Brightness in Visual Field at Borderline between Comfort and Discomfort (BCD).” Journal of Illuminating Engineering Society November (1949): 650‐670.

Hopkinson, Ralph G. “Evaluation of glare.” Illuminating Engineering, (1957): 305-316.

Ngai, Peter and Boyce, Peter. “The Effect of Overhead Glare on Visual Discomfort.” Journal of Illuminating Engineering Society November (2000): 29-38.

Velds, Martine. “User Acceptance Studies to Evaluate Discomfort glare in Daylit Room.” Solar Energy 73, No. 2 (2002): 95‐103.

Osterhaus, Werner. “Discomfort glare assessment and prevention for daylight applications in office environments.” Solar Energy 79-2 (2005): 140-158.

Linney, Andrew Scott. “Maximum Luminances and Luminance Ratios and their Impact on Users’ Discomfort Glare Perception and Productivity in Daylit Offices.” Master thesis, Victoria University of Wellington. 2008.

Wymelenberg, Kevin Van Den. “Evaluating Human Visual Preference and Performance in an Office Environment Using Luminance-based Metrics.” PhD diss., University of Washington, 2012.

Suk, Jae Yong, Schiler, Marc, and Kensek, Karen. “Development of new daylight glare analysis methodology using absolute glare factor and relative glare factor.” Energy and Buildings 64 (2013): 113-122.

SHADOW BOXES – RE-ENGINEERED

Results from technical research and project design

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ABSTRACT

This paper provides information about an in-house research project for shadow box design. During this research project, several mockups with sensors for heat and relative humidity were produced and tested under two different laboratory conditions: one with artificial sunlight and one in an outdoor temperate climate.

The outdoor test provided information about temperature changes in the shadow box due to air infiltration and exfiltration. Further, it also provided information about the conservation of solar energy in the air cavity behind the spandrel glass and adjacent materials. Temperature sensors on the interior surfaces of the façade produced data that was used to draw conclusions about the heat flow from inside the shadow box to the interior ambient air via the façade profiles. It was also used to develop a two-dimensional simulation tool to show heat development and heat flow in the shadow box.

The test under laboratory conditions with artificial sunlight showed that the correct choice of glass type and color of the opaque back layer highly influences heat development in the shadow box cavity. The test results also illustrate that the size of ventilation openings and the depth of the air layer only slightly influence heat built-up in this cavity.

The shadow box is a very complex system that should be designed and manufactured so as not to have a detrimental effect on the thermal performance of the facade. To maintain precise and consistent reproduction and to improve the thermal performance, a new PVC shadow box profile was developed. PVC is a poor thermal conductor and, therefore, the heat flow from the shadow box construction into the interior becomes interrupted, consequently improving the heat transfer coefficients of the façade and the panel construction. Furthermore, the PVC profile has been designed as a four sided mitered and sealed frame insert to enable easy attachment of the opaque back layer, thus creating a weather tight assembly within the curtain wall day light opening.

KEYWORDS

Curtain wall, energy efficiency, thermal break, condensation, physical testing, mockups

INTRODUCTION

Over several decades, many fully glazed façades were designed for office buildings all around the world. Although these fully glazed facades provide a uniform appearance on the outside, they are divided into transparent and opaque areas. One method used to create the opaque façade areas is the so-called shadow box. It is used for several office building façades in markets such as the Middle East, UK, USA, Europe and Asia. This paper provides information about the different construction principles of the shadow box, its aesthetical advantages and its technical issues. Furthermore, it describes how mockup tests and simulations lead to a new kind of shadow box design that addresses and reduces the technical problems in project specific designs.

Figure 1: The aesthetical appearance of a shadow box in a curtain wall. Cork University Maternity Hospital, Cork, Ireland. Photo courtesy of Schueco Int. KG.

BACKGROUND

CONSTRUCTION AND BASIC COMPONENTS

(cf. C. K. Boswell et al. 2005)

The architect's reason for using a shadow box is to create a uniform exterior appearance between spandrel and vision areas within the same facade. This is achieved by having an air cavity between the back of the glass and an opaque back panel, creating a *depth-of-view* through the outer glass unit. The inside surface of the opaque back panel is thermally insulated, which in turn is covered by a vapor barrier to comply with physical requirements (Fig. 2). All shadow box components are installed in a frame of façade profiles, built from aluminum or steel, regardless of construction (unitized or stick) and system (standard or customized).

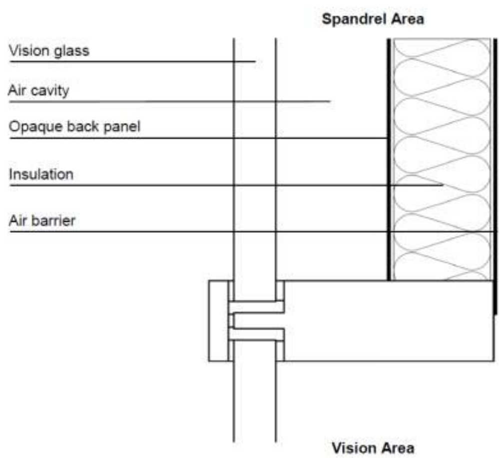


Figure 2: The basic components of the shadow box.

The glass used for shadow boxes ranges from single to double to triple glazed, with tinted or clear panes, and can be coated for heat or sun protection reasons. Glass choice is driven by the similarity to the transparent areas and the physical requirements of the specific project.

The air cavity between the glass and the opaque back panel typically varies between 50 mm and 100 mm (CWCT, 2014) depending on the aesthetical depth-of-view effect, the overall energy performance requirement and the limitations of the façade system. The air cavity can be hermetically sealed, pressure equalized or ventilated (M. Migno, 2009).

The opaque back panel separating the air cavity from the insulation material is used to give the shadow box a specific appearance. In most current projects, it is made from sheet, color coated, or anodized aluminum, but other materials such as steel, wood, fabric, etc. can also be utilized.

The choice of the insulation material and its thickness is driven by the required thermal performance of the specific project. The material can be soft or hard, but additional requirements like fire resistance, hydrophobic properties and accurate installation should be taken into account.

The shadow box assembly and insulation must be isolated from the internal environment by using a vapor barrier to prevent warm and humid air entering the assembly. The vapor barrier can be made from an air permeable foil / membrane, aluminum, or steel, which could be designed in such a way to stiffen the façade construction, too.

Carefully choosing and correctly combining the above-mentioned shadow box components are essential to meet the architect's design and performance requirements, and are crucial when trying to avoid technical problems in advance.

SHADOW BOX ISSUES

(cf. A. Lang, 2010)
Shadow Box case studies as well as literature research identify persistent issues for shadow box design: 1) Condensation, 2) Overheating 3) Thermal bridging and 4) Contamination (Fig.3).

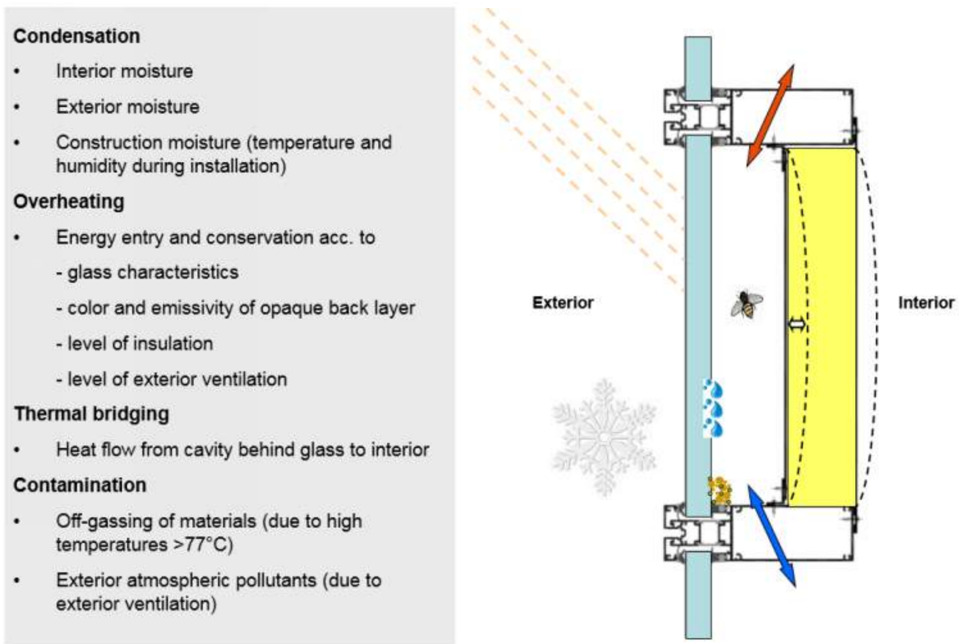


Figure 3: Summary of issues known from shadow box projects.

Condensation, in general, occurs when warm and humid air meets cold surface temperatures that are below the dew point temperature. This could happen on any surface facing the air cavity of the shadow box, on the reverse surfaces within the curtain wall profiles and shadow box assembly, or in the insulation, if warm and humid air from inside the building enters the shadow box assembly. For example, when warm and humid air comes in to contact with the inner surface of the glass pane, which is cooled below the dew point by heat emission to the outside, condensation occurs.

Bauer, Bauer and Bäumler (M. Bauer et al., 2015) describe another situation where condensation may occur in a system comparable to the shadow box in the ventilated air cavity of a compound window. According to them, warm and humid outside air enters the ventilated cavity via the ventilation openings and condensates on the inner glass surface. The amount of condensation rises by an increase in the cross-sectional ventilation area.

Condensation on the inner glass surface is visible from the outside of the building and is usually aesthetically unacceptable. Furthermore, it can have technical consequences if the design does not allow for condensation to be removed from the shadow box. Therefore, most of the current shadow box designs provide drainage and ventilation openings to the outside.

Another issue for shadow boxes is the phenomenon of overheating, which occurs when solar energy passes through the glass layer and the air cavity, and meets the opaque back panel. The color and the emissivity of the opaque back panel will vary the amount of the solar energy that is absorbed within the shadow box and transformed into heat radiation. High thermal insulation properties of the glass unit limits the heat transfer to the outside. This causes a temperature increase in the air cavity. Ventilation openings to the outside reduce heat build-up, by allowing fresh outside air to enter the cavity via bottom openings and releasing hot air at the top.

Additionally, if there is no thermal separation from the shadow box air cavity to the inside, excessive heat build-up can lead to problems within the façade construction. This can affect the surface temperatures on the surrounding profiles and inner vapor barrier, specifically if they are made from sheet metal or other thermal conducting materials. This needs to be considered when configuring the building's HVAC (Heating, Ventilation and Air Conditioning) system.

Contamination in the shadow boxes can also be an issue. It may arise due to overheating, as temperatures can get up to 77°C (A. Lang, 2010), or even up to 100°C is possible, depending on the shadow box design. A careful choice of materials compatible with those high temperatures is necessary. Otherwise, these high temperatures can make some materials emit toxins & gasses that lead to a contamination within the cavity, the surrounding materials and the inner glass surface, possibly having an impact on thermal and weather performance as well as aesthetics.

The above mentioned ventilation openings that prevent overheating and allow for drainage of condensation water can in turn lead to contamination from the exterior. The level of contamination depends on the size of the ventilation openings and the level of atmospheric pollutants in the surroundings.

METHOD

The problems described above are known from already built shadow boxes. One can imagine just how complex the shadow box system is and how minor changes in design can affect performance and aesthetics. To reduce the complexity of dealing with so many variables, a matrix (Fig.4) was developed that shows the main technical influences on the shadow box and the variety of combinations. An in-house research project was launched where different combinations were tested and evaluated in moderate climate. To reduce the degree of complexity, it was assumed that the shadow boxes were carefully manufactured, making it possible to neglect a leakage of the vapor barrier to the interior.

Glazing Option	Ventilation of air cavity			Insulation of transom	
	Sealed	Pressure equalized	Ventilated	Insulated	Not insulated
SGU					
DGU					
TGU					

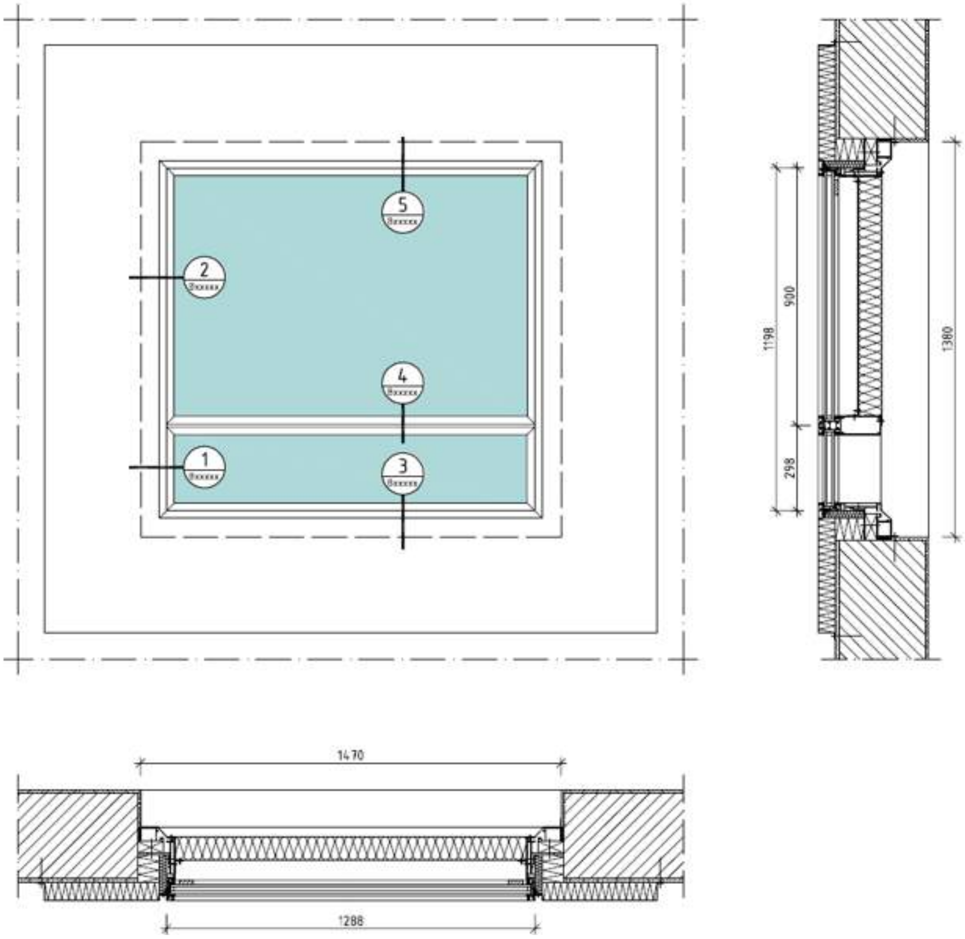
Figure 4: Matrix with main technical influences on the system shadow box.

For the first test setup, a shadow box mockup was fabricated with the following features from the above matrix (Fig.4):

- DGU with a neutral tone and sun-protective coating (61/33), to partly reflect the solar radiation, but still have a high grade of light transmittance similar to the glazing in the transparent area.
- Pressure equalized air cavity with one pressure equalization hole to the outside environment in order to reduce pressure build-up within the air cavity; this reduces the risk of leakages. The openings for pressure equalization were as small as possible to minimize the possibilities of contamination by exterior pollutants.
- Horizontal and vertical profile walls adjacent to the air cavity were not insulated, because this is the method seen in most shadow box assemblies today.

The secondary parameters like depth of cavity, color of opaque back panel and color of façade profiles were discussed with architects and cladding designers to meet most popular aesthetic requirements. The stationary physical performance was simulated with a 2D thermal modelling software to determine the required insulation thickness (Fig.5). During the fabrication process, several sensors were installed to measure temperature and humidity at the exterior, inside the shadow box and interior (Fig. 6).

The target of this test was to gain more knowledge about heat development in the shadow box, the influence of ventilation openings and heat transfer to the inside. Therefore, it was decided to test the mockup under real climate conditions.



Shadow Box Panel:
Aluminum sheet 2mm
Mineral wool 040 80mm
Aluminum sheet 2mm, RAL 9006
Air layer

Glass:
Ipasol neutral 61/33
8 ESG /16/6 ESG
Ug= 1,1 W/m²K

Figure 5: Elevation and sections of the mockup tested in real climate conditions.

The chosen location for the test was a building in Bielefeld, Germany, where the mockup was installed in an unshaded, south facing façade. This was important in order to let the maximum solar radiation affect the shadow box throughout the year. To get test results that are close to reality, the interior of the building was conditioned to standard office climate (20°C, 45% - 55 % relative humidity).

Figure 6: The shadow box mockup with sensors from the interior (left) and from exterior without glass (right)

DATA

The following chart shows the measured values for the days with the highest temperatures during the testing period of two years. This data was measured on 10.03.2014, which was a very sunny day, around midday. The position of the relevant sensors and the measured data (temperature and relative humidity) can be seen in Figure 7. The overall solar radiation for 10.03.2014 at 12:00 was 580 W/m² (source climate data: Meteonorm).

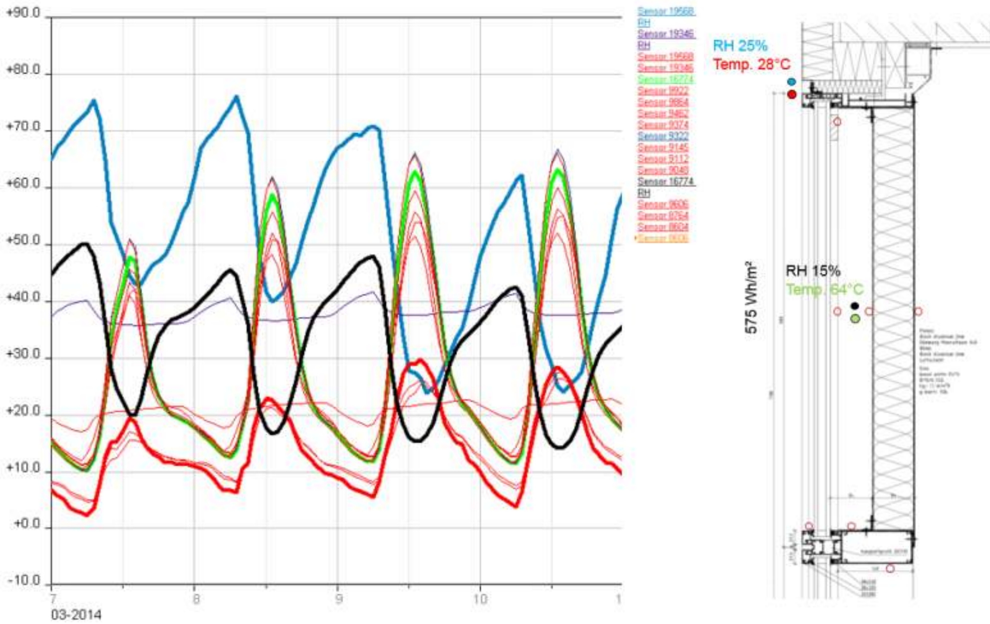


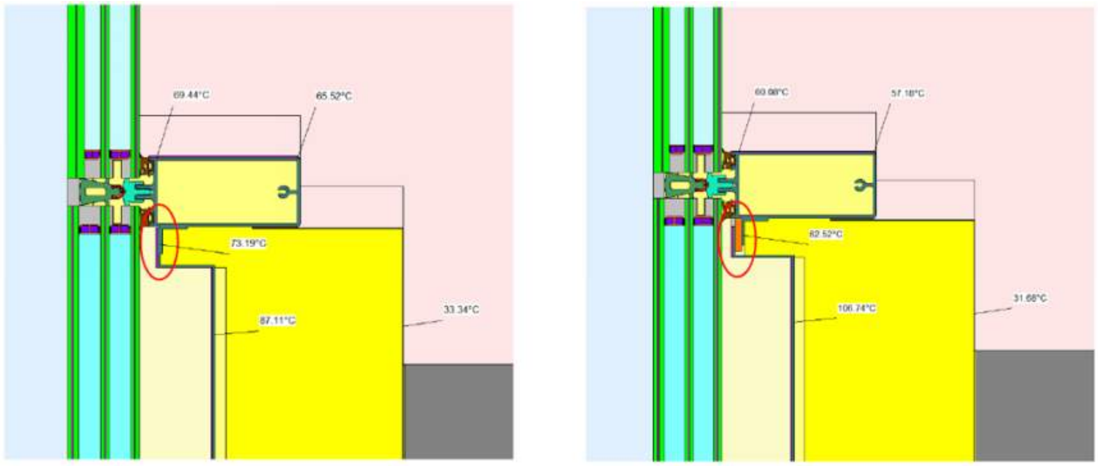
Figure 7: Position of the sensors in the mockup and measured data for the day with hottest air cavity temperatures.

EXPLANATION

During spring and autumn, the sun in Bielefeld around midday is much lower than in summer; therefore, the angle of incidence to the shadow box is lower. This creates a more direct solar radiation effect in the shadow box, which led to the biggest heat development during those seasons. Knowing the initial data, several further analyses were done to gain a deeper understanding of the shadow box system.

THERMAL SIMULATION MODEL

With the help of the initial data from the shadow box test, a two-dimensional thermal simulation model was developed to simulate the heat build-up inside the shadow box. Furthermore, the heat flow from the shadow box to the interior can be analyzed and, with it, the necessity for a thermal break between the opaque back layer, air cavity and façade profiles. Figure 8 shows the simulation of a customized shadow box for a project in Russia. The thermal break between opaque back layer and façade transom causes lower temperatures on top of the transom but much higher temperatures inside the shadow box.



Parameter:		**Vision glass:**	
Period:	Summer	U_g - value:	0,6 W/m²K
Orientation:	West	g - value:	43 %
Global radiation:	800 W/m²	**Spandrel:**	
Temperature outside:	18°C	Ug – value glass:	0,8 W/m²K
Temperature inside:	21°C	g – value glass:	43 %
Relative humidity inside:	50%	Color metal sheet:	RAL 9007

Figure 8: Thermal simulation model of the shadow box with cold bridge (left) and with reduced cold bridge (right).

MOCKUP TESTS WITH ARTIFICIAL SUN

To solidify the knowledge gained from the first shadow box tests, several indoor tests with artificial sunlight were performed to gain insight into the influence of the following parameters of heat build-up in the shadow box (A. Carabillo, 2015):

The color of the opaque back layer has a large influence on the heat build-up inside the shadow box. Three mockups were tested, the first with a pure aluminum back layer, the second with a powder-coated in RAL 9005 (deep black) and the third in RAL 9006 (white aluminum). The distance between back panel and glass layer was 100 mm. The test showed temperatures on the back layer from 100°C (RAL 9005) to 80°C (RAL 9006) to 59°C (pure aluminum). The differences can be explained by the absorption coefficients of the different colored aluminum sheets.

The next test was done with different sized openings for the incoming and outgoing air to ventilate the air cavity. For this purpose, the interior glazing gaskets were complete with either no opening for ventilation and pressure equalization (sealed cavity) or opened with a diameter of 2000 mm² or 4000 mm² to allow for free area for ventilation & pressure equalization. The surprising result was that the change in free area for ventilation had nearly no effect on the heat growth in the cavity.

Furthermore, the influence of the air cavity depth between the glass unit and the opaque back layer (this time coated in RAL 9005 deep black) was examined. Mockups with an air layer depth of 25mm, 100mm and 150mm were fabricated and tested in artificial sunlight. The temperatures measured on the front of the opaque back layer ranged from 87°C (25mm) to 83°C (100 mm) down to 79°C (150 mm). The depth of the air layer influences the ratio of cavity air temperature to back layer and transom surface temperature, and therefore, the degree of heat flow to the interior.

Lastly, the influence of different glazing types was analyzed. For this test, three shadow box mockups were constructed: one with a standard clear float DGU without any surface treatments, another with a clear float DGU with sun protective coating and another with a clear float monolithic glass pane (Fig.9). The measured data showed that the glazing options also have a large influence on the temperature build-up within the shadow box air cavity, which was 82°C, 67°C and 56°C respectively.

Glazing Option	Light transmittance	G-value	U_g-value
Iso iplus top 1.1 (6/16/4)	80 %	63 %	1,1 W/m²K
Iso ipasol ultra select (6/16/4)	62 %	29 %	1,0 W/m²K
ESG (6 m)m	90 %	87 %	~ 6 W/m²K

Figure 9: Properties of the tested glazing options

The test results are quantified in the following matrix (Fig.10):

	Quantified parameter			
	Color back panel	Size ventilation openings	Depth air layer	Types of glazing
Influence on overheating	***	*	**	***

Figure 10: Quantification of influences on the overheating of a shadow box air cavity tested under laboratory conditions.

DESIGN OF A SHADOW BOX PROFILE

In both of the aforementioned testing processes, the influence of the cold bridge from the air cavity via the façade profiles to the interior was a major issue. In summertime, this results in high surface temperatures of up to 70°C that could cause burns if touched. Furthermore, the influence of this cold bridge (Fig. 3) in all seasons should be taken into consideration when calculating the HVAC requirements. This leads to an increase in operation costs for the building.

To overcome the large effect of the cold bridge, a special shadow box profile was designed for a customized unitized façade (Fig.11). The profile is built from PVC (which has a low thermal conductivity) and therefore, greatly reduces the heat flow from the inside of the shadow box to the surrounding profiles and internal environment. Additionally, the use of the shadow box profile results in a better thermal performance of the overall façade system by improving the heat transfer coefficients of the façade. The shadow box profile hosts special features for the installation of the opaque back layer and the glass, which simplifies fabrication and reduces the risk of condensation.

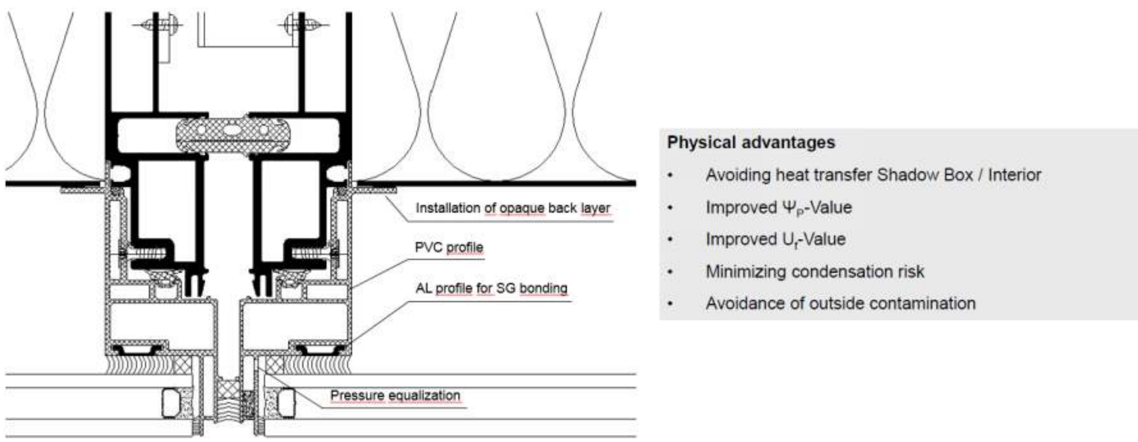


Figure 11: Detail of the new designed shadow box profile with physical advantages

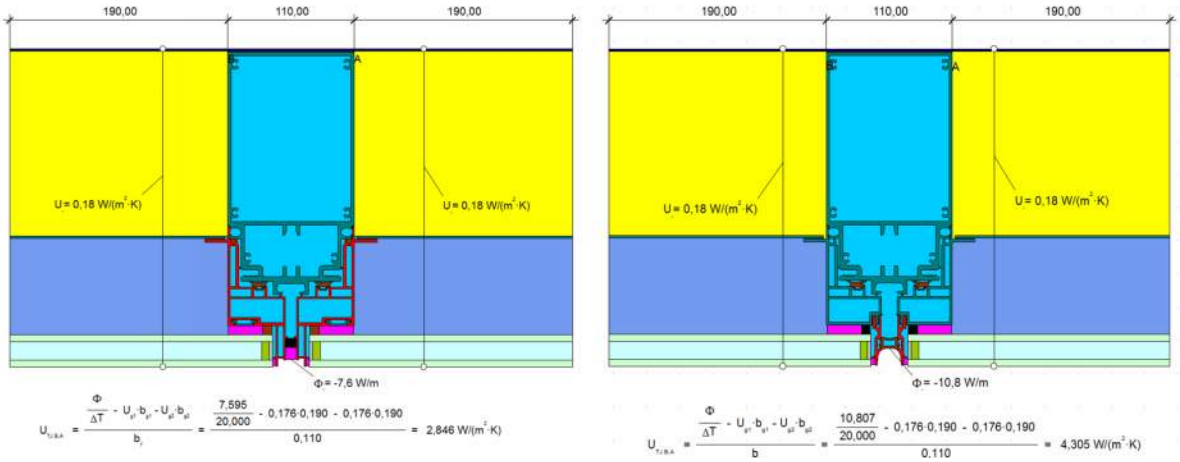


Figure 12: Comparison of thermal performance (UTJ-value) between shadow box with or without new designed shadow box profile.

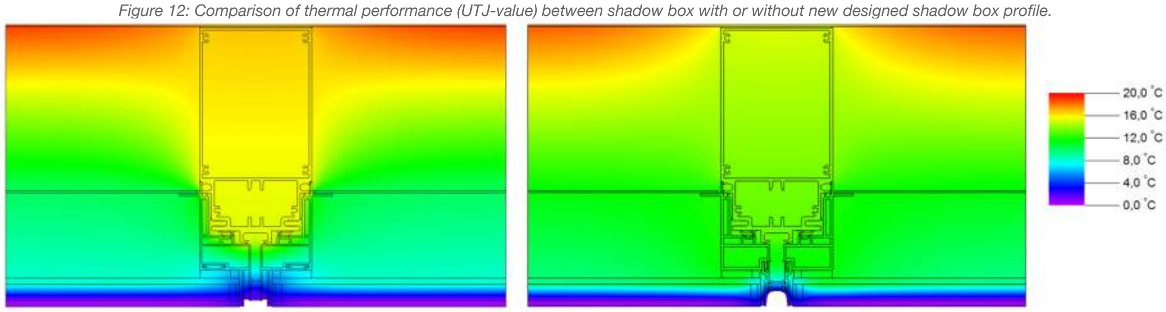


Figure 13: Comparison of thermal performance (temperature field) between shadow box with or without new designed shadow box profile.

CONCLUSION AND FUTURE WORK

In summary, the mockup tests under real climate conditions and with artificial sunlight gave interesting answers for the shadow box system. These results combined with some additional findings from literature are consolidated in the following list of design recommendations for shadow boxes in moderate climates.

Glass

- Insulation glass / heat strengthened to withstand temperature variations
- Good u-value to prevent against low surface temperatures in cold seasons
- Good g-value to prevent against high temperatures in warm seasons

Air cavity

- Pressure equalized to the outside
- Optionally ventilation / drainage to the outside acc. to simulation
- Carefully sealed to the inside to prevent against air leakage (humid inside air)

Opaque back panel

- Fixed with ability to accommodate expected movements

Insulation

- Soft material (e.g. mineral wool) installed without gaps to avoid heat bridges

Inner vapor barrier

- Fully sealed as vapor control barrier against humid air from the interior

General

- Dark surface colors should be avoided to reduce cavity temperatures
- Assembly should not be done in warm, humid conditions that could seal elevated moisture in the panel
- Aesthetical issues like visible condensation and contamination from the exterior can be minimized but not entirely avoided!

The newly designed shadow box profile offers the possibility to open new horizons in thermal performance and fabrication quality of shadow boxes. So far, thermal performance of the newly developed profile has been estimated with thermal simulation tools. It is the recommendation of the author to verify the simulated performance in an additional set of open-air tests under real climate conditions.

Furthermore, the results of the influence of the ventilation openings concerning temperature build-up should be reviewed. The test was done under laboratory conditions with artificial sunlight. If a shadow box is installed in a building, these results could differ due to the microclimate (vertical heat flow and wind turbulences) directly in front of the façade.

Finally, the technical research in the field of shadow boxes and the management of several projects during the period of this research led to a deeper understanding. This experience can be applied in further project consultancy.

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REFERENCES

A. Carabillo, Entwicklung eines Berechnungstools zur Untersuchung des Zusammenhangs zwischen Temperatur und Belüftungsverhalten eines Brüstungselements mit anschließender praktischer Verifizierung, Master Thesis at the University of Paderborn, Germany, 2015

A. Lang, Design Considerations for Shadow Boxes in Curtain Wall Glazing, Abstract for: International Conference on Building Envelope Systems and Technologies, 2010

CWCT TN94, Shadow Boxes, CWCT, 2014

C. K. Boswell, J. R. Walker, “Shadow Boxes”- An Architect and Cladding Designers’ Search for Solutions, Abstract for: Glass Performance Days, 2005

M. Migno, K. Cole, Analysis and Design of Spandrel and Shadowbox Panels in Unitized Curtain Walls, Abstract for: Glass Performance Days, 2009

Max Bauer, Martin Bauer, A. Bäumler; Hinterlüftung und Tauwasserausfall bei Verbundfenstern, in: Bauphysik 37 (Heft 4), Ernst & Sohn Verlag, 2015

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THE EFFECTIVENESS OF FIXED SOLAR SHADING

A case study

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ABSTRACT

External fixed sun shading devices are currently being incorporated into the design of many modern buildings, especially in cooling dominated climates. For many architects, shading devices have become an attractive solution to solar heat gain and glare concerns because, in addition to their function, they can add a signature design element to the building. Often, the optimization of their size, shape, orientation and spacing is based on static studies of the shadow pattern produced on the solstices and equinox in early morning, noon and late afternoon. This paper is a case study of one such sun shading system designed for the Miami Beach Convention Center renovation and expansion project. It explores an analysis tool developed to assess annual solar shading effectiveness and poses the question of what should be the metrics of success.

KEYWORDS

Solar shading, case study, energy efficiency, design optimization, sustainability, curtain wall, façades

INTRODUCTION AND BACKGROUND

A significant trend in recent architectural façades has been the integration of external sun shading devices, especially in cooling dominated climates. Some have experimented with the use of active devices, for example, the Institut Arabe in Paris completed by Jean Nouvel in 1987 and more recently the Al Bahar Towers in Abu Dhabi completed by Aedas Architects in 2012. However, due to the significant first cost expense and the ongoing maintenance cost of operable systems, the most common type of exterior sun shades implemented are fixed. For many architects, shading devices have become an attractive solution to solar heat gain and glare concerns because, in addition to their function, they can add a signature design element to the building. While the concept of sun shades is a simple one, the implementation of effective, orientation tuned, shading strategies is more complicated. This paper is a case study of the development of one such sun shading system for the Miami Beach Convention Center.

The Miami Beach Convention Center, originally built in 1957 with renovations and expansions undertaken in 1968, 1974, and most recently in 1986, was in need of significant renovation to re-establish it as a state-of-the-art convention facility and to reinvigorate its place in the community. The project includes the complete renovation of approximately 1,100,000 sq. ft. of existing building area and the addition of approximately 385,000 sq. ft. of new area to include, among other things, a new 80,000 sq. ft. ballroom and rooftop pavilion.

Miami has seen a development and architectural renaissance in recent years with new projects either constructed or proposed by Rem Koolhaas, Zaha Hadid, Herzon & de Meuron, Renzo Piano, Bjarke Ingels Group (BIG) and others. The Miami Beach Convention Center is the venue for one of the most important modern and contemporary art expositions in North American, Art|Basel. So, in this context, it was critically important to the Miami Beach City Commissioners and convention center management that the newly renovated center be seen as an important modern architectural contribution to the rich urban fabric and serve as an economic engine by attracting new visitors to the area. However, the existing façade, a legacy of the 1986 renovation, was a tired example of Post-modern architecture (Figure 1). So, the design team was tasked to replace it with an exciting, sleek, modern design, worthy of its important place in the community.

Figure 1 – Existing Miami Beach Convention Center Postmodern Facade (Image courtesy of Fentress Architects)

At 25.7 degrees north latitude, Miami Beach is located in climate zone 1 according to the ASHRAE and IECC climate zone map. This area is characterized by hot, humid weather with a mean annual high temperature of 83 deg F, an annual extreme high temperature of 98 deg F, and 4,233 mean annual cooling degree-days. Recognizing the impact that solar heat gain plays on energy consumption in South Florida, the 2014 Florida Energy Conservation Code, in the prescriptive provisions, limits vertical fenestration to a maximum 30 percent of the building envelope, the u-value of the glazing to a modest 0.50 Btu/hr-sq.ft.-deg F and the solar heat gain coefficient (SHGC) to a very restrictive value of not more than 0.25. To complicate matters the existing main building entries and adjacent major pre-function spaces, which based on function are required to be highly glazed and transparent, are oriented to the east and west respectively. So, in this cooling dominated climate, employing a strategy of reducing solar heat gain through the glazed areas by the use of shading devices seemed like a natural and intuitive response to the climate.

Based on the above considerations, the building façade is composed predominantly of a thermally-broken, unitized curtain wall glazed with double-pane, 1-5/16 inch laminated-insulating glass units having a center-of-glass u-value of 0.29 Btu/hr-sq.ft.-deg F and SHGC of 0.25. The curtain wall is complemented with a system of fixed sun shading devices to both further protect the glazing and provide the building with a new and unique identity (Fig. 2 and 3). The design concept, including the notion of solar protection, was presented to the City Commissioners and embraced as the iconic vision of the future they were looking for.

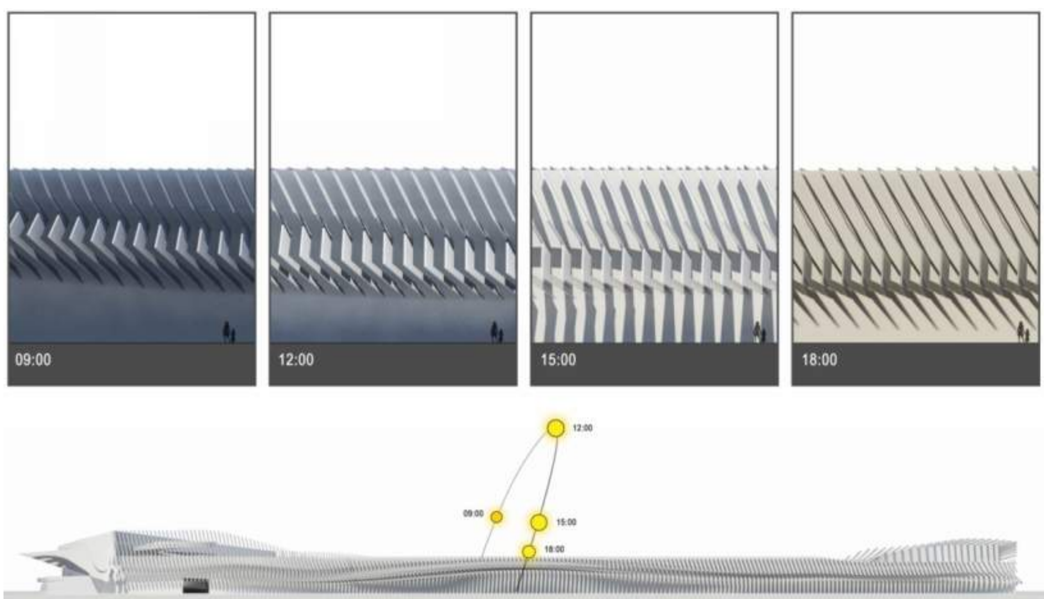

Figure 2 – Early Façade Concept Indicating Shading Benefit of Proposed Design (Image courtesy of Fentress Architects and Arquitectonica)

It should be stressed that the value of employing this sun shading approach was largely an intuitive one and the form that the sun shades took was based more on aesthetic concerns than shading efficacy. Using rules of thumb for the effectiveness of fixed shades on east and west oriented facades, the initial design provided for vertical shades aligned with each mullion at approximately 5 feet on center. The design was further refined to incline the shades at 30 degrees to the north while maintaining a 5 foot on center spacing. Finally, during the guaranteed maximum pricing of the project, the CM-at-risk offered a "value engineering" cost reduction of approximately $2M to space the sun shades at 6 feet on center instead of 5 feet on center. This option, which was accepted, was studied carefully for its aesthetic impact but tested less rigorously for its reduction in shading efficacy because the peak air conditioning load in the building is driven by the sensible heat load of the occupants rather than building envelope gains.

Figure 3 – Concept Design Approved by Miami Beach City Commission (Image courtesy of Fentress Architects in association with Arquitectonica)

The sun shade geometry was studied and documented utilizing a combination of scripts and parametric tools in Grasshopper, Rhinoceros, Excel, Dynamo and REVIT. However, during design, the same sophisticated computational approach was not employed to understand the overall real-time impact to shading effectiveness of design modifications. The purpose of this investigation was, in hindsight, to develop and test a methodology for assessing and comparing the overall shading effectiveness of a few of the alternatives considered for the Miami Beach Convention Center in order to form a procedure for incorporating this methodology into future design studies of complex fixed shading strategies.

INVESTIGATION METHOD

For the purposes of this study, and in order to reduce computational time, rather than model the entire façade two representative sections of the west facing façade were used to determine the shading efficacy of several design concepts. One façade test section measures approximately 45 feet tall by 80 feet long and has an orientation of slightly north of due west. The second façade test section measures 51 feet tall by 80 feet long and has an orientation of slightly south of due west. Four simulations were run of each. The first case simulation is a baseline case with no sun shades. The second case represents the initial project design with sun shades aligned vertically at each mullion approximately 5 feet on center. The third case represents the final design that was bid with sun shades inclined at 30 degrees and spaced 5 feet on center. The fourth and final case represents the "value engineered" solution of sun shades inclined at 30 degrees with spacing increased to 6 feet on center (Figures 4 - 11).

The curtain wall and sun shades were modeled in Rhino. Using the Ladybug plug-in developed for Grasshopper the wall surface was divided into a computational surface grid with each cell measuring 0.5 feet high by 0.5 feet wide. With the longitude and latitude of Miami Beach provided as inputs, a script calculates the total number of hours that each computation surface is in sunlight for an entire year. The results (total annual hours of sunlight) for each computation surface were added together and then divided by the total number of such surfaces to arrive at the average annual hours of sunlight for the entire sample section of wall. By subtracting the average annual solar incidence of any case from the base case and dividing that result by the average solar incidence of the base case the effective shading in terms of a percentage is derived (Figure 12).

DISCUSSION OF RESULTS

At the most basic level, the results indicate that the vertical sun shade orientation is effective and protects the wall from direct sunlight for better than one-third of the year. The data also confirm the designer's intuition that inclining the sun shades at 30 degrees to the north improves performance and, in fact, the improvement is significant at approximately 10 percent. Finally, the data indicate that increasing the sun shade spacing by 20 percent from 5 feet on center to 6 feet on center results in a reduction of performance of approximately 3 percent. The overall shading benefit provided on the east and west facades, in reality, significantly exceed these values because the typical shading fins extend to become a very deep shading canopy at each main entrance.

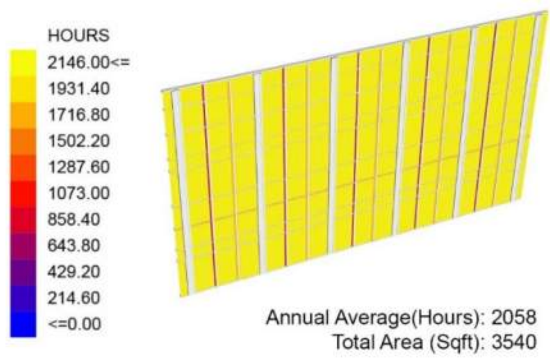

Figure 4 – Average Annual Solar Incidence on Representative Northwest Facing Wall

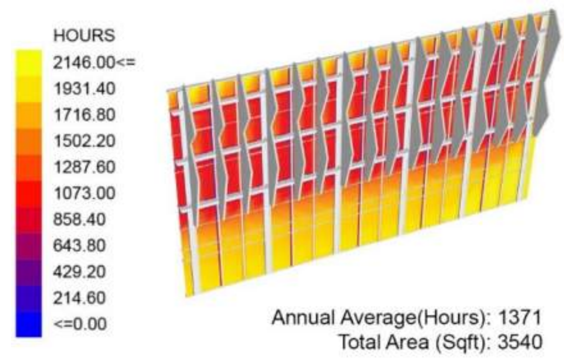

Figure 5 – Average Annual Solar Incidence on Northwest Facing Wall with Vertical Sun Shades Aligned with Mullions

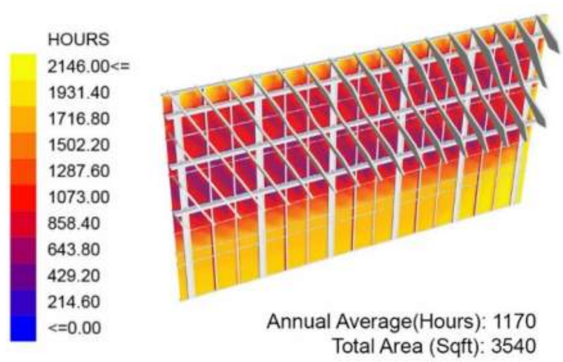

Figure 6 – Average Annual Solar Incidence on Northwest Facing Wall with Inclined Sun Shades at 5 ft. on Center

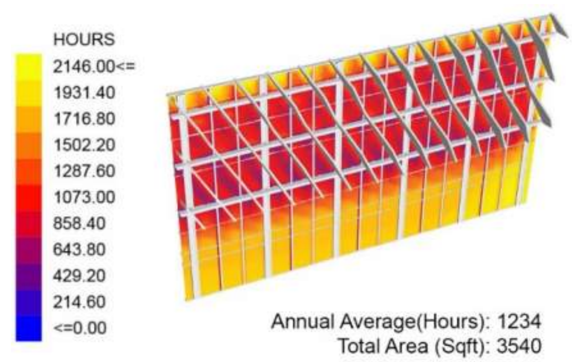

Figure 7 – Average Annual Solar Incidence on Northwest Facing Wall with Inclined Sun Shades at 6 ft. on Center

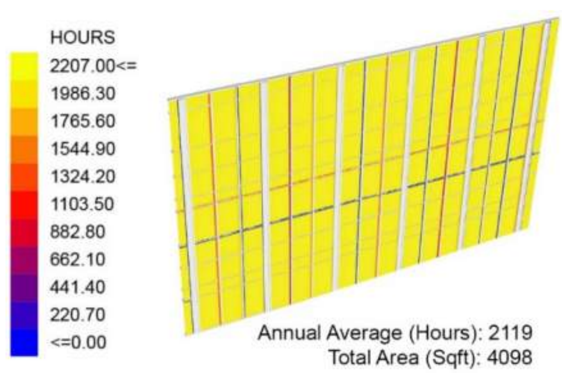

Figure 8 – Average Annual Solar Incidence on Representative Southwest Facing Wall

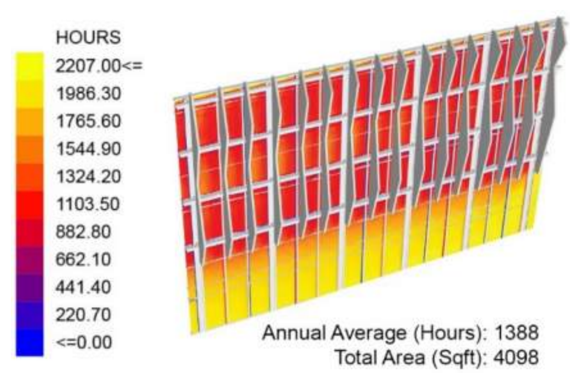

Figure 9 – Average Annual Solar Incidence on Southwest Facing Wall with Vertical Sun Shades Aligned with Mullions

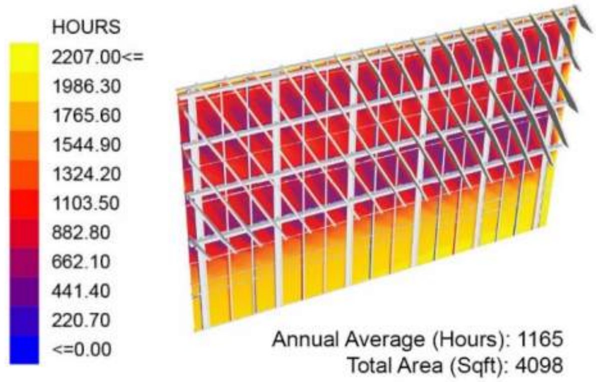

Figure 10 – Average Annual Solar Incidence on Southwest Facing Wall with Inclined Sun Shades at 5 ft. on Center

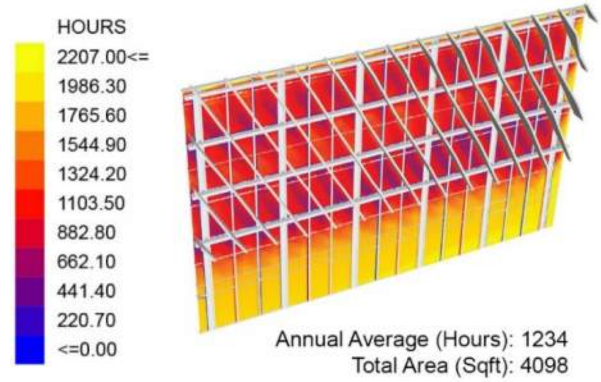

Figure 11 – Average Annual Solar Incidence on Southwest Facing Wall with Inclined Sun Shades at 6 ft. on Center

Case #	Case Description	Total Area (sq. ft.)	Annual Average Solar Incidence (hours)	Shading (%)
1NW	No Sun Shades - NW	3540	2058	0.00%
2NW	Vertical Sunshades at Mullions - NW	3540	1371	33.38%
3NW	Inclined Sunshades at 5 ft. on center - NW	3540	1170	43.15%
4NW	Inclined Sunshades at 6 ft. on center - NW	3540	1234	40.04%
1SW	No Sun Shades - SW	4098	2119	0.00%
2SW	Vertical Sunshades at Mullions - SW	4098	1388	34.50%
3SW	Inclined Sunshades at 5 ft. on center - SW	4098	1165	45.02%
4SW	Inclined Sunshades at 6 ft. on center - SW	4098	1234	41.76%

Figure 12 – Data Summary

The data indicate that the sun shades do, in fact, provide a significant shading benefit. This simple study also shows that computational tools can be used to tune the shades' efficiency using shape, spacing, orientation and inclination as parametric inputs. While not employed for this project, such a computational model could provide the designer with real-time feedback when considering the functional impact of aesthetic decisions.

Another aspect of the design that this type of study could shed light on is to calculate the effective solar heat gain coefficient (SHGC) of the overall curtain wall assembly considering the shading effect provided by sun shades. In this particular case study, the designers selected glazing that, by itself, meets the prescriptive energy code requirement of SHGC = 0.25. However, one can image a desire to provide a design using much clearer glass with a higher SHGC. This would require supplemental shading in order to be energy code compliant. This type of study could then be used to support a calculated effective SHGC that would be the result of the actual measured value of the glazing alone reduced by a factor derived from the benefit provided by the sun shades.

Another important follow-on topic that this study does not address is the annual energy savings associated with the proposed fixed shading. Many more parameters and their interaction would need to be considered to provide an accurate and meaningful estimate of the associated energy savings. At a minimum, these parameters would need to include the coincident time of day and time of year that shading is provided, the heat gain associated with unprotected portions of the glass, and the coincident overall building heating or cooling load. The simulation would also need to be run on the entire building façade and not just on representative wall samples.

However, the question of energy savings raises the value proposition associated with solar shading strategies in general.

Cost benefits are usually derived from both the reduced life-cycle cost related to energy consumption and also the first cost saving associated with a reduction in the required size of mechanical equipment. As noted above, in this particular building type peak cooling demand is predominantly based on occupant load; the contribution from the building envelope load is much less significant. So, the question is should the value of an energy saving strategy like the sun shades employed at the Miami Beach Convention Center be measured on a commercial basis only by its payback period or do energy savings of any kind have an intrinsic value? Further, should we also measure the lifetime energy savings of a particular sustainable design feature against the embodied energy of manufacturing, shipping and installing that portion of the construction? In this regard, double-skin façades also come to mind as a strategy that may provide energy and comfort benefits at great initial expense in both cost and embodied energy.

Finally, it should also be noted that the function of the shading devices studied in this case is for solar shading only; they are not intended nor are they effective in controlling glare in the current configuration. Additional studies, not included in this paper, were performed to develop an effective strategy to supplement the shading fins and address glare control.

DESIGN PROCUREMENT AND EXECUTION

Construction of the project began in December 2015. Prior to this design drawings of and specifications for the façade were developed by the Architect and formed the basis for a design-assist procurement strategy. After the Design-Assist Subcontractor was selected on a best-value basis they worked closely with the Architect, sharing and trading digital models, to develop the final design and engineering of the curtain wall and sun shading system. A sample design detail and its complementary final shop drawing detail can be seen in Figure 13 and 14 respectively.

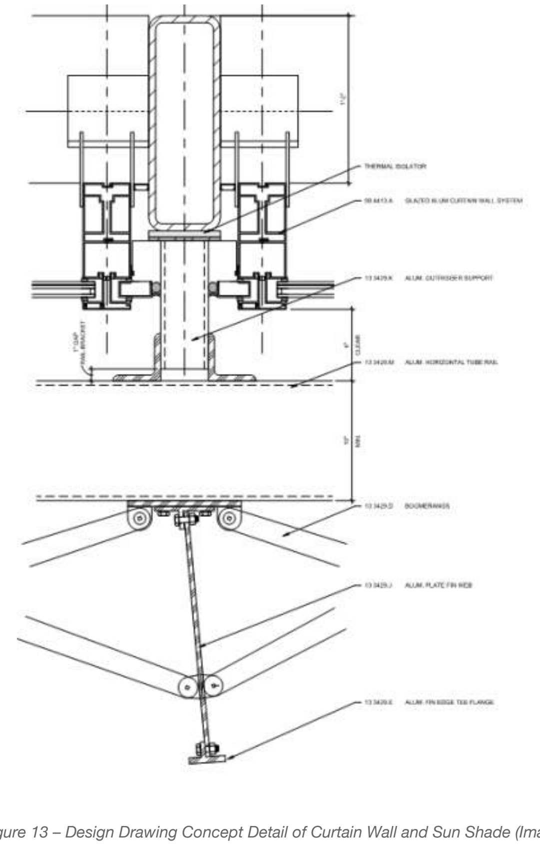

Figure 13 – Design Drawing Concept Detail of Curtain Wall and Sun Shade (Image courtesy of Fentress Architects)

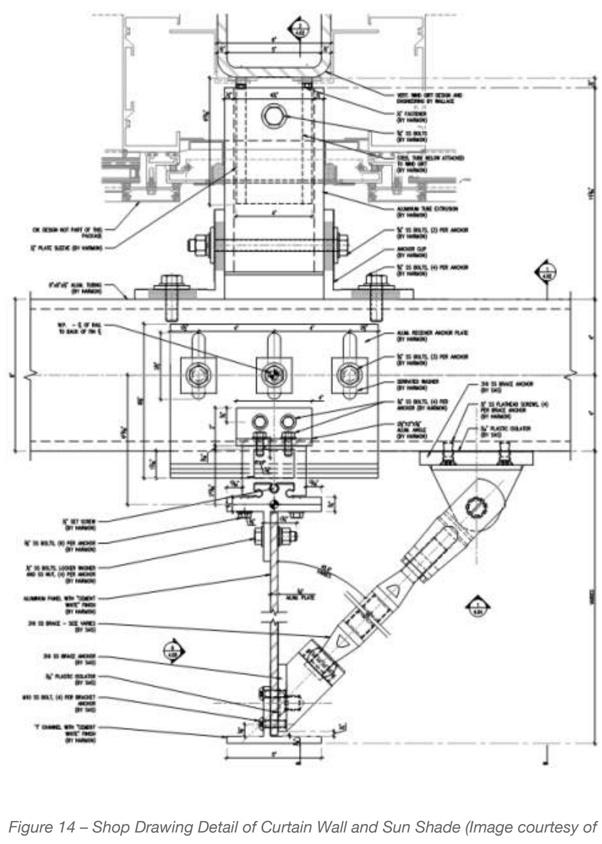

Figure 14 – Shop Drawing Detail of Curtain Wall and Sun Shade (Image courtesy of Harmon, Inc.)

The curtain wall system required laboratory mockup testing to obtain Miami Dade County approval for both high wind loads and large missile impact. The performance mockup was also used as a visual mockup to confirm the appearance of a sun shade fin (Figure 15). Construction completion is scheduled for July 2018.

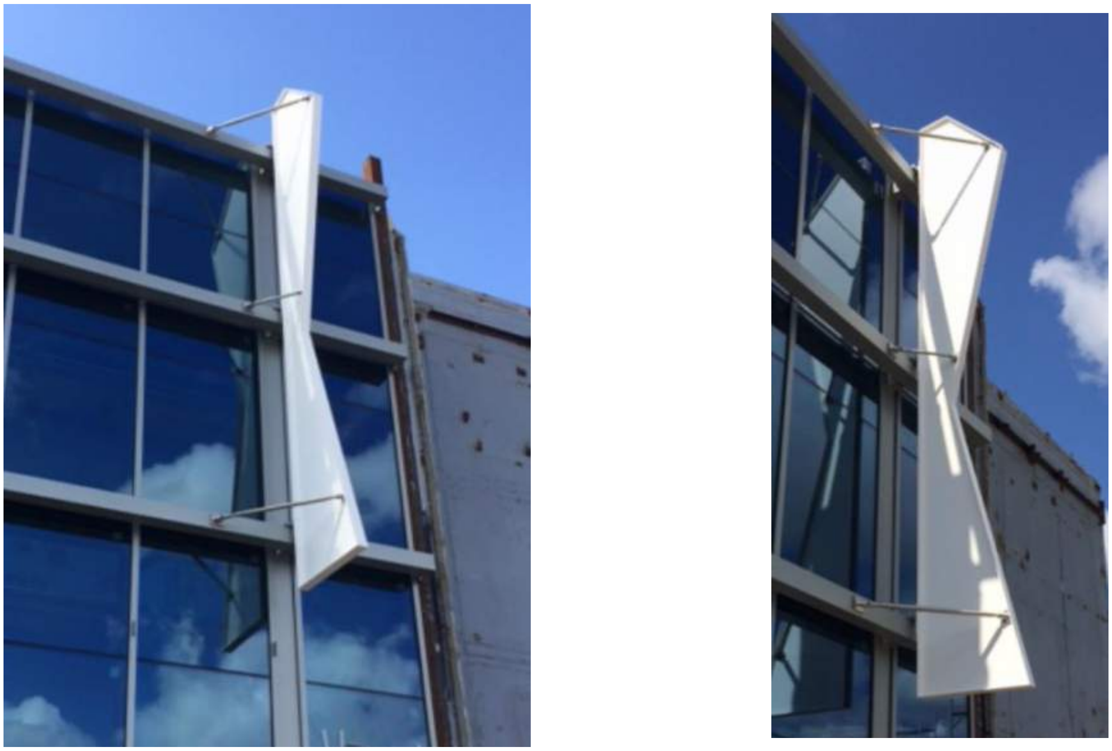

Figure 15 – Curtain Wall Performance Mockup with Visual Mockup of Sun Screen Fin (Image courtesy of Fentress Architects)

CONCLUSION

The signature design of the Miami Beach Convention Center renovation and expansion derives from its digitally developed, varying profile, sun shading devices, which provide an undulating and dynamic surface reminiscent of ocean waves. It is a design that captivated the imagination of city leaders and was widely endorsed early in concept design.

Based on the location of the project in the hot, humid, cooling dominated climate of Miami Beach, the designers assumed that incorporating architectural elements to shade the east and west facades that are highly glazed because of their use as the primary registration and pre-function spaces for the center, would be a responsible and even required design approach. A few point-in-time studies of the proposed shading devices at the solstices and equinox were performed to demonstrate the shading effect but no comprehensive quantitative studies were performed as part of the design process. This study demonstrates that the actual shading value provided by the final design is at least 40 percent.

The study also opens the door to a range of questions that should be considered when embarking on a façade design that is conceptually generated by its function as an effective sunscreen. If a parametric model providing real-time data feedback had been used during the design phase, could the design have been more functionally effective without compromising the signature design? Should the value of the sun shading system be determined by the ratio of the added cost of the construction compared to future cost savings, or is there both an intrinsic and aesthetic value which transcend the commercial? When façade loads are relatively small compared to overall building energy consumption based on other factors is the benefit of providing a high performance building envelope worth the increased construction cost?

It is clear that the digital tools now available, which provide both geometric freedom and fast analysis, have had and will continue to have a profound impact on how buildings, and in particular facades, are designed.

ACKNOWLEDGMENTS

I would like to acknowledge the contribution of Ron Shvartzman, architectural and computation designer at Fentress Architects, for his assistance in developing the digital and computational model from which the results of this study were derived.

AVOIDING THE DREADED DEATH RAY

Controlling facade reflections through purposeful design

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ABSTRACT

Solar reflections are a fact-of-life for many who live in cities. However, modern architecture with high window-to-wall ratios and curved, organic forms can lead to building facades that reflect sunlight in unanticipated ways. Reflective facades have the potential to both scatter and concentrate solar reflections; at a minimum, this can be a nuisance, but at its worst can lead to serious safety concerns. Visual impairment of aircraft or vehicle operators and even concentrated thermal "death rays" have been observed in climates as diverse as London, Boston, Las Vegas, and Calgary. This paper aims to inform facade design in order to avoid features that lead to visual and thermal reflection issues. It discusses critical decisions and design trade-offs that may need to be considered. As well, for the case of existing solar reflection issues, the paper offers potential post-construction measures to mitigate problematic reflections. The design and mitigation methodologies are supported with computer simulation results and on-site measurement data from real-world case studies.

KEYWORDS

Facade, glare, computational design, design processes, glass, education

INTRODUCTION

Solar glare has long been a nuisance within cities. However, recent events have thrust this often-ignored aspect of urban living into the spotlight. Sunlight reflected from building facades has been blamed for issues ranging from distracting train operators (City A.M. 2012) to damaging property (Wainwright 2013), and even personal injury (NBC News 2010). The ensuing media coverage has caused many in the facade design community to take pause and wonder if their design will be the next "death ray". The challenge to facade designers is that despite the potential risks from uncontrolled reflections, there is little guidance available from regulators and the scientific community on how to assess and categorize the impact of a building's reflections on its neighbors. While progress is being made in addressing this issue (Danks, Good and Sinclair 2016), there is a lack of a widely accepted standards for assessing the visual and thermal impact of reflections. This means that, in many cases during the design of new buildings there is little or no effort in assessing reflected sunlight. Many tools exist that can compute the paths of reflected light. However, software that can accurately predict the intensity and duration of reflections is limited and effective use of the software often comes with steep learning curves and long simulation run times, which interferes with the design process. Despite the challenges, a good understanding of the physics of reflecting light and learning from past problems from other buildings can provide the design team with the knowledge to identify design features that increase the likelihood of reflection related issues. Allowing them to mitigate, or ideally, prevent those potentially dangerous issues from occurring.

THE PHYSICS OF REFLECTIONS

Before delving into a discussion on urban glare, we must first review the physics of reflected light. When light moves from one medium to another (i.e. air to glass), some light transmits through the interface into the second medium, and the rest is reflected back into the first medium. Light reflections can be either *specular* or *diffuse*, i.e. the reflected light travels in a single direction or it is scattered, as shown in Figure 1 below.

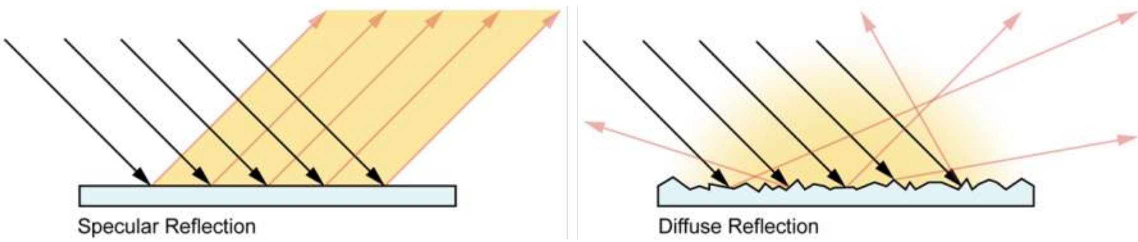

Figure 1: A schematic comparing specular and diffuse reflections.

In reality, all reflections consist of a specular and diffuse component with the relative roughness of the interface defining the distribution. Smooth, glossy materials tend to reflect light specularly, while rough or matte surfaces create diffuse reflections. Of these two types of reflections, specular reflections are the more problematic, as they retain more of their initial energy and travel in a single direction. This can lead to situations where multiple specular reflections converge in the same area, concentrating their energy, potentially causing significant heat gains to surfaces.

The direction of a specular reflection can be determined using Snell's Law and the fraction of light reflected is computed using the Fresnel Equations. A critical consequence of the Fresnel Equations is that the amount of light reflected by a specular surface is ***not*** a fixed value. Regardless of the material, as light rays strike the surface at more glancing angles, the fraction of light reflected increases rapidly. Figure 2 illustrates this effect for a single pane of 6mm (0.25") clear glass; whereas 8% of incident light is reflected when it strikes the glass perpendicularly (0° in the Figure), that fraction rapidly rises when light strikes at angles beyond 50°. The data in Figure 2 was generated using Lawrence Berkeley National Laboratory's WINDOW software (LBNL 2015).

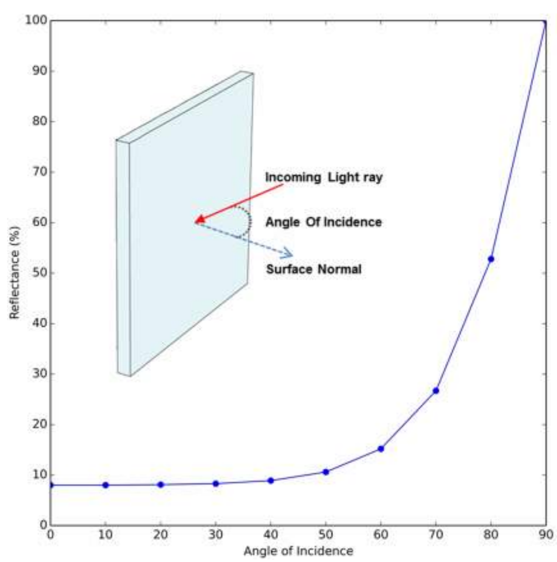

Figure 2: Plot of surface reflectance as a function of light incidence angle for a 6mm (0.25") pane of clear glass.

This variability is important to understand because the reflectivity value specified by manufacturers is typically for light striking perpendicular to the surface. Thus, depending on the position of the sun, even a nominally low reflectivity glazing can reflect significantly more light than one would expect based on the manufacturer's data. As an example, when light strikes the glazing at 60°, the glazing is approximately twice as reflective as the manufacturer's specified reflectance value and more than 6.5 times as reflective at 80°. It is also important to know that this effect occurs not only in glass, but also in any specular surface, including some photovoltaic solar panels and polished metals.

DESIGN CONSIDERATIONS

With an understanding of the underlying physics of reflections, one can now investigate how different aspects of a facade's design interact with the physics and how that influences reflection impacts.

LOCATION & ORIENTATION

In the northern hemisphere, designers are taught that the southern facades are the "sunniest" (and vice-versa in the southern hemisphere), so it is this exposure which typically receives the most attention during design for solar related issues. While this is true in terms of the cumulative solar insolation, and is important for applications such as mid-day shading of summer solar gains, solar reflections do not follow the same rules-of-thumb. Unwanted reflections often occur at low sun angles when direct or glancing reflections align with the line-of-sight of pedestrians and more importantly drivers, causing a potentially dangerous visual distraction. As discussed previously, the intensity of these glancing reflections can also be some of the highest that a facade will create. As well, unlike an overhead solar angle, a glancing reflection will potentially travel further from the facade affecting a larger area of the urban surrounds and thus have a greater potential for offending neighbors. Therefore, the most "unruly" reflections from a visual glare standpoint will often occur while the sun is lower in the sky, in the first few hours before sunset or after sunrise. Conversely, this also means that the impacts of visible reflections from overhead (southern, midday) can be less problematic as the angle of incidence is less likely to align with the required line of sight of a pedestrian or driver. (However, it is important to note that the *thermal* impacts of reflections during midday periods are more of a concern due to the greater intensity of solar insolation at these times.) As an example, Figure 3 is a sun path diagram for Los Angeles, note how the sun will cover over 225° of azimuth during a summer day, exposing not just the southern facades but potentially the entire building envelope to direct sunlight and potentially cause glare. Also notable is that low solar inclination angles (say below 30°, which is outlined in black) can occur from ENE to SSE and from SSW to WNW depending on the time of year. Thinking that low angles come strictly from the east or west would lead to a limited understanding of potential reflection issues.

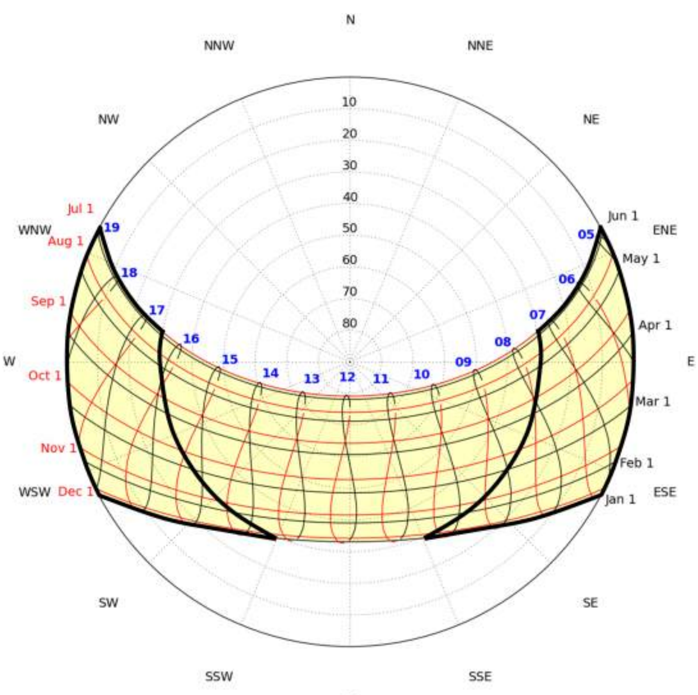

Figure 3: A sun path diagram for Los Angeles with solar elevations below 30° outlined.

FORM

As a pioneer of organic, free-form architecture, it should be no surprise that Frank Gehry was among the first architects to discover the unintended consequences of reflections from such designs. The polished stainless steel cladding of the Walt Disney Concert Hall in Los Angeles combined with its numerous concave (i.e. inward curving) facade features, concentrated reflections into a small area, leading to heat gain and visual nuisance issues on nearby homes, motorists and pedestrians (Schiler 2009). While the panels at the Disney Concert Hall were continuously curved concave metal, similar problems were reported at the Vdara Hotel in Las Vegas (NBC News 2010) and the 'Walkie Talkie' Building (20 Fenchurch) in London (Wainwright 2013) from concave surfaces that are "facetted" by individual, flat glazing units. Concave facades (facetted and smooth) can act like parabolic mirrors, in that reflected light rays intersect at a focal point some distance away. The thermal effects of the reflections at this point are additive and have the highest potential to cause damage or injury. The relative efficiency of a concave facade or facade element to concentrate reflections is proportional to the number of elements causing reflections. A low number of facets creates a less intense focal point than the focal point created by a high number of facets, with a smooth continuous curve creating the highest intensity. This focusing effect leading to extreme thermal damage is what the media have dubbed "death rays".

However, many buildings with concave facades do not cause problems; so what distinguishes these buildings from their infamous counterparts? One positive design feature is a lack of a single monolithic facade. Compare the images on the left and right in Figure 4. While both buildings feature concave facades, the facade on the left is vertically continuous, whereas the facade on the right features discontinuities.

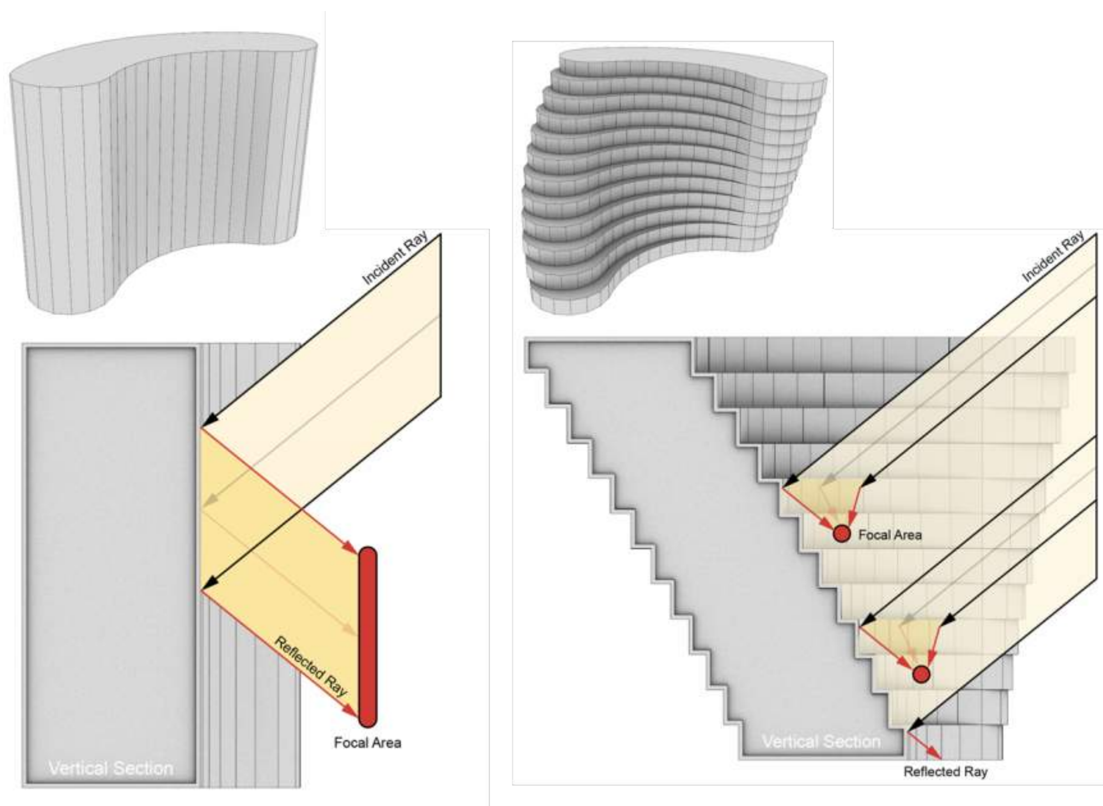

Figure 4: Schematic of the impact of facade continuity on reflections.

The discontinuity of the facade results in multiple lower intensity focal areas, rather than a single very intense one. The smaller focal areas also tend to occur in midair or on rooftops below, keeping them out of the pedestrian realm. However, rooftops can be converted to amenity spaces and buildings may occupy neighboring airspace in the future so it is still important to understand the locations and intensities of these new focal points. Facade discontinuity can be accomplished through changes in curvature radius, orientation, the use of podiums, setbacks or though canopies.

Deep canopies extending from the facade can intercept high solar angle incident light as well as reflections; potentially reducing glare inside the building as well as outside. Given a canopy depth and spacing, simple mathematics can be used to determine the solar angles at which they will obstruct light (Figure 5).

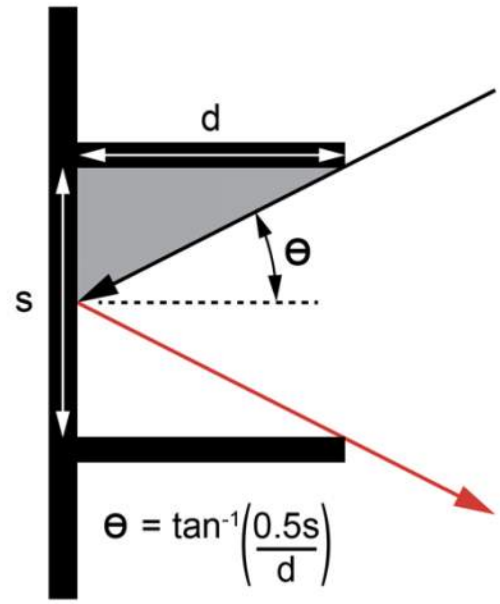

Figure 5: Schematic illustrating the relationship between canopy depth (d), spacing (s) and the solar angles intercepted.

While concave reflections are the usual culprit behind so-called “death rays”, convex and flat facades can also cause significant glare impacts. Convex (i.e. outward curving) facades will scatter reflections (Figure 6) and depending on how the facade is facetted, a stationary observer could be subjected to frequent, short duration “pinwheel” reflections for much of the day. While this kind of reflection is unlikely to cause heat gain related issues, it can lead to visual nuisance over a very large area due to the scattering of the light

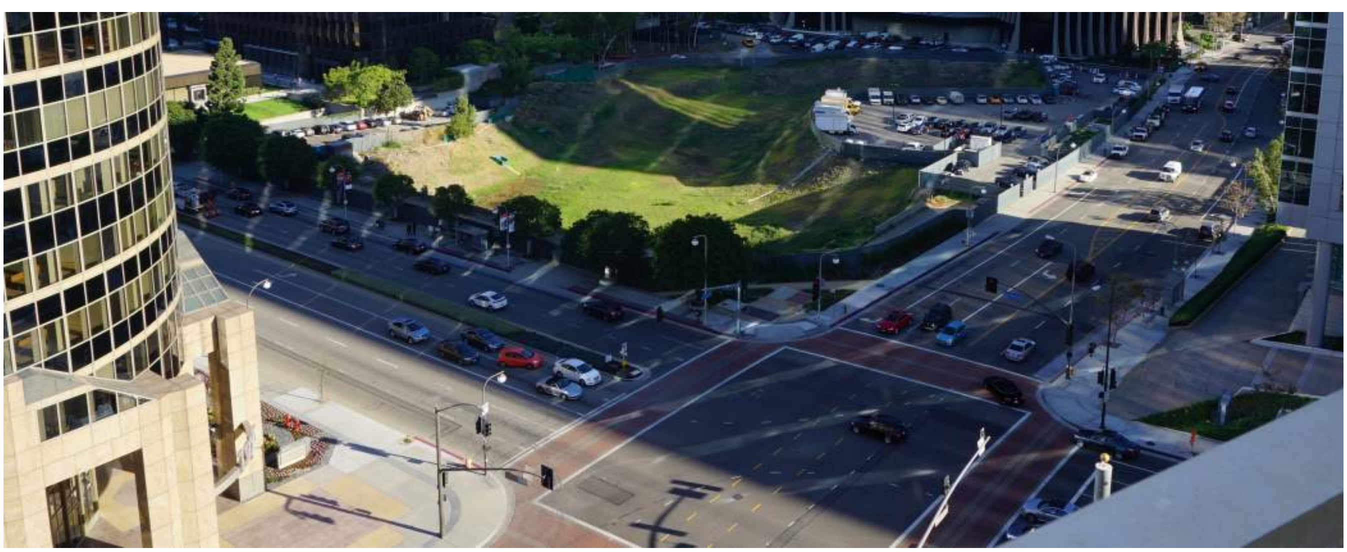

Figure 6: Photograph of reflection pattern caused by a facetted convex facade.

A flat facade, while not concentrating or scattering light can create long duration reflections depending on the size of the reflective area. If sufficiently intense, these long duration reflections can potentially lead to heat gain issues and certainly cause visual nuisance. However, the most common glare issues related to flat facades is the impact of glancing reflections affecting drivers, as described in the previous section, and/or causing visual nuisance to the occupants of neighboring buildings. A less common issue is multiple flat facades arranged in such a way that reflections from them intersect leading to impacts similar to that of a concave facade. The sources of these intersecting reflections could be from the same building, or more rarely, multiple nearby buildings. Figure 7 below illustrates reflection patterns for the three facade forms discussed here, produced using a custom simulation tool (Danks and Good 2016).

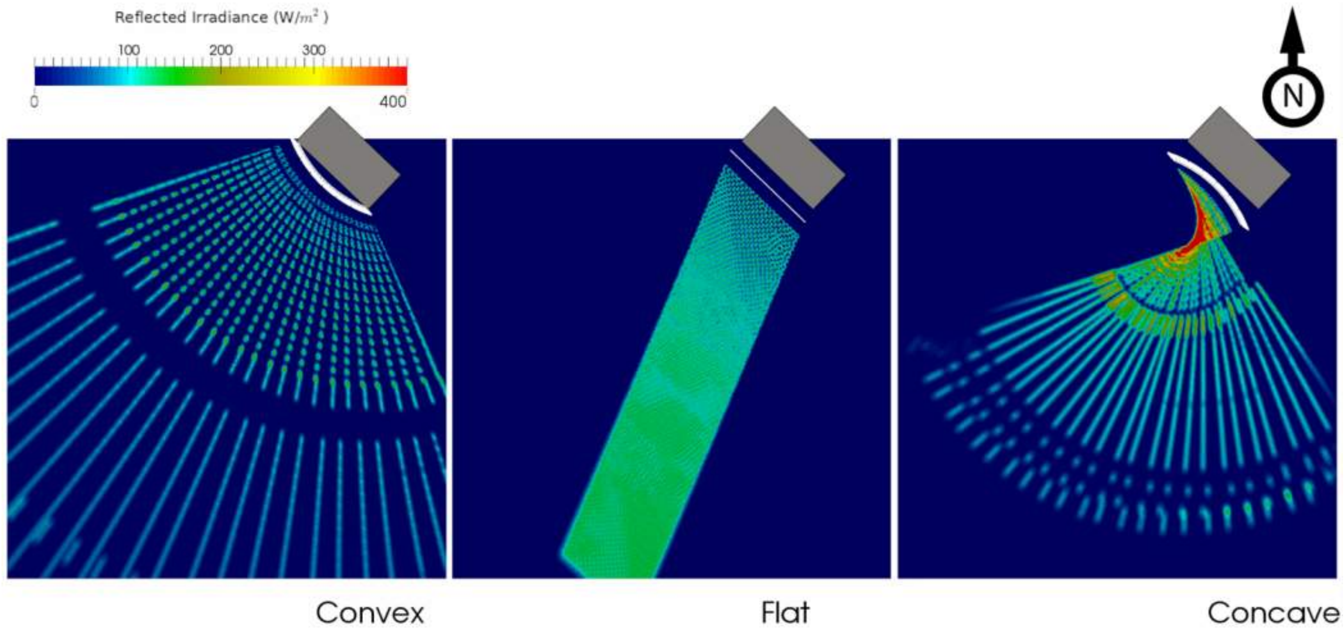

Figure 7: Simulation results illustrating reflection location and intensities for three prototypical facades.

It is also important to note that, while highly glazed facades are the more likely source of urban glare, smaller residential windows can also cause reflection related damage to vehicles (Wornick 2012) and cladding (Hart, et al. 2011). In many cases, the reason behind this issue in residential windows is a deflection of the panes due to pressure differences between ambient and the air gap, which makes the normally flat window concave. When this is coupled with an unfavorable orientation to the sun, significant surface heating can occur, particularly when the facade material is reflecting significant amounts of solar energy.

MATERIALITY

As noted above, reflection problems in the built environment are primarily a result of specular reflections. In the context of facade design, glazing is the most common source of such reflections. Advances in glazing technology have yielded so-called “high performance” glazing, which feature improvements to the glazing unit’s thermal performance. In addition to features such as multiple panes, low-conductivity gas fills and improved thermal breaks, high performance systems typically employ a low-emissivity coating (often referred to as ‘low-e’) on one of the panes. These coatings selectively reflect thermal radiation, while allowing visible light to pass through unobstructed (Figure 8). Consequently, much of the sun’s thermal energy (which is approximately half of the total energy) can be reflected into the surrounding environment while the visible light is not. This can lead to situations where a reflection may not appear to be intense (due to its dimness) but is in fact able to cause significant heat gains in objects exposed to it, particularly when the reflections are at glancing angles.

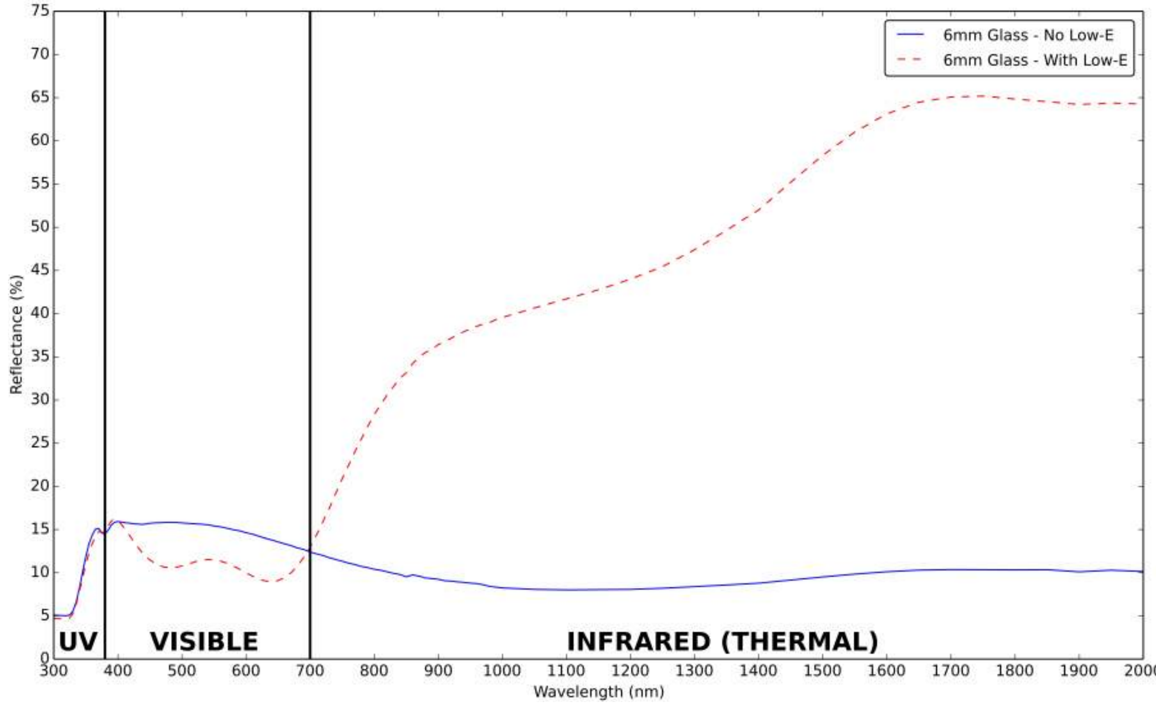

Figure 8: Surface reflectance for glass with and without a low emissivity coating for various wavelengths of solar radiation, as computed using WINDOW.

Thus, when selecting glazing is it important to understand both the visible and thermal reflectance of the glazing, and compare the external “visible” reflectance to the “full spectrum” reflectance of the product indicted by the manufacturer. The full spectrum reflectance is the weighted-average reflectance of the glazing across the full solar spectrum, and is also referred to as “solar energy reflectance”, “solar radiant heat reflectance” or “total solar energy reflectance”.

In addition to coatings, the reflectivity of glazing systems is influenced by its color and the presence of fritting. The impact of colored glass on reflectance is intuitive, darker colors absorb more solar energy and thus are less reflective. Fritting on the other hand has a less intuitive impact. As an example, Viracon’s standard VRE1-59 glazing unit has a visible and full spectrum reflectance of 30% and 38% respectively (Viracon Inc. 2016). If we then applied a 50% frit pattern, (i.e. half of the surface has frit), one might naively assume a 50% reduction in reflectance since the window is now “darker”. However, the application of a 50% frit only results in a 30% reduction in visible and full-spectrum reflectance values. This discrepancy is because frit is not applied to the exterior surface, and therefore has no effect on the first (and strongest) reflection that occurs when the light strikes the outermost surface of a glazing unit. The frit only reduces reflections from the interior surfaces, which have a lower contribution to the overall reflectance since the light rays weaken as they pass through the outer pane. In fact, some fritting can actually increase reflectance depending on its color and finish.

While this section has focused on glazing, it is not only the material that should be scrutinized. Photovoltaic panels (Hayward 2012) and polished metals (Schiler 2009, Markusoff 2014), have also caused significant visual and thermal reflection impacts and much of the above discussion and guidance also applies to these materials. Glossy clear-coats on smooth stone surfaces could also have similar impacts. Polymer films such as ethylene tetrafluoroethylene (ETFE) and polytetrafluoroethylene (PTFE) are another increasingly common facade material. Their low weight and high light transmittance, make them particularly popular for roofs and canopies. Due to their naturally high level of light transmittance, the amount of light reflected by such materials is often low. However, in some cases, ETFE/PTFE films and cushions are treated to reduce the amount of light transmitted through them, and depending on the implementation, the treatment could increase the potential impact of reflections from the film (i.e. specularly reflective fritting or low-e coatings). Given the proprietary nature and variety of ETFE/PTFE products, it is advisable to engage the manufacturer directly to discuss the potential for reflection related concerns. Water features also have some potential to cause reflection related issues. However, in built-up areas the greater amount of shading provided by the built environment ameliorates the risk compared to more open bodies of water. Regardless of the material chosen, it is also important to remember that the reflectance of a material to both visible and thermal energy will be enhanced for light striking the surface at glancing angles because of an unfavorable orientation to the sun, and due to the concentration of reflected rays from a concave form.

MITIGATION APPROACHES

Ideally, facade features that would lead to problematic reflection issues would be identified early in design. However, in cases where reflection impacts slipped through the design process, the impacts would not be apparent until they occurred. It is typically too late at this point to change form and facade orientation so the mitigation options for such impacts generally fall into two categories, modification of reflecting surfaces and obstructing the reflections.

SURFACE MODIFICATION

In the case of the Walt Disney Concert Hall, the reflection issue was successfully mitigated by hand sanding the offending metal panels (Schiler and Valmont 2005). This roughened the surface, diffusing the reflections and their impact. This option was available due to the choice of the material as well as the relatively small area that caused the problems. While this approach may be suitable for opaque building elements (i.e. metal panels or spandrel), it would be problematic for a vision application due to impacts on occupant views and the difficulty in cleaning (remember, to have any impact on exterior reflectance, one must modify the *outermost* surface of the facade).

Applying an anti-reflective coating to the exterior glazing surface is another option to mitigate existing reflections. Such coatings either absorb some portion of the solar spectrum or cause destructive interference to reflected light, which significantly reduces the reflectivity of glazing, often below 10%. The performance will change based on the wavelength of light as well as the angle of incidence the sun's rays make with the film. This means that many coatings are tailored for either visible or thermal energy glare reduction, not both. This dependence can also lead to changes in the perceived color of the glazing and reduced effectiveness for glancing angle reflections. Another significant consideration with anti-reflective coatings is that, since their goal is to reduce reflected light, there must be a corresponding increase in solar energy absorbed by and/or transmitted though the facade which will alter the solar heat gain to the spaces adjacent to the facade. These additional heat gains were not considered when the building's HVAC systems were designed and thus could lead to larger cooling requirements or, if capacity is exceeded, to occupant discomfort. These technical implications must be carefully considered. Though the biggest challenge with coatings being applied post-construction is often more practical in nature, the issue of application and maintenance. These coatings require manual application, and because they are exposed to the elements, they will degrade and require similarly labor-intensive removal and re-application, typically in 5-7 year intervals. The amount of specialized manual labor required represents a significant ongoing maintenance expense, although this is a much less intrusive approach than roughening or replacing glazing units.

OBSTRUCTING REFLECTIONS

A more pragmatic approach is often to simply obstruct the path of reflections with opaque elements. This can be done at the facade itself or along the path between the reflecting material and the location of impact.

Using building shape and extensions to create shade has always been a basic tenet of good architectural design. Solutions range from traditional elements such as the *mashrabiya* or *sudare* (from traditional Middle Eastern and Japanese architecture) to more modern examples such as the *brise-soleil*, popularized by Le Corbusier. Traditionally these features were used to break up sunlight entering a space, but they can also be used to break up the reflections that leave one, as was the case for the brise-soleil designed for the Walkie Talkie (shown in Figure 9). The shading device can take many forms but must intercept the solar rays before they reach the facade or shortly after being reflected. As such, a full brise-soleil may be excessive and for the more common case of glancing reflections, simple mullion fins may be sufficient. The same mathematics shown in Figure 5 (used in plan, rather than elevation) can also be used to understand the depth and spacing of mullion fins that would be needed to obstruct reflections of a given incidence angle. Regardless of the implementation, building mounted shading features should be studied to understand their effect on facade wind loading, ice and snow build up as well as aero-acoustic effects. Without a holistic understanding of their impact, building mounted shades may fix one problem and cause another.

Figure 9: Photograph of a brise-soleil being installed on the “Walkie Talkie” building (20 Fenchruch) in London, UK. (Photo courtesy of Albert Brooks.)

Although it is typically preferable to intercept the reflection as close to the facade as possible, there may be specific scenarios when one can reduce the visual and thermal impact of reflections by erecting localized shading devices within the pedestrian realm. While a designer can employ common, low-cost shading devices, (i.e. canopies, umbrellas, landscaping) this approach is not without challenges. Firstly, reflections are transient and as the shading device is located further away from the reflection source, the size of the area needing to be covered could become unfeasibly large due to the movement of a focal area throughout the year. Furthermore, if the reflections are particularly intense and/or consistent they can lead to significant heat gains in the shading materials. This can cause heat related damage or premature wearing on the components, and in the case of trees, potentially affect the health of the plant. In the worst case, a surface may get hot enough to pose a danger to people who touch it.

As a practical example, Figure 10 illustrates a measurement apparatus used by the authors to measure the intensity of the focused reflections from a concave curtain wall of an under-construction building (Danks and Good 2016). During the study period, temperatures of various surfaces were recorded before and after the focused reflection passed over the apparatus. The graph in Figure 10 plots the increase in temperature experienced for various surfaces against the measured reflection intensity. In the 20 minutes it took for the focal area to pass over the objects, surface temperatures were observed to routinely exceed 44°C (111°F) which is a typical threshold temperature for safe object handling with bare skin (Ungar and Stroud 2010). In some cases, the objects were heated nearly to the point of material damage. More importantly, this graph also highlights that surface temperature gains depend on more than simply the reflection intensity. The surface’s material, orientation to the reflected energy and ambient wind speeds in particular played a large role in the temperature increases. Therefore, much like building mounted shades, careful consideration is required to ensure a holistic solution.

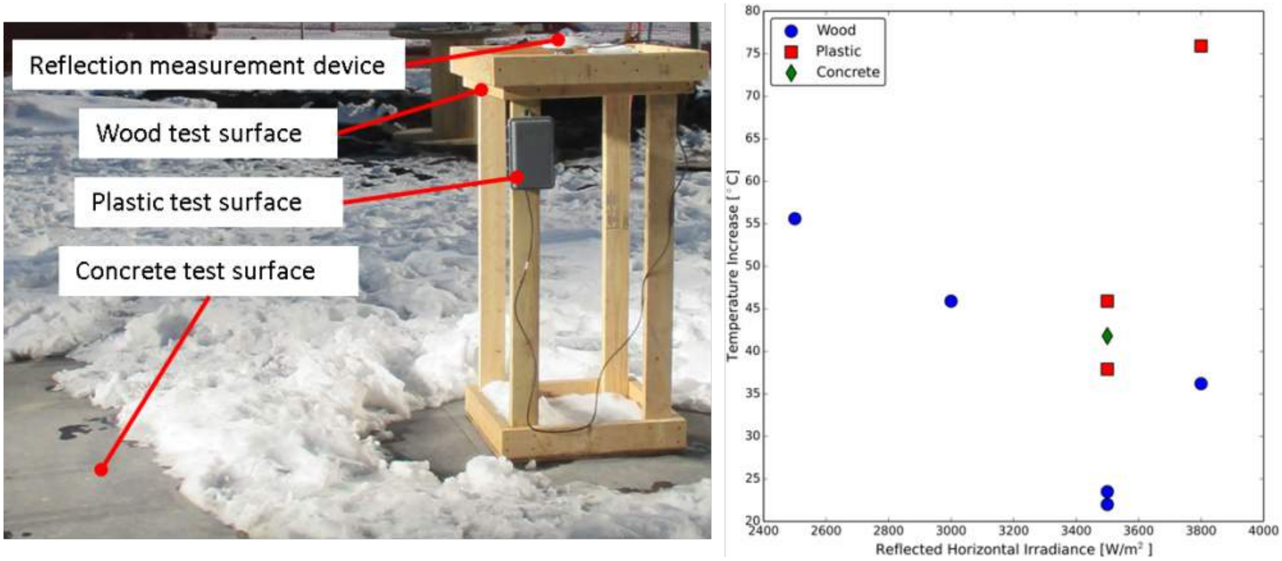

Figure 10: Plot of measured temperature gains as a function of measured reflection intensity for three surfaces.

CONCLUSIONS

There is currently very little regulation around solar reflections in the built environment. This means that a facade designer has little guidance on how to ensure their facade does not inadvertently cause dangerous thermal or visual impacts. This paper has identified key aspects of the physics of reflected light as well as design features that can contribute to the negative impacts of solar reflections. Key points to keep in mind are:

- The reflectance of a facade element is not constant; it will vary depending on the material, angle of incidence of incoming light and the type of solar energy (visible/thermal).
- Facade form has a direct impact on the types of possible glare impacts; Concave facades focus reflections, convex facades scatter them, and flat, continuous facades result in longer durations.
- The size of a reflective surface does not correlate to its potential for causing glare problems - both small residential windows and multi-story curtain walls have caused damage due to their reflections.
- All facades need due consideration for potential reflection problems; depending on latitude the entire building envelope will have at least some exposure to direct sunlight and lower incidence angles can result in the most problematic reflections.
- Areas that may be particularly sensitive to reflected light (i.e. roads, parks, flight paths) need to be identified and the potential for reflection impacts understood.
- Mitigating solar reflection issues post-construction is possible, but is often expensive and may conflict with aesthetic intent.
- Any planned mitigation measures should be studied in a holistic fashion. Issues related to internal heat gains, external wind loading, snow and ice buildup and aero-acoustics are a few examples of problems which can arise from improperly understood glare mitigation options.

By understanding these factors, designers can gain a better understanding of how a proposed building will interact with the sun eliminating the need for costly mitigation options and avoiding becoming the latest “death ray”.

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REFERENCES

City A.M. Dazzling Shard Has Inadvertent Effect of Blinding Train Drivers. September 19, 2012. http://www.cityam.com/article/dazzling-shard-has-inadvertent-effect-blinding-train-drivers (accessed March 27, 2015).

Danks, Ryan, and Joel Good. "Urban Scale Simulations of Solar Reflections in the Built Environment: Methodology and Validation." 2016 Proceedings of the Symposium on Simulation for Architecture and Urban Design. London, 2016.

Danks, Ryan, Joel Good, and Ray Sinclair. "Assessing Reflected Sunlight from Building Facades: A Literature Review and Proposed Criteria." Building and Environment, July 2016: 193-202.
Hart, R, C Curcija, D Arasteh, H Goudey, C Kohler, and S Selkowitz. Research Needs: Glass Solar Reflectance and Vinyl Siding LBNL-5022E. Lawrence Berkeley National Laboratory, 2011.
Hayward, Mark. "Airport controllers complain of solar panels' glare." New Hampshire Union Leader. August 30, 2012. http://www.unionleader.com/article/20120830/NEWS02/708309966/0/SPORTS.
LBNL. "WINDOW Vers. 7.3." Lawrence Berkeley National Laborarory, 2015.
Markusoff, Jason. "When art attacks: City pulls sculpture after visitor's jacket singed by reflected rays." October 8, 2014. http://www.calgaryherald.com/news/calgary/when+attacks+city+pulls+sculpture+after+visitor+jacket+singed+reflected+rays/10276470/story.html (accessed February 20, 2015).
NBC News. "'Death Ray' at Vegas hotel pool heats up guests." Septeber 30, 2010. http://www.nbcnews.com/id/39403349/ns/travel-news/t/death-ray-vegas-hotel-pool-heats-guests/#.VdcnWNVVhBc (accessed March 28, 2015).
Schiler, Marc. "Examples of Glare Remediation Techniques." PLEA 2009: Proc. 26th Conf. Passiv. Low Energy Archit. Quebec City, 2009.
Schiler, Marc, and Elizabeth Valmont. "Microclimatic Impact: Glare around the Walt Disney Concert Hall." Proceedings of the Solar World Congress 2005 Joint American Solar Energy Society / International Solar Energy Society Conference. Orlando, 2005.
Ungar, Eugene, and Kenneth Stroud. "A New Approach to Defining Human Touch Temperature Standards." Proc. 40th Int. Conf. Environ. Syst. Barcelona, 2010.
Viracon Inc. VRE1-59 Datasheet. March 28, 2016. http://www.viracon.com/search-by-appearance?construction=1&silk=0&argon=0&substrate=1&coating=6 (accessed April 20, 2016).
Wainwright, Oliver. "Walkie Talkie architect 'didn't realize it was going to be so hot'." September 6, 2013. http://www.theguardian.com/artanddesign/2013/sep/06/walkie-talkie-architect-predicted-reflection-sun-rays (accessed July 22, 2015).
Wornick, Susan. "Melting cars, homes tied to energy-efficient windows." WCVB Boston. July 6, 2012. http://www.wcvb.com/investigative/Melting-cars-homes-tied-to-energy-efficient-windows/15409652#!bDU8o6.

RETROSPECTIVE OPTIMIZATION

Balancing openings and shading devices for Kahn's psychiatric hospital

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ABSTRACT

Prior to the availability of energy analysis software, benefits of passive design techniques incorporated into buildings could only be painstakingly understood through analogue analytical techniques popularized by brothers Aladar and Victor Olgyay in their 1957 book *Solar Control & Shading Devices*. As architects, the Olgyays applied scientific principles toward works of seminal architects of the time, reinforcing the notion that performance alone is not a determinant of successful architecture, but rather compliments visual effects derived from form and enclosure details. Interest in the thermal benefits of passive design has waned and reemerged within a context of advancements in building systems, materials and performance standards. Despite advances, the design process remains intuitive, and the evaluation of performance criteria is largely distinct from visual analysis. Additionally, a paucity of energy analysis of historic buildings, particularly cannon, has hindered capacity to understand and compare them with contemporary buildings that incorporate advanced technologies.

This paper includes insight gained from digital energy analysis of a Louis Kahn designed building featured in *Solar Control and Shading Devices*. An intention is to clarify the effectiveness of façade devices incorporated into the existing building, and to understand how composition contributed to daylighting benefits and thermal efficacy. Results gained through this energy and visual analysis are related to potential modifications to the building enclosure, including adjustments to shading devices and aperture extents. By isolating thermal, daylighting and aesthetic variables at the location of the building enclosure, the author seeks to demonstrate that design can balance feedback gained from data, with visual factors, in a manner that does not undermine the fundamental contributions realized by talented designers when capacity to design with quantitative data was limited.

KEYWORDS

Energy, Optimization, Thermal, Shading, Historic

INTRODUCTION

Contemporary building technology and analytical techniques allow for sophistication of outcomes and performance verification that was inconceivable decades ago. Although vernacular traditions have produced outcomes that are typically more sympathetic to local climatic conditions than contemporary buildings, vernacular traditions did not account for climate mitigating technologies such as air-conditioning that heightened comfort potentials, but complicated the effectiveness of traditional forms, particularly passive thermal strategies. Today, utilizing analytical software, architects can balance insulation levels, manage air-infiltration, and off-set mechanical systems use with energy generation to create net zero-energy buildings. In theory this allows for optimized buildings if evaluation criteria factor out desirable buildings characteristics that are diminished in order to minimize energy use.

BACKGROUND

OPTIMIZATION AND DESIGN

Some of the characteristics that complicate arrival at net zero-energy performance are measurable, including building costs and the psychological benefits of daylight, which in many climates compromises thermal performance. More importantly, for architects, the expressive potential of architecture, and its associated meanings, elude reduction to numerical targets. The complicated nature of the design process also resists quantification, and the ability of computers to replicate design thinking (Malgrave. 2013). Designers have the ability to cut across ill-defined situations, sometimes called "wicked problems" and learn about design problems by posing solutions .(Lawson & Dorst. 2009).

PERFORMANCE AND AESTHETICS

It is the nexus of art and science where the Olgyay brothers practiced, studied architecture, and disseminated their ideas together in the United States from the late 1950s through the 1960s. Their book Solar Control & Shading Devices published in 1957, and Design with Climate, published by Victor Olgyay in 1963, included detailed studies of building designs in various climatic conditions supported by detailed drawings, diagrams, calculations, and narratives. Aside from the thoroughness of the studies, and their relevance to the austerity of the post-war era, the factor that made them most appealing to architects was the connection of expressive architecture form with building performance. The acknowledgement and featuring of notable forms has since been a key aspect to the reception of architectural knowledge that can help underpin better performing buildings. Because the calculations undertaken by the Olgyay brothers were exhaustive, and difficult to accommodate in the brief period of form shaping in practice, most of the concepts from the book when applied were derived intuitively. Similarly today, early design phase decisions are usually intuitive, with software used later in the design process to verify decisions. Verification of performance concurrent with early phase design activity, through construction, allows for greater perspective of the effectiveness of building.

DATA IN SUPPORT OF DESIGN

Despite the use of analytical software to understand energy performance and daylighting, numerical study results are rarely shared across the academic design community. Even when available, performance data does not accompany case studies in professional journals and monographs, which are important vehicles for learning about projects, celebration of design, and the distribution of ideas. Lack of information does not correlate to non-performance in recognized designs. Rather, due to compliance with voluntary sustainable design standards, many notable buildings are identifiable as providing exceptional energy performance. Historic buildings are also studied, but without the benefit of perspective on energy performance and related factors, limiting points of comparison, and evaluation.

This paper features an analysis of a mid-century modern building in Philadelphia designed by renowned architect Louis Kahn during a time when ability to calculate the effects of shading devices on energy performance was limited. Considering that Kahn would have benefited from the analytical tools available today, holding for available materials and systems, the building form would likely have been different. Improvements in Kahn's building would result from a combination of factors including a better relationship between building form, fenestration, articulation and thermal performance. Accepting aesthetic standards of his day, this study challenges the notion that the design of a gifted architect cannot be improved without undermining the overall read of well-proportioned and articulated composition. By focusing on performance at the level of building enclosure, the paper touches on questions of the boundaries of where modifications that improve performance either enhance or undermine the original authorship and intent.

OBJECTIVES

A primary goal of the study is to support the notion of design as human endeavor situated in a context in which the designers and other participants negotiate possibilities, limits, and tradeoffs. Optimization in this context is an extension of this process in which the decision making process is enhanced and results improved. However, the way that architects see works of canonical architects limits perspective to one of completion or perfection. The study of a lesser-known works by renowned architects offers opportunity to revisit the design without offending established legacies, and provides an avenue to generate interest in the intersection between form and performance (Mussauvi. 2006).

Figure 1*: Photograph of Radbill addition to the Philadelphia Psychiatric Hospital circa 1953 (Source: The Louis I. Kahn Collection, University of Pennsylvania and the Pennsylvania Historical and Museum Commission).*

SUBJECT

The study subject is a psychiatric hospital at the western edge of the city of Philadelphia designed by Louis Kahn and constructed between 1950 and 1953, and featured on a two pages in *Solar Control and Shading Devices* (Olgyay & Olgyay. 1957). When first opened, the addition was linked to the main hospital building by a narrow corridor. Named the Radbill Building, the 30,000 sf building was originally clad with slate panels, exposed concrete and steel windows. The lowest level contained a kitchen and cafeteria, the first floor communal spaces and offices, the second long overnight patient rooms, and the uppermost floor contained active patient treatment spaces (Fig. 2).

The building has three stories of exposure on the front façade and four stories of exposure at the rest of the elevations due to elevation change. Horizontal ribbon windows are shortest on the upper level, and progressively become taller on the lower levels, which corresponds to the use patterns inside. The southwestern and southeastern facades of the building incorporate shading devices that include terracotta chimney flue units used to create perforations set in extension of the concrete floor slabs. The extension of the shading devices roughly corresponds with the height of the windows so that they extend further at the lower levels of the buildings with the extents repeating themselves above the middle two levels at Southeastern exposure (Fig. 3).

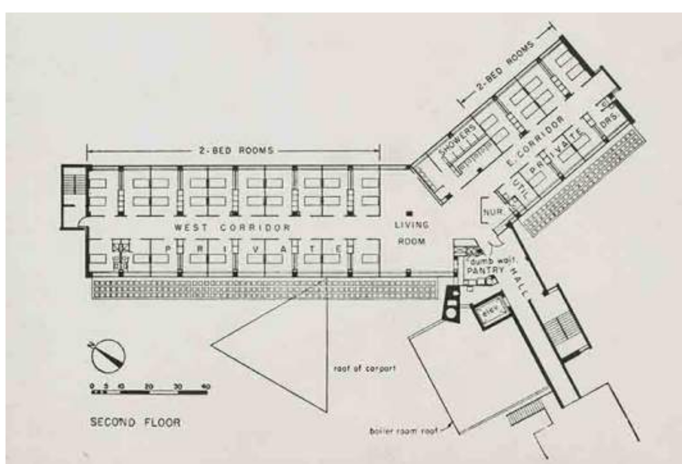

Figure 2: Plan drawing of second floor of Radbill addition to the Philadelphia Psychiatric Hospital, circa 1953. (Source: The Louis I. Kahn Collection, University of Pennsylvania and the Pennsylvania Historical and Museum Commission).

HISTORICAL CONTEXT

When Kahn designed the hospital in the early 1950's, the United States had recently emerged from the resource scarcities and rationing of materials caused by World War II. Concentrated building activity due to the postponement of construction during the war, and the returning veteran population contributed to continued acuteness of material and skilled labor scarcity. The post-war era contained the first iteration of non-vernacular energy conscious design, supported by scientific advancements in understanding that included the relationships between environment, building materials, and design. Significant in this effort was the introduction of the R-value concept to building materials after 1945 in the United States (Moe. 2014). R-value was a manageable method of understanding thermal performance of building components across different interests in the building industry including designers, product manufactures, and building officials.

During the period between the introduction of R-value and the 1970's when mandated national testing standards made R-values associated with assemblies more reliable, architects' use of R-values along with climate information, solar-dome templates, and other diagrams were crude at best. Architects' ability to anticipate thermal performance was limited to their ability to mesh material and climate data with design parameters through simplified calculations or intuitive judgments based on notions of how specific design strategies might mitigate the effects of climatic extremes on thermal performance and energy use. For an architect like Kahn, improved thermal performance would be a bonus feature, complementary to functional and aesthetic objectives. Additionally, time limitations and change during the design process limited the viability of utilizing the type of exhaustive calculations demonstrated by the Olgyay brothers in their seminal books. Difficulty connecting calculations to designs was evidenced by the fact that the case studies in *Solar Control and Shading Devices* were not accompanied by the detailed analysis outlined in the first half of the book.

METHDOLOGY

For purposes of this study, the building was modeled in Revit, allowing for compatibility with common energy analysis software platforms and to allow for detailed modeling of façade elements, including the custom shading elements. The basis for the model came from dimensions available from the original architectural and engineering construction design drawings, currently archived at the University of Pennsylvania (Fig. 2). Historical and contemporary photographs of the building were used to check the accuracy of the construction drawings. The building extent was drawn at the edge of the bar shaped program spaces adjacent to the circulation element that connects the new wing to the original hospital building. This circulation element contains vertical transportation elements that were not factored allowing for isolation of primary usable spaces at the perimeter of the building. The geometry of the circulation mass was included in the model for context. Thermal resistance values of the original building construction provided a point of comparison with contemporary insulation values. The study used the default environmental systems performance standards internal to the analysis software.

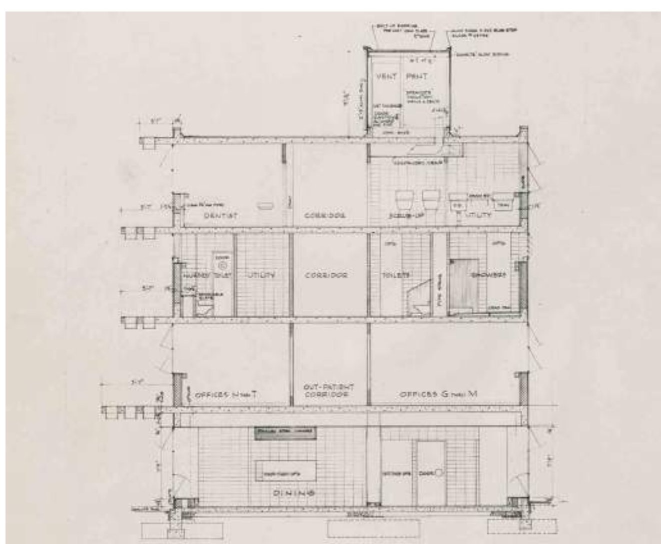

Figure 3*: Section of the Radbill addition to the Philadelphia Psychiatric Hospital. (Source: The Louis I. Kahn Collection, University of Pennsylvania and the Pennsylvania Historical and Museum Commission).*

BASE SCENARIOS

A digital model based on the existing materials and geometry served as the basis for four analytical energy simulations. A purpose of the comparisons was to establish the impact the shading devices had on the overall energy performance of the building. The first modeling scenario (#1), used as a baseline, reflected the given building geometry and shading device extents. An alternate scenario (#2) involved removing all of the shading devices from the analysis to determine the overall effect of the shading devices on energy use. Two other scenarios (#3 and #4) involved removing the shading devices from one wing of the building, while retaining the devices on the other wing. The intention of the later comparison was to determine which shading devices had the greatest effect on positive energy performance. Energy simulations of different scenarios were run through Sefaira, which was chosen for fluidity of testing geometrical alternatives and its suitability for use by architects in early design phases.

VISUAL ANALYSIS OF BUILDING GEOMETRY

A key intention of the study was to learn about the effectiveness of the shading devices and point to adjustments in the devices or openings that would contribute to increased energy efficiency. The vertical extent of windows on each floor of the existing building are based on a regular increment of 32 inches so that the ratio of windows on the different levels are 32 inches, 64 inches and 96 inches (A, B, and C in Figure 4). Because of the regular increase in heights, correspondence with program, and limited room for additional height at the highest window, these dimensions are fundamental to the symmetrical nature of the design.

Although an initial observation can lead to the conclusion that the shading devices increase in extent based on a comparable increase in window heights, further analysis determined that they loosely correspond. The extents of the shading devices are 43 inches, 67 inches and 91 inches equating to a ratio of ***1:1.6:2.1***. This compares to the ***1:2:3*** ratios of the window heights [figure 4]. A close examination of the shading device section points to conditions that contributed to the irregular progression of device extents at the different levels. First, the devices incorporate standard terracotta chimney inserts, which are vertically aligned at all levels. Second, the distance between the inserts and the front edge of the devices are consistent at all levels (Fig. 5). This left the dimension between the innermost insert and façade edge as the variable dimension.

The apertures formed by the chimney inserts are vertical and do not contribute to encouraging light transmission when the sun is low in the horizon as opposed to when it is higher during the warm season. Kahn could have rotated the inserts on their horizontal axis, although the ridged geometries favored in the era and by Kahn across his career would have formed a point of resistance to this type of deviation. Kahn would have also been interested in the visual effect of light reflected through the apertures, which is evident in the photographs commissioned at the time of the building commissioning [Figure 1.]. This effect would still occur if the apertures where not directly aligned and most likely was less critical to the design team than the regularity of the building section.

SCENARIO ANALYSIS RESULTS

Analysis included different scenarios, including historic insulation, contemporary insulation and two different uses scenarios. The Rabill wing is an inpatient facility with private rooms on one floor and cafeteria and support on another. The remaining two levels were for treatment and resembled a hospital. For these reasons, scenarios were tested using a hybrid of heath and residential load factors. Under all conditions, the results showed similar contrasts, the most important being that the shading devices on the short wing provided over two times (2.08 for original construction and 2.1 for contemporary construction) the overall net benefit to the energy performance of the building. Considering that the long wing contain 66% of the overall length of shading devices, the overall effectiveness of the short elevation shading devices is 4 times as effective than those of the long elevation which is closer to a western facing elevation than a southern elevation. This prompted tests of the adjustments to the short wing devices. Decreasing the depth of the devices reduced overall energy performance, and extending them increased the performance confirming their effectiveness.

OPTIMIZATION

The building's ribbon windows are consistent in height along the west and south exposures and their height generally corresponds to program needs. In this case, the upper level functions are more private, warranting less glazing. Without sacrificing the module, there is little room to expand the vertical extent of the glazing. Little scope to adjust fenestration, and economy of space heights in the early fifties, pointed to the shading devices as the flexible component of the design.

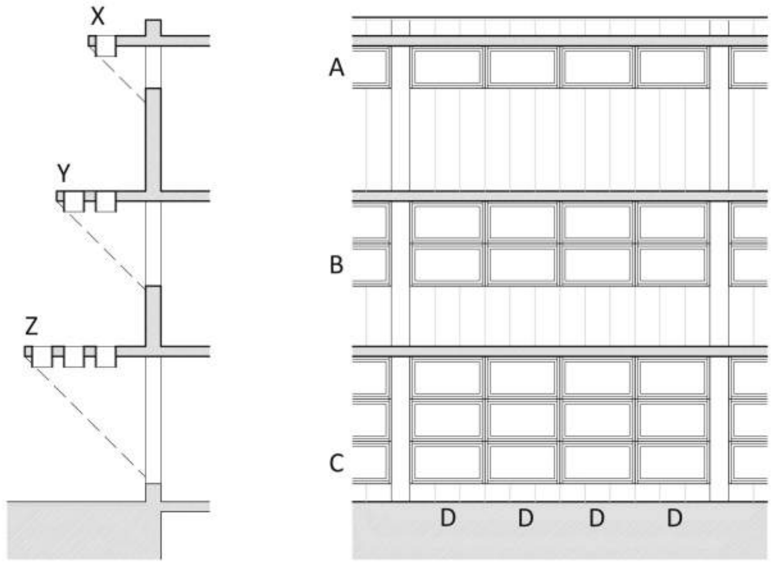

Figure 4: Diagram Section and Elevation (Drawings by author).

FINDINGS

Simulations performed for this study revealed that the shading devices on the long front elevation of the hospital do not perform a net positive benefit to building energy performance under multiple energy use and building construction scenarios. The shading devices on the short wing of the building do provide a positive benefit under the same scenarios. Extending the depth of the shading devices on the short wing did result in better performance, however the extent of the shades is already long for the construction standards of the era of construction and contemporary times, exclusive of extreme cantilevers. Since the shading depths progressively increase toward the lower levels, the fist level shades should have extended two feet further to match the basement level device. This could have occurred without upsetting the rules in play for the design. Increasing a device depth on the short wing would also have significantly less impact on the read of the building since it is oriented inward on the site.

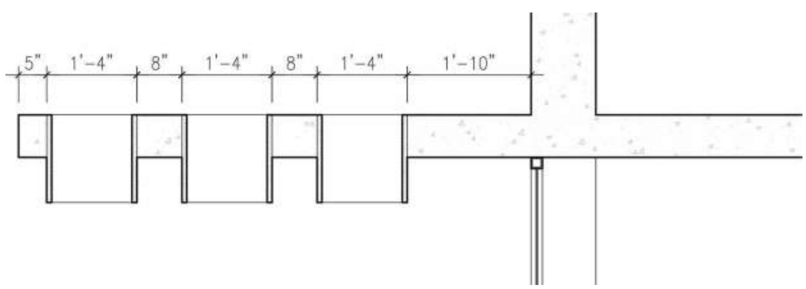

Figure 5: Detail Section at Lower Level Shading Device (Drawings by author).

Eliminating or significantly altering the shading strategy on the long wing would have greater implications toward the read of the building. Introducing vertical shading devices would imply a difference between the two wings and compromise the reading of light reflected through the baffles across the façade. Vertical elements would also counter the horizontal read of the ribbon windows. Another alternative would have been to eliminate the shading devices on the long wing altogether in the original design. The later would have required a radical reconsideration of how arrive at visual interest on the façade and would have eliminated the positive effect of technological action from a design leader.

FUTURE IMPLICATIONS

The study of the history of architecture, including building technology and project delivery methods, is important despite the forward perspective that many practitioners and academics maintain. Although discourse on many of the characteristics that shaped practice in the past receives peripheral attention, study of the work of seminal architects persists. Attention to the work of these architects typically is celebratory and limited to visual significance, limiting knowledge that can be gleamed from the work. Although many buildings have been lost, or modified, opportunities to digitally model buildings and gain information from the models offers opportunities to gain greater understanding of the buildings without necessitating in-person visits. Knowledge derived from the study of older buildings can be freely shared, something that current practitioners are reluctant to do with recent work. The virtual world also allows for experiment and adaptation, making older buildings ripe candidates for revision in light of contemporary techniques.

REFERENCES

Boubekri, M. 2008. *Daylighting, Architecture and Health: Building Design Strategies*, Architectural Press, Oxford.

Lawson, Bryan & Dorst, Kees, 2009. *Design Expertise*, Oxford, Architectural Press, Oxford.

Malgrave, Harry Francis, 2013. *The Architecture of Embodiment: The Implications of the New Sciences and Humanities in Design*, Routledge, New York.

Meek, Christopher & Van Den Wymelenberg, Kevin. 2015. *Daylighting & Integrated Lighting Design*. Routledge, New York.

Moe, Kiel. 2014. *Insulating Modernism: Isolated and Non-Isolated Thermodynamics in Architecture,* Birkhauser, 2014.

Mussavi, Farshid. 2006. *The Function of Ornament*, Actar, New York.

Preiser, Wolfgang & Davis, Aaron. 2015. *Architecture beyond Criticism*, Routledge, New York.

Olgyay, Victor. 1963. *Design with Climate: A Bioclimatic Approach to Architectural Regionalism*, Princeton.

Olgyay, Aladar & Olgyay, Victor. 1957. *Solar Control & Shading Devices*, Princeton.

CIRCADIAN DAYLIGHT IN PRACTICE

Determining a simulation method for the design process

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ABSTRACT

Light is essential. It enables our perception of form, color, and texture. It is critical to human health, influencing circadian rhythms and our energy, mood, and productivity. Light is the major synchronizer of the human circadian system and suppresses melatonin, the hormone that induces sleep and can cause drowsiness, loss of productivity and insomnia. People spend much of their time in buildings, and the building façade is the membrane that allows and controls access to daylight and thus circadian function.

Emerging research into circadian stimulus led the Well Building Standard to propose and implement new metrics for assessing the circadian stimulus provided by both daylight and electric light. These new metrics require innovative approaches to simulation and means of interpreting data to assess circadian lighting potential during the design process.

Though designers are beginning to look to electric lighting to provide improved circadian function, the first step in designing to support circadian system function should be to ensure access to daylight through massing and façade optimization. Undertaking daylight simulation early in the design process is critical to carry this out for any complex building design. This team has developed two distinct circadian daylight simulation workflows for analyzing the effectiveness of a building design for delivering circadian system benefits, as measured using Equivalent Melanopic Lux (EML). The first method is based on illuminance on a horizontal plane. The second examines multi-directional vertical illuminance. This paper explains each simulation process and evaluates the comparative benefits of undertaking each simulation method.

Daylight is the most effective way to provide the health benefits of circadian lighting, and new methods for measuring and simulating daylight in buildings are critical to ensuring that façade and building designs respond to the most appropriate drivers.

KEYWORDS

daylighting - glare - shading, circadian lighting, WELL Building Standard, design processes, codes - standards - rating systems
computational design, advanced numerical computations, design optimization, Radiance, Honeybee, Grasshopper, DIVA

INTRODUCTION

The provision of lighting that delivers circadian system benefits is growing to be an important health factor in the built environment. Burgeoning research on this topic is contributing to an ever-increasing body of evidence that our circadian response to sky glow, light trespass, glare and over- or under-illumination affect our health and well-being (Panda et. al. 2015). While the scientific research linking circadian light, health, and buildings is still emerging, the impetus seems clear – to the extent possible, building design should enable occupant access to optimal levels of daylight whenever possible, supplemented with appropriate electrical light when necessary.

Practically speaking, implementing this imperative can be tricky and difficult to verify in terms of effectiveness during the course of design process. For daylighting in a project, well-known rules of thumb are useful as initial design guidance for simple buildings. However, buildings with complex floorplates, ambiguous or changeable floorplan layouts, and heterogeneous façade strategies require more detailed analysis to verify that the design fulfills the intent to provide quality circadian lighting primarily through daylight.

This paper seeks to explore and elucidate two viable methods for conducting daylight simulations that verify whether a design achieves effective implementation of circadian daylight. The purpose is to weigh the relative efficacy of each of these emerging analysis methods, as well as their relative merits in interaction with other daylighting metrics.

The proposed simulation methods reinterpret standard daylight simulation results in light of emerging circadian lighting metric. Neither of these simulation methods have been verified or benchmarked against actual circadian stimulus performance in a built project, although the underlying Radiance and Daysim simulation engines have been extensively validated (Reinhart, 2009).

BACKGROUND

The WELL Building Standard recently emerged as a viable benchmarking standard for the human health and wellness performance of a building. GBCI, the same certification body that manages LEED project certifications, administers certifications under the standard. The WELL Building Standard uses evidence-based metrics for measuring and monitoring the performance of building features that affect health and well-being, including circadian lighting. The illumination guidelines of WELL Building Standard for Light are aimed to minimize disruption to the body's circadian system, enhance productivity, support good sleep quality and provide appropriate visual acuity where needed (WELL, 2016).

The WELL Building Standard uses Equivalent Melanopic Lux (EML) as a metric for measuring the biological effects of light on humans. Photosensitive retinal ganglion cells (ipRGCs) regulate the human circadian response to light. These are non-image forming photoreceptors within the eye. Lux is the traditional SI measurement of illuminance and the eye's response to light, and is associated with the cones within the eye. EML as a metric is weighted to the ipRGCs response to light and translates how much the spectrum of a light source stimulates ipRGCs and affects the circadian system (WELL, 2016).

Below is an excerpt from the WELL Building Standard describing the proposed measurement method for the circadian lighting requirement:

> "Light models or light calculations (which may incorporate daylight) show that at least 250 equivalent melanopic lux is present at 75% or more of workstations, measured on the vertical plane facing forward, 1.2 m [4 ft] above finished floor (to simulate the view of the occupant). This light level is present for at least 4 hours per day for every day of the year" (WELL, 2016).

The EML metric, measurement method, and type of analysis proposed above is easier to apply in a fully resolved design with established workstation locations. It is more difficult to apply to a design that is not fully developed or a project with a program with flexible workspaces where the location and orientation of workstations may change throughout the day and year.

At the time this paper was written, the WELL Building Standard certified just eight projects and the authors were unable to find published case studies showing applications of an analysis method for the WELL EML requirement. As such, design teams adopting this metric face the challenge of interpreting the language of the standard despite a lack of background information or precedent. For a design that is in flux, what is the best way to approach the EML metric to evaluate design options?

One of the most important factors to evaluate when designing to meet the EML target is the availability of daylight. Not all light sources are equal in terms of circadian stimulus (CS). Daylight is the best option for both energy efficiency and CS because it requires no energy input and the wavelength spectrum of daylight closely aligns with circadian stimulus (al-Enezi, 2011). If daylight is not available or sufficient, electric lighting can be used to provide circadian stimulus, but requires additional energy and has a greater first cost. Color variable LEDs are available that are designed to provide circadian stimulus with low energy consumption. During the design process, the energy efficiency of a light source should be weighed against its performance as a circadian stimulus. If the design team does not optimize a building for daylight access while considering the EML requirement, the project will require a more expensive electric lighting system that consumes more energy than would otherwise be needed in order to achieve the EML target. This results in increased lighting first cost, operational cost, and carbon emissions over time. See the table below, provided by WELL building standard that shows the factors applied to each light source's efficacy with respect to melanopic lux:

CCT (K)	LIGHT SOURCE	RATIO
2700	LED	0.45
3000	Fluorescent	0.45
2800	Incandescent	0.54
4000	Fluorescent	0.58
4000	LED	0.76
5450	CIE E (Equal Energy)	1.00
6500	Fluorescent	1.02
6500	Daylight	1.10
7500	Fluorescent	1.11

Table 1: Melanopic Ratio provided by the WELL Building Standard (WELL, 2016)

Table 1 assigns a melanopic lux ratio to each source of light based on its Correlated Color Temperature (CCT). It is clear in looking at the Melanopic ratio table, daylight is one of the most effective light sources for melanopic lux. Daylight is a source of 'free' lighting if the tradeoffs with solar heat gains and thermal losses are carefully controlled.

METHOD

Two methods used to determine achievement of the Equivalent Melanopic Lux metric are compared here. These methods can be used early in the design process, when floor plans may not be determined, to assess circadian daylight potential. These proposed methods also allow for the integration of dynamic façade controls and automated blinds, which significantly affect daylight levels, but are not accounted for in the WELL standard.

This study does not account for other considerations that may influence the introduction of useable daylight in a space, including useful illuminance levels, potential for glare, thermal comfort, and heat gains.

METHOD 1 – TRANSFORMED HORIZONTAL ILLUMINANCE

The WELL standard requires a circadian lighting level of 250 lux at the vertical eye level, which translates to 227 lux from daylight when the daylight multiplier from the WELL Appendix Table L1 is applied. The vertical illuminance at eye level from daylight is estimated by dividing the horizontal illuminance at the workplane by two, which is based on the calculation methodology described in "Conceptual design metrics for daylighting" (Leslie et al, 2011). Based on this calculation, an analysis point on the horizontal plane achieves circadian autonomy when it demonstrates at least 466 lux from daylight for at least four hours a day.

An annual daylight analysis was conducted for a grid of points applied to the horizontal workplane of a typical office floorplate using DIVA for Rhino, a graphical interface for the Radiance ray-tracing program suite. The Radiance analysis produces an illuminance file that contains a daylight illuminance level at each point for every hour of the year. A python script was used to post-process the file and determine which points met the circadian daylight threshold for the minimum hours per day. The results were re-imported into Rhino for visualization as well as to determine the area of the floorplate meeting the WELL threshold.

METHOD 2– MULITI-DIRECTIONAL VERTICAL ILLUMINANCE

This method does not use horizontal values to estimate vertical illuminance, but instead accounts for differences in orientation and location by testing vertical illuminance in multiple orientations for a grid of points applied across a study area. The vertical illuminance for every hour of every day in eight evenly oriented directions was calculated for each point using the Radiance program accessed through the Rhino/Grasshopper/Honeybee environment, which allows for detailed manipulation of daylight simulations. The resulting illuminance file was then post-processed with a custom python scrip that determined the number of days per year that each orientation for each point met the WELL Building circadian standard.

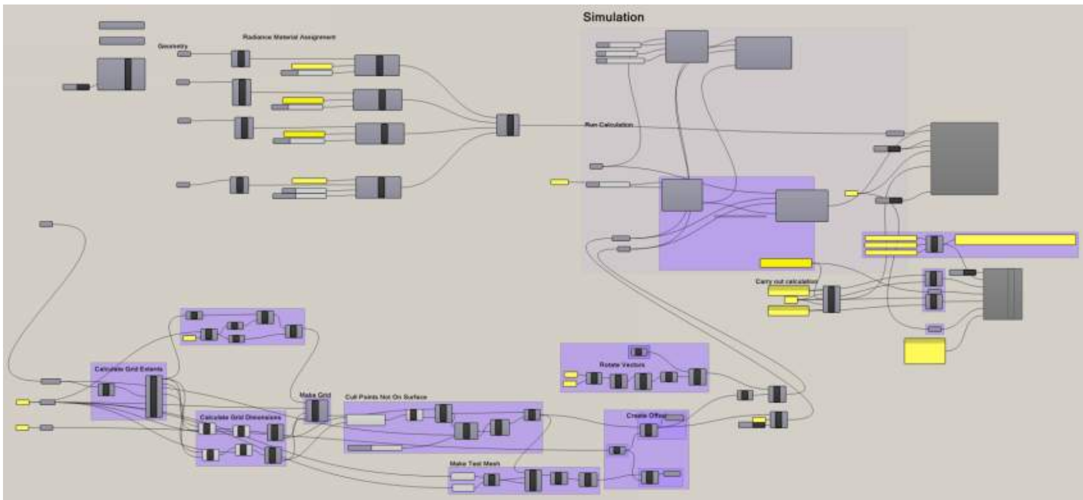

Figure 1: Grasshopper definition used to calculate vertical illuminance in multiple orientation for multiple points (Image courtesy of the author).

DATA

The results for both methods, tested on a typical office floorplate are shown below. A detailed comparative study of the two methods is also included.

METHOD 1 RESULTS – TRANSFORMED HORIZONTAL ILLUMINANCE

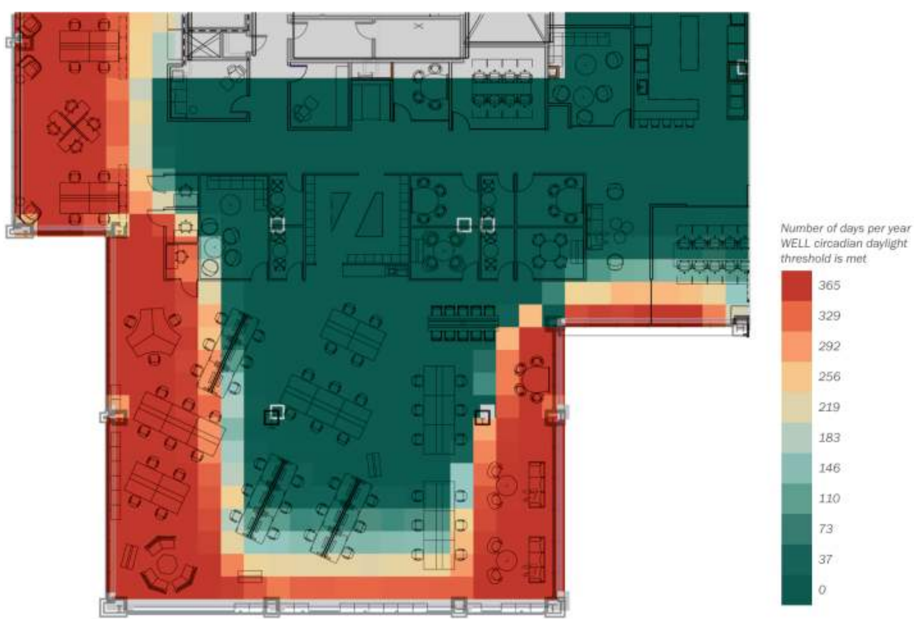

Figure 2: Method 1 circadian daylight results. The areas in red are projected to meet the threshold of at least 4 hours per day every day of the year (image courtesy of Atelier Ten).

METHOD 2 RESULTS – MULITI-DIRECTIONAL VERTICAL ILLUMINANCE

Figure 3: Method 2 circadian daylight results. A point with a view facing any of the yellow orientations in a given location meets the WELL circadian threshold (image courtesy of Atelier Ten).

COMPARATIVE RESULTS – DETAILED STUDY

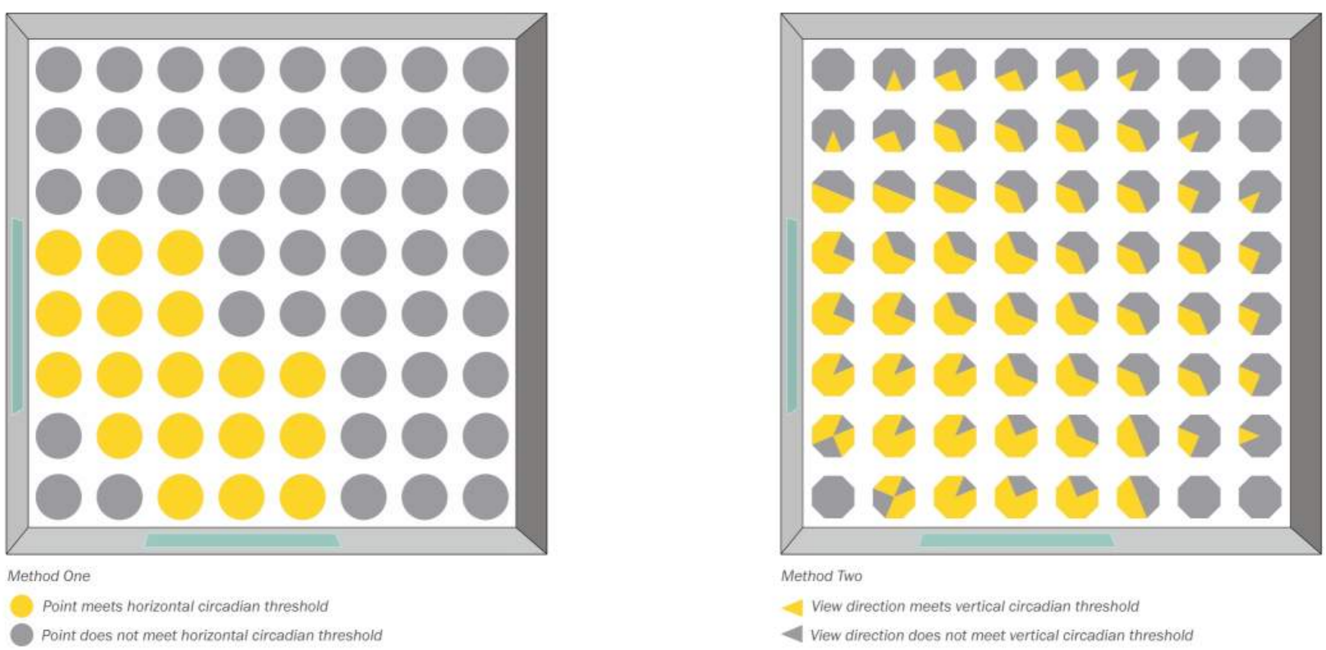

Figure 4: Results showing a direct detailed comparison of the two simulation methods (image courtesy of the author).

DISCUSSION

Method 1 can be simulated in Radiance through DIVA for Rhino or other Radiance interface and can be post-processed from a standard illuminance file produced with less computational resources than Method 2. Method 2 requires approximately eight times the computational resources than Method 1 because multiple illuminance values are calculated for each point.

While Method 1, the horizontal plane analysis method, allows a relatively quick general indicator of the circadian daylight level achieved, this study shows that it underestimates access to circadian daylight at a given point on the plane. This method does not account for directionality of light and workstation orientation at any location, but gives a good general idea of circadian daylight levels in a space and the simulation can be run quickly. Because the method does not account for the directionality of daylight when translating horizontal illuminance to vertical illuminance, the results may not accurately reflect the amount of circadian light available to an occupant, because light levels at the eye will change depending of the orientation of the occupant. However, the quick computation time and general assessment of circadian daylight can be useful to a designer. Also, the metric and representational method of a graduated color scale indicates whether a point is close to the threshold, allowing designers to assess whether design changes will be effective in increasing the area with circadian daylight.

Method 2, which shows multi-directional vertical illuminance, while more complex to set up and run, gives a clearer understanding of the opportunities available to maximize access to circadian daylight at each point on the grid. The directional display allows seating layout and orientation to be optimized to provide view orientations that achieve circadian levels through daylight alone. By correlating seating layout views to the circadian daylight available, as well as strategically placing transient program areas in locations that do not have adequate access to circadian daylight, the necessity for supplemental circadian electric lighting in workstation areas can be minimized. As currently displayed, Figure 3 shows whether a direction at a point meets the circadian daylight standard—essentially binary compliance/non-compliance information. This limits the amount of information available to a designer.

Figure 4 shows a direct comparison of the two methods and illustrates how Method 1 underestimates the amount of circadian daylight available within a space. The complaint area in Method 1 is clustered near the windows, which the Method 2 compliant areas are spread throughout the space, although weighted towards the window. The orientation of the view at each point also significantly affects compliance in Method 2. Overall, about 40% of the area included in the Method 2 study is compliant, while almost 30% of the area is compliant in Method 1. Comparing the simulation methods shows that Method 2 should always be used when time and computational resources allow because of increased accuracy and finer grained results. The translation of horizontal to vertical illuminance in Method 1 introduces problematic risk of inaccuracy into the results, making this method only appropriate as an initial general indicator and not for detailed design decision making.

DAYLIGHT ASSESSMENT LIMITATION

Circadian daylight does not operate independently of other daylight metrics. Because the WELL building standard uses a minimum daylight level to show compliance, the potential for over-illuminance is not considered. High levels of illuminance, including direct daylight, may cause localized glare causing occupants to draw blinds or orient away from the light source, which reduces the potential for circadian stimulus not accounted for by the metric. Because the WELL standard does not explicitly call for blinds to be part of the simulation, simulations may overestimate the circadian daylight available. Automated blinds may be preserve more of the useable daylight in a space, but manual blind deployment is unpredictable and occupants may leave blinds deployed when daylight is available, eliminating the desired circadian stimulus.

The circadian metric may not accurately reflect useable daylight within a space because it is based on a minimum threshold of four hours a day. Meeting the WELL circadian standard does not demonstrate useable daylight in a space. Useful Daylight Illuminance or Spatial Daylight Autonomy is more appropriate to determine useable daylight as these metrics are percentage based and account for all potential daylight hours.

CONCLUSION AND FUTURE WORK

Either of the proposed analysis methods can be used throughout the design process to assess circadian daylight in a space. Because both metrics assess circadian daylight across the entire floorplate, neither metric complies perfectly with the WELL Building standard. However, the results can be used early in the design process to determine if progress is being made towards the standard.

Method 1 is easier and faster to implement, but is less accurate and may be appropriate for quick circadian studies for making massing and rough electric lighting decisions. It may be only appropriate for comparative studies of multiple options when time and computational resources are constrained.

Method 2 is approximately eight times more computationally intensive than Method 1, but more accurately reflects circadian daylight within a space by accounting for directionality. Use of this method can help make fine-grained decisions about use zoning within a building, floorplate layout, and workstation orientation and further refine a design.

The proposed circadian daylight analysis methods easily integrate into the design process to assess circadian daylight potential, but do not holistically address the full range of daylighting concerns in a project. Circadian daylight simulation should be used early in the design process, but must be coupled with traditional daylight analysis to evaluate illuminance levels and glare potential throughout the year. Because the proposed simulation methods look at such a narrow issue, the impact of design decisions based on circadian daylight need to be assessed in relation to potential for increased energy consumption from conditioning energy, visual glare potential, and useable daylight.

FUTURE WORK

Using these results, this team will develop a tool to verify designs for the WELL building standard. This will ideally take place in collaboration with WELL or GBCI, to verify the methodology and get approval for use of this type of analysis within the benchmarking workflow. Analysis option 2 may be appropriate for documenting compliance with the WELL Building Standard 54 Circadian lighting design, which could eliminate or reduce the need to simulate each workstation individually in a flexible workspace, reducing the time needed to produce documentation.

Method 2 requires further refinement of the graphic representation to convey more information to the designer about degree of compliance with the circadian lighting threshold, not only compliance/noncompliance information.

Future work to integrate dynamic electric lighting into simulations can determine the minimum amount of electric lighting needed to provide sufficient circadian daylight, minimize energy consumption, and reduce first cost of combined electric lighting system and automated shading system. In addition, a more detailed assessment of how circadian daylight interacts with other daylight metrics including glare and useable daylight is needed.

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REFERENCES

al-Enezi, Jazi, Victoria Revell, Timothy Brown, Jonathan Wynne, Luc Schlangen, Robert Lucas, "A 'Melanopic' Spectral Efficiency Function Predicts the Sensitivity of Melanopsin Photoreceptors to Polychromatic Lights," *Journal of Biological Rhythms*. 26 (2011) 314-23. Link to paper accessed June 17, 2016. http://personalpages.manchester.ac.uk/staff/robert.lucas/al%20enezi%20et%20al%2011.pdf

Reinhart, Christoph, Pierre-Felix Breton, "Experimental Validation of '3ds Max Design 2009' and 'Daysim 3.0'." Paper presented at Building Simulation 2009, Eleventh International IBPSA Conference, Glasgow, Scotland. July 27-30, 2009.

Illuminating Engineering Society of North America*, IES Spatial Daylight Autonomy (SDA) and Annual Sunlight Exposure (ASE). IES LM-83-12.* New York, NY: IES, 2012.

International Well Building Institute, *The Well Building Standard v1.* New York, NY: Delos Living LLC, 2016.

Leslie, RP, LC Radetsky, and AM Smith, "Conceptual design metrics for daylighting," *Lighting Research & Technology* 0 (2011): 1–15. Link to paper accessed June 17, 2016. http://lrt.sagepub.com/content/early/2011/10/20/1477153511423076.full.pdf+html

Lucas, Robert J, Stuart N. Peirson, David M. Berson, Timothy M. Brown, Howard M. Cooper, Charles A. Czeisler, Mariana G. Figueiro, Paul D. Gamlin, Steven W. Lockley, John B. O'Hagan, Luke L.A. Price, Ignacio Provencio, Debra J. Skene, George C. Brainard, "Measuring and using light in the melanopsin age," *Trends in Neurosciences*, 37-1 (2014.): 1-9. Link to paper accessed June 17, 2016.
http://personalpages.manchester.ac.uk/staff/robert.lucas/Lucas%20et%20al%2014.pdf

Panda, Satchidananda, Frederick Marks, "Circadian Lighting for Health," *ASHRAE Journal* 57-11 (2015): 84-86.

Rea, Mark S, Mariana G Figueiro, Andrew Bierman, John D Bullough, "Circadian Light," *Journal of Circadian Rhythms* 8-2:(2010).

THE EFFECTIVENESS OF "SUDARE"

External shading for energy efficient and visibility quality in Jakarta


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ABSTRACT

Nowadays, existing modern office high-rise buildings in Jakarta have used high performance curtain glass wall without shading devices. This practice has resulted in high cost building construction, operational and maintenance. It also decreases the thermal comfort of the outside environment and contributes to the urban heat island phenomena. Recently, Jakarta has implemented a new standard for new building construction to reduce the energy consumption of office buildings. It has to meet the minimum Overall Thermal Transfer Value (OTTV) of 35 watt/m2. With this standard, it is almost impossible to use normal curtain glass. The only option is using very high performance glass or reducing the window to wall ratio (WWR) and using shading devices.

In tropical countries, the most effective way of passive design strategy is using shading devices. They will block or reflect direct solar radiation before reaching the facade. The amount of solar radiation that can be blocked by the shading devices depends on their physical characteristics, while building regulation also requires an outside view from inside the building to reduce the sick building syndrome. Dense shading will increase the effectiveness of reducing energy consumption but will decrease the quality of opening visibility. Sudare is a traditional Japanese blind made from bamboo. It has been used in Japanese houses since a long time ago, especially in summer. It originally has a function to prevent direct solar radiation and introduce natural ventilation. The form characteristic of Sudare makes it possible to see-through objects outside the house.

The aim of this research is to identify an alternate way of facade configuration using external horizontal blind based on the Sudare form to meet the minimum standard of SNI with better efficiency in terms of thermal energy used to minimize the use of energy consumption and maintain the visual comfort. It will change the mindset and the way architects design new buildings and retrofit the existing or old buildings using shading devices as part of their designs.

Ladybug and Honeybee inside the Grasshopper plugin of Rhinoceros 3D with the Energy plus engine will be used to simulate standards building as baseline performance and buildings that use different dimension and spacer of Sudare blind as shading device parametrically.

Based on this study, the optimum form of Sudare blind with a diameter of 10.01 mm and 5 mm spacer have achieved 66% decrease of OTTV and 36% efficiency of thermal energy used compared to the baseline building. The performance is close to Tint Glass with solar heat gain coefficient of 0.2 and T vis 0.2. The visibility value of this configuration is 2.65, close to the visibility of tint glass with T vis of 0.2 (2.92), and the privacy is 4.27, much better than tint glass (3.38).

KEYWORDS

SUDARE, horizontal shading, Energy Conservation, Parametric Analysis, energy efficiency, OTTV

INTRODUCTION

It is estimated that at present, buildings contribute as much as one third of total global greenhouse gas emissions, primarily through the use of fossil fuels during their operational phase. The building sector contributes up to 30% of global annual greenhouse gas emissions and consumes up to 40% of all energy (UNEP-SBCI, 2009). Architects who 'play a key role' in building design have a responsibility to minimize the use of energy through good and environmentally friendly building design. They have to design buildings that use less energy in the design phase, construction phase and operational phase, even sometimes by retrofitting existing or old buildings.

In Jakarta, the capital of Indonesia, the sun is always available the whole year. The weather is hot and humid with an average outside temperature 29oC and average humidity 75%. The thermal energy problem in this area is the high demand of cooling energy. Nowadays, people like to have buildings with curtain glass wall as the facade. Not only does this phenomenon increase the cooling energy demand, it also changes the micro climate around the buildings, which causes urban heat island. To control the use of energy, the Government of Indonesia released some standards regarding the performance of building skin. One of the standards that has to be followed when designing building façade is the overall thermal transfer value (OTTV). It is the average value from the solar radiation through fenestration surface, conduction from glass material and conduction from wall surface. In 2011, the Government of Indonesia has set the standard for OTTV, which is 35 watt/m2 (BSNI, 2011b), while before 2011 the standard was 45 watt/m2. The impact of this new standard is the decrease of cooling energy demand for buildings. This regulation is appropriate to be implemented in high-rise buildings, and most of the high-rise buildings in Jakarta are office buildings and mix-used buildings between commercial and office buildings. This kind of buildings has used energy mostly for cooling system and lighting system. Cooling energy is influenced by external gain from their envelope. The components that affect the solar heat gain are glazing material, fenestration area, and orientation. This regulation has changed the way architects design the façade of buildings. Façade design becomes an important design element not only in maintaining the energy consumption but also in the architectural aspect. Façade also consumes a large portion of the construction and maintenance budget. The other function of façade is to connect with the environment. Each of the function can be measured from its thermal performance and visual performance. More opening will increase the visual performance. However, it will decrease the thermal performance.

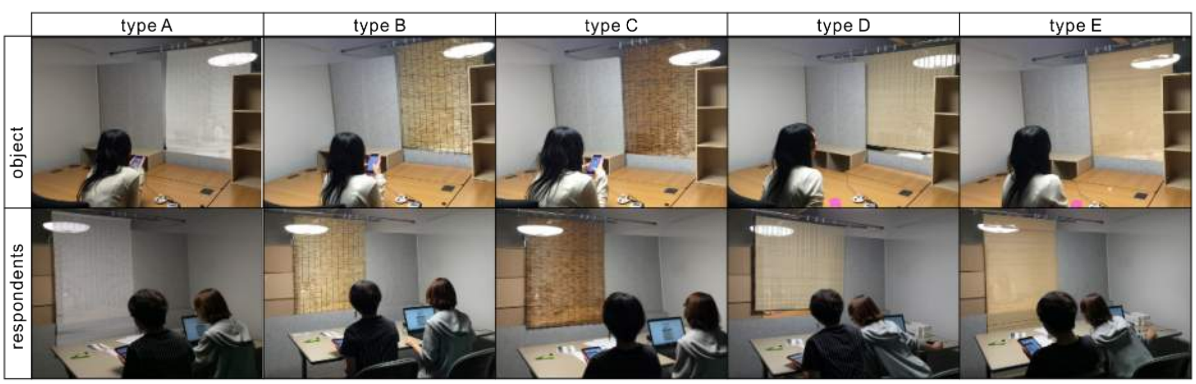
In Japan, Sudare has been used as an external shading and internal partition. Many traditional Japanese houses use Sudare as external shading to maintain thermal comfort inside the houses in the summer; it protects the houses from direct solar radiation but still introduces natural ventilation (figure 1). This passive design strategy is effective for landed houses in the sub urban area where the environment is still good and natural. Like in some Islamic architecture buildings, which use traditional porous wall, it can create uniform distribution of illuminance in the interior, resultin in a more direct relationship with the external environment and visual comfort condition (Ruggiero, Florensa, & Dimundo, 2009). As an internal partition, Sudare can divide a space into two or more different spaces with different functions and levels of privacy. In some conditions, people inside the room can see activities on the other side of the room or outside the house, although people outside the house could not see the activities inside. In an office building, another requirement for green building is to have an outside view for indoor health and comfort (IHC) criteria (GBCI, 2012). This condition makes Sudare have the potential to be implemented in high-rise buildings as a shading device with some modifications on material and construction technology.

There has been some research on visual comfort indices, but the scope of the index is mostly about glare and light amount or light quality (Carlucci, Causone, De Rosa, & Pagliano, 2015); the visibility of the outside view as a visual comfort index has not been researched yet. In theory, with the shading control strategy, it is also possible to optimize the visual comfort and reduce the energy demand of office buildings as part of the optimization of passive solar design strategy (Stevanović, 2013). From the perspective of architects, the optimizing strategy will be efficient when architects can simulate every strategy or the combination of strategies and estimate the performance of buildings using some energy simulation software (Shi & Yang, 2013).

Figure 1: Sudare blind in Japanese traditional building (view from outside to inside and inside to outside)

BACKGROUND

Sudare as a partition has a different perceived visibility value from occupants inside the building to outside, influenced by the different value of illuminance between the inside and outside. The more contrast illuminance value between them will result in a high visibility value. Some types of Sudare have been tested using a questionnaire involving 121 respondents in the experimental room with a controllable dimming light from 0 to 1000 Lux divided by Sudare blind (figure 2). The results show that the ratio of illuminance between different rooms is the main factor that affects the value of visibility. The combination of whiteness factor, scale, and the ratio between diameter and spacer of the Sudare has a correlation with the distribution band of the visibility value for each condition. In the low illuminance ratio, a bigger scale has a better visibility value, but in the high illuminance, a small scale has a better visibility value (Agus & Fukuda 2015).



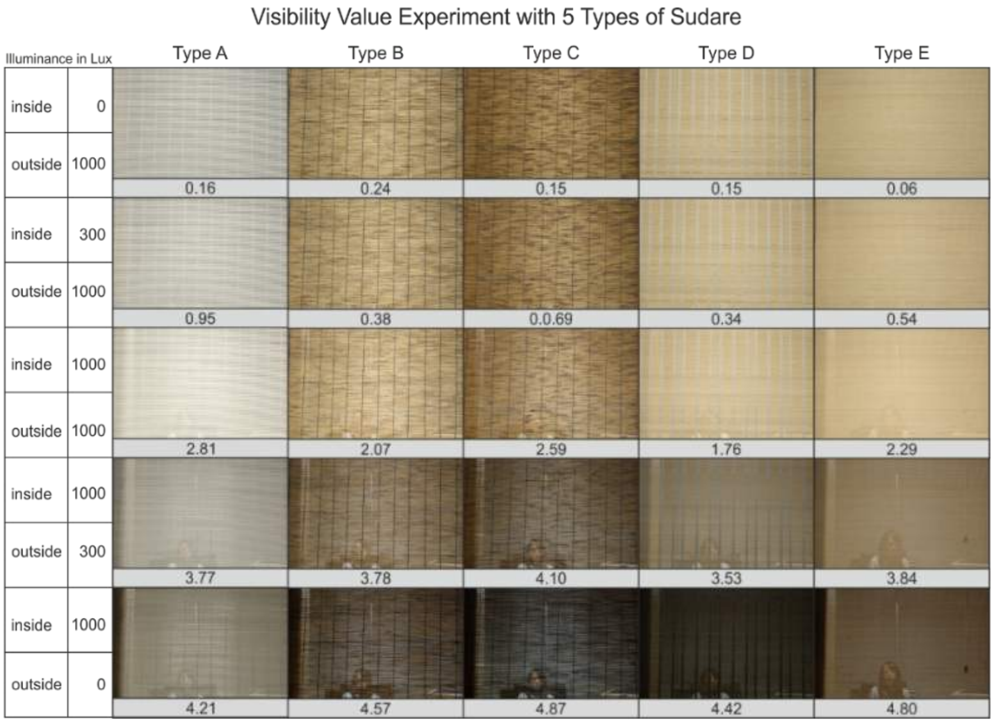
(source: Agus and Fukuda, 2015)

Figure 2: Experiment of visibility value base on illuminance different using questionnaire

The experiment was re-run using an image from the last experiment for 211 respondents. The results show the same tendencies like the previous experiment (figure 3). The meanings of each value are:

- 0: Cannot see the object;
- 1: Recognize the silhouette of the object;
- 2: Recognize the silhouette and the colour of the object;
- 3: Recognize the object and colour but not really clear;
- 4: Recognize and start to see the object and colour but does not catch the details;

- 5: Can see the object and colour and catch some details;
- 6: Can see the object clearly (identified the detail, colour).



(source: Agus and Fukuda, 2015)

Figure 3: Re-run Experiment of visibility value base on illuminance different

The visibility value between 0 and 2 is considered low, which means only a silhouette is seen, but the object is not recognized. However, for privacy it is considered high. The visibility value 3 is considered medium, which means not only a silhouette is seen, the object and colour are recognized although they are not clear. It means that the level of privacy is also medium. Meanwhile, the visibility value between 4 and 6 is considered high and useful for occupants to see outside but for privacy it is considered to be low because people can see what happens in the other side. In the daytime, the value of illuminance level is always more than 5,000 Lux and usually 10,000 Lux or more. It means that with a value more than 3 in the experiment in a condition in which 3 becomes the standard level of illuminance 300 Lux for the inside, in the practice this blind will always have higher visibility.

METHOD

The research was done in three steps. The first was finding the configuration of fenestration area or window to wall ratio (WWR) to meet the Indonesian National Standard (SNI) using a different glass material with different solar heat gain coefficient (SHGC) without using any shading device as baseline building. The second was modifying the clear glass baseline building by adding Sudare in front of each window as shading device, then analyzing the improvement of OTTV value and the impact of thermal energy consumption. The third is finding the visibility perception of modified model that meets the new standard of OTTV 35 watt/ m^2 using a questionnaire from the rendering image of clear glass and tint glass of baseline building and modified building.

GENERATING A 3D SIMULATION MODEL

Model geometry for the simulation was made in Grasshopper parametric software of Rhinoceros 3D. The Ladybug and Honeybee, two open source plugins for Grasshopper and Rhinoceros, helped to explore and evaluate the environmental performance. Ladybug imported the standard EnergyPlus weather files (.EPW) into Grasshopper and provided a variety of 3D interactive graphics to support the decision-making process during the initial stages of design. Honeybee connected the visual programming environment of Grasshopper to four validated simulation engines - specifically, EnergyPlus, Radiance, Daysim and OpenStudio - which evaluated building energy consumption, comfort, and daylighting (Sadeghipour Roudsari

M., Pak M., 2013). These plugins were used to prepare the simulation data for Energy Plus to get the OTTV value and thermal energy consumption (figure 4).

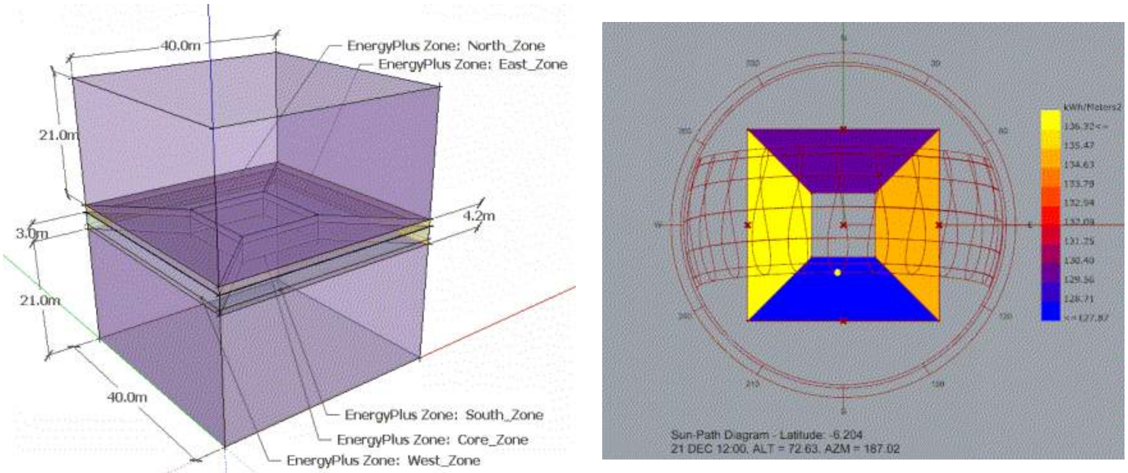


Figure 4: Grasshopper definition for parametric simulation in Grasshopper Rhinoceros 3D to Energy Plus from Ladybug and Honeybee plugin

The following is the building assumption for EnergyPlus 8.4 inside Ladybug and Honeybee:

- Building type : Office
- weather data (.epw) : JakartaDowntown.epw
- Building Orientation : 0°
- Typical floor area : 1,600 m^2
- Floor to floor height : 4.2 m
- Floor to ceiling height : 3.0 m
- WWR : 10% - 70%
- Number of floor : 11
- Number of zone : 5
- Simulated floor : 6 of 11
- Simulation period : Jan 1 to Dec 31
- External Wall : Plaster (15 mm) – Hebel block (100 mm) - Plaster (15 mm)
- U-value (wall) – with film : 1.039 W/m^2-K
- HVAC System : Ideal Load
- Indoor Illuminance level : 300 Lux (based on Indonesia National Standard for office building (BSNI, 2011a))
- Opening glass types :

Type	Name of Glass	Ufactor	SC	SHGC	Rel. Ht. Gain	T vis
		W/m^2-K			W/m^2	
1	Bekaert Specialty Films, Silver 20 OSW-SREX, NFRC ID 278	5.895	0.230	0.200	187	0.177
2	Bekaert Specialty Films, 4 Mil Quantum/Silver/Quantum 10, NFRC ID 263	5.987	0.346	0.301	260	0.103
3	DuPont Butacite® 0360900, NFRC ID 1112	5.687	0.461	0.401	331	0.090
4	Panasap Dark Blue 8.0, NFRC ID 1200	5.744	0.579	0.504	406	0.494
5	Asahimas-Panasap Dark Blue 5.0, NFRC ID 1246	5.848	0.692	0.602	477	0.624
6	Asahimas-Indoflot Clear 15.0, NFRC ID 1219	5.515	0.816	0.710	554	0.833
7	DuPont SentryGlas® Plus, NFRC ID 1123	5.657	0.920	0.801	621	0.887
8	AGC Clearvision 8, NFRC ID 4336	5.745	1.036	0.901	694	0.911

Table1.

Source: WINDOW6.3

SIMPLIFICATION OF MODEL FOR MODIFIED BUILDING SIMULATION

Due to the limitation of Energy plus when recognizing the minimum dimension of surface in modelling, it can only recognize surface less or equal than 10 mm. Then, the minimum diameter of Sudare that can be made in the research is 10.01 mm. There were 4 types of Sudare with the same diameter but a different spacer, 20mm, 10 mm, 5 mm, and 2.5 mm.

There were 224 simulations that need to be run. If the models used a full shape of Sudare, it needed around 2 hours for 1 simulation. Then, the Sudare model was simplified and compared the result of the full shape and simplified model to choose the close similar value of OTTV and thermal energy consumption. Two types of simplified model were compared with the original full shape geometry (circle shape) for the OTTV and thermal energy in each direction. The result shows that the cross shape has a closed value to the original full shape model (figure 5). The result shows that the cross shape has the closest value with the full shape model. In this step, the WWR for the model was 70% with clear glass SHGC 0.7. This will show the maximum result effect from the Sudare as shading device.

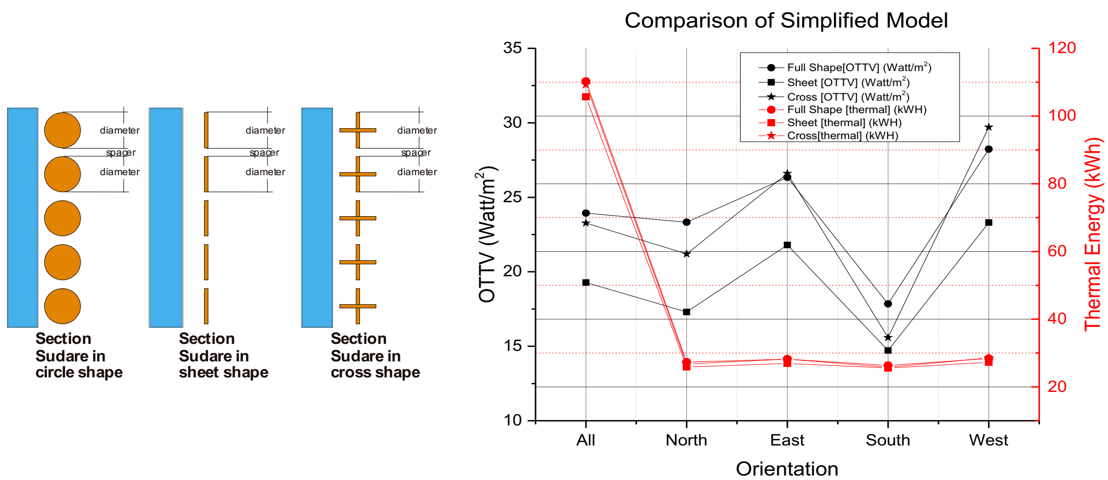


Figure 5: Comparison of OTTV and thermal Energy consumption between two types of simplification geometry of Sudare and full shape of Sudare

RENDERING OF MODIFIED BUILDING MODEL

After simulating the baseline and modified model with Energy Plus, all configurations of the model were rendered using Autodesk 3DS Max. The rendering capability of 3ds Max can represent the real world scene and has been validated in the Experimental Validation of Autodesk ® 3ds Max ® research (Reinhart & Breton, 2009). The setup condition for each configuration was decided using the previous experiment condition to get the visibility value using the questionnaire (figure 6). The sequence of illuminance for the outside is from 0 lux until 1000 lux while the inside will be maintained at 1000 lux. After the outside illuminance level reaches 1000 Lux, the inside illuminance will gradually change from 1000 Lux to 0 Lux. Using this method, the visibility level and privacy level can be measured. From the inside to outside, the aim was to get a high value of visibility. Meanwhile, from outside to inside, the aim was to get smaller visibility which means high privacy.

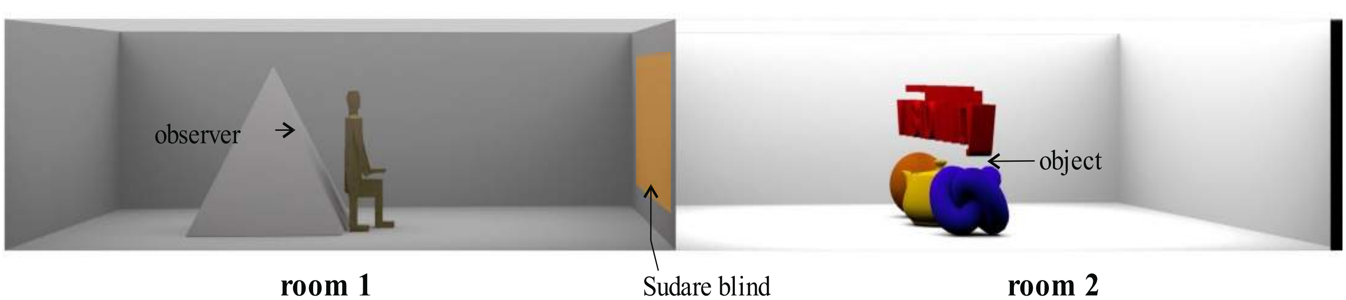


Figure 6: Setup room for visibility visualization using 3DS Max render

DATA AND ANALISYS

Results of the OTTV values for baseline building show the position and effect for each different condition of fenestration area between 10%-70% of window to wall ratio (WWR) with different SHGC values between 0.2 and 0.9. It shows that with SHGC values between 0.2 and 0.9, the standard OTTV 35 watt/m^2 could only be achieved with WWR 20% (figure 7). Using this WWR, the thermal energy consumption is between 105 and 135 kWh/m^2 annually.

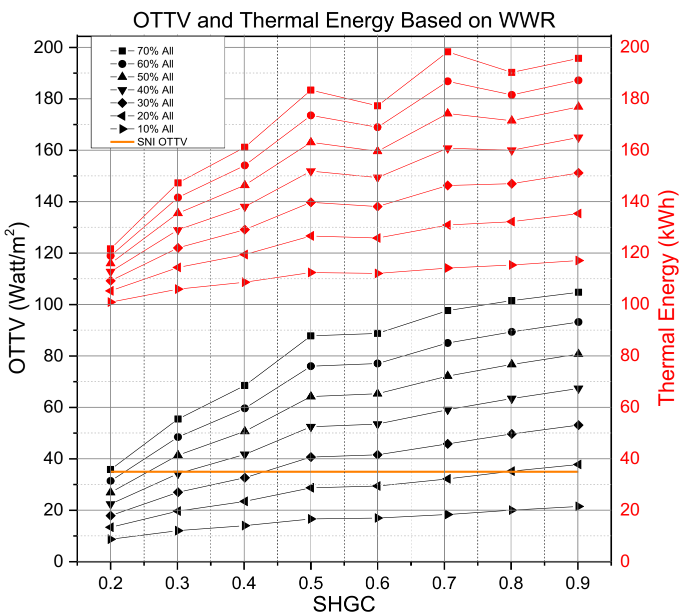


Figure 7: Comparison of OTTV and Thermal Energy with different SHGC glass

In the breakdown of each orientation using 20% WWR, only north and south side have OTTV less than 35 watt/m^2. Meanwhile, the highest OTTV was in west orientation, 48.26 watt/m^2. Although it is possible to meet the standard using a combination of different WWR in each window orientation by minimizing the opening in east and especially west direction (figure 8), it will be very difficult for architects to develop the creativity for façade opening.

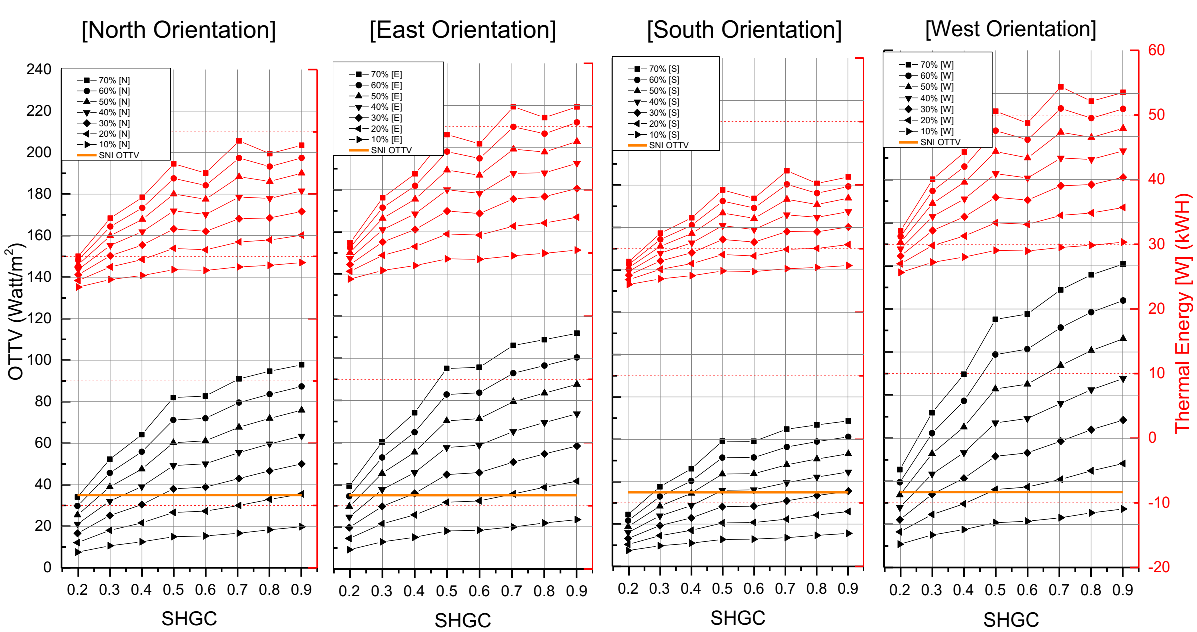


Figure 8: Breakdown OTTV and thermal energy consumption of baseline building in 4 orientation

In the second step, by comparing the OTTV value from the modified building with the baseline building, it can be seen that Sudare as shading device can reduce OTTV significantly (figure 9). The effectiveness of Sudare increased due to the decrease of the spacer, but the number of material for the Sudare also increased. The comparison of common clear glass material with SHGC 0.7 with tint glass (SHGC 0.2) and the types of Sudare can be analyzed in figure 1 and Table 1. The OTTV below 35 watt/m^2 can be achieved by Sudare with 5mm spacer (33.22 watt/m2) by decreasing 66% from baseline building with 126.417 kWh thermal energy or 36% smaller compared to the baseline building.

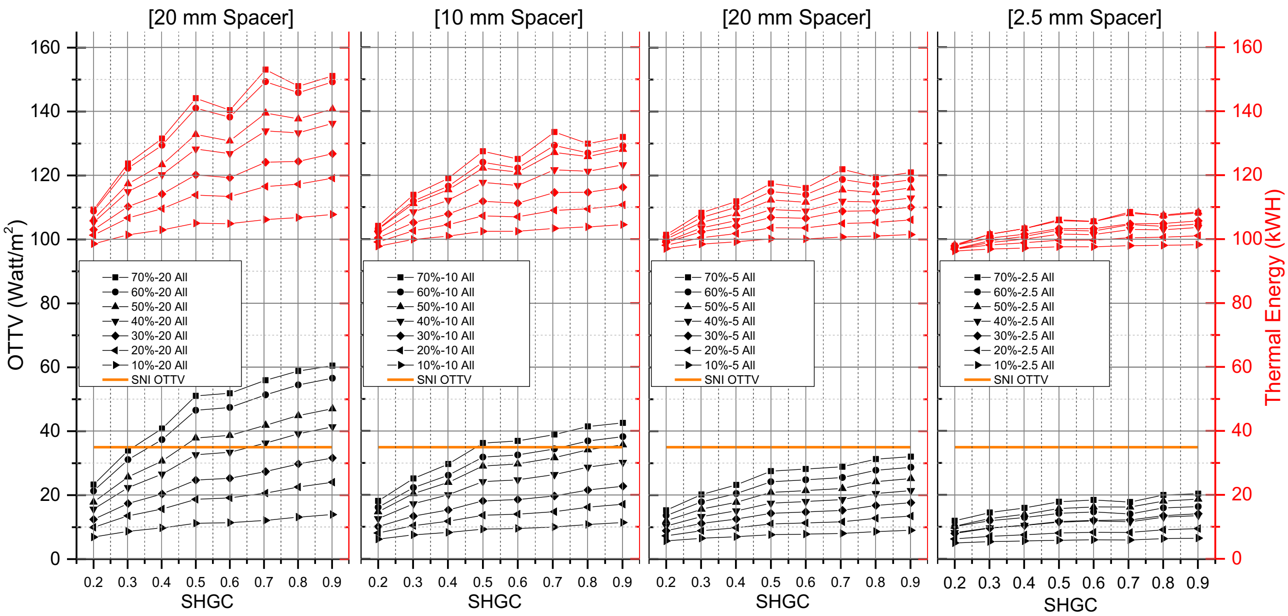
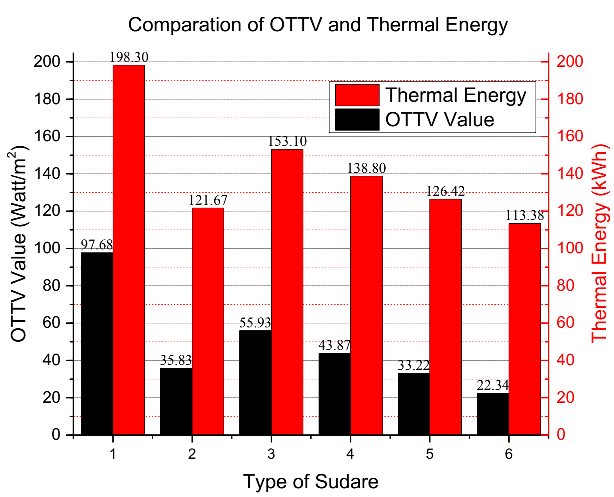


Figure 9: OTTV and thermal energy consumption of 4 types modified building

Compared to the tint glass with SHGC 0.2, Sudare with 5 mm spacer has better OTTV. Although the thermal energy consumption is still above the tint glass windows, it is not far. Sudare with 2.5 mm spacer has much better OTTV and thermal energy value compared to the tint glass (figure 10).



Type of Sudare	
1	No Sudare, Clear Glass SHGC 0.7 T vis 0.8
2	No Sudare, Clear Glass SHGC 0.7 T vis 0.2
3	20 mm spacer
4	10 mm spacer
5	5 mm spacer
6	2.5 spacer

Figure 10: OTTV of all direction and thermal energy consumption of modified building

After comparing the result, the next step is reviewing the visibility value using the questioner from the rendering image. There were 5 conditions compared. Condition 1 and 2 were used to test the visibility value from outside to inside or privacy for inside, where the illuminance of the outside was higher than the illuminance inside in daytime. Compared to the normal condition (type I), tint glass (type II) and Sudare (type III-Type VI) have low visibility value which means they have high privacy value. Condition 3 was to test the visibility and privacy when the illuminance level between inside and outside were the same. Condition 4 and 5 were to test the visibility value from inside to outside. Sudare with 20 mm spacer has a better visibility value compared to tint glass and other different spacers. Sudare with 10 mm and 5 mm spacer have close visibility value compared to tint glass. This value will be better in the real application where the illuminance level will increase for the outside; it means that this type of Sudare is potential to be implemented (figure 11).

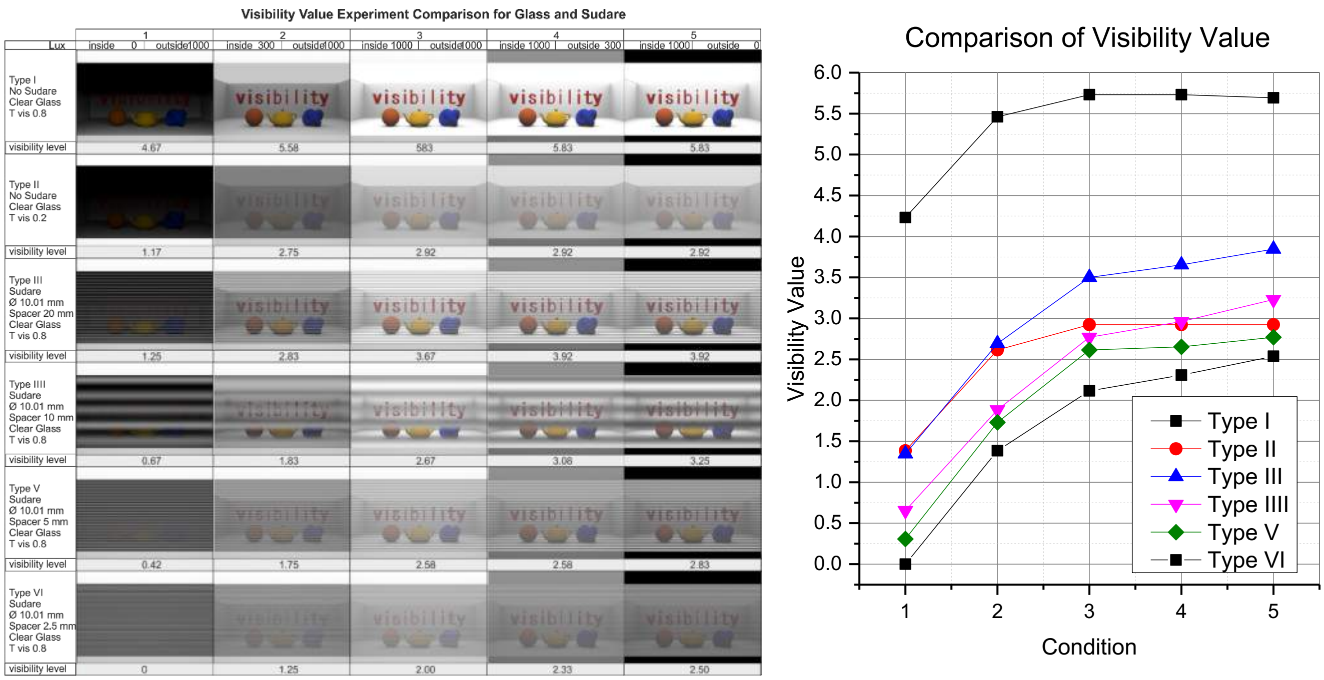


Figure 11: Visibility perception of rendering image

Table 2. Efficiency value comparison of modified model

No	Type	Volume of Sudare	OTTV Value [	Efficiency [%]	Thermal Energy [	Efficiency [%]	Visibility (indoor	Privacy
1	No Sudare, Clear Glass SHGC 0.7 T vis	0.00	97.68	0	198.30	0	5.73	0.54
2	No Sudare, Clear Glass SHGC 0.7 T vis	0.00	35.83	63	121.67	39	2.92	3.38
3	20 mm spacer	0.93	55.93	43	153.10	23	3.65	3.31
4	10 mm spacer	1.40	43.87	55	138.80	30	2.96	4.12
5	5 mm spacer	1.86	33.22	66	126.42	36	2.65	4.27
6	2.5 spacer	2.23	22.34	77	113.38	43	2.77	4.62

The result from the rendering image experiment has a lower value compared to the previous experiment using a real Sudare blind. This happened because the diameter scale of Sudare was bigger than the real Sudare, which has been noticed in the previous experiment. A smaller diameter of Sudare has a better visibility value even with the same ratio between diameter and its spacer.

CONCLUSION AND FUTURE WORK

CONCLUSION

Based on the analysis results, the geometry of Sudare shows effectiveness in reducing the OTTV and thermal energy value by maintaining the visual quality of visibility and privacy of occupants from inside to outside view. This condition gives more flexibility and creativity for architects to design building façade. Minimum fenestration areas to achieve OTTV 35 watt/m^2 have increased significantly from 20% when using glass with SHGC 0.2 to 70% when using normal clear glass SHGC 0.7 with Sudare 10.01 mm diameter and 5 mm spacer. The efficiency of this configuration decreases 66% of OTTV and 74% efficiency of thermal energy used compared to the baseline building, and compared to tint glass; it has better OTTV and close thermal energy value. The visibility value of this configuration is 2.65, close to the visibility of tint glass with T vis 0.2 (2.92), and the privacy is 4.27, much better than tint glass (3.38). This condition will be better in the real application where illuminance difference is much higher between inside and outside compared to maximum illuminance condition of the experiment room.

FUTURE WORK

The implementation of Sudare blind in high-rise buildings should consider the material and structural aspects. It will be impossible to use natural materials due to durability and maintenance problems. In Indonesia, the humidity is high in all days, around 80-90 % of relative humidity. The outdoor temperature is also high, around 30-34°C which makes materials easily dry. The fluctuation of material condition will make natural materials easily break. Metal will be the best choice to make the blind. Investigating the thermal behavior of metal materials is very important in this selection. Research on metal sheet for perforated and non-perforated regarding materials and colors has been done comparing galvanized steel sheets and anodized aluminum sheet. The results indicate that galvanized steel sheets reached temperatures between 4 and 5°C higher than the anodized aluminum, and black-painted sheet performed with temperatures between 6-8°C than white lacquer-coated sheets (Blanco, Arriaga, Rojí, & Cuadrado, 2014). Another result regarding material and color for perforated metal shows that galvanized steel, closely followed by white aluminum, is considered the most appropriate combinations (Blanco, Buruaga, Rojí, Cuadrado, & Pelaz, 2016).The modification of Sudare form is also necessary to improve the strength and possibilities to implement it outside window glass.

Improving the effectiveness of the energy efficiency can be further analyzed by modifying the form of Sudare to be able to put in front of glass effectively without much work on additional structure just for Sudare blind. Titanium metal as a material which offers better strength, lightness and durability compared to aluminum should be introduced. Further, it is also possible to change from static Sudare to dynamic Sudare in order to change the variation of spacer based on the outside illuminance level condition. There is a possibility to modify the form of Sudare blind to improve the efficiency of material used and visibility perception.

ACKNOWLEDGMENTS

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REFERENCES

Blanco, J. M., Arriaga, P., Rojí, E., & Cuadrado, J. (2014). Investigating the thermal behavior of double-skin perforated sheet façades: Part A: Model characterization and validation procedure. *Building and Environment*, *82*, 50–62. http://doi.org/10.1016/j.buildenv.2014.08.007

Blanco, J. M., Buruaga, A., Rojí, E., Cuadrado, J., & Pelaz, B. (2016). Energy assessment and optimization of perforated metal sheet double skin façades through Design Builder; A case study in Spain. *Energy and Buildings*, *111*, 326–336. http://doi.org/10.1016/j.enbuild.2015.11.053

BSNI. (2011a). *SNI 03-6197-2011 Konservasi Energi pada Sistem Pencahayaan*. *Sni 03-6197-2011*. Badan Standarisasi Nasional Indonesia.

BSNI. (2011b). *SNI 03-6389-2011 Konservasi energi selubung bangunan pada bangunan gedung. 1.* Badan Standarisasi Nasional Indonesia.

Carlucci, S., Causone, F., De Rosa, F., & Pagliano, L. (2015). A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. *Renewable and Sustainable Energy Reviews*,

47, 1016–1033. http://doi.org/10.1016/j.rser.2015.03.062
GBCI. (2012). *GREENSHIP RATING TOOLS GREENSHIP untuk Gedung Baru*.
Reinhart, C., & Breton, P. F. (2009). *Experimental Validation of Autodesk ® 3ds Max ®*. *Leukos* (Vol. 6). http://doi.org/10.1582/LEUKOS.2009.06.01001
Ruggiero, F., Florensa, R. S., & Dimundo, A. (2009). Re-interpretation of traditional architecture for visual comfort. *Building and Environment*, *44*(9), 1886–1891. http://doi.org/10.1016/j.buildenv.2009.01.006
Shi, X., & Yang, W. (2013). Performance-driven architectural design and optimization technique from a perspective of architects. *Automation in Construction*, *32*, 125–135. http://doi.org/10.1016/j.autcon.2013.01.015
Stevanović, S. (2013). Optimization of passive solar design strategies: A review. *Renewable and Sustainable Energy Reviews*, *25*, 177–196. http://doi.org/10.1016/j.rser.2013.04.028
UNEP-SBCI. (2009). *Buildings and Climate Change*. *UNEP-SBCI*.

VISUAL AND THERMAL COMFORT ANALYSIS

Enhancing occupant comfort in the Crystal Cathedral

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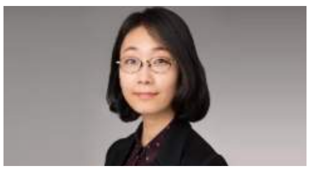

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ABSTRACT

The Roman Catholic Diocese of Orange's acquisition of the legendary Crystal Cathedral is an opportunity to re-imagine the entire 34-acre campus as the focal point for Orange County's Catholics and a global center for Catholic life, with Philip Johnson's iconic cathedral at its center. Thirty years after the original design, the new design team endeavors to convert the open, all-glass evangelical ministry headquarters into a cathedral that can accommodate the centuries-old traditions embodied in the Catholic faith.

Of the many challenges the sustainability engineering team faces, this paper will deal primarily with the visual and thermal comfort issues resulting from the existing, all-glass façade. However, glare is only one of many drivers for the design of the façade design solution, and context will also be provided through discussions of others – architectural, structural, lighting and acoustical design were all weighed in the decision making process. The solution to this multi-faceted design quandary was a virtually new building within the existing building. A system of triangular metal panels will cover most of the cathedral's 10,000 glass panes

This paper will walk the audience through the journey the sustainability engineering team went on to evaluate daylight, glare and thermal heat gains through the façade. Intuitive design and solar diagrams coupled with state-of-the-art simulation tools like DIVA-for-Rhino and computational fluid dynamics yielded solutions that enhanced the interior metal panel "quatrefoils" to significantly improve the experience of future devotees.

This case study illustrates two very important concepts – how parametric design and analysis can be applied to reduce daylight glare issues, and how such a workflow fits within the context of so many competing priorities.

KEYWORDS

daylighting - glare – shading; double-skin; building information modeling (BIM); parametric workflows; metal panel; adaptive reuse

INTRODUCTION

The Roman Catholic Diocese of Orange's acquisition of the legendary Crystal Cathedral is an opportunity to re-imagine the entire 34-acre campus as the focal point for Orange County's Catholics and a global center for Catholic life, with Philip Johnson's iconic cathedral at its center. Thirty years after the original design, the new design team endeavors to convert the open, all-glass evangelical ministry headquarters into a cathedral that can accommodate the centuries-old traditions embodied in the Catholic faith.

From a birds' eye view, one can see the pointed cross-shaped footprint of the renamed "Christ Cathedral" – with the long axis extending due east-west, and the short axis in the north-south directions. The footprint is almost symmetrical in both axes, except for a pointed notch at the northeast that served as an enormous opening for natural ventilation (to be discussed more below). The building is wrapped entirely in curtainwall – including all vertical surfaces as well as the three large, sloping surfaces that make up the roof – making it one of the largest glass building in the world. The glass is single-thickness lites of a dark, reflective substrate.

Figure 1. The Crystal Cathedral is shown on its campus in Garden Grove, California. Image courtesy of Google Earth.

Once inside the Crystal Cathedral, the crisscrossing tube-steel members of the structural truss system and the incredible Hazel Wright Organ come into view. The exposed triangular patterns in the structural system repeat thousands of times in a six-foot depth inside every glazed surface in the massive volume. The organ is one of the largest in the world, with 273 pipes encased in huge wooden structures on both the north and south balconies. After a $2 million refurbishment in Italy by Fratelli Rufati, the organ will once again contribute to the awe inspired by the Cathedral's interior.

There are many challenges inherent in the cathedral's renovation that the design team must overcome. This paper focuses on those impacted by the existing all-glass enclosure, and an integrated design solution that transforms the interior aesthetic while enhancing thermal, daylight and glare performance, and even acoustics. Although the case study is a once-in-a-lifetime re-design opportunity, the integrated workflow of the team, and the application of analyses and software tools can provide guidance to teams designing highly glazed buildings.

The design solution was a system of "quatrefoil" panels that attaches to the interior side of the truss system. The quatrefoil system concept was developed by the team at Johnson Fain, and was tuned to balance the other performance factors mentioned above. Each of the four main quatrefoil panel configurations has four triangular pieces of perforated metal that point toward the center. The four pieces are tilted outward (toward the curtainwall) at static angles of either 0, 15, 30 or 45 degrees to vary the amount of openness of the panel as a whole. The 45-degree panel was also used to mount a light fixture one of the four pieces.

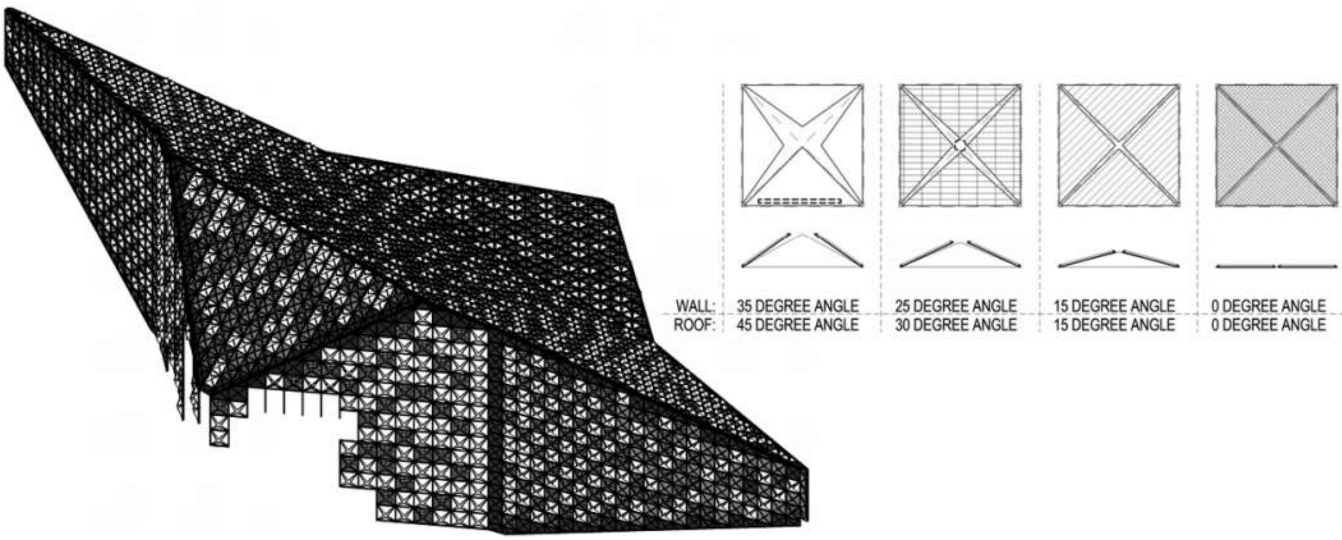

Figure 2. There are four types of quatrefoil panels shown in the diagram to the right, which are distributed as shown in the diagram to the left. Image courtesy of Johnson Fain.

The paper will summarize how thermal and daylight performance factors were affected by the quatrefoil system, and will look more thoroughly at the daylight glare analyses that were conducted to help improve visual comfort in the all-glass cathedral.

BACKGROUND

DAYLIGHT GLARE PROBABILITY (DGP)

Daylight Glare Probability (DGP) is a metric used to predict the appearance of discomfort glare in daylit spaces proposed in 2006 by Jan Wienold and Jens Christoffersen , who were at Fraunhofer Institute for Solar Energy Systems in Germany, and Danish Building Research Institute, respectively, at that time. This metric uses a combination of an existing discomfort glare algorithm and an empirical approach. It considers the overall brightness of the view, position of glare sources and visual contrast. The algorithm also includes user-polling conditions from two independent experiments conducted at the Danish Building Research Institute (SBi, Denmark) and at the Fraunhofer Institute for Solar Energy Systems (ISE, Germany). As a result, DGP showed very careful measurement and a very strong correlation with the user's response regarding glare perception (Wienold and Christoffersen, 2006).

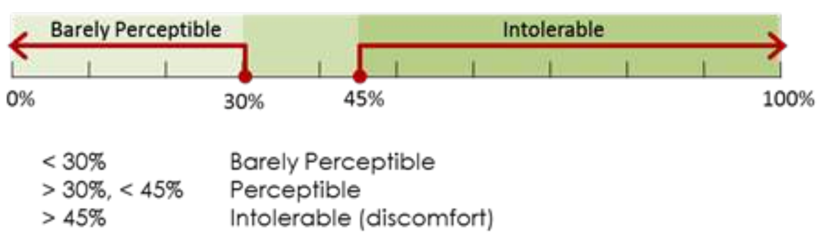

Figure 3. Daylight Glare Probability (DGP) analysis results in a single probability that falls within a range from "barely perceptible" to "intolerable."

METHOD

DAYLIGHT GLARE ANALYSIS

One of the most significant issues that arose from the all-glass design of the cathedral was also the most difficult to evaluate. Glare is difficult to evaluate because it is impacted by both quantity and quality of daylight. Daylight quantity is easy enough to measure, but daylight quality depends on how people perceive light, which factors in many subjective elements that are not as well understood, and not captured in most commonly used simulation tools. DGP was selected as the most comprehensive metric available in a software tool which the sustainability engineering team had access to.

To begin the DGP analysis, the team had to select an initial view perspective from which to run simulations and identify intolerable glare conditions that could be reduced through modifications to the quatrefoil system design. The view would represent a human's field of vision, and needed to have a high probability for glare. The first analytical view was from the Bishop's Cathedra (seat) on the north side of the raised central Predella platform, facing due south. The team felt this was both an important view, and one that was likely to identify glare conditions as the sun moves along the southern half of the sky throughout the year in the Southern California climate. A second view more representative of a view from the audience was evaluated following the exact same methodology, so the paper will focus on the former to illustrate the workflow and concepts.

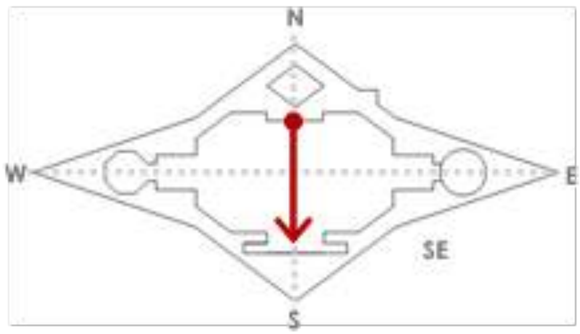

Figure 4. The diagram shows the first view perspective from the Bishop's Cathedra facing south. A secondary perspective was considered and discussed in the Data section, but not discussed at length. Architectural rendering (left) provided courtesy of Johnson Fain.

The first analytical step was to perform an annual glare simulation to evaluate the baseline condition. The results provide a DGP metric for each hour of a simulated year using an algorithm in the DAYSIM tool within DIVA-for-Rhino. This "annual glare map" is provided below for reference and initial understanding.

Figure 5. Annual glare simulation results are illustrated using an Annual Glare Map that organizes the x-axis by day of the year and y-axis by hour of the day.

The results of the annual glare simulation were evaluated for trends that identified specific times in the analysis to be analyzed using point-in-time analyses and renderings to provide a better idea of the root cause of glare and, more importantly, how to reduce it. Large blocks of red indicated these trends within a close proximity of days and times, while additional data analysis also showed intolerable glare hours trending more broadly throughout the year. The team selected three points that seemed to represent significant glare issues.

The next round of analyses evaluated specific points-in-time to provide visual renderings for qualitative and quantitative information to identify the root cause of glare. The team created sun path diagrams for those times to illustrate where the sun was for that time relative to the cathedral, and ran Point-in-Time Glare Simulations to provide a 180-degree fish-eye rendering to perform the DGP calculation and to analyze subjectively.

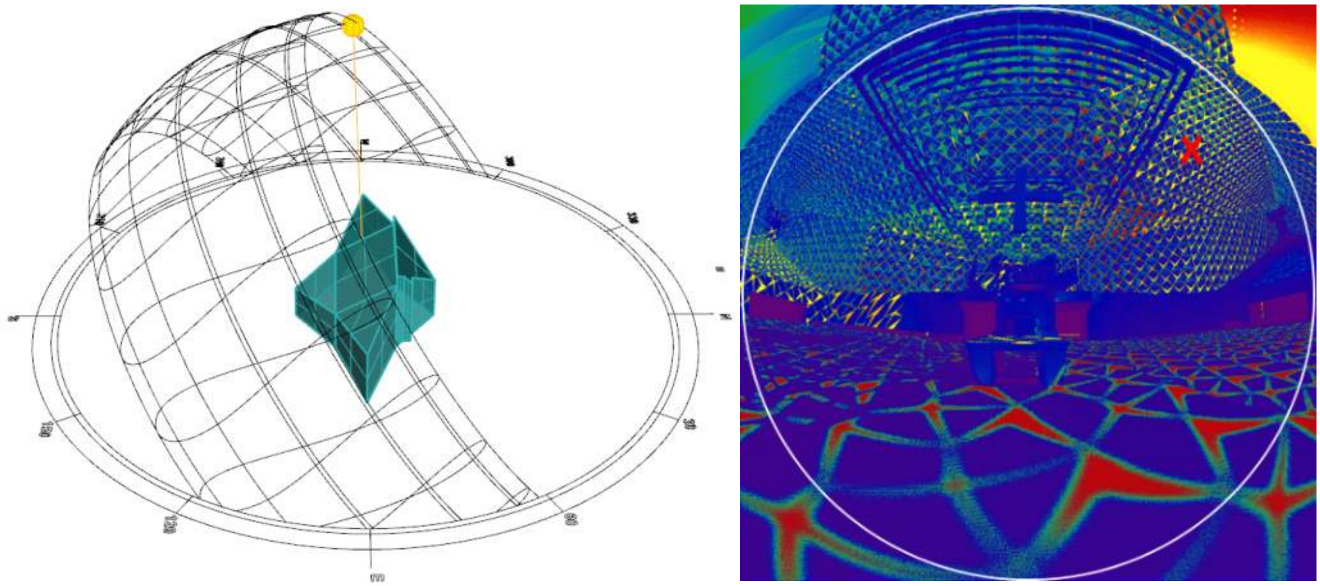

Figure 6. Sun path diagrams (left) helped to understand the sun's location while analyzing the false color fisheye renderings from the point-in-time glare simulations (right).

The third step in the glare analysis was to analyze the results of the point-in-time glare studies and hypothesize potential mitigation measures with the design team. Although this phase was less analytical, it still required the sustainability engineering team to provide diagrams and results in a way that everyone could understand and help prioritize design modifications. Sun path diagrams were developed, and simulation renderings were matched to available architectural renderings for reference.

Once design modifications were developed, they were implemented in the Rhino model used for the simulation where further simulations could be run to evaluate the impact on the annual glare simulation.

DAYLIGHT ILLUMINANCE ANALYSIS

Fenestration provides an opportunity to use natural daylight as the primary means of meeting lighting requirements inside a functional space. This allows an electric lighting system to be dimmed or turned off completely, saving energy during daytime operating hours. Providing too much daylight, however, causes overheating and other major issues like glare, so the amount of daylight is something that must be evaluated.

The existing all-glass cathedral provided more than enough daylight during the day for lights to be shut off. With the introduction of the quatrefoil system, the design team felt it important to analyze their impact to balance this impact with the other performance factors.

The sustainability engineering team used the same modified Rhino model from architectural team to perform a daylight illuminance analysis using DIVA-for-Rhino. The analysis included the quatrefoil system, and the calculation was for a working plane that was defined above the floor of the main sanctuary and east and west balcony seating areas.

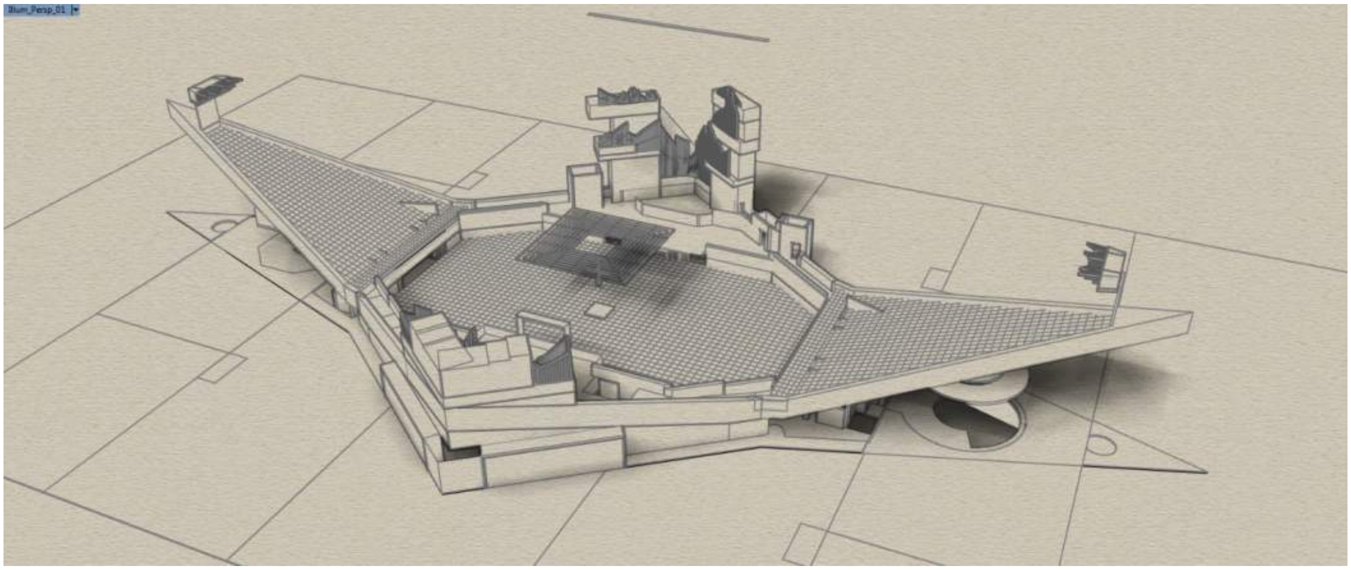

Figure 7. A 3D model geometry was exported from the architect's Revit model and imported into Rhinoceros software for daylight illuminance and glare analyses.

THERMAL CFD ANALYSIS

Solar gains are the single greatest contributor to the cooling load for the project. The sustainability engineering team was very interested in leveraging the ability of the quatrefoil system to reduce cooling load and, hence, mechanical equipment sizes and the energy consumption thereof.

The original cooling concept for the Crystal Cathedral was to utilize motor-actuated windows to promote natural cross- and stack-ventilation. A large door to the northeast, window-sized openings on the north and south facades, and openings at the top of the cathedral worked in concert to promote this flow of outside air. This approach, however, did not provide sufficient comfort with larger internal loads and the new owner decided it would be necessary for a mechanical system to replace the ineffective natural ventilation approach as part of the renovation.

The proposed concept for the new heating, ventilating and air-conditioning system for the cathedral was a displacement ventilation (DV) system that utilizes low velocity diffusers in the floor to introduce supply air. The conventional air-conditioning approach uses overhead air distribution that mixes all of the air in a space to ensure a more consistent temperature distribution. This DV approach allows the cool, dense air to be concentrated at the low level where occupants reside, encouraging warmer air to rise up and away, reducing space conditioning load and energy consumption throughout the year.

The DV design requires a tighter control and understanding of building physics, and, therefore, requires additional analysis to ensure successful operation as compared with the conventional overhead mixing approach. The best way to validate performance in this case is to use computational fluid dynamics (CFD).

The CFD analysis from the sustainability engineering team was done in two steps. The first utilized a “slice” model to understand how the quatrefoil system affected radiant, convective and conductive heat transfer from the exterior to the occupied zone. The second model represented the whole volume of the worship space, applying the results of the first analysis to a single representative building skin to reduce simulation time and complexity.

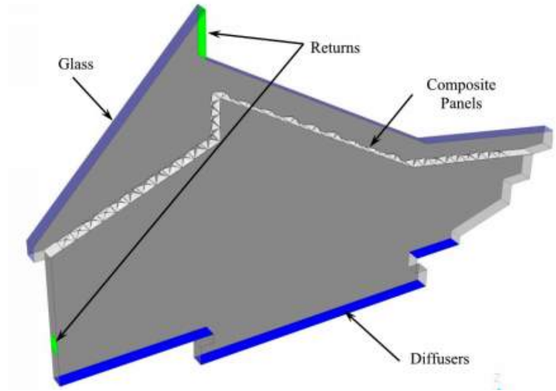

Figure 8. The figure shows a screenshot from the "slice" CFD model used to study the impact of the quatrefoil system on heat transfer in order to apply a simplified composite panel system to the larger model used in further detailed analyses. Image provided courtesy of Syska Hennessy Group, Inc. and Price Industries, Limited.

DATA

DAYLIGHT GLARE ANALYSIS

The first annual glare simulation for the Bishop's Cathedra view indicated 706 hours of intolerable glare (DGP of 4.5 and higher), which is 16% of daylight hours during a typical year. For reference, the simulation run *without* the quatrefoil system (which also did not have the structural system modeled due to geometry complexity and simulation time) indicated 2,658 intolerable hours in a typical year. This is a 73.5% reduction in glare from that condition. This first result representing the current proposed design served as the baseline against which to compare further results.

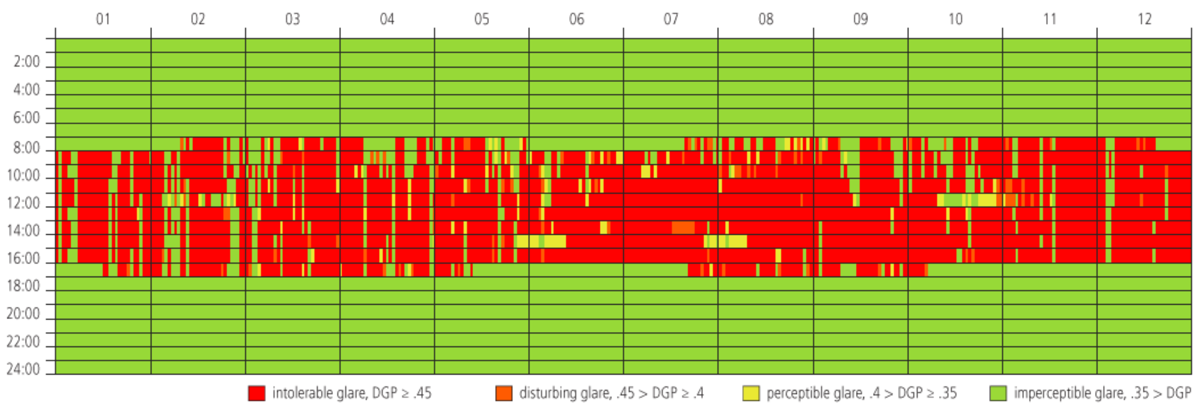

Figure 9. The existing condition (modeled without structural system) from the Bishop's Cathedra view showed 2,658 hours of intolerable glare in the annual glare simulation.

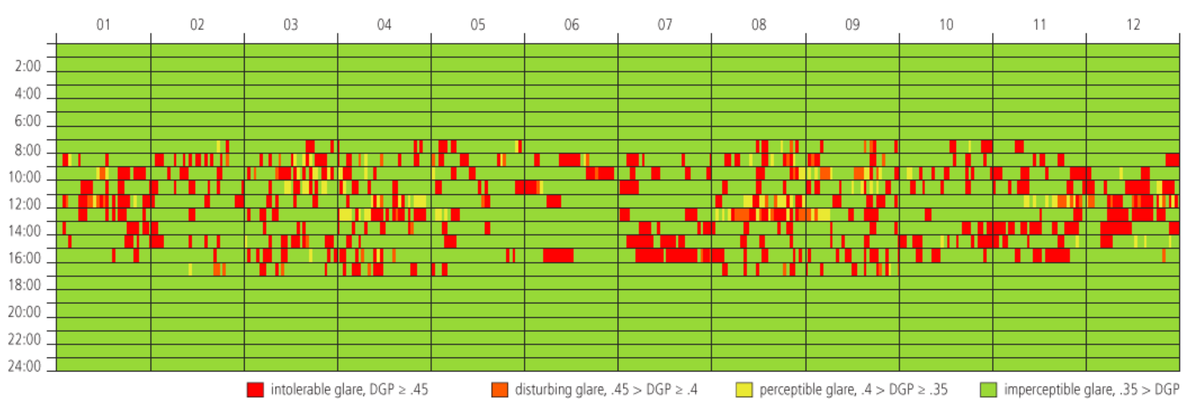

Figure 10. The as-designed condition from the Bishop's Cathedra view showed 706 hours of intolerable glare in the annual glare simulation shown in the Annual Glare Map.

In order to zoom in and understand the root cause of glare during the intolerable conditions, the sustainability engineering team used pivot tables to analyze trends throughout the year. Specific months and times of day during those months were found to show the highest number of hours of intolerable glare.

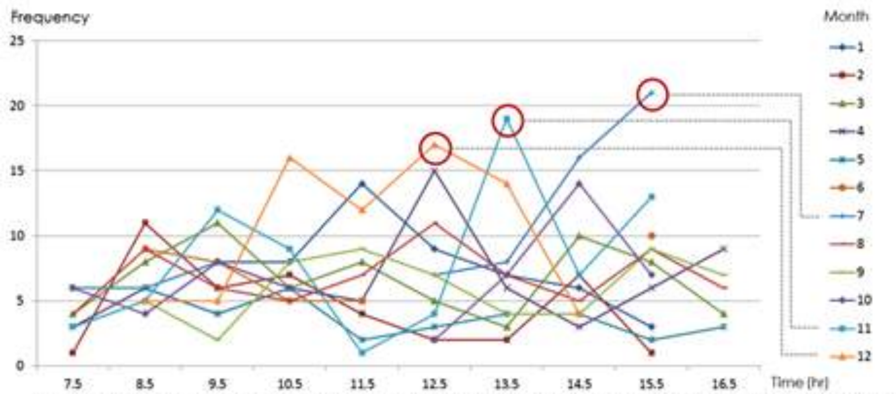

Figure 8. Pivot tables show the frequency of intolerable glare conditions by month and throughout each day for the as-designed condition from the Bishop's Cathedra view.

Each month identified above was studied in detail, and specific times were selected for further analysis. These three times were July 13th at 3pm, November 14th at 1pm, and December 12th at 2pm.

Point-in-time glare simulations were conducted that provided RADIANCE renderings in greyscale, false color renderings with a luminance scale, and fish-eye DGP renderings. The latter is the only image used for the DGP algorithm and is, therefore, provided below for each point-in-time. Accompanying the DGP renderings are the sun path diagrams created for each time to illustrate diagrammatically the sun position relative to the cathedral for each rendering.

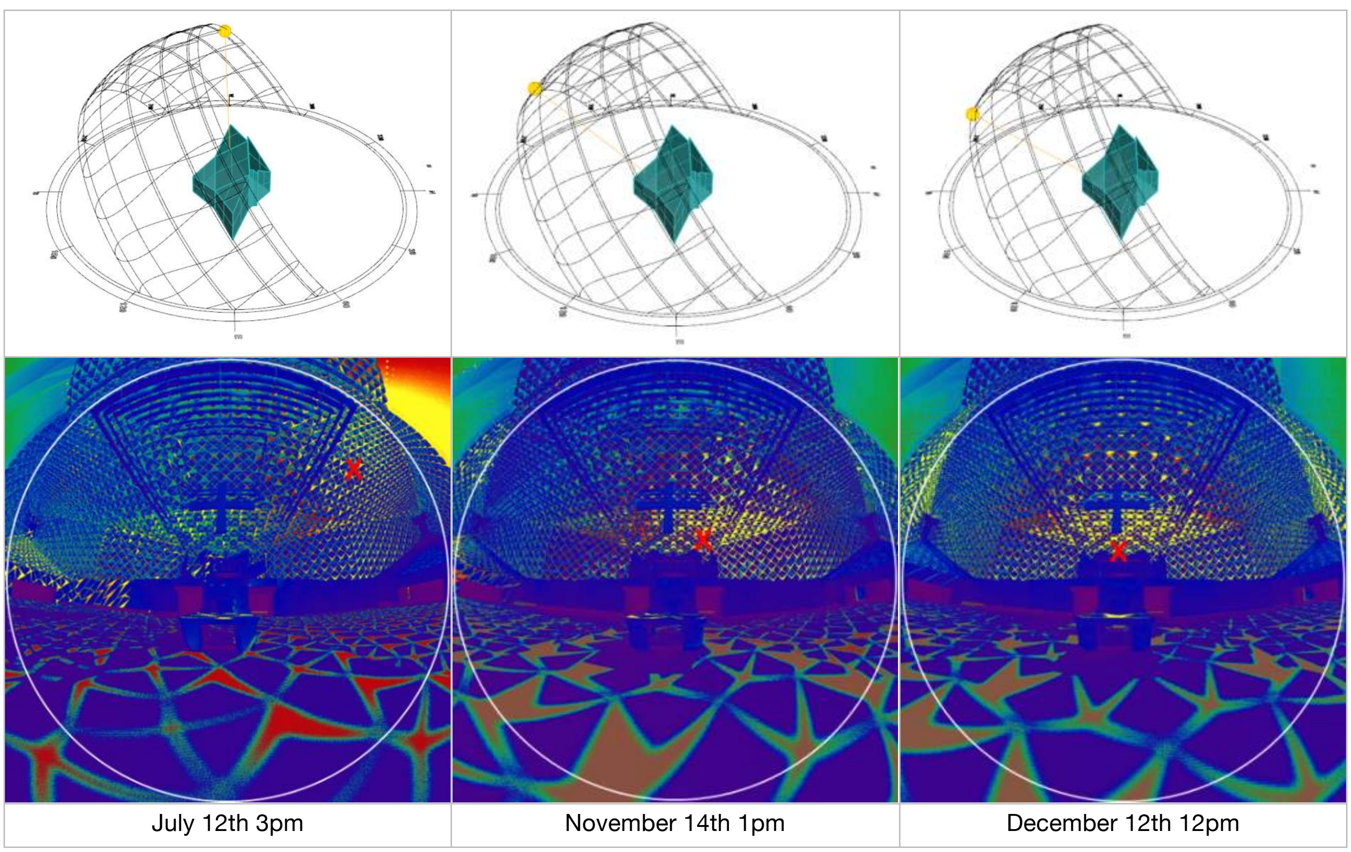

Figure 11. For three problematic times, 3D sun path diagrams (top) and point-in-time DGP renderings (bottom) indicated the major source of glare.

Critical points all indicated the majority of issues were coming from direct solar rays through the two sloped south roof surfaces. The analysis focused on the 45-degree panels on these two, sloped roofs because they were the most open panel, and because one leaf of the panel was flattened to 0-degrees from its mounting plane in order to accommodate a light fixture. The configuration brought in a significant amount of sunlight compared with the other panel configurations.

The figure below provides a graphical summary of all the design alternatives that were studied, and their resulting total number of hours of intolerable glare for the simulation year. Each design alternative focused on modifications to the 45-degree (most open) panel that had a single leaf folded down flat to accommodate the mounting of a light fixture, as these panels let in considerably more light than the others.

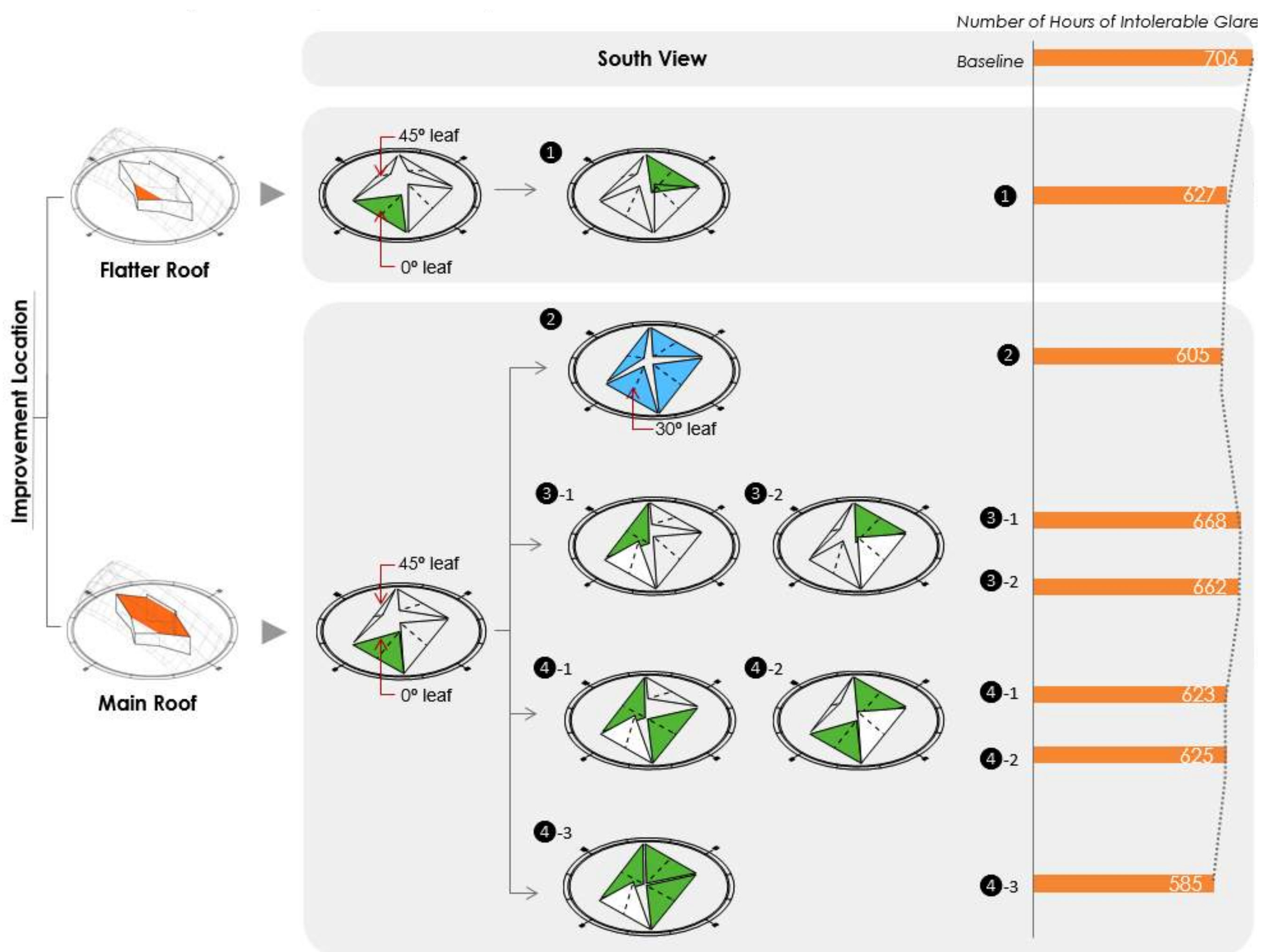

Figure 12. The figure above provides a graphical summary of the design alternatives evaluated and their resulting impact on total hours of intolerable glare for the Bishop's Cathedra view.

Although not described in as great of detail, a second perspective view was studied to validate the recommendations provided and calculated performance thereof. The second view was from a seated occupant on the ground level, near the front row on the west side facing the center of the cathedral in the southeast direction.

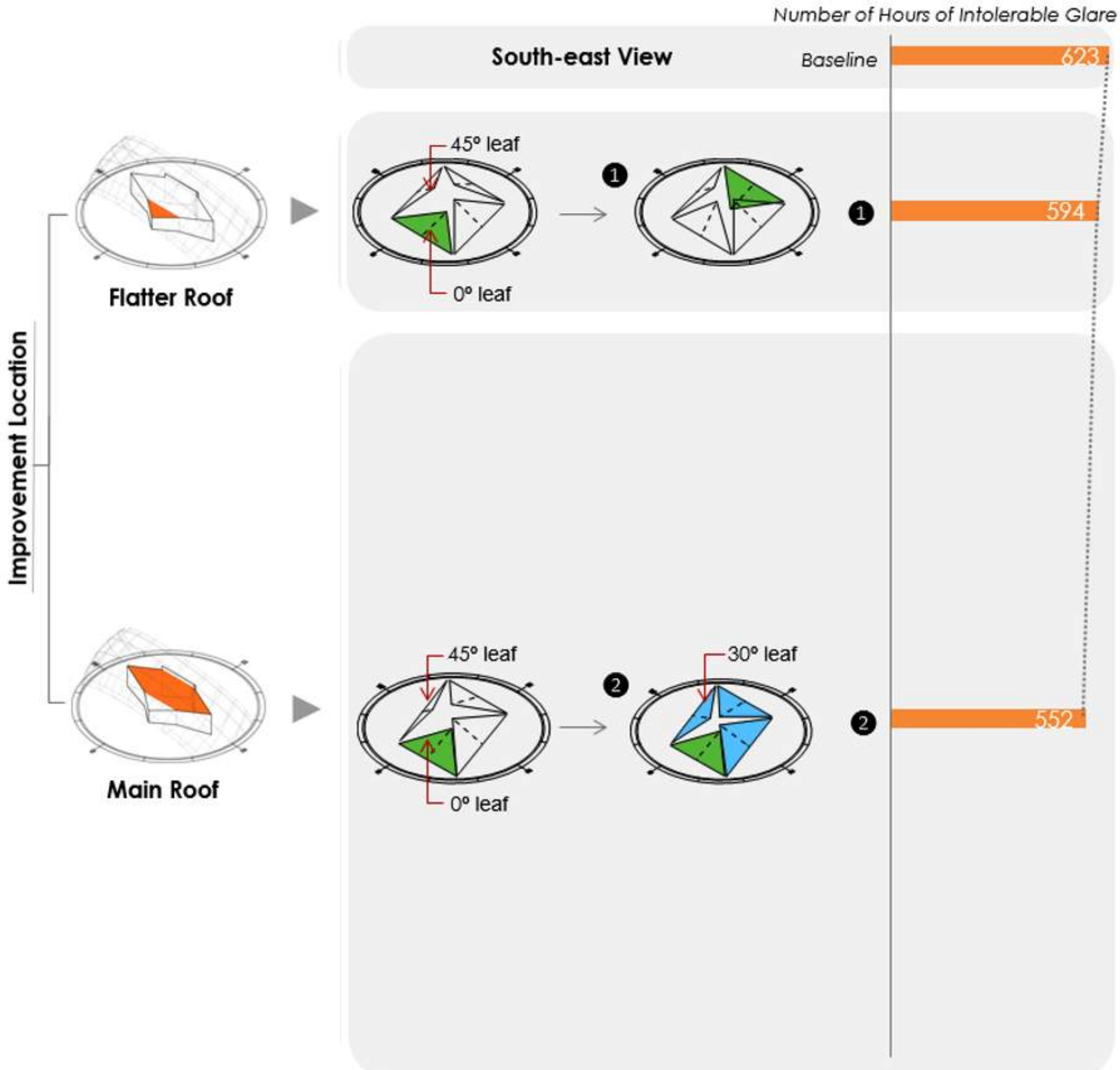

Figure 13. The figure above provides a graphical summary of the design alternatives evaluated and their resulting impact on total hours of intolerable glare for the second view from the ground level facing the southeast.

DAYLIGHT ILLUMINANCE ANALYSIS

The analysis of daylight illuminance for the cathedral with the quatrefoil system provided illuminance results in foot-candles across working planes defined at approximately 30 inches above the worship floor and the two sloped balconies to the east and west. Results indicated an average illuminance of 102 foot-candles for the cathedral.

The illuminance images show that the majority of points along the working plane grids achieve useful illuminance in the range of 23.8 to 36.1 foot-candles. However, there are several grids where the illuminance jumps up significantly to 700+ foot-candles, indicating an inconsistent distribution of light through the curtainwall, truss and quatrefoil systems.

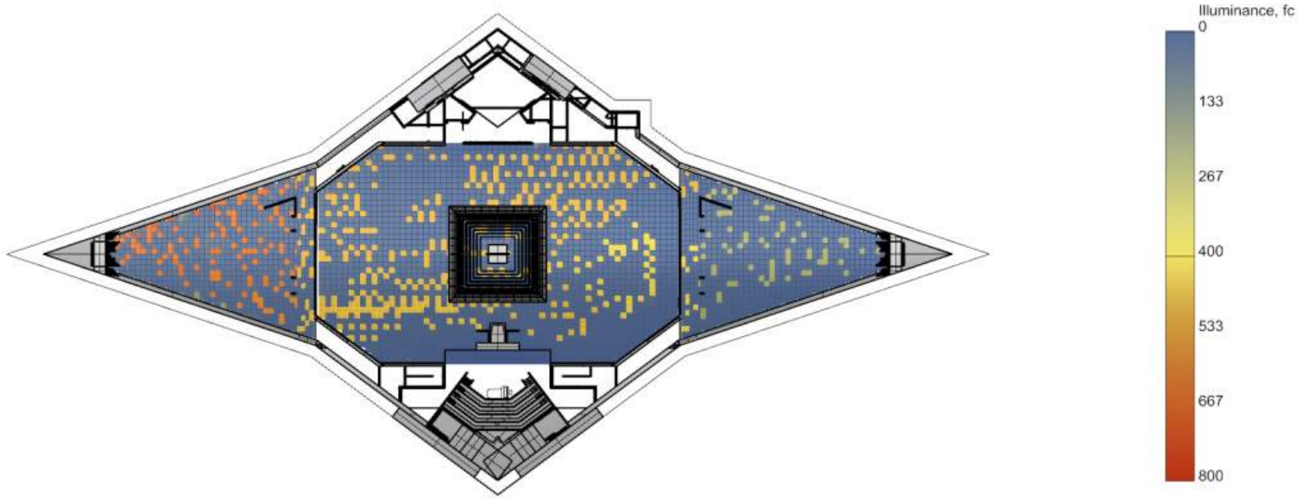

Figure 14. Daylight illuminance results show values in grids on three working planes – at the worship level and two sloped balconies at east and west.

THERMAL CFD ANALYSIS

The thermal analysis conducted using CFD modeling and analysis involved many steps and iterations to understand heat transfer through the quatrefoil system and to validate the design of the displacement ventilation air-conditioning approach. The summary results relevant to studying how the quatrefoil system impacts building performance and comfort have been provided below.

The first round of CFD simulations using the slice facade model indicated that the direct solar radiation transmitted through the glazing either continues through the openings in the quatrefoil panels to the occupied space below, or is converted to indirect, diffuse radiation and convection through the panels themselves. The overall impact is a reduction in total heat transferred to the occupants below, and diffusing the radiation that is transmitted so that it is distributed more uniformly across surfaces in the cathedral.

The analysis was not conducted to compare the proposed design with quatrefoil system against the existing building without. However, early cooling load estimates assumed a solar gain reduction in the range of 50-75% to determine the total airflow, and the CFD analysis helped validate these assumptions within about 5% of these estimates. The resulting temperature distribution of the worship level sanctuary and balconies are shown in a color contour temperature plot in the figure below. The figure shows the vast majority of points in these occupied areas fall within a range of 64 to 79 degrees Fahrenheit.

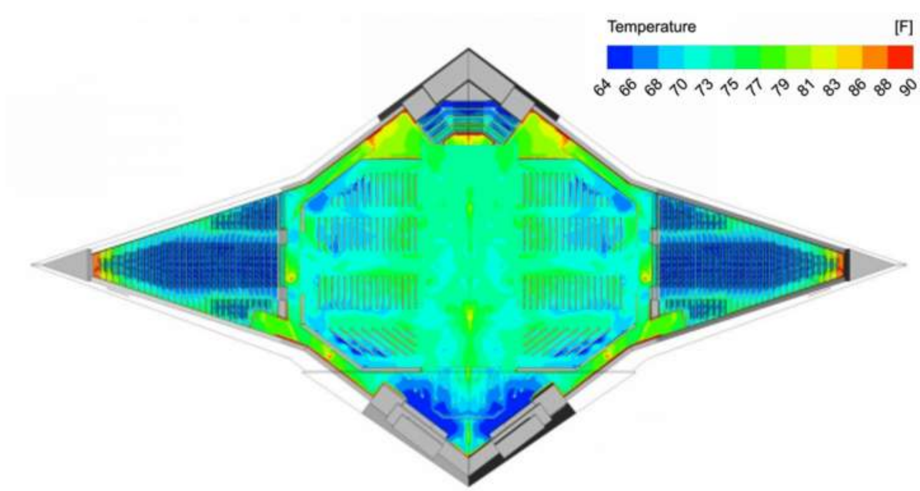

Figure 15. CFD modeling iterations were able to validate the displacement ventilation air-conditioning system design as shown in the temperature contours for planes 42" above the floors of the worship level sanctuary and balconies. Image provided courtesy of Syska Hennessy Group, Inc. and Price Industries, Limited.

EXPLANATION

DAYLIGHT GLARE ANALYSIS

The initial simulations and annual glare analyses indicated the months and hours of the day that resulted in the most frequent intolerable glare conditions, allowing the sustainability engineering team to direct further analysis at those points. The first view from the Bishop's Cathedra facing south indicated that the majority of glare occurred during the middle of the day when direct sunlight entered the viewer's field of vision through the two south sloping roof surfaces, which agreed with the sun path diagrams and the team's early suspicions.

Improvements focused on the most open (45-degree) quatrefoil panels that held the light fixtures because they showed the highest rate of improvement. This clearly indicates that the main issue is that the quatrefoil system still lets in too much direct sunlight.

The individual improvements that showed the greatest merit for the smaller, less sloped south roof was rotating the 45-degree panel by 180 degrees so that the flattened panel that held the light fixture was to the north where it could block more direct rays. That same improvement on the larger, more steeply sloped roof actually let in *more* direct rays, resulting in additional intolerable glare hours. Therefore, the best recommendation for that surface was to keep the 0-degree petal facing south, but reducing the angle of the other three petals from 45 to 30-degrees.

It's important to note here that the improvements that were analyzed and recommended were developed through collaboration with the architect, lighting designer, structural engineer, and acoustical consultant. The main driver for the quatrefoil design was aesthetically driven as the architect's concept introduced movement and diversity that the owner felt strongly was the right solution. The lighting design team also required the modified 45-degree panel to mount a light fixture and reflect indirect light into the space below. Therefore, the improvements were subtle reconfigurations of the panels and yielded subtle improvements in the overall glare conditions of the two views that were analyzed.

The analysis did prove that the as-designed quatrefoil system was a significant improvement over the existing cathedral with respect to daylight glare. It also helped to prove that intolerable glare conditions were scattered throughout the year and the adjustments that could be made within the constraints of the design yielded results that were also scattered and subtle improvements, allowing them to be outweighed by aesthetic and lighting impacts.

The study did validate a collaborative, integrated workflow that could be applied to other projects. If applied earlier in the design process and/or to a design that could accommodate greater design changes, it could certainly yield an even greater impact.

DAYLIGHT ILLUMINANCE ANALYSIS

Natural daylight provides a higher quality source of daylight than electric lighting systems. In addition, it allows the electric lighting to be dimmed or turned off entirely, resulting in operational savings throughout the life of the building. However, providing illumination beyond the levels needed for intended tasks no longer has a benefit, and actually has a detrimental impact. Light brings heat with it that needs to be cooled, and excess light often results in discomfort due to glare, which the team has proved through focused studies.

The daylight illuminance studies conducted by the sustainability engineering team for the cathedral project determined that the quatrefoil system resulted in an average illuminance level that was useful and not excessive. It also indicated scattered bright spots that may cause controllability issues depending on where the daylighting system's photocells are placed, and a high potential for glare due to the contrast between light and dark.

The analysis also validated that the quatrefoil system provided a significant reduction in illuminance while still providing useful daylight during the majority of daytime hours.

THERMAL CFD ANALYSIS

The major benefit of the quatrefoil system from a thermal standpoint is the conversion of direct solar radiation to convective heat transferred into the air on the inside of the panels. Without the quatrefoil barrier, the direct radiation would transfer to the occupants below, whereas the majority of the convective heat is captured by the upward current inspired by buoyancy and the displacement ventilation air-conditioning system.

The analyses also validated a cooling load reduction based on a significant decrease in solar gains to the occupied space. The existing condition was not modeled directly, but the correlation is clear and consistent with the hypothesis. Therefore, it is reasonable to attribute a significant cooling load reduction to the quatrefoil system.

CONCLUSION AND FUTURE WORK

The three types of building performance analysis described herein show that the new quatrefoil system added to the interior of the existing curtainwall and truss system provides a significant benefit with respect to useful daylighting, daylight glare, cooling load and energy as compared with the existing cathedral. Useful daylighting is maintained while preventing much of the heat and contrast that excessive daylight brings with it. Intolerable glare conditions are expected to be reduced from over 2,500 hours to around 600 hours or less (depending on the final improvements selected). The cooling load was able to see a significant reduction in solar gains to the occupied space, yielding a sensible load reduction in the range of 17% below the existing building condition.

Although no significant future work is planned for this project beyond what has been presented herein, there were considerable lessons learned that may be implemented on future projects. The collaborative workflow that allowed the sustainability engineering team to utilize the architect's 3D models to perform daylight illuminance and glare analyses can be replicated in increased efficiency in the future. The process of creating sun path diagrams may be utilized as a reasonably simple way to visualize how the sun may interact with a building at different times of the year, leading to better decision making early on in the design process. As with the majority of building performance analysis, it became clear that consideration of performance aspects should be considered earlier, allowing greater flexibility in design decisions and a more significant impact.

ACKNOWLEDGEMENTS

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All figures not specifically credited to others were provided courtesy of the sustainability engineering team at Syska Hennessy Group.

REFERENCES

Jan Wienold & Jens Christoffersen. 2006. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras, Energy and Buildings 38: 743–757.

Chanyang Shin, Greg Collins, 2016. Daylight glare analysis for an all glass cathedral: integrating simulation with common sense to improve visual comfort, ASHRAE and IBPSA-USA SimBuild 2016 Building Performance Modeling Conference, Salt Lake City, UT.

Solemma LLC. 2014. Diva for Rhino, Version 3.0.

Kera Lagios. 2016. Diva for Rhino. http://diva4rhino.com/

WELL RETROFIT CASE STUDY

Balancing opportunities and challenges

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ABSTRACT

Views and daylight through the building envelope are considered positive assets in defining beautiful and desirable work environments. The exact health benefits, translated as tangible and positive impacts to human performance have been less quantifiable. Even with compelling evidence-based design studies such as Roger Ulrich's 1984 "View Through a Window May Influence Recovery from Surgery", the industry's understanding of integrated strategies to support all aspects of health, comfort and energy reduction through the building envelope are often misunderstood. This can lead to poorly applied building technology and mandatory code required glazing reductions focused on one dimension of building performance, energy.

In October 2015 Delos rolled out the WELL Building Standard, a new standard focused on occupant health in our built environment. The standard benchmarks seven categories in support of health and wellness, including a new metric for circadian lighting. This case study evaluates the implications of overlaying the WELL Standard's circadian lighting criteria within the context of meeting CA Title 24, Chapter 6 and LEED Silver requirements. Applied to a deep building footprint with poor existing daylight, we found these requirements challenging and at times in conflict. Daylight studies revealed that manual shading effectively blocked daylight availability, while automatic shading maximized daylight availability and provided circadian lighting for up to 33% the spaces. Separate electric lighting studies analyzed several strategies that in absence of daylight, increased lighting energy use above energy allowances for LEED or energy code.

This reveals how critical a well daylit space is to satisfy energy goals and provide circadian entrainment. As these standards are more widely applied, we will gain a deeper understanding of the overlay in these criteria and the industry will be better equipped to balance these collective priorities.

KEYWORDS
Circadian, WELL, Daylight, Lighting, LEED, Energy, Glare, Shading, LPD

INTRODUCTION

The WELL Building Standard (WELL) is an interdisciplinary approach drawing from scientific research, defining both performance and prescriptive criteria to promote and improve human health and well-being within the built environment. This standard is distinctive from known green and environmentally conscious building standards such as LEED and The Living Building Challenge. WELL focuses on seven dimensions of performance: Air, Water, Nourishment, Light, Fitness, Comfort and Mind. This project is approximately 800,000sf of interior building retrofit, with requirements to meet LEED Silver and evaluate the feasibility of requirements for WELL Silver certification for New and Existing Interiors. There is approximately a 20% overlap between WELL Silver (achieving all 37 preconditions) and LEED Silver (achieving minimum 50 credits) requirements. Example criteria addressed by WELL, without LEED overlap include; Nourishment, Fitness, Mind, and Water. For example, water as addressed in WELL speaks to the quality and accessibility of water versus quantity as in LEED.

The case study focuses on the mandatory design criteria of the WELL Standard "Light: Circadian Lighting Design". The lighting design community has been aware of lighting's impact on the circadian system for some time now, but there was no benchmark standard to apply the research to the built environment. WELL's new circadian lighting requirement, incorporating the melanopic lux metric, is the first design parameter focusing on circadian lighting. The design team was optimistic these criteria could enhance the existing building's poor daylight with electric circadian lighting needed due to existing deep floor-plates, and optimize an otherwise poorly designed building, but also concerned with the potential visual impact and energy increase. Meeting the base WELL circadian criteria, balanced with our energy reduction targets (benchmarked against Title 24 and ASHRAE) and confidence we were not introducing additional glare into the space was the basis of the following integrated design process and subsequent studies.

The existing building retrofit (EBR), located in the Los Angeles metropolitan area, transforms a traditional office building with assigned perimeter offices and internal 6' foot high cubicle workstations to one that is a free address (non-assigned work stations), flexible and open floor plan that encourages collaboration and connection. The existing building has a combination of insulated and single paned gray glass, horizontal strip windows, with manual shades across the entire perimeter. The original building, built in the 1980s, has a deep floor plan with daylight only accessible to 30% of the perimeter floor area. The occupants have reported visual and thermal discomfort. The "U" shaped building has a south facing courtyard and no significant overshadowing from adjacent structures. The north side of the building receives reflected light from an adjacent building. The retrofit project's scope covers full interior renovation and zone level lighting and HVAC system redesign but does not allow any major changes to the building envelope. The project goal is to maximize usable daylight within the building, meet WELL Building Prerequisite 54 Circadian Lighting Design and minimize capital cost. While LEED and WELL are compatible in many ways, the authors immediately recognized the opposing nature of the LEED's energy reduction goals and WELL's circadian lighting prerequisite. Given the deep floorplate of the EBR, it was clear that daylight's contribution would not be able to supply circadian light levels for 75% of the workstations, and electric lighting would be required. The relatively high light levels on a vertical plane required for circadian entrainment.

BACKGROUND

LIGHT AND THE CIRCADIAN SYSTEM

The circadian system is a multifaceted biological function that assists in regulating variations in physiology and behavior which exhibit cycles close to a 24 hour period, even in the absence of external cues (Duffy and Czeisler 2009). Embedded in our genes, these daily biological patterns, such as our sleep patterns, mood, blood pressure, alertness, etc. are timed by the circadian clock (Foster 2013). In the absence of external cues, the average human circadian rhythm is just over 24 hours. Without proper entrainment, the circadian clock becomes out of sync, leading to "Sleep and Circadian Rhythm Disruption" (SCRD). Research has revealed a myriad of health problems resulting from SCRD, such as reduced immunity, abnormal metabolism, increased stress, and abnormal information processing by the brain (Foster 2013). External cues can help regulate the circadian clock, such as food intake, exercise, and social interactions, but the most important is light (Figueiro, et al. 2008).

The retina, located at the back of the eye, is constructed of complex and interlocking layers of cells that convert light radiation into a neural signal interpreted by the brain. In 2001, a new cell was discovered that does not contribute to the visual system, dubbed Intrinsically Photosensitive Retinal Ganglion Cells (ipRGC). ipRGC's operate separately from the visual system and were found to operate even in visually blind people.

While the daytime (photopic) visual system has a peak sensitivity at 555 nm (green light), the ipRGC's peak spectral sensitivity has been measured at 484 nm (blue light). (Figueiro, et al. 2008). It was later found that, while the ipRGC is perhaps the most important photoreceptor for the circadian system, input from other photoreceptors also significantly contributes to the response (Lucas, et al. 2014; Figueiro, et al. 2008). This contribution broadens the spectral sensitivity of the circadian system while remaining centered in the blue spectrum.

Once captured, optical radiation is converted into neural signals delivered to the suprachiasmatic nerve (SCN) in the hypothalamus of the brain via a dedicated neuropathway called the retinohypothalamic tract (RHT) (Figueiro, et al. 2008). The SCN serves as the master clock for the circadian system, and is the primary regulator for the system. (Stevens, et al. 2007). When the neural signal reaches the SCN, it suppresses the production of melatonin, a hormone that is secreted at night and helps prepare the body for sleep (Khullar 2012). Figure 1 diagrammatically illustrates the process.

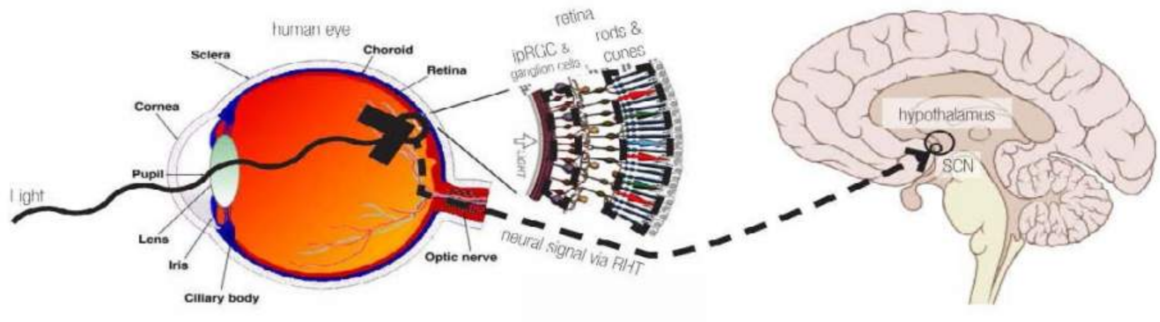


Figure 1: Diagrammatic explanation of how light affects the circadian system. (Diagram by the authors. Image of eye and retina layers by Kolb 2016. Image of Brain by Patrick J. Lynch via Wikipedia with Creative Commons license).

In practical terms, light spectrum, duration, timing, and history of light exposure all play a role in light's impact on the circadian system. Bright light exposure in the morning helps to suppress melatonin, promoting wakefulness and kicking off the day, while exposure at night suppresses melatonin and disrupts the sleep-wake cycle. Since the circadian system has peak sensitivity in the blue spectrum and very little sensitivity to the red spectrum, cool white light is more effective than warm light; a higher light level requires less exposure time, but a lower light level can be effective if exposure time is elongated.

THE WELL BUILDING STANDARD CIRCADIAN LIGHTING REQUIREMENT

Light levels have long been expressed and calculated in the lighting community as the illuminance value lux (metric units). Lux quantifies the amount of light striking a given surface, and is prorated based on the spectral sensitivity of the human visual system. While this makes sense for traditional lux, it inaccurately weights the impact of a given spectrum of light for circadian stimulus since the spectral sensitivity to different wavelengths of light for the circadian system is different from the visual system (Fig. 2).

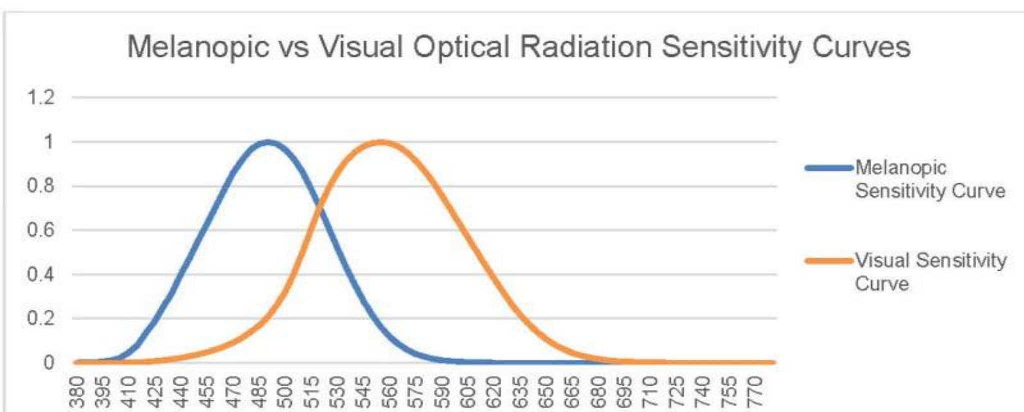


Figure 2: The relative sensitivity of the circadian system (Melanopic Sensitivity Curve) compared to the visual system. While the visual system's sensitivity peaks in the green spectrum (555 nm), the circadian system peaks in the blue spectrum (484 nm). Traditional lux gives less weight to light in the blue spectrum, and therefore inaccurately weighs a light source's impact on the circadian system. (Image by the authors)

In 2014, Lucas and others proposed a new metric, Equivalent Melanopic Lux (EML) (Lucas, et al. 2014). Similar to traditional lux, it quantifies the amount of light reaching a surface, but weighs the spectrum of light based on the circadian system's sensitivity. The Well Building Standard (WELL) uses this method to provide a calculation ratio to convert the lux level from a given light source to EML as shown in Table 1 below.

CCT	Light Source	EML to Lux Ratio
2700K	LED	0.45
3000K	Fluorescent	0.45
2800K	Incandescent	0.54
4000K	Fluorescent	0.54
4000K	LED	0.58
6500K	Daylight	1.10

Table 1: Comparison of EML to Lux ratios of various common sources from Table L1 of WELL

The WELL offers two compliance paths. All light levels are calculated on a vertical plane 4' off the ground to simulate eye level while seated.

Path 1: 250 EML for a minimum of 4 hours for 75% or more of workstations. The light level may incorporate daylight.
Path 2: With electric lighting only, provide maintained EML on the vertical plane greater than or equal to the lux recommendation for the vertical target given in IES RP-1-12, all day long.

In practical terms, using a typical source of 4000K LED, the designer would need to increase the light level of the system by a minimum of 72% just to meet Path 2. This is a large increase in the amount of vertical illumination and highlights the need for high light levels to stimulate circadian entrainment. The implications are far reaching: lighting delivered by traditional methods from the ceiling are inherently inefficient for vertical illumination, so boosting the vertical illumination for circadian entrainment could double or even triple the wattage for the lighting. Without ample daylight contribution, it may be impossible to meet energy code and LEED energy goals while providing circadian lighting.

METHOD

DESIGN APPROACH

A multi-tiered approach was used to study both daylight and electric lighting to provide the WELL circadian lighting requirement for the EBR project. Daylight and electric light designs were developed separately, then integrated to define daylit, circadian lighting and electric circadian lighting zones in the EBR project. The following key analyses shaped this approach:

USABLE DAYLIGHT ANALYSIS

This analysis is performed to estimate the ability of the indoor environment to provide adequate quantity and quality of light. The study uses circadian autonomy and useful daylight illuminance as the metric. Useful daylight illuminance is a method to assess daylight in buildings using annual time series of absolute values of illuminance predicted using simulation (A Nabil 2005). Circadian autonomy is a metric that was developed for this analysis by the authors and is not an existing metric. The concept of circadian autonomy is adapted from an existing metric - daylight autonomy. For the purpose of this study, circadian autonomy is defined as percentage of annual daytime hours that a given point in a space is above the melanopic illumination criteria and duration established in the WELL standard. There are several variables that affect human circadian rhythm, and the relationships between these variables have not been fully researched or documented. Since there is no established framework to guarantee circadian entrainment, the study is based upon the following hypotheses:

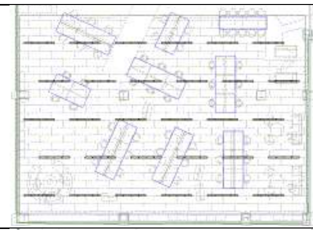
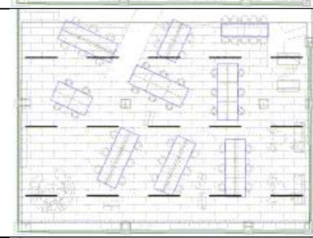
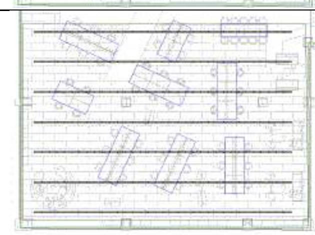
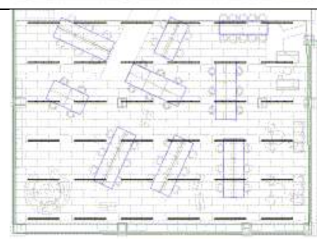
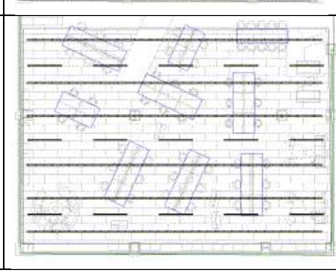
The WELL requires 250 melanopic lux for at least 4 hours a day, which translates to 227 lux from daylight. Converting horizontal illuminance to vertical is achieved by dividing simulated horizontal illuminance by a factor (of 2) (Leslie, Radetsky and Smith n.d.). The analysis was performed for two variations of fenestration treatment, manual and automated blinds. The manual shades are assumed to be drawn down for all daylit hours to mimic occupant behavior in EBR project.

ELECTRIC LIGHTING STUDY

A series of studies were conducted to test electric lighting strategies to meet the circadian lighting prerequisite. These studies used Lighting Analysts' lighting calculation software AGI32. The Baseline cases target 200 lux maintained on the workplane, the minimum required light level for WELL (a separate requirement from circadian lighting). All studies used 3500K CCT (except for Circadian Option 4, discussed below) and assumed a light loss factor of 0.765 to calculate maintained light levels

(0.85 for lamp lumen depreciation, and 0.9 for dirt depreciation). Spectral power distribution data was collected for Nichia 757 LED chips for both 4000K CCT 80+ CRI and 3000K CCT 80+ CRI, but 3500K CCT was not immediately available at the time of the study. The EML to Lux Ratio was calculated for both the 4000K and 3000K data using the method described in Table L2 of the WELL (0.689 and 0.533, respectively). The ratio for 3500K was approximated by linear interpolation to be 0.611. Since all electric light sources were the same (except for Circadian Option 4, discussed below), the light level target was prorated as follow:

Path 1: 250 EML ÷ 0.611 EML/lux = 409 lux for four hours minimum per day.
Path 2: 150 EML ÷ 0.611 EML/lux = 245.5 lux for the whole day.
Table 2 below summarizes the studies.

Study Name	**General Description**	**Fixture Wattage and Initial Delivered Lumens**	**Plan View Snapshot**
Baseline 1	8' long recessed linear downlights with diffuse lens, spaced 12' x 10' O.C. (Focal Point Seem 4 Series).	29W; 625 lumens/foot	
Baseline 2	8' long direct/indirect pendant, spaced 16' x 18' O.C. (Lumenwerx Cava Series)	98 W; 750 lumens/foot uplight, 500 lumens/foot downlight	
Circadian Option 1	Continuous rows of recessed linear with increased output, spaced 8' O.C. (Focal Point Seem 4 Series)	12.75W/ft; 1,000 lumens/ft	
Circadian Option 2	8' direct/indirect pendants with increased light output, spaced 12' x 10' O.C. (Lumenwerx Cava Series)	120 W; 750 lumens/foot uplight, 7500 lumens/foot downlight	
Circadian Option 3	8' direct/indirect pendants with increased light output, spaced 16' x 18' O.C. (Lumenwerx Cava Series) and 2 rows of continuous recessed linear with increased output spaced equally between the pendants (Focal Point Seem 4 Series)	Pendant: 120W; 750 lumens/foot uplight, 750 lumens/foot downlight Recessed Linear: 7.25W/ft; 625 lumens/foot	

Circadian Option 4	Baseline 1 + Table mounted glowy task light, with 2700K LED A-lamp; centered in table, one to either side of each workstation, with (Artemide Castore Series)	Recessed Linear: 29W; 625 lumens/foot Table Lamp: 12 W, 1,300 lumens	

Table 2: Summary of the electric lighting studies.

Option 4 tests the hypothesis that bringing the light source closer to the occupant's eyes allows for a reduction in light output and energy use. The glowing table lamp uses the Philips 12 W 2700K CCT LED A-lamp. The lux level target discussed above was prorated based on a 3500K CCT LED source, so the output of the table lamp required adjustment. Using the EML ratio from Table L1 of WELL for 2700K CCT LED (0.45), a factor of 0.7365 was used in the calculation for the table lamp to derate the 2700K CCT output relative to the melanopic lux ratio of the 3500K source. While there are cool white LED A-lamp options, the authors did not find one with more light output than the 12 W Philips LED A-lamp, even after prorating for melanopic lux, at the time of the study.

THE ANALYSIS GRID

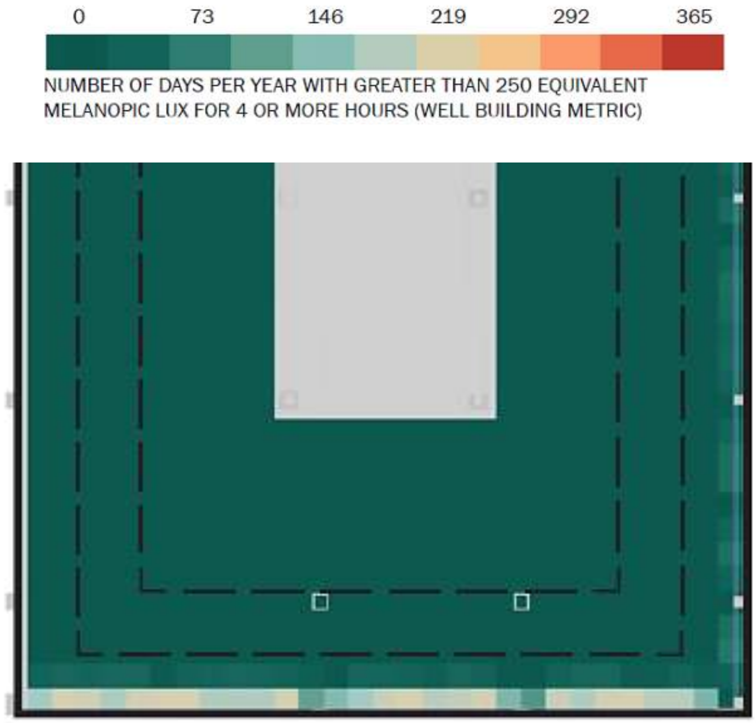
The furniture layout strategy of the project complicated the analysis grid. Conceptually, the furniture is completely flexible. This not only allows employees to choose their workstation on a "first-come-first-served" basis, but also, furniture can be moved to satisfy team requirements. Thus, no location or view angle is fixed. For this feasibility study and to align with the daylight studies, we used a vertical calculation grid located 4' AFF, with the calculation nodes facing towards the exterior walls, and stepping every 5' inward from the exterior walls. From an electric lighting perspective, this is arguably a worst case scenario, since the distribution of electric light tends to decrease around the edges of an open office plan. Daylight was not considered for the electric lighting study.

DATA

USABLE AND CIRCADIAN DAYLIGHT STUDY

The results for a southeastern portion of the floor, comparing the impact of manual vs. automated blinds on usable daylight is summarized below.

MANUAL BLINDS



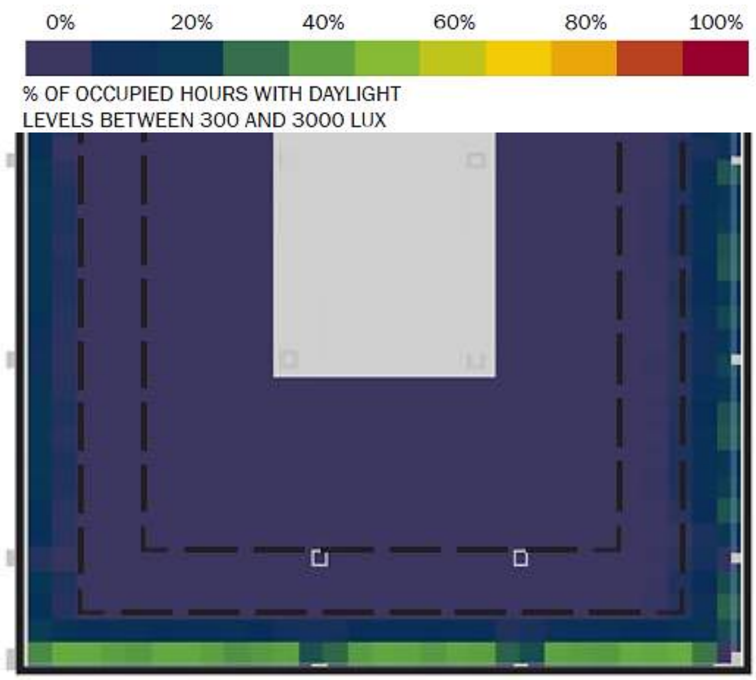
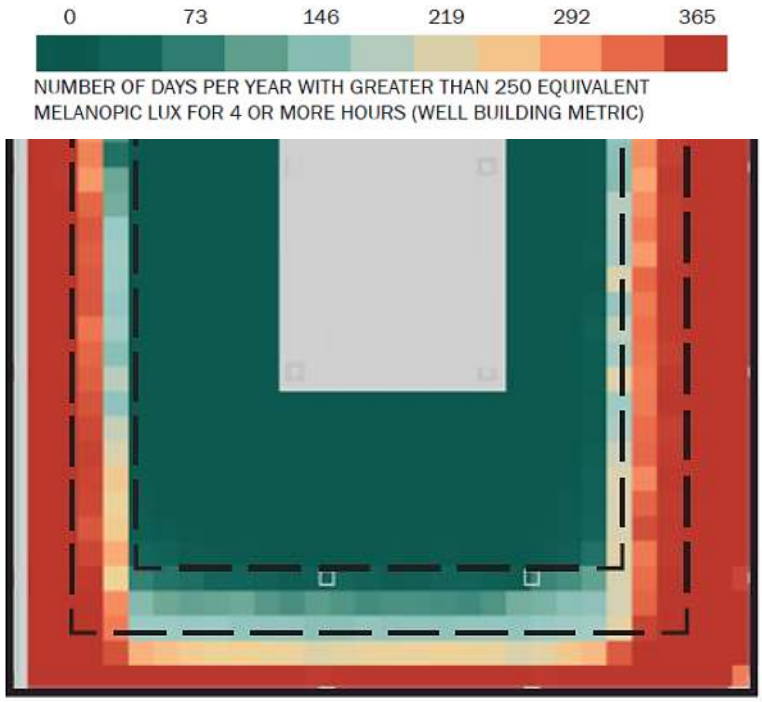


Figure 3: Circadian Daylight Performance on a Vertical Grid for Manual Blinds, Circadian Autonomy (above), Useful Daylight Illuminance (below) (courtesy of Atelier Ten)



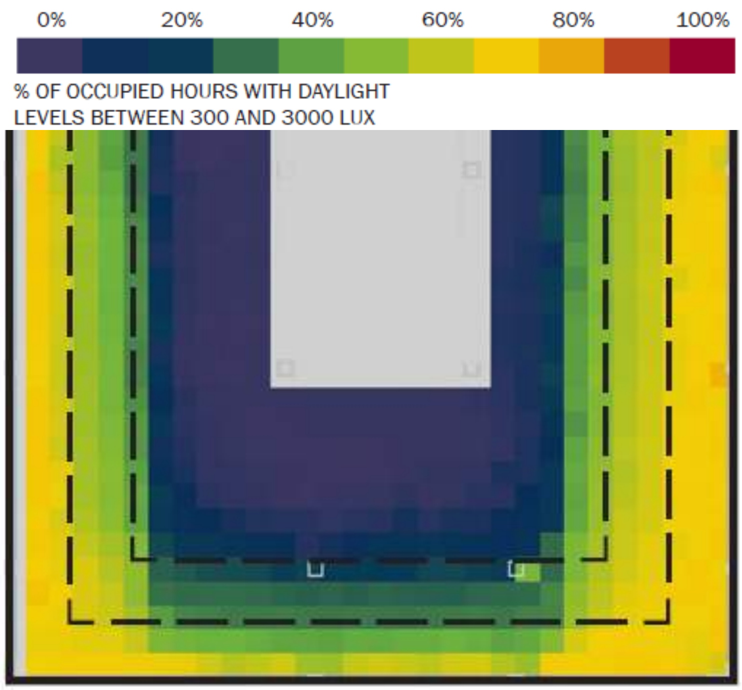


Figure 16: Circadian Daylight Performance on a Vertical Grid for Automated Blinds, Circadian Autonomy (above), Useful Daylight Illuminance (below) (courtesy of Atelier Ten)

ELECTRIC LIGHTING STUDY

The results are summarized in Table 3 below.

Study Name	Calculated Workplane Lux	Calculated EML Range	Meets WELL?	LPD	% of LEED v4 CI (0.93 W/sf)	% of Title 24 (0.75 W/sf)
Baseline 1	280 lux	108 lux – 151 lux average vertical starting at 10' offset (17 lux at 5' offset)	Path 1: NO Path 2: NO	0.37 W/sf	-60%	-51%
Baseline 2	254 lux	108 lux – 161 lux average vertical starting at 10' offset (43 lux at 5' offset)	Path 1: NO Path 2: NO	0.32 W/sf	-66%	-57%
Circadian Option 1	925 lux	237 – 516 lux average vertical starting at 10' offset (86 lux at 5' offset)	Path 1: YES 15' from window and deeper Path 2: YES 10' from window and deeper	1.30 W/sf	+40%	+73%
Circadian Option 2	689 lux	236 – 430 lux average vertical starting at 10' offset (97 lux at 5' offset)	Path 1: YES 20' from window and deeper Path 2: YES 10' from window and deeper	0.91 W/sf	-2%	+21%
Circadian Option 3	839 lux	312 – 430 lux average vertical starting at 10' offset (86 lux at 5' offset)	Path 1: YES 15' from window and deeper Path 2: YES 10' from window and deeper	1.05 W/sf	+13%	+40%
Circadian Option 4	340 lux	291 – 323 lux average at work stations	Path 1: NO Path 2: YES	0.50 W/sf	-46%	-33%

Table 3: Summary of the electric lighting study results

INTEGRATION OF DAYLIGHT AND ELECTRIC LIGHTING

Resulting zones for daylit-circadian light and electric circadian lighting are shown below.

Figure 5: Zones defining the proposed integrated daylight and circadian electric light approach (courtesy of Atelier Ten)

EXPLANATION

USABLE AND CIRCADIAN DAYLIGHT SUMMARY

Daylight remains a reliable source of circadian light. However, availability and access of daylight does not guarantee a visually comfortable working environment. As the operation of manual blinds and therefore access to required melanopic lux levels is occupant dependent, manual blinds cannot be relied upon for providing required melanopic lux exposure. Electric circadian lighting throughout the space then becomes critical, thereby potentially increasing the capital cost, energy use and operating cost of the building.

Automated blinds on the east and west façades provide 80% useful daylight illuminance for the perimeter spaces. For the EBR project, manual blinds are recommended on the south façade as they are likely to stay down for more than 50% of the occupied year due to high illumination levels. The automated blinds option provides 250 melanopic lux via daylight for at least 4 hours daily for 33% of the floor area. This area is optimized for visual comfort, daylight usability and circadian daylight exposure and can be designed with regular (non-circadian) electric lighting. The resulting LPD of the space can be reduced by *approximately 30% by this approach.*

ELECTRIC LIGHTING STUDY

The two Baseline studies were lighting approaches considered to provide the general ambient lighting for the open office spaces of the EBR project. The initial studies to test the circadian light levels revealed that the baseline condition did not meet either compliance path for WELL, and that supplemental lighting would be required.

Circadian Options 1 – 3, which use ceiling mounted lighting strategies, resulted in dramatic increases in the wattage usage for the lighting, as well as dramatic increase in the workplane light level. While LEED v4-CI Prerequisite allows 0.93 W/sf for open office area, the local energy code, Title 24, allows only 0.75 W/sf. Thus, none of the ceiling mounted options can meet the local energy code, and only one met the LEED prerequisite. Further, light levels fall below the thresholds near the perimeter wall. For Path 1, this can easily be supplemented with daylight, as illustrated above. Path 2, however, would require that workstations be at least 10' away from the glazing.

In theory, if Path 2 were pursued by a design team, the lighting could be reduced deeper in the space to save energy and reduce the light level in the middle of the space compared to the studies. This can be achieved by either reducing the light output of the light fixtures or by spacing light fixture further apart in the middle of the space. Both carry visual and design implications that may be detrimental to some projects and would need to be evaluated during the design process.

Bringing the light source closer to the occupants, as in Option 4, had the least impact on energy use, and satisfies both Title 24 and LEED. But by limiting the light output of the table lamp to within a comfortable range for visual system (e.g. not cause glare), this strategy only met Path 2, requiring the task lights to remain on all day regardless of user needs or wants.

CONCLUSION AND FUTURE WORK

The initial study of the electric lighting reveals that there are serious design implications to projects exploring Well Building Standard certification. The circadian lighting requirements of WELL require either a significant increase in the amount of light and energy use, or a light source located close to occupants, if not met with daylight alone.

Perhaps the most troubling is the impact on the visual experience of the space. The high light level required to entrain the circadian clock requires bright light sources. When supplied by electric light, there is a high potential for glare and an uncomfortable visual scene. This could potentially lead to a series of unintended health and productivity consequences, such as eye strain, headaches, and difficulty focusing. Design teams are advised to closely study and vet the potential impact to worker productivity and comfort when designing circadian electric lighting.

The strategy of a table mounted task light is an interesting one that keeps energy use low, but also raises practical concerns for the space. How would employees feel about having a bright light source on all the time adjacent to their computer screens? How does this impact productivity and visual comfort? Is it ethical to force a bright light source on an employee without their ability to turn it off or dim it? How does research connect migraines to similar spectrums of electric lighting affect people? Further study is needed to answer these questions.

The most effective way to deliver circadian light levels is through a well-designed, daylit building. In this sense, the WELL circadian lighting requirement can complement LEED and even Net Zero goals. Daylighting typically focuses on delivering light levels to work surfaces while balancing glare and visual comfort from direct sun exposure. Several rules-of-thumb and design guides have been developed to help guide architects and designers to design daylit spaces to provide adequate lighting on work surfaces. Very little study has been conducted about the amount of daylight required to adequately light a space from a circadian entrainment point of view. Currently the WELL does not address this context of designing light with visual comfort, usable daylight and required melanopic lux as an integrated requirement, which is needed for successful implementation.

Lighting for the circadian system is relatively new to the design community. It is an exciting opportunity for architects and designers to develop new and interesting approaches for building forms and lighting designs. When we look at delivering daylight from a circadian perspective, does it change how we daylight a space? Or how we craft a building form in order to provide the higher light levels without glare? Is there an ideal furniture arrangement that maximizes circadian lighting from daylight while minimizing glare? Are there creative, beautiful, and comfortable ways to supplement circadian daylighting with electric light sources? This is the challenge brought forth to the design community by the WELL metric and our growing understanding of the circadian system.

ACKNOWLEDGMENTS

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REFERENCES

A Nabil, John Mardaljevic. 2005. Useful daylight illuminance: a new paradigm for assessing daylight in buildings. Sage Journals.

Acosta, I, R. Leslie, and M. Figueiro. 2015. "ANALYSIS OF CIRCADIAN STIMULUS ALLOWED BY DAYLIGHTING IN HOSPITAL ROOMS."

Cromie, William J. 1999. Human Biological Clock Set Back an Hour. July 15. Accessed April 17, 2016. http://news.harvard.edu/gazette/1999/07.15/bioclock24.html.

Dilouie, Craig. 2011. ASHRAE Releases 90.1-2010-Part 1: Design, Scope, Administrative Requirements. April 18. Accessed May 15, 2016. http://lightingcontrolsassociation.org/content/whitepapers/ashrae-releases-90-1-2010-part-1-design-scope-administrative-requirements/.

Duffy, Jeanne F., and Charles A. Czeisler. 2009. "Effect of Light on Human Circadian Physiology." Journal of Clinical Sleep Medicine (National Institutes of Health PubMed Central). Accessed December 2, 2016. http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2717723/.

Figueiro, Mariana G., G. C. Brainard, S. W. Lockley, V. L. Revell, and R. White. 2008. Light and Human Health: An Overview of the Impact of Optical Radiation on Visual, Circadian, Neuroendocrine, and Neurobehavioral Responses. Technical Memorandum, New York City, New York: Illuminating Engineering Society.

Foster, Russell. 2013. "Waking Up to the Link between a Faulty Body Clock and Mental Illness." The Guardian. July 22. Accessed May 21, 2016. https://www.theguardian.com/science/blog/2013/jul/22/body-clock-biological-circadian-sleep.

Joseph, Anjali. 2006. "The Impact of Light on Outcomes in Healthcare Settings." The Center for Health Design. August. Accessed December 2, 2015. https://www.healthdesign.org/sites/default/files/CHD_Issue_Paper2.pdf.

Khullar, Atul. 2012. "The Role of Melatonin in the Circadian Rhythm Sleep-Wake Cycle." Psychiatric Times, July 09. Accessed May 20, 2016. http://www.psychiatrictimes.com/sleep-disorders/role-melatonin-circadian-rhythm-sleep-wake-cycle.

Kolb, Helga. 2016. "Simple Anatomy of the Retina." Webvision. Accessed May 21, 2016. http://webvision.med.utah.edu/book/part-i-foundations/simple-anatomy-of-the-retina/. Used under Attribution, Noncommercial, No Derivative Works Creative Commons license.

Leslie, R.P, L.C Radetsky, and A.M Smith. n.d. "Conceptual design metrics for daylighting." Lighting Research and Technology.

Lucas, Robert J., Stuart N. Peirson, David M. Berson, Timothy M. Brown, Howard M. Cooper, Charles A. Czeisler, Mariana G. Figueiro, et al. 2014. "Measuring and Using Lighting in the Melanopsin Age." Trends in Neuorsciences 37 (1). Accessed November 17, 2015. http://www.cell.com/trends/neurosciences/pdf/S0166-2236(13)00197-5.pdf.

Maury, Eleonore, Kathryn Moynihan Ramsey, and Joseph Bass. 2010. "Circadian Rhythms and Metabolic Syndrome: From Experimental Genetics to Human Disease." Circulation Research (National Institutes of Health PubMed Central). Accessed December 8, 2015. http://www.ncbi.nlm.nih.gov/pubmed/20167942.

Schernhammer, Eva S. , Francine Laden, Frank E. Speizer, Walter C. Willett, David J. Hunter, Ichiro Kawachi, and Graham A. Colditz. 2001. Rotating Night Shifts and Risk of Breast Cancer in Women Participating in the Nurses' Health Study. Journal Report, Oxford: Oxford University Press.

Stevens, Richard G., David E. Blask, George C. Brainard, Steven W. Lockley, Ignacio Provencio, Mark S. Rea, and Leslie Reinlib. 2007. Meeting Report: The Role of Environmental Lighting and Circadian Disruption in Cancer and Other Diseases. Meeting Report, National Institute of Environmental Health Science.

Integration <> Adaptation

ELECTROCHROMIC GLASS

Maximizing the performance through optimum zoning and control strategies

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ABSTRACT

Fenestration with dynamic solar control, such as electrochromic (EC) glazing is, according to the DOE, a key component of a net zero energy façade system. The energy performance is such that buildings can be designed with more glazed area without compromising energy performance, allowing designers to achieve the transparency and daylighting they desire while still creating a building with excellent energy performance and which is thermally and visually comfortable for the occupants. Moreover, EC glass has the ability to automatically control the sunlight glare by tinting down to a very low visible light transmission, which allows occupants to achieve visual comfort while still maintaining a view to the outside, thus avoiding the "blinds down, lights on" situation often present in today's office buildings.

With electrochromic glazing, similarly to shades and blinds, there is a trade-off between controlling the system to achieve occupant comfort (glare control and thermal comfort) and controlling the system for optimum energy performance. There is a competing need to tint the glass fully (or pull a shade) to control the glare, yet still allow sufficient daylight admission for occupants and to offset electric light, and also tune the solar heat gain to control HVAC loads. In addition, for electrochromic glazing, color rendering in the interior is yet another factor to control. Zoning of EC glass, where different panes, or portions of panes, are controlled independently, is critical to balancing these competing needs and delivering the optimum performance for occupant comfort and for building energy efficiency.

This paper demonstrates, using evidence from daylight modeling, the optimal control and zoning strategies for EC glass when used in façades that deliver the appropriate balance of glare control, color rendering, daylight admission and energy performance. There are significant implications from this study for architects when designing with EC glass, especially in floor to ceiling applications. An appropriate zone layout must be developed based on the specific application. Such zoning solutions can be achieved by either (i) adding horizontal framing members to create separate EC panes within the façade, or (ii) using EC glass with in-pane zoning if larger lites and less metal is desired architecturally or (iii) a combination of both.

KEYWORDS

Dynamic façades, IEQ performance, daylighting and glare, electrochromic glazing, energy efficiency, dynamic glazing

INTRODUCTION

According to the US Department of Energy (DOE) fenestration with dynamic solar is a key component of a net zero envelope solution, with a potential of saving up to 2.6 Quads (10^{15} BTUs) annually in the US if widely implemented as part of an integrated façade system (Arasteh 2006). Dynamic solar control can be implemented through conventional mechanical systems such as exterior moveable louver systems or automated blind/shades integrated in a double skin curtain wall, or by using electrochromic (EC) glazing where the dynamic solar control is contained in the glass itself. These systems can block unwanted heat gain during cooling times and admit it during heating times, and at all times work in tandem with electric lighting controls to offset electricity usage.

Energy efficiency is clearly a key consideration for 21st century building design. But so is creating indoor environments that promote occupant health and well-being. By 2020 the world health organization predicts that cardio-vascular disease and mental health disorders, will be the top two diseases globally (World Health Organization). These disorders, plus other health, well-being and productivity related issues can be significantly impacted by the built environment, and since we now spend more than 90% of our time indoors, the health of the population and the planet are equally important imperatives when designing buildings.

Bringing in daylight and providing views to the outside plays an important role in creating healthy indoor environments because of the impact on circadian rhythm entrainment, mental alertness and stress reduction (World Green building council, 2014, Terrapin Bright Green, 2012). However, daylight brings with it the dual problems of excessive heat gain and conductive heat losses that increase the loads on the heating, ventilation and air conditioning (HVAC) system, and thermal discomfort and disabling glare for occupants. Indeed thermal and visual discomfort can completely negate any of the positive human benefits of daylight and views (Heschong Mahone Group 2003, Seppanen 2006) and so occupant comfort must be managed carefully in any daylight design.

EC glass is an effective tool for balancing these competing objectives, because of the ability to tint and clear the glass based on the exterior conditions to control solar heat gain and glare and optimize daylight admission. When integrated with dimmable lighting controls, electrical energy usage can also be minimized. For example, more glass can be used on the envelope to achieve sufficient daylight penetration, yet because it can be tinted when needed it can prevent over-lighting and glare, and manage solar loads. Regarding conductive losses, EC glass can be integrated into high thermally performing framing systems, and used in triple pane format for more northern climates when thermal performance is important. In general, larger commercial buildings tend to be cooling dominated, so in these cases the dynamic solar heat gain performance will be the most critical for optimizing energy performance.

Because electrochromic glass reduces the complexity of the sun management solution by condensing it into the glass itself, it can provide a more flexible solution for architects allowing them to design with more glass and in more interesting ways (Fig. 1). The ability for EC glass to reduce peak loads can also enable the use of more sustainable heating and cooling solutions such as natural ventilation, chilled beam and radiant systems (Fig.2).

Figure 1: Project examples of the architectural design freedom offered by EC Glass. Left image: Butler County Healthcare and Rehabilitation Center, David City, NE, where EC glass was used to create a large, segmented sloped curtain wall that maintains large expansive views of the outside countryside and a comfortable day-lit interior to support faster patient recovery. This design would have been almost impossible to realize with conventional shading systems. Photo courtesy of Daubman Photography. Right image: The Frost School of music, Miami, FL where EC glass was used in large triangular format to create a unique design that could not have been realized if exterior shading was used for sun control. Photo courtesy of Moris Moreno.

However, in order to deliver the optimum building performance in terms of daylight admission, glare control, energy efficiency and light color quality the EC glass has to be controlled effectively. This paper reviews the key strategies for EC glass control which most effectively balance these often competing goals.

Figure 2: Interior view of the student services center at Chabot College, Hayward, CA. This highly glazed south facing atrium features EC glass on 3 sides and because of the peak load reductions provided, the architect was able to create a naturally ventilated space with no mechanical cooling.

BACKGROUND

Just like the use of shades and blinds (interior or exterior), there is a trade-off between blocking glare and admitting sufficient daylight and energy performance. For example, when a blind is pulled down over a window to block glare (or EC glass is fully tinted), daylight admission is also reduced, which then increases the use of electric lights. When manual shades are used (or manually controlled EC glass), occupants do not actively manage the retraction of the blind or shade (Van Den Wymelenberg, 2012). These devices are left down long after the glare condition has passed, reducing daylight admission, increasing lighting energy use and blocking the view – negating both the human and energy efficiency benefits of the daylight design (Fig. 3). In particular, one study in Switzerland by ESTIA (Paule et al. 2015) and a second in New York by Urban Green (Urban Green, 2013) showed, respectively, that on average 57% and 59% of the window area of buildings was covered by shades or blinds.   Moreover, with conventional shading systems, which are “top down”, the top of the window which is the optimum for daylight penetration is always the first area to be blocked.

Figure 3: Typical sight of office building with shades down even when the sun is not directly on the façade. This photo was taken of the northeast corner of a building in San Francisco at 5pm in the afternoon. Most of the shades are pulled down over most of the window area even though the sun is on the other side of the building and has been for many hours.

Other work by Dyke et al. (Dyke, 2013 & 2015) demonstrated how manual blind usage not only negated the daylight design by reducing the daylight autonomy, but it also reduced energy performance by 28% because the daylight admission is blocked and electric lights must be utilized.

The first solution to this issue is to automate the response to glare, wherein the system automatically removes the shade, or in the case of EC glass, increases the light transmission, after the glare condition has passed. However, this does not fully optimize daylight admission when the glare condition is present for either mechanical or EC solutions nor the need for dynamic solar heat gain management.

Moreover, for EC glass, an additional factor that must be balanced is the light color quality in the space, since the glass tints to a blue-gray color. If all the glass is tinted, the light coming into the space will have a blue hue. Previous work by Mardaljevic et al. has demonstrated that a neutral daylight illumination is achieved using EC glass if 10-15% of the glass area remains in the highest transmission state (Mardaljevic, 2016). This is because the light coming through the highest transmission state at 60 percent visible light transmittance is essentially neutral and washes out the bluer light coming through the rest of the glass area that is tinted and has a much lower visible light transmission.

Figure 4: An example of zoning of electrochromic glass in a vertical glazing application. In this case there are 4 zones – top row, middle top row, middle bottom row and bottom row. There are actually only 2 separate EC panes, since the top EC pane is separated into 3 independently controllable zones (in-pane zoning). In this instance the top zone is fully tinted to 1%T to control the glare, the bottom zone is in the highest transmission state (60%T) to control light color quality, and the middle zones are at appropriate transmissions (6%T and 20%T) to manage heat gain and tune the daylight admission. Photo © Jeffrey Totaro, 2015.

However, EC glass has another important control lever – zoning – that can be used to minimize the apparent compromise between glare control and daylight admission, and also deliver good light color quality. Zoning is the ability to group panes, or sections of panes, together and control them separately and independently from other groups of panes/sections of panes (fig.4). In figure 4, EC glass spans the floor to ceiling height using two panes separated by a horizontal framing member. Within each of the larger upper panes, the EC glass is split into 3 independently controllable segments (sub-panes), creating 4 horizontal zones in total: Upper sub-panes, upper middle sub-panes, bottom middle sub-panes and bottom panes. Each zone can be independently controlled according to the location of the sun and the specific needs of the occupants. The daylighting simulations described herein demonstrate how zoning can manage the balance between the competing needs of glare control, daylight admission, energy performance and light color quality in different applications.

METHOD

The results of two different daylight simulations are described herein. One looks at the south facing elevation of a building in Sacramento and compares glare control and daylight admission at the equinox and daylight admission and solar heat gain control during the summer. The second study focuses on the difficult challenge of controlling glare on a west elevation while still allowing enough daylight to enter and controlling light color quality.

BALANCING DAYLIGHT, GLARE AND SOLAR HEAT GAIN

The Diva plug in for Rhino (Diva is a daylighting modeling module based on Radiance that can be used within the 3D computer aided design software, Rhinoceros or Rhino) was used to model EC glass in a south facing office building located in Sacramento, CA (Fig. 5). Three horizontal EC zones were modeled for the glass from desk height to ceiling. Opaque spandrel panel was positioned below desk height (Fig. 5). Given that there are 4 different tint levels available for the EC (60%, 20%, 6%, 1%T), and there are 3 zones, there are 64 (4 x 4 x 4) different zone patterns possible. Each zone pattern is given a 3 digit number for identification. The first digit corresponds to the transmission state of the bottom zone, the second digit corresponds to the transmission state of the middle zone, and the third digit to that of the top zone. Numbers 0, 1, 2, 3 correspond to the 60%, 20%, 6% and 1%T states respectively. For example, zone pattern "012" has the bottom zone at 60%T, the middle at 20%T and the top zone at 6%T. The pattern shown in figure 5 is "000" – all zones at 60% transmission.

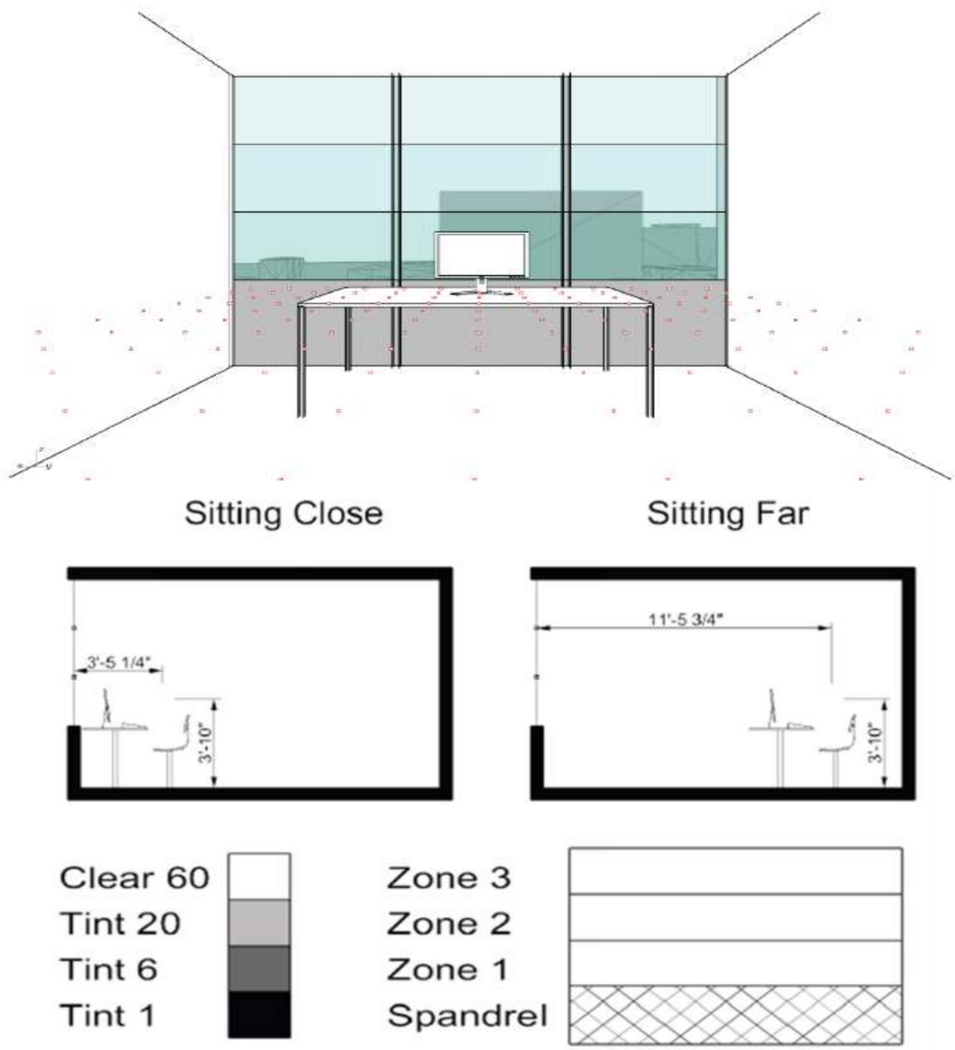

Figure 5: South facing office model with three zones – top, middle and bottom. There are two view points – sitting close to the window and sitting far away from the window. Red dots indicate the points on the work plane where daylight illuminance is calculated. Each zone can be in any one of four different tint states.

A daylight simulation was done for each of these zone patterns on 21st June (summer), 21st September (equinox), and 21st December at noon. Daylight glare probability was assessed for two different view points in the room - one close to the window and one far back from the window – for all the zone patterns. The illumination at the work plane across the entire office area was also calculated and the results are shown as a percentage of the office area that achieves at least the 300 lux target illumination through daylight admission. This gives a measure of how well a given zone pattern daylights the space. For each zone pattern an effective solar heat gain coefficient was calculated by taking an average of the solar heat gain coefficients associated with each EC glass tint state (table 1), assuming equally sized zones.

Table 1: Solar heat gain coefficient (SHGC) and visible light transmittance for EC glass

EC tint state visible light transmittance	SHGC (center of glass)
60%	0.41
20%	0.15
6%	0.10
1%	0.09

CONTROLING GLARE AND COLOR RENDERING WHILE STILL DAYLIGHTING A SPACE

In this second simulation, Radiance was used to simulate the glare, illuminance and color rendering performance in a typical deep (10m, 30ft) open plan, west-facing office (fig.6) at the equinox, for:

- 3-zone EC glass,
- 1-zone EC glass,
- Standard static glass (a triple silver low emissivity (low-e) product with 60%T),
- Standard static glass with automated fabric shades of 5-7% transmission

Figure 6: Interior image of simulated west facing open office space

The location chosen was in Oakland, California, but the results are representative of most west elevations in north America and Europe. The control strategies for the EC glass and shading system are provided in table 2 which were derived initially by verifying that the daylight glare probability was maintained at an acceptable level. Also, the impact of light striking the back wall was reviewed to determine that even late in the afternoon the top zone needed to remain at 1%T. The priority for the control strategy was firstly to control direct sunlight glare, followed by maximizing daylight admission.

To visualize the color rendering of the light in the space, 6 squares in standard colors (turquoise, pink, yellow, red, green and blue) were placed on one of the walls in the office. The rendering of these colors in the images are used to qualitatively assess the light color quality in the space at different times during period from 1pm to 6pm.

Table 2: Control strategy for shades and EC glass in west facing office from 1:00 to 6:00pm

Time	1:00pm	1:30pm	2:00pm	2:30pm	3:00pm	3:30pm	4:00pm	4:30pm	5:00pm	5:30pm	6:00pm
Fabric shade distance closed, m (ft)	0.3 (1.0)	1.2 (4.0)	1.8 (6.0)	2.1 (7.0)	2.4 (8.0)	2.4 (8.0)	2.7 (9.0)	2.7 (9.0)	2.7 (9.0)	2.7 (9.0)	0 (0)

Single zone EC tint state		60%	20%	6%	6%	1%	1%	1%	1%	1%	1%	60%
Three zone EC state (number in parenthesis is the EC state using numbering convention 0,1,2,3)	Top zone	60% (0)	20% (1)	6% (2)	6% (2)	1% (3)	1% (3)	1% (3)	1% (3)	1% (3)	1% (3)	60% (0)
	Middle zone	60% (0)	60% (0)	20% (1)	20% (1)	20% (1)	6% (2)	1% (3)	1% (3)	1% (3)	1% (3)	60% (0)
	Botto m zone	60% (0)	60% (0)	60% (0)	60% (0)	60% (0)	60% (0)	60% (0)	60% (0)	60% (0)	60% (0)	60% (0)

DATA AND EXPLANATION

BALANCING DAYLIGHT, GLARE AND SOLAR HEAT GAIN

The simulation data for the south facing office on 21st September (fig. 7) shows that only 12 zone patterns can adequately control sunlight glare for occupants at this point in time. Of those 12 zone patterns only 3 adequately maintain daylight levels in the space (over 90% of the area achieving 300 lux). These zone patterns are 013, 023 and 033 and they achieve 300 lux or more in 100%, 95% and 90% of the office area respectively. Note that in all cases, one of the zones is at 60%T, which allows enough daylight in to the room to offset electric lighting and also maintains its color neutrality. In all of the three zone patterns the effective solar heat gain is low, between 0.22 and 0.20, thus effectively managing the solar loads too. This solar heat gain coefficient compares extremely favorably with that of high performance triple silver low-e on clear glass of 0.27.

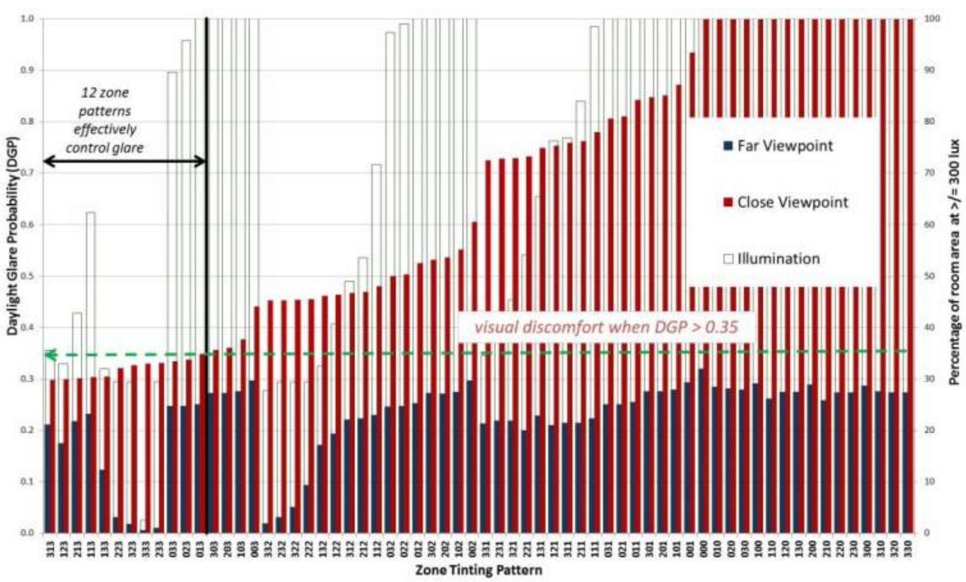

Figure 7: Daylight glare probability for close and far view points and percentage of room area achieving at least 300 lux illumination from daylight for south facing office at noon on September 21st.

It is interesting to note that the zone pattern (333), in which all zones are at 1%T, controls glare well, but only 2% of the room area achieves 300 lux through daylight. This means that if no zoning is used and with the entire glass area held at 1%T, even though visual comfort is achieved, the room would be too dark. And because there is no area that is fully clear, the light in the room would also be blue, providing a poor color rendition (see next section). Even though the solar load is low because of the effective solar heat gain coefficient of 0.09, because of the increased use of electric lights, this zone pattern is also not necessarily the most energy efficient solution for an occupied space.

One might think that the daylighting performance would be better if the entire area was held at say 6%T or 20%T rather than 1%T. However, the data shows that this is not the case: The (222) zone pattern (all at 6%T) results in too much glare for the near view point, and less than 30% of the area is sufficiently day-lit (fig. 7). The (111) zone pattern (all at 20%T) has better daylighting performance (98% of the area reaches 300 lux) but the glare would be extreme (fig. 7).

In the summer, glare is not such a problem because of the high sun angles (fig. 8). However, the tinting of the glass must be optimized to maximize daylight admission while minimizing solar gains. The trade-off between effective solar heat control and daylight admission is demonstrated in figure 9. While it might be possible to keep the entire window wall at 60% visible light transmission (000), the solar heat gain coefficient is quite high at 0.41 and the space is close to being over-lit at an average illumination level of ~3000 lux. Given that it is summer, the building is in cooling mode. It is therefore better to tint the EC glass to reduce solar loads. The zone patterns demarked by section C in figure 9 appear to have the best trade-off between maximizing daylight illumination and minimizing solar heat gain. Note that all patterns have one zone in the clear state that not only ensures good daylight admission, but also neutral color rendering of the light. The two best zone patterns within that group are (201) and (210) which have effective solar heat gain coefficients of 0.22 and have close to 100% of the office area day-lit. Reducing solar heat gain further (zone patterns in section A, fig.9) reduces daylighting effectiveness and electric lighting use will offset cooling load reduction and so are not optimal. However, these patterns would be excellent choices for unoccupied times when daylight admission and color quality are not important. Zone patterns within section B have lower daylight performance without improving solar heat gain coefficient. Those within section D provide good daylight admission yet have higher than necessary solar heat gain.

The optimum zone patterns for minimizing glare and maximizing daylight admission on December 21st at noon are (330), (230), (130). All have one zone in the clear state to provide the daylight admission, and good color quality. Pattern (131) almost achieves 100% space illuminance, and is the next best in terms of balancing glare and daylight admission, but with all zones tinted will not provide as good a color quality, and not as much solar heat gain, which can be important in winter to offset heating loads. Pattern (333) – all zones fully tinted – controlled the glare as effectively as (330), (230) and (130), but did not provide adequate illumination. Only 0.5% of the space achieved 300lux. Pattern (222) did not sufficiently control the glare.

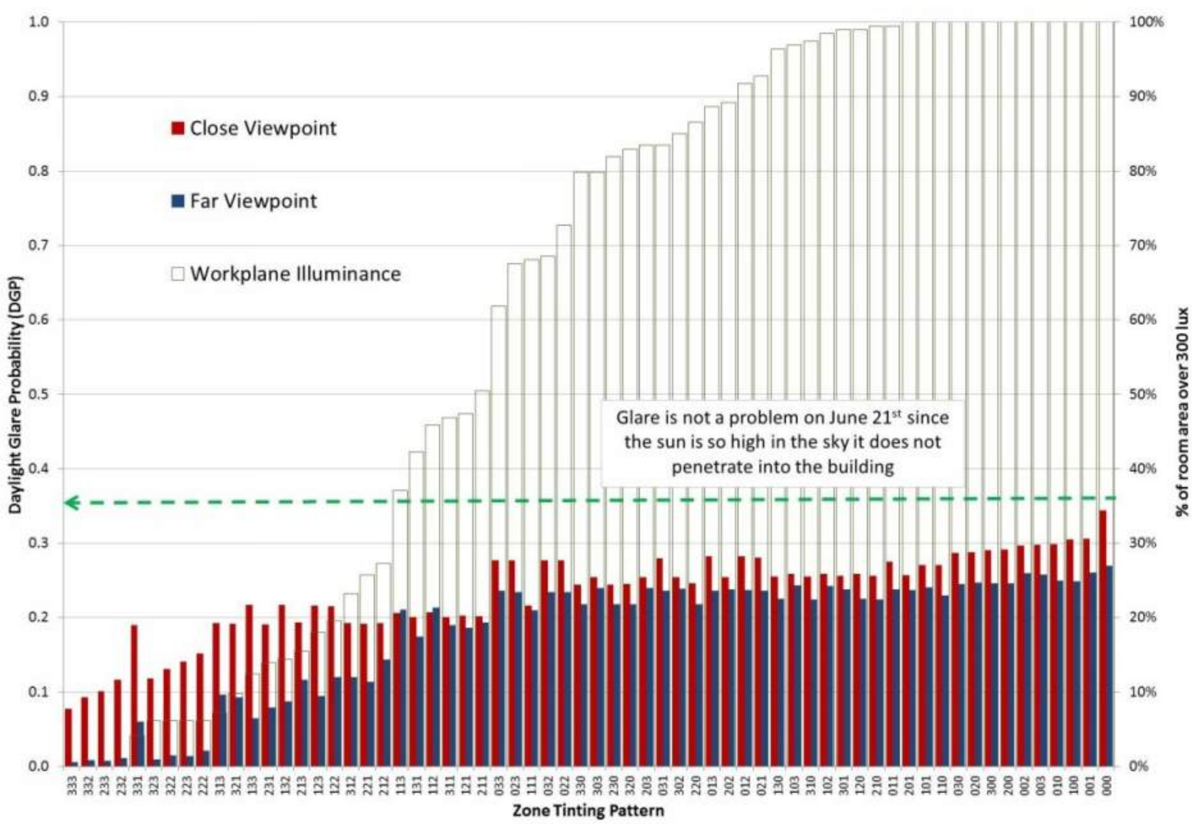

Figure 8: Daylight glare probability and percentage of room area achieving at least 300 lux daylight illumination for 64 zone patterns for south facing office in Sacramento at noon June 21st.

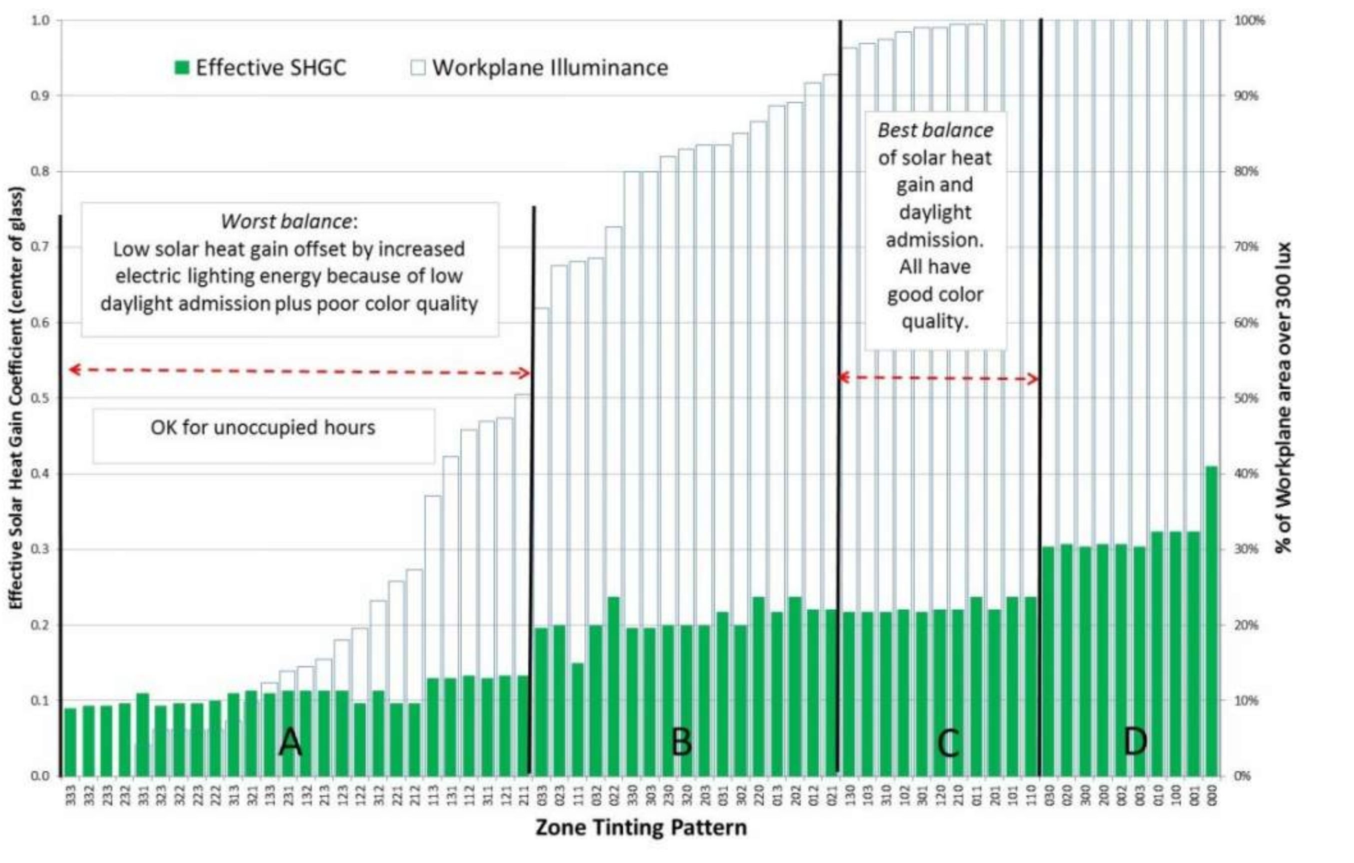

Figure 9: The effective solar heat gain and simulated daylight illumination performance of the 64 possible zone patterns in a south facing office building in Sacramento at noon on 21st June. The graph is divided in to sections A-D (see text for details).

CONTROLING GLARE AND COLOR RENDERING WHILE STILL DAYLIGHTING A SPACE

The Radiance simulations of the west facing open plan office with four different façade options (fig. 10) show that the 3-zone EC glass solution provides good color rendering at all times, very similar to that of shaded and unshaded triple silver low-e options, and significantly better than the single zone EC option. It also provides as good a daylight admission as the conventional glass with fabric shade but, unlike the latter, preserves the view to the exterior. The unshaded conventional system would be an impractical situation during this time because of the disabling glare from the direct sunlight admission, but it is shown to compare color rendering performance.

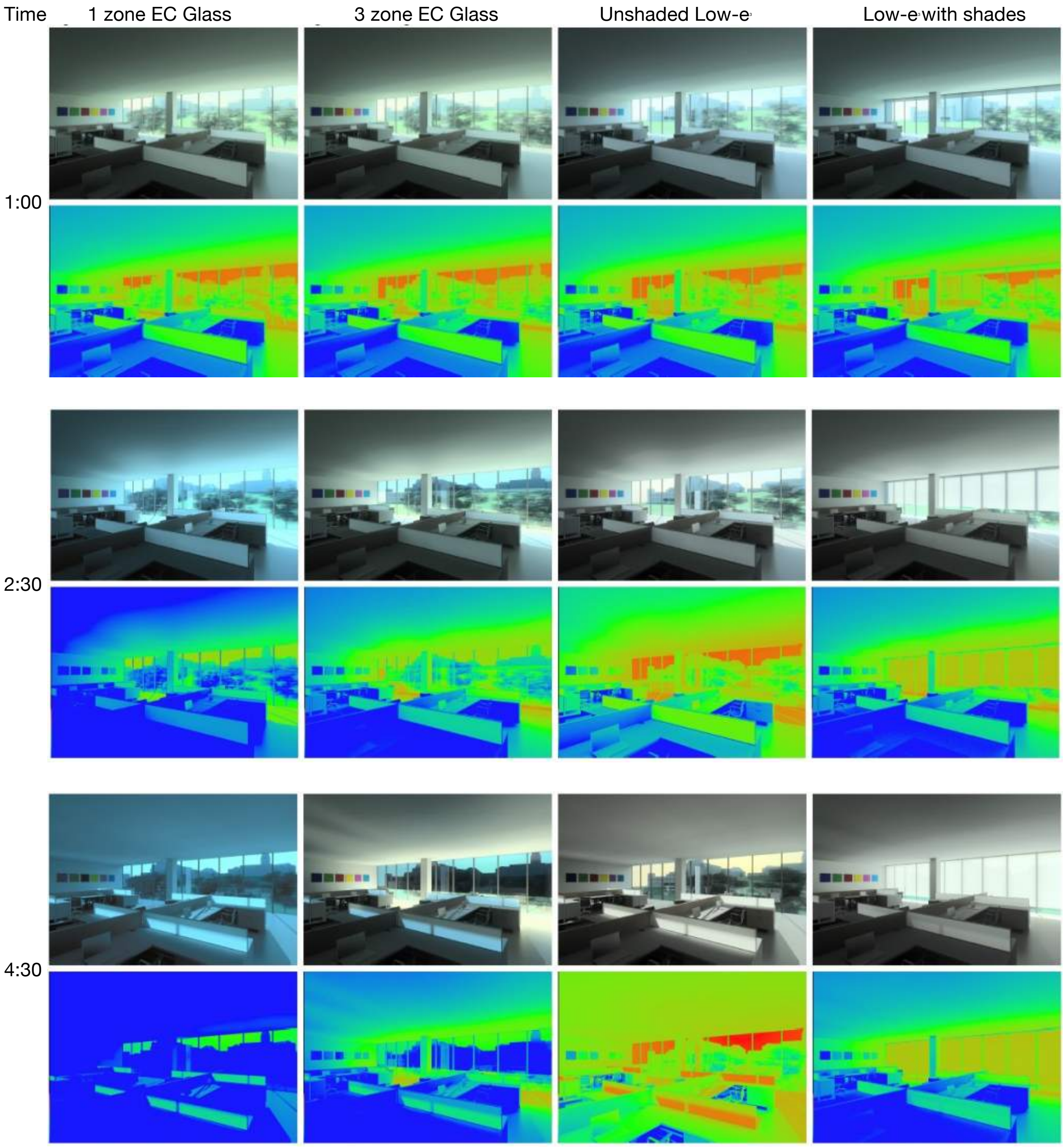

Figure 10: Radiance renderings and companion high dynamic range images of the west facing office building with (left to right) single zone electrochromic, 3-zone electrochromic, unshaded triple silver low-e glass, and shaded triple silver low-e glass respectively at 1:00pm, 2:30pm and 4:30pm. Color panels on the wall demonstrate the good color rendering performance of 3-zone EC glass system compared to the conventional systems. EC tint states and shade positions per table 2.

CONCLUSION

The data from the simulation studies clearly demonstrate that zoning of electrochromic glass in vertical glazing applications is critical to effectively balancing the competing goals of glare control, daylight admission, energy efficiency and light color quality. In contrast to shades and blinds, the top of the window, which is best for daylighting, can also be kept in a high transmission state when not causing glare, thus better optimizing daylighting performance. Furthermore the view is maintained at all times.

The optimum zone patterns will depend on the specific application, orientation, the weather, and the time of day, year etc. However, some rules of thumb are indicated:

- **Glare control**: When direct sun is present, the zone(s) through which the occupants can see the sun should be held at 1%T to adequately control glare.
- **Daylighting and color**: At least one zone should be left in the highest transmission state at any one time. This provides a strategy that not only creates a neutral color rendering, it also provides sufficient daylight admission to offset electrical lights. The other zones can then be tinted as needed to manage glare and optimize solar heat gain (minimize in cooling times, maximize during heating times).
- **Unoccupied times**: The requirements related to occupant comfort are eliminated. The EC glass is then controlled solely to maximize energy performance without additional constraints.
- **Good daylighting design:** Using light reflective interior surfaces and low interior partitions support EC performance optimization.

There are significant implications from this study for architects when designing with EC glass, especially in floor to ceiling applications. An appropriate zone layout must be developed based on the specific application. Such zoning solutions can be achieved by either (i) adding horizontal framing members to create separate EC panes within the façade, or (ii) using EC glass with in-pane zoning if larger lites and less metal is desired architecturally or (iii) a combination of both. An example of the latter combination is shown in figure 4 where four horizontal zones optimize performance. For floor to ceiling applications a minimum of 3 zones are recommended to deliver the needed performance, especially for deep spaces.

ACKNOWLEDGMENTS

Unless otherwise stated in the figure caption, building images are courtesy of SAGE Electrochromics, Inc.

REFERENCES

Arasteh, D., Selkowitz, S., Apte, J., LaFrance, M. "Zero Energy Windows, Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings", August 13-18, 2006. LBNL report number 60049.
Dyke, C. Van Den Wymelenberg, K., Djunaedy, E., Steciak, J., "Comparing Whole Building energy Implications of Sidelighting Systems with Alternate Manual Blind Control Algorithms", Buildings 2015, 5, 465-496.
Dyke, C., presentation at Radiance Workshop, 2013. https://www.radiance-online.org/community/workshops/2013-golden-co/VanDenWymelenberg_blindsControlAlgorithms.pdf
Heschong Mahone Group, "Windows and Offices: a study of worker performance and the indoor environment" (technical report) for California Energy Commission, 2003.
Mardaljevic, J., Kelly Waskett, R., Painter, B., Neutral daylight illumination with variable transmission glass: Theory and validation, Lighting Res. Technol. 48 (2016): 267-285.
Paule, B., Boutillier, J., Pantet, S., "Global Lighting Performance" prepared by Estia for Swiss Federal Office for Energy, 2014.
Seppanen, O., Fisk, W. Lei, QH., "Effect of Temperature on Task Performance in Office Environment", LBNL report 60946, 2006.
Terrapin Bright Green LLC., "The Economics of Biophilia: Why designing with nature in mind makes financial sense", 2012.
Urban Green, New York Chapter of the USGBC, "Seduced by the View", December 2013.
Van den Wymelenberg, K., "Patterns of Occupant interaction with window blinds: A literature review", Energy and Buildings, 51 (2012) p165-176.
World Green Building Council, "Health, wellbeing & Productivity in Offices", 2014, and references therein.
World Health Organization, http://www.who.int/whr/2001/media_centre/press_release/en/ (accessed 18 July 2016).

STRUCTURAL SKIN

Integrating structure and cladding

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ABSTRACT

Many prominent, recent buildings feature forms suggesting structural surface while their enclosures are really non-load-bearing curtain wall. At the same time, we instinctively read the increasing proportion of opaque area on the facade required by the energy codes as solid, an opportunity to augment the primary building frame with perimeter structure. We have evident aesthetic desire to see structural form, and technical incentive in the form of increased opaque surface area to use the exterior enclosure as structural skin to make buildings more efficient, and more sustainable.

Preliminary modeling of a 24-story braced moment-frame with a 90' x 90' floor plate shows that structural cladding occupying the same depth as a conventional curtain wall has the capacity to limit lateral drift and reduce tonnage of the primary steel frame. The study evaluates three different schemes of moment-connected mullions braced by infill plate or diagonal rods. Each version replaces conventional aluminum mullions with stronger and stiffer hybrid mullions of steel and aluminum cassette glazing frames.

The initial expectation was that the skin would allow reduction in tonnage of the primary frame, resulting in reduced embodied CO2. It turns out that the reduction of steel in the primary frame is more than offset by the amount of steel added to the cladding in each case, but the net result in the last iteration is a reduction of embodied CO2 in the frame and skin due to the relatively high embodied CO2 of the replaced aluminum.

Next steps include refining details and exploring the potential of shaped or corrugated surface and structural laminated glass to enhance structural skin. This preliminary investigation shows that integrating structure and cladding, and using steel instead of aluminum in the enclosure framing, can save embodied energy.

KEYWORDS

Façade- curtain wall, innovative; *Performance*- energy efficiency, carbon; *Sustainability*- energy and carbon; *Material*- steel and aluminum (metal); *Other*- future trends, structural cladding.

INTRODUCTION

> *We are given an area which is to be covered, a space which is to be enclosed. We know the movement conditions of the external forces. If we set ourselves the task of sustaining these forces by transferring the reactions to the supports in a simple manner, by using the space-enclosing surface itself to carry the load…this is a general, but, finally, the only interesting problem.*
>
> B. Lafaille, 1936.(Angerer).

Structure expressed on the building surface is often the most aesthetically important element of architecture. The figural masses and quality of repose of the classical orders, the mysterious spaces and seemingly tensile forms of Gothic masonry, and the bio-morphic shapes of recent sculptural buildings all show the animating power of apparently structural form. This suggests that aesthetics and structure should be conceived in concert. But in modern design practice and education, aesthetic and technical aspects of architecture are commonly dealt with by separate 'design' and 'technical' groups, and structure is usually concealed by the non-load-bearing veneer of the curtain wall. Although the extra effort required to integrate different types of construction has kept structure and cladding separate in most modern buildings, a desire to integrate them appears in many current high-profile projects. One example is the Broad Museum in Los Angeles. The minimally sculpted box appears to be a structural dia-grid shell, its light-controlling apertures shaped as if carved from solid concrete. But the 'veil' enclosure is made of thin, lightweight glass fiber reinforced concrete panels attached to a steel framework supported by the interior structure of the building (Vaillancourt) (Fig. 1, Broad).

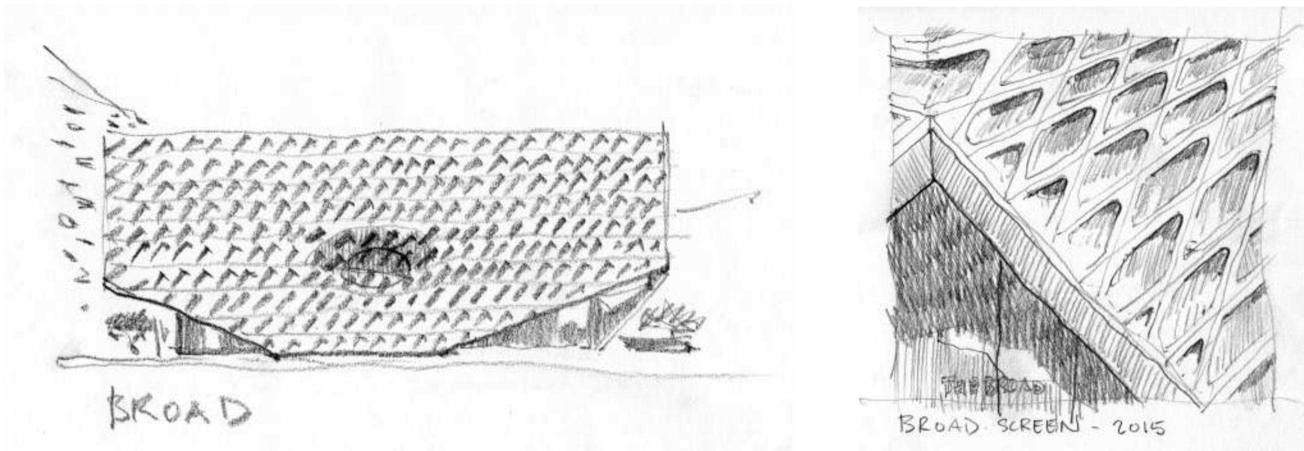

Figure 1: Broad Museum, Los Angeles, 2015, DS+R Architects. Elevation and close-up views. The façade reads as a perforated structural shell, but is made of thin GFRC panels on a curtain wall framing system.

The growing realization that climate change is accelerating is incentive to make building systems more efficient by integrating them, making material perform multiple functions in order to use less of it. Digital design technology makes analyzing hybrid frame and skin structure much easier than it once was. Meanwhile, evolving energy codes mandate a higher proportion of opaque surface on building exteriors. This is surface that we tend to read intuitively as mass or structure, and it could possibly be that in reality. The 2010 ASHRAE 90.1 prescriptive method for determining energy performance of exterior walls has decreased the baseline proportion of vision glass from 50%, previously, to 40% of total wall area, and the 2012 International Energy Conservation Code baseline is 30% (ASHRAE).

This study examines the potential for the enclosure framing to reduce wind drift in a high-rise structure, replacing steel tonnage in the primary frame. The curtain wall represents a significant amount of building mass, weighing 10 to 15 pounds-per-square-foot on the façade of an average mid- to high-rise building. In comparison, the primary structural frame weighs 15 to 20 pounds per square-foot of floor space.

The concept of structural surface is counter to the prevalence of the non-load-bearing curtain wall skin in the modern era, and some critics have dismissed it as impractical, or contrived. E. Ford, in The Details of Modern Architecture, credits Le Corbusier's romantic infatuation with the airplane, an invention that only came into existence during the lifetime of the first modern architects, with being the source of a modernist fixation on exposed structure for appearance's sake (Ford). The new incentives to explore integral structure and enclosure may help illuminate the underlying appeal of the airplane: it is a construct with almost all dead weight eliminated.

BACKGROUND

As buildings that account for no net CO2-equivalent emissions in operation of their heating and cooling systems become a practical reality, minimizing 'embodied' CO2—emissions caused by manufacturing and fabrication of material-- by getting rid of redundant or unnecessary components will be a big next step in improving the sustainability of the built environment. Studies have estimated that the CO2-equivalent emissions embodied in a high-performance building can range from between 40% to 300% of the amount resulting from energy used during operation in its lifespan (Airaksinen & Matilainen; Thormark). In a 'net-zero' energy-use building, the embodied energy theoretically accounts for 100% of related CO2 emissions.

EMBODIED CO2 IN ALUMINUM AND STEEL

Using less material would suggest less embodied CO2, but some materials require more energy to produce than others. According to two industry-published metrics, steel production results in .73 tons of CO2 per ton of steel, while aluminum production results in 2.2 tons of CO2 per ton of aluminum (American Institute of Steel Construction, Aluminum Association). Other sources give different values. The Bath University Inventory of Carbon and Energy lists aluminum, with international average of 33% recycled content, at 8.16 tons of embodied CO2 equivalent per ton. Steel, which averages 59% recycled content, compares at 1.37 tons embodied CO2 per ton in the Bath index (G. Hammond & C. Jones). The object of this study is not to advocate for a particular material, but rather to advocate questioning the conventions of construction systems to find more sustainable approaches, with estimates of embodied CO2 being a significant criterion.

CURTAIN WALL AND STRUCTURAL CLADDING

Ease of construction, minimal obstruction of view and light, minimal maintenance requirement, design flexibility and, after more than a century of evolution, familiarity to builders has made the curtain wall independent of the structural frame the standard mode of enclosure on modern buildings, and this basic approach is unlikely to change in the near future (Fig. 2, Curtain Wall).

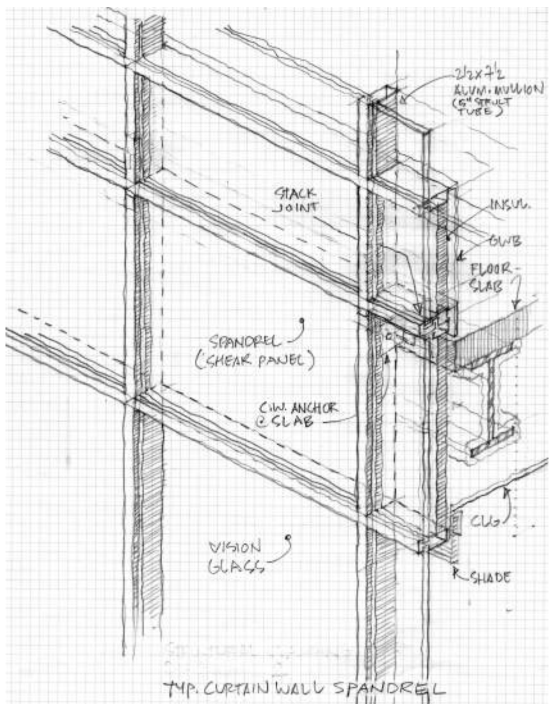

Figure 2: Typical Curtain Wall Panel Assembly.

Still, there is precedent for integrating structure and enclosure in recent and not so recent buildings. Early green houses, such as at Bicton Gardens, constructed in the 1820's, used the glass as a shell stiffening the frame of iron glazing bars (J.C. Loudon) (Fig. 3, Bicton).

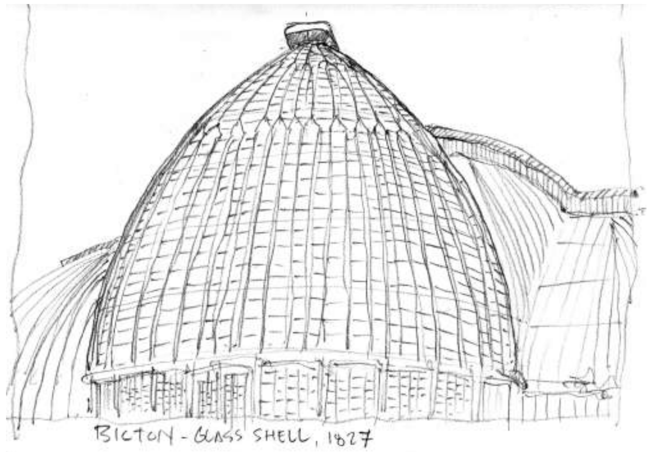

Figure 3: Palm House, Bicton Glasshouses, Bicton Botanical Gardens, Exeter Devon, England. 1820's. Thin wrought iron glazing bars form a flexible network supporting panes of glass which stiffen the enclosure by acting as a compressive shell.

There are projects from the latter half of the 20th century with facades integral to their primary structural frames, such as Corbusier's exposed concrete Unite d'habitation block (1952) and B. Fuller's Dymaxion House (1930), modeled after a grain bin of riveted sheet metal. Mies van der Rohe's steel facades of 860-880 Lake Shore Drive (1951) are engaged with the concrete and steel frame by welded studs, similar to the steel stressed-skin exterior of the Daley Center in Chicago designed by Jacques Brownson of C.F. Murphy (1964) (Fig. 4- Daley Center). During the design of the Daley Center, the structural engineers raised concerns that a continuous structural skin would have problems with thermal expansion and other building movements. Brownson argued correctly that the skin could absorb the stresses of these movements, just as welded railroad track does (Chicago Architects Oral History, and personal conversation c. 2004). The glazing frames 'float' to allow for drift and deflection of the structural wall around them.

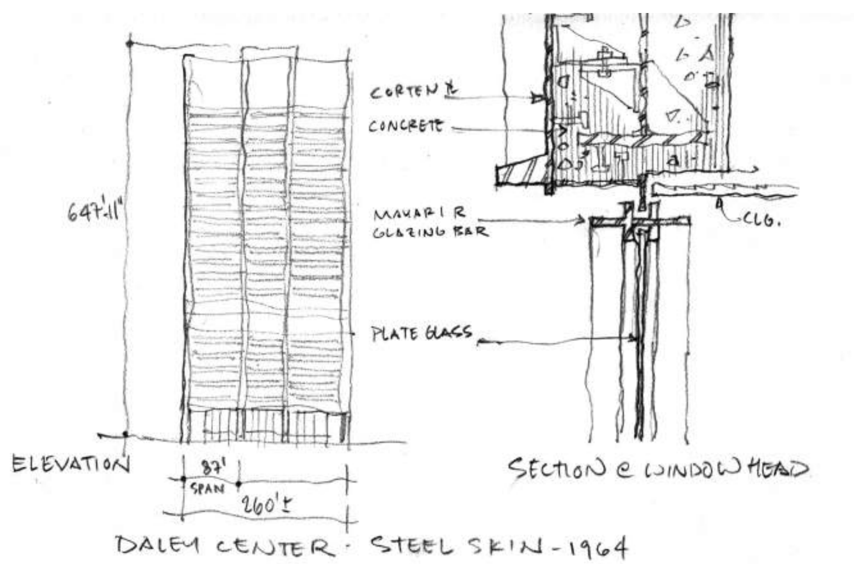

Figure 4. Daley Center, Chicago (orig. Chicago Civic Center), 1964. Joint venture C.F. Murphy Associates, Skidmore, Owings & Merrill and Loebl, Schlossman, Bennett & Dart. The Cor-Ten steel skin is structural, acting as formwork for the concrete encasing the steel frame, in an assembly similar to the steel cladding and composite frame of 860-880 Lakeshore Drive (1951), by Mies van der Rohe. The steel skin intentionally contributes to the stiffness of the tower against wind.

The structural tube concept employed in tall buildings since the 1960's uses the enclosure as lateral bracing and for gravity loads, creating what the engineer W. LeMessurier called the steel or concrete "bearing wall," (LeMessurier). This perimeter wall was thicker than the curtain wall, and had a much greater percentage of opaque surface than the normal frame enclosure. The 54-story Dravo Tower, by Welton Becket and Lev Zetlin Associates, built in 1984 in Pittsburgh, is a perimeter-framed tube with unprotected painted steel plate cladding that forms a stressed skin limiting wind-induced sway. The steel skin is not relied upon for any code-required strength, but provides comfort-related limit of drift (Tomasetti). Port hole-like window openings in the steel plate were glazed with gaskets, and the 3-story by 10' plates were attached using neoprene seals. According to the designers, the stressed skin allowed reduction of the depth of spandrel beams.

In the last decade or so, a number of researchers have explored the potential for double façade armatures to become structural cages contributing to the stiffness of high-rise buildings, limiting wind-induced drift (Moon; Azad & Samali). There were studies published in the 1980's and 1990's on the idea of using cladding connections to dissipate seismic energy by using springs or friction devices in the anchors (Whole Building Design Guide; Cohen & Powell). However, this work has been mostly speculative. Double facades are expensive and it is difficult to quantify their performance. Shock absorbers for cladding connections may work, but they are, almost 50 years after viscous dampers were installed at the perimeter of the World Trade Center Towers, uncommon in buildings. The influence of these concepts on the conventions of commercial construction has been limited because of their complexity and high initial cost, the problems of exposing structure to the elements, and the floor-space they take up.

The framed-tube model that uses closely spaced columns to create a dense perimeter wall has drawbacks of limiting view and flexibility, and the few projects that employed steel stressed skin cladding had limited influence. Maintenance and thermal bridging are two common problems with exposed steel, along with fire-safing and initial cost. It could be more practical to make structural use of the material already typically in place on the building surface in the market's preferred construction model-- the long-span frame and the curtain wall-- if there is sufficient structural capacity in this thin layer.

METHOD

DESIGN INVESTIGATION

The current proposal adds a stiffening membrane over a moment frame with a braced core. The wall only limits drift for comfort's sake, which would improve serviceability—wear and tear—of the skin as well. This keeps the skin distinct from the primary structure, with the advantages of separating design and construction of different types of assemblies: heavy primary structure can be built to a different set of tolerances and finish standards than surface, and design of the primary frame can be developed for beginning construction without finishing the skin design. Gravity members, columns as well as elements that brace them against buckling, are separate from lateral bracing, consistent with the way the building code has historically not required fire protection for structural members designed to take only lateral wind or seismic force. The concept could be expanded to include primary structure, and in construction temporary lateral bracing of the frame could be removed when the structural skin is put on. The spandrel and column-cover area of the façade could easily incorporate fire protection if necessary (**Fig. 5**, Opaque Assemblies on Spandrel & Column Cover).

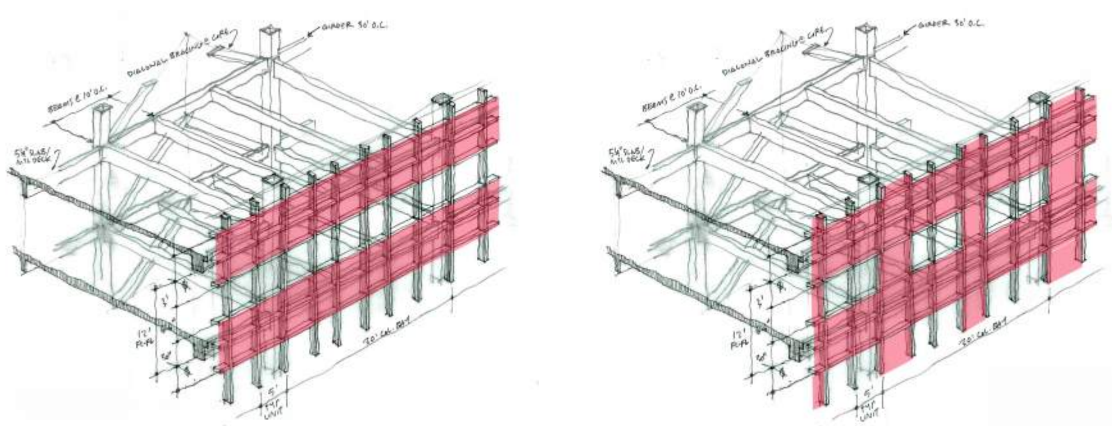

Figure 5: Varying degrees of opacity and structural potential on the elevation correlate to spandrel area; spandrel and column area.

The aluminum mullions in the façade would be too flexible to control inter-story displacement adequately, so the structural body of them is replaced with steel. With the column covers included in the diaphragm area, only two mullions per bay are exposed. With intumescent paint or other cover for fire protection, if necessary, these could contribute to the façade stiffening.

A 2x5x5/16 HSS (8.15 plf) is used for the mullion, and a ¼” steel plate infill occupies the spandrel area in the first iterations of the structural model. Lighter ½”-diameter rods replace the plate in the final scheme. The rods could extend to the vison area, which would increase the strength of the system. The HSS is about 50% heavier than a standard aluminum mullion (which is about 5 plf).

The glazing frame part of the enclosure will still be aluminum (Fig. 6, aluminum mullion and aluminum-and-steel hybrid). This hybrid assembly uses the two materials for their respective advantages—aluminum for its malleability, facilitating extrusion into shapes that receive gaskets and fasteners, and for its corrosion resistance at the weather surface; steel on the interior for its stiffness and strength. This is in the spirit of recent developments in automobile manufacturing that employ steel and aluminum and other structural materials in combination according to their different properties in ‘lightweighting’ strategies for improving mileage and fuel efficiency, such as putting aluminum bodies on steel frames in small trucks. The assembly is similar to ‘piggy-back’ arrangements used on spaceframe enclosures and monumental façade systems for many years.

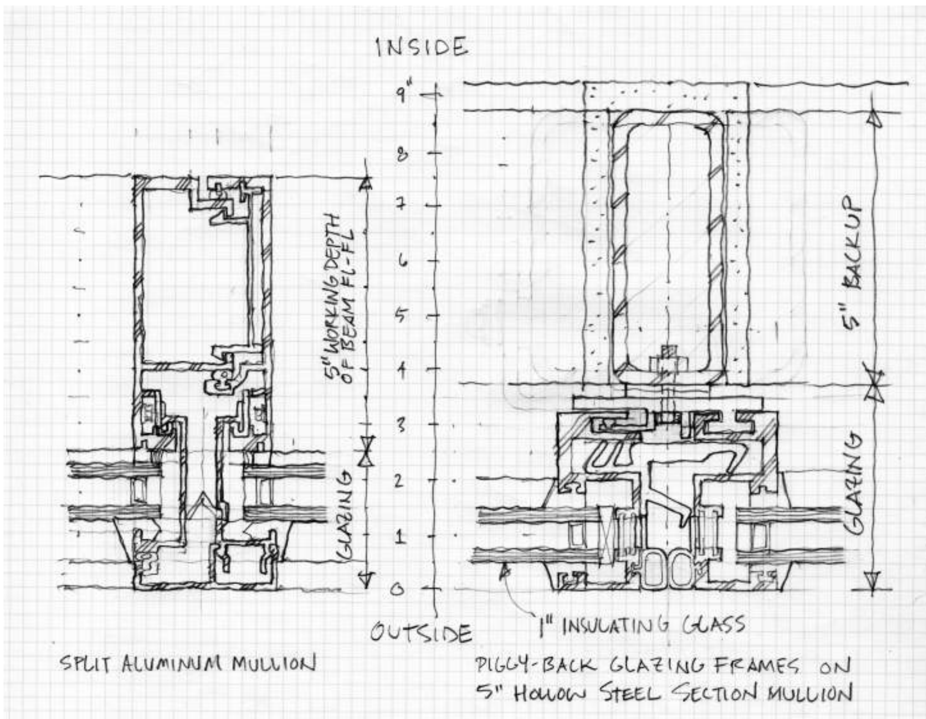

Figure 6: Plan of aluminum split mullion, and aluminum cassette frames on steel backup mullion.

Aluminum has been the default choice of material for framing in the non-load-bearing curtain wall. Aluminum has higher strength relative to weight than steel, is more corrosion resistant, and is easily worked and extruded to receive gaskets and fasteners. However, aluminum is only a third as stiff as steel, most aluminum alloys are not as strong as steel, it costs more per ton than steel, and it has more embodied carbon per ton than steel. It is also more conductive than steel, creating higher levels of thermal bridging. The smaller carbon footprint per ton of steel relative to aluminum is offset by the greater weight by volume of steel—a cubic foot of aluminum weighs about 170 pounds, a cubic foot of steel weighs 500 pounds.

The infill panel in the structural skin would occupy the same space as the conventional spandrel panel of glass or metal. Connections could be accomplished with stick-framed or unitized steel panels. The system proposed can function with a basic stack joint splice at each floor line designed to accommodate live-load deflection and to take shear and moment. (Fig. 7- Slab Edge Detail Sketch).

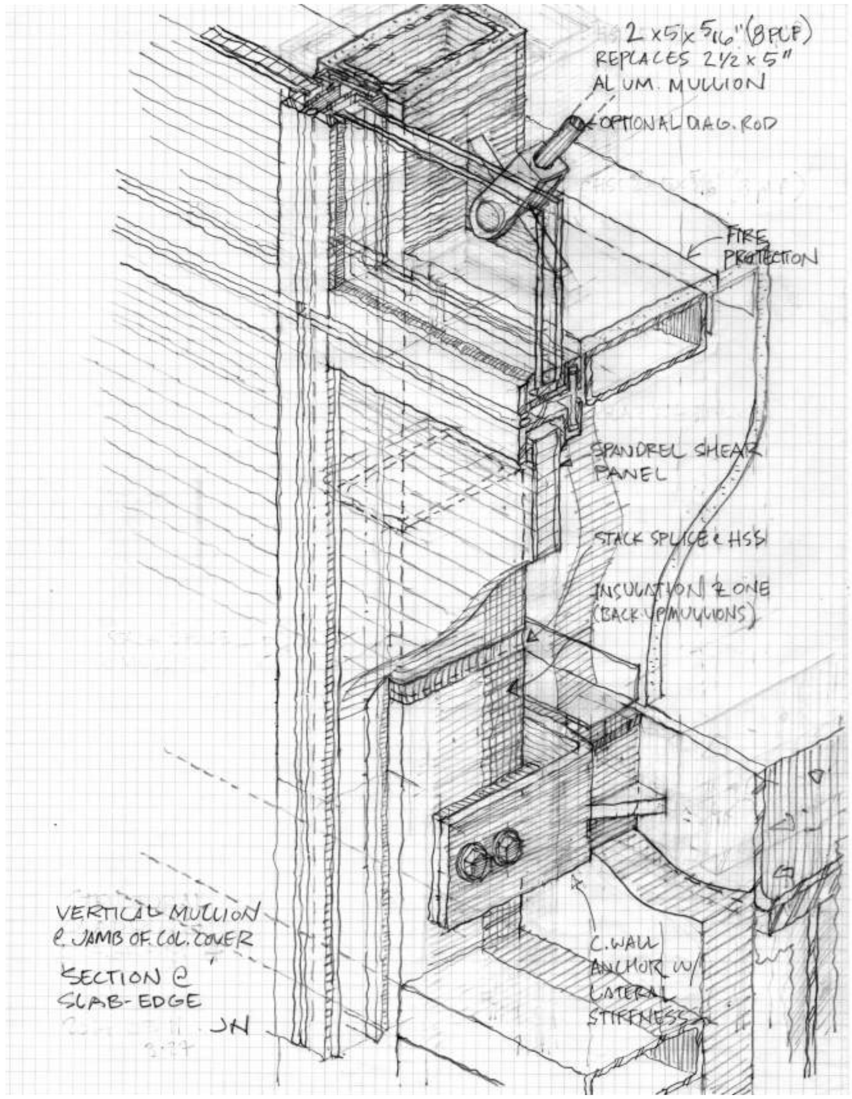

Figure 7: Cutaway sketch of wall at slab-edge.

CASES

The schemes analyzed here were devised in a collaboration between architect and engineer. The variations on the infill panel follow the architectural outlines of common spandrel or column cover areas, relating to the energy code limits on vision glass. The engineering balanced capacity of members and connections and attraction of load, suggesting schemes mixing panels and rods.

To assess the structural potential of the skin, we take a simplified 24-story braced frame with a 90’x90’ footprint. In the variants on the structural enclosure framing, we look at capacity to reduce drift, excluding the ground floor enclosure to leave access unimpeded. Wind load is based on 115 mph 3-second gust.

With a floor plate based on a 3-bay 30’ structural grid, the face of the exterior wall offset from center of structure making the footprint 95’ face-to-face, and a floor-floor height of 12’, with a 4’ parapet, the area of the exterior wall is 106,400sf. (380 lf of perimeter x 12’ fl-fl= 4,560 sf of wall/ fl x 23 flrs = 104,880sf of wall plus 4-0”” parapet x 380’= 1,520 sf).

The study comprises four structural scenarios which were modeled in the structural analysis program ETABS. Comparisons of tonnage of steel (in kips), tower deflection and total embodied CO_2 in the primary structure and the cladding framing are shown in Figures 13, 14 and 15.

DATA

CASE 1

Braced frame designed to take all wind load in conventional fashion, as a baseline for comparison (**Fig. 8,** 3-D model view from ETABS, drift by story and elevation diagram with deflection). Total steel in kips = 3183. Maximum deflection approximately 7.5" or H/460. The total aluminum in the base-case curtain wall enclosure can be estimated at 2.25 psf x 106,400 sf= 240 kips. (27 lf of mullion per 5' x 12' panel at 5 plf = 135 lbs/60= 2.25 psf. This does not include the aluminum in the glazing or cassette zone common to all of the cases). Total tons of embodied CO_2= 1,162 for steel, plus 264 for aluminum = 1,426, per industry metrics.

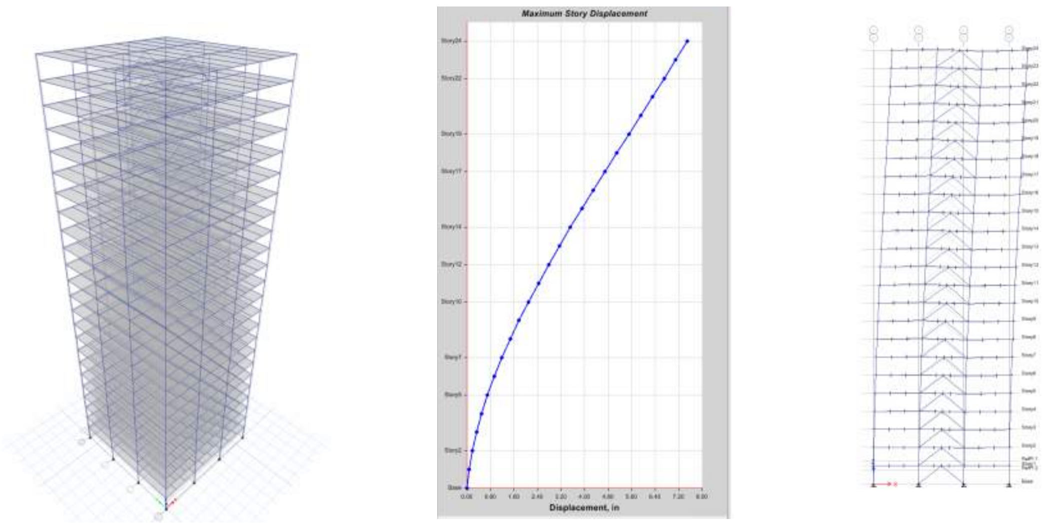

Figure 8: Case 1, 24-story Braced Frame. 3-D view of ETABS model, wind drift graph and elevation diagram showing deflection under wind load. (HOK).

CASE 2

Braced frame with structural cladding, 67% opaque surface moment-frame structural mullion network with plate infill on spandrels and columns. (**Fig. 9,** 3-D model view from ETABS, drift by story and elevation diagram with deflection). The primary frame is reduced in strength and weight from Case 1. Total steel in kips= 2,909 in the frame, and 1,349 in the structural cladding. Maximum deflection of approximately 3" or H/1,152. This is extremely stiff. The degree of fixity of the connection of skin to frame is reduced along with extent of shear plate in the next case. Total tons of embodied CO_2= 1,554 for steel, per industry metrics.

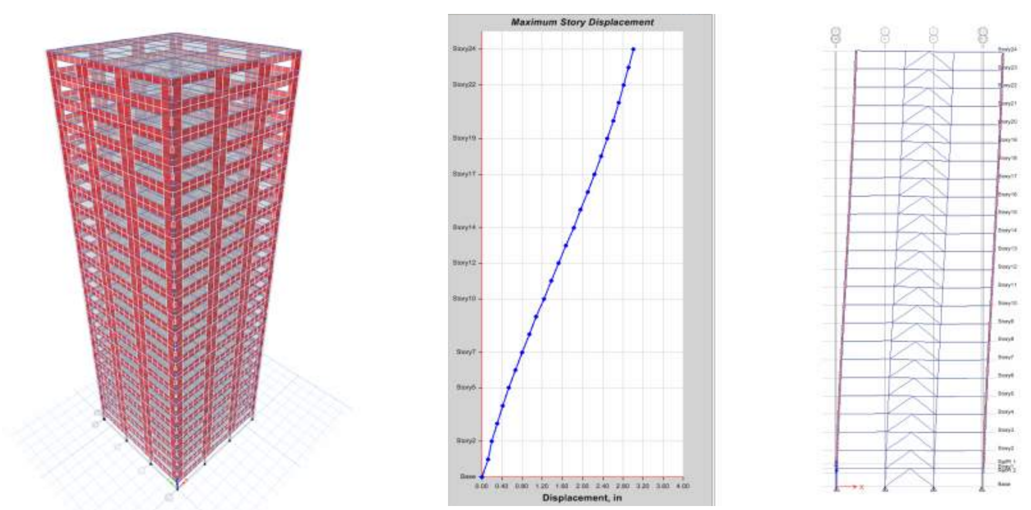

Figure 9: Case 2, 24-story braced frame with steel plate structural cladding. 3-D view of ETABS model, wind drift graph and elevation diagram showing deflection under wind load. (HOK).

CASE 2 BRACED FRAME ONLY

The Case 2 reduced-weight frame without any cladding illustrated the magnitude of the cladding's contribution to stiffness. Total steel in kips = 2909 in the frame. Maximum deflection was approximately 11" or H/300. This is significantly more than the normal range of H/400-600 for wind drift of structures clad with curtain wall.

CASE 3

Braced frame with structural cladding, 67% opaque surface moment-frame structural mullion network with plate infill on columns, x-rod bracing on spandrels. (**Fig. 10,** 3-D model view from ETABS, drift by story and elevation diagram with deflection). Total steel in kips = 2,944 in the frame, and 988 in the structural cladding. Maximum deflection of approximately 6" or H/575. This is at the high end of the normal stiffness for wind design. Total tons of embodied CO_2= 1,435 for steel, per industry metrics.

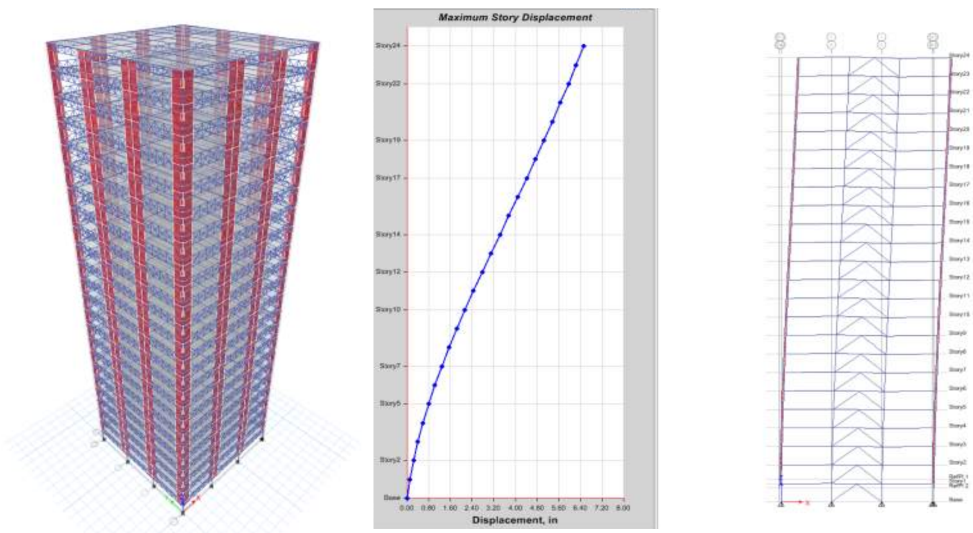

Figure 10: Case 3, 24-story braced frame with steel plate at columns and x-rod braced structural cladding. 3-D view of ETABS model, wind drift graph and elevation diagram showing deflection under wind load. (HOK).

CASE 4

Braced frame with structural cladding, 67% opaque surface moment-frame structural mullion network with x-rod bracing. (**Fig. 11**, 3-D model view from ETABS, drift by story and elevation diagram with deflection). Total steel in kips = 2,921 in the frame, and 601 in the structural cladding. Maximum deflection of approximately 7.5" or H/460. This is at the low mid-range of the normal stiffness for wind design. Total tons of embodied CO_2= 1,285 for steel, per industry metrics.

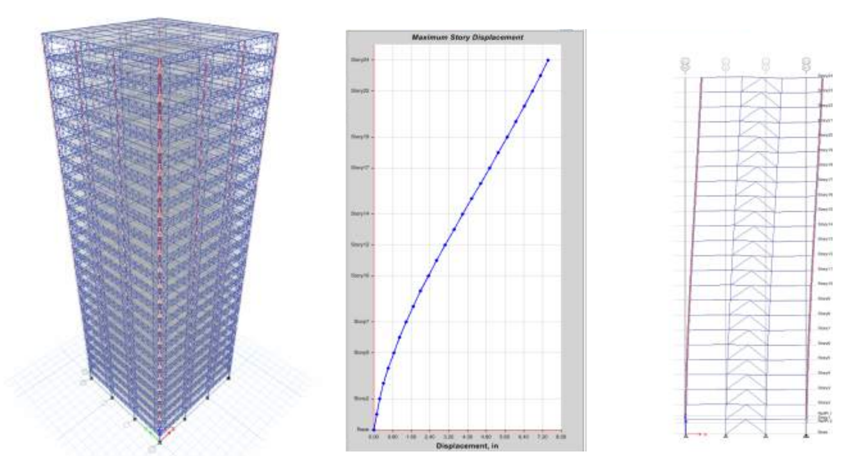

Figure 11: Case 4, 24-story braced frame with x-rod braced structural cladding. 3-D view of ETABS model, wind drift graph and elevation diagram showing deflection under wind load. (HOK).

All of the structural cladding schemes function as a thin moment-resisting framework. The force diagram from the structural model of Case 4 shows how the members react to wind acting from the left (**Fig. 12**, Typical floor of cladding framing showing stresses).

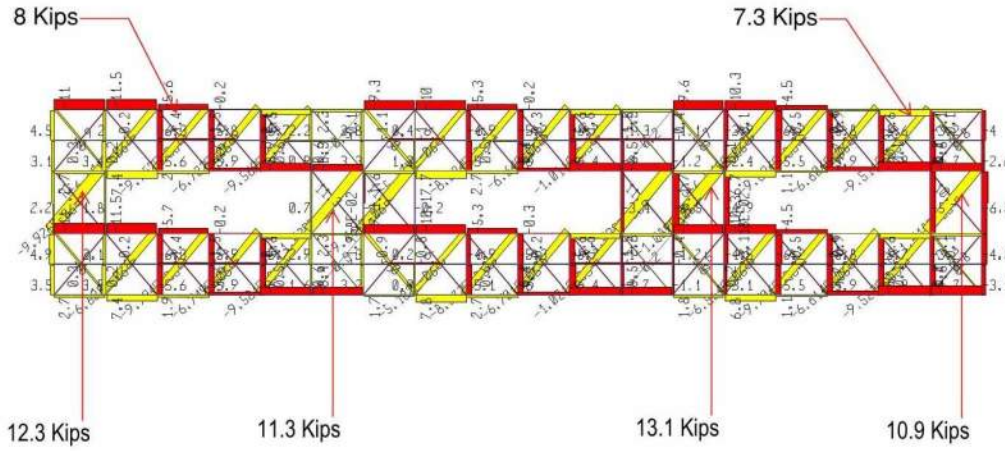

Figure 12: Case 4, 24-story braced frame with x-rod braced structural cladding. Elevation diagram of typical floor (Level 16) showing stresses under wind load. (HOK).

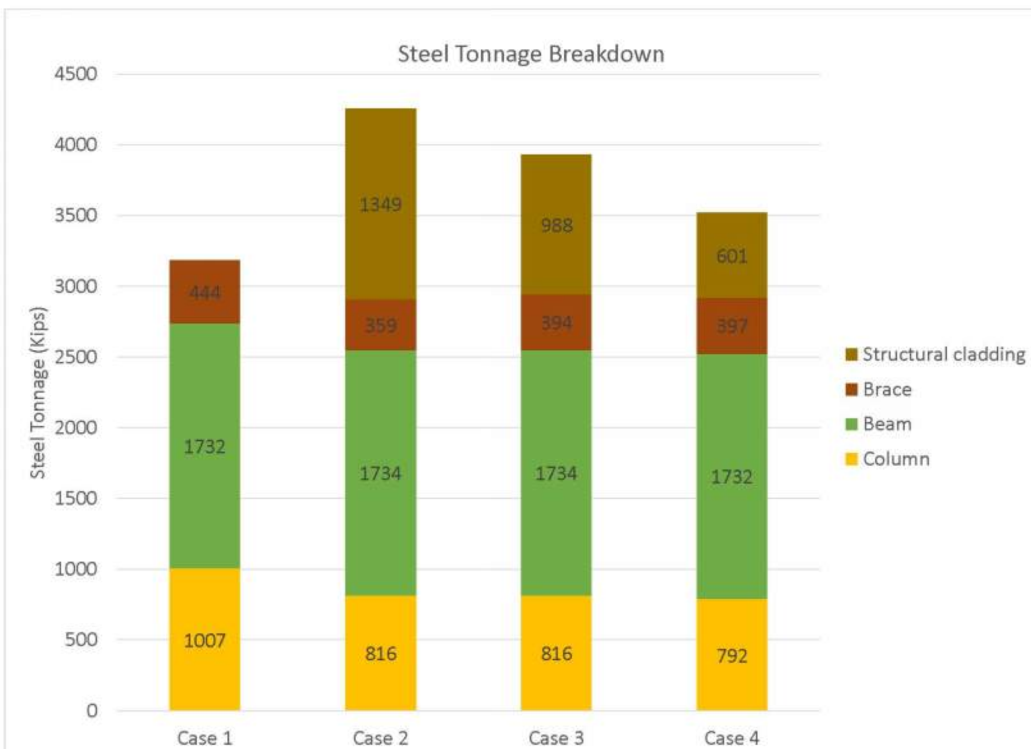

Figure 13: Steel tonnage comparison. (HOK).

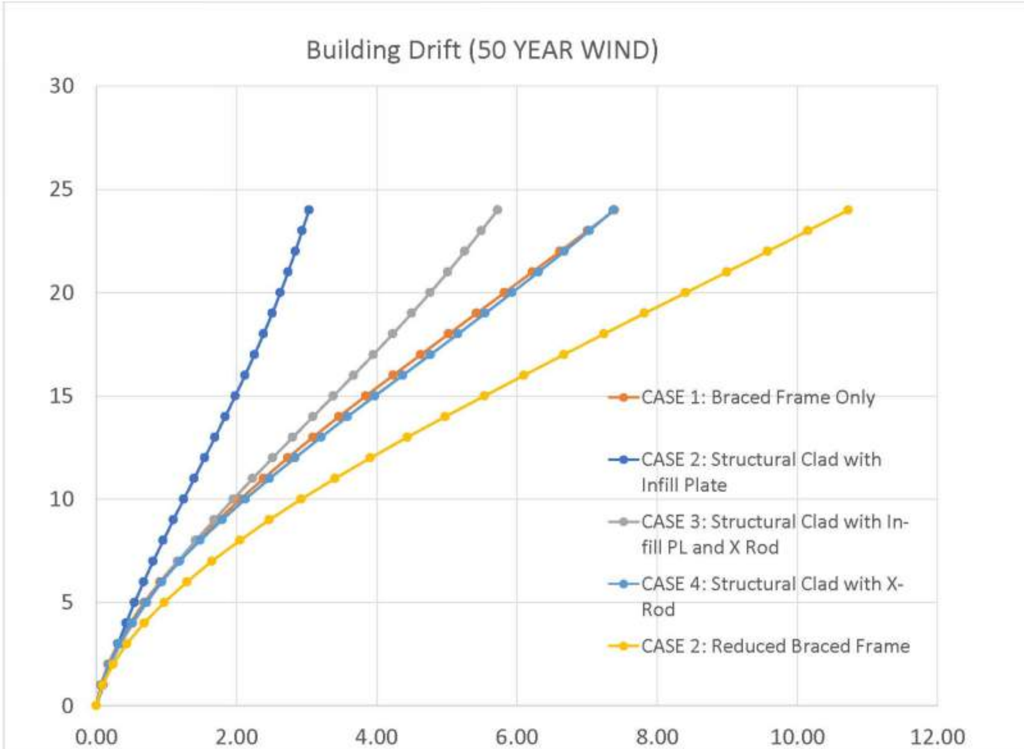

Figure 14: Deflection comparison. (HOK).

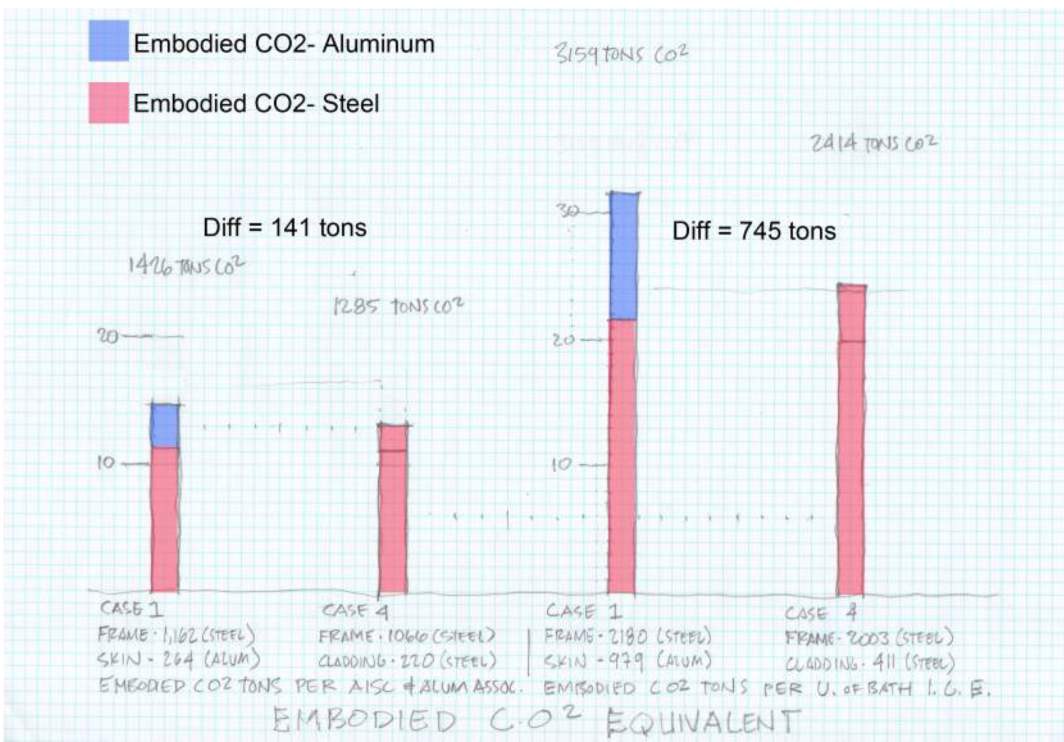

Figure 15: Embodied CO2 comparison, Case 1 normal Braced Frame and Case 4 reduced stiffness Braced Frame with structural cladding, embodied CO2 per AISC and Aluminum Association and according to Inventory of Carbon and Energy, Bath University.

EXPLANATION

Case 4 with x-rod bracing in the cladding framing saves about 140 tons of embodied CO2 relative to the base case, using the industry-published metrics for steel and aluminum, or roughly 10% of the total, which is not a great deal but is still measurable. Using the University of Bath Inventory of Carbon and Energy metrics, the structural cladding produces a savings of 745 tons of embodied CO_2, or almost 25%. With refinement of the structural cladding concept, this result will improve.

FUTURE WORK AND CONCLUSION

FURTHER STUDY

Despite the extreme thinness of the conventional building enclosure, structural cladding of that nominal thickness works to provide lateral bracing and reduce the weight of the primary structural frame, and the concept has potential for development. Next steps for research would include (Fig. 15, Notes on further study):

- Detailing of connections that could control stiffness of the skin to avoid attracting too much force, also potentially damping drift with flexible or soft connections.
- Thermal analysis of connections.
- Shaping of the building surface to create intrinsic stiffness of curved or folded forms that could enhance the capacity of the surface membrane.
- Study of larger bracing configurations to improve efficiency.
- Capitalizing on the compressive strength of glass itself.

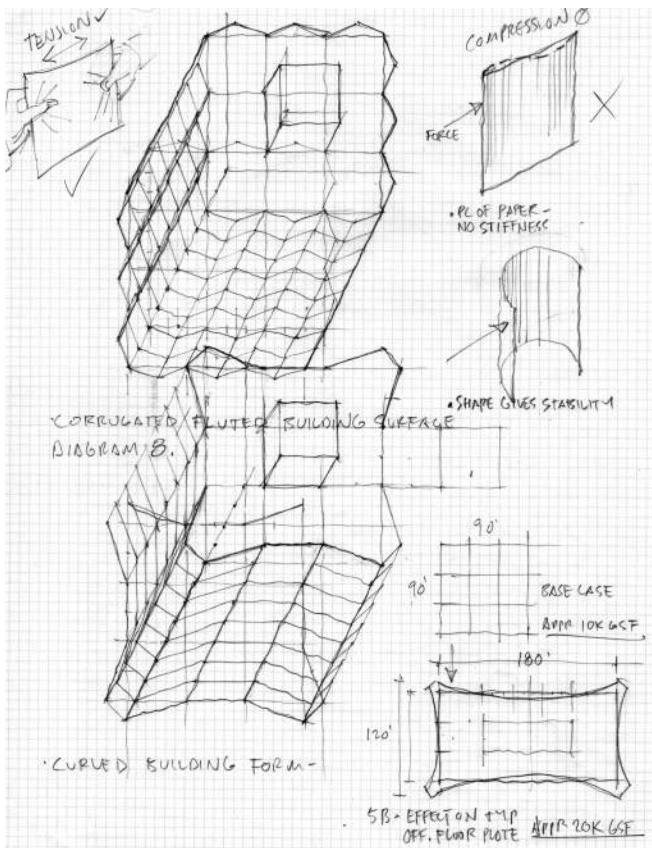

Figure 15: Future study will examine the potential for structural contribution of curved and corrugated surfaces.

CONCLUSION

Since Greenough, Ruskin and Sullivan connected form and function in the 19th century, modern architectural theorists, including engineers like Nervi and Arup, have argued for honest expression of structure as an ethical and aesthetic imperative (Greenough; Ruskin; Sullivan; Nervi; Arup). Meanwhile critics, such as Ford in his Details of Modern Architecture arguing that modern building is by nature layered not monolithic, and G. Scott in The Architecture of Humanism at the start of the 20th century, who critiqued the ideal of expression of structure as a “mechanical fallacy,” have treated this as a naive idea (Ford; Scott). It seems clear that the potential advantages, in terms of sustainability, of making surface into visible structure suggests that aesthetics—the appeal of seeing structure-- should be heeded as a promise of functional benefit in architecture.

The re-integration of structure and cladding seems to resonate with the words of Eiffel when he wrote:

> *Because we are engineers, is one to believe we give no thought to beauty in our designs or that we do not seek to create elegance as well as solidity and durability? Is it not true that the very conditions that give strength also conform to the hidden rules of harmony?* The Eiffel Tower. (Eiffel)

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REFERENCES

M. Airaksinen and P. Matilainen, “A Carbon Footprint of an Office Building,” Energies, 2011, No.4. P. 1197-1210. www.mdpi.com/1996-1073/**4**/8/1197/pdf, accessed 2016-05-08.

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. ANSI/ASHRAE/IES Standard 90.1-2010, Energy Standard for Buildings Except Low-Rise Residential Buildings (I-P Edition). 2010.

Aluminum Association, 2011, http://www.aluminum.org/sites/default/files/Aluminum_The_Element_of_Sustainability.pdf, accessed 2016-01-09.

American Institute of Steel Construction, 2009, http://www.aisc.org/uploadedFiles/Steel_Solutions_Center/Conceptual/My_Project/Files/Talking%20Points%20-%2010.2009.pdf, accessed 2016-01-09.

F. Angerer, Surface Structures in Building. Alec Tiranti, 1961. P. 53.

Art Institute of Chicago, Chicago Architects Oral History, ed. Betty Blum, 1997. http://www.artic.edu/research/archival-collections/oral-histories/jacques-calman-brownson-1923-2012, accessed 2016-05-08.

O. Arup, “Key Speech,” 1970. http://publications.arup.com/publications/o/ove_arups_key_speech Accessed 2016-07-24.

A.Azad, B. Samali, T. Ngo, “Control of Wind Induced Motion of Tall Buildings using smart façade systems,” 23rd Australasian Conference on the Mechanics of Structures and Materials, 2014. http://epubs.scu.edu.au/cgi/viewcontent.cgi?article=1167&context=acmsm23, accessed 2016-05-08.

J.M. Cohen & G.H. Powell, “Design Study of an Energy- Dissipating Cladding System,” Earthquake Engineering & Structural Dynamics, Vol 22. Issue 7, 1993, http://onlinelibrary.wiley.com/doi/10.1002/eqe.4290220706/full, accessed 2016-05-08.

G. Eiffel, B. Lemoine, ed., The Eiffel Tower, Taschen. 2008. P. 7.

E. Ford, The Details of Modern Architecture, Vol. 2. MIT, 2003, P. 9.

H. Greenough, Form and Function: Remarks on Art, Design, and Architecture. University of California, 1947 (essays originally published 1852, 1853).

G. Hammond & C. Jones, Inventory of Carbon & Energy (ICE), University of Bath, 2011. https://www.google.com/webhp?sourceid=chrome-instant&ion=1&ie=UTF-8&rct=j#q=bath+university+inventory+of+carbon+and+energy, accessed 2016-05-15.

W. LeMessurier, “Return of the Bearing Wall.” Architectural Record, Vol. 132, No. 1, 1962. Pp. 168-171.

J. C. Loudon, Encyclopedia of Cottage, Farm and Villa Architecture. Longman Brown Green and Longman, 1846. P. 980. Cited in: M. Wigginton, Glass In Architecture, Phaidon. 1996. P. 35.

K.S. Moon, “Structural Design of Double Skin Facades as Damping Devices for Tall Buildings.” 12th East Asia Conference on Structural Engineering and Construction, 2011. http://ac.els-cdn.com/S1877705811012471/1-s2.0-S1877705811012471-main.pdf?_tid=a34b3dd0-1542-11e6-886b-00000aacb362&acdnat=1462728843_296dd68e6006254128a0d3ba45d0c377, accessed 2016-05-08.

P.L. Nervi, Technology and Aesthetics in Building, Harvard.1966.

J. Ruskin, The Seven Lamps of Architecture, Dover. 1989 (orig. published 1880). Pp. 29 ff. “The Lamp of Truth.”

G. Scott, The Architecture of Humanism; A study in the history of taste. Norton. 1999 (orig. pub. 1914).

L. Sullivan, “The Tall Building Artistically Reconsidered.” Lippincott’s Magazine, #57. March 1896. Pp. 403-09.
C. Thormark, “A low energy building in a life cycle - its embodied energy, energy need for operation and recycling potential,” Building and Environment, Volume 37, Issue 4, April 2002, Elsevier. Pages 429–435. http://www.sciencedirect.com/science/article/pii/S0360132301000336, accessed 2016-05-08.
Tomasetti, et.al, “Development of thin wall cladding to reduce drift in hi-rise buildings.” Int’l Assoc. for Bridge and Structural Engineering Symposium,1986, http://retro.seals.ch/cntmng;jsessionid=73CD772F91BA28B1CEF86E4F4C6AEB65?type=pdf&rid=bse-re-003:1986:49::36&subp=hires. Accessed 2016-05-09.
Vaillancourt, Ryan, “Behind the Scenes of Building the Broad,” Los Angeles Downtown News, August 6, 2012. http://www.ladowntownnews.com/news/behind-the-scenes-of-building-the-broad/article_d3f63976-ddbf-11e1-986d-0019bb2963f4.html. Accessed 2016-07-27.
Whole Building Design Guide, “Seismic Safety of the Building Envelope,” https://www.wbdg.org/resources/env_seismicsafety.php, accessed 2016-05-09.

3D GLASS IN COMPLEX FAÇADES

Annealed bent glass

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ABSTRACT

The paper focuses on all the key questions to take into consideration when designing with 3D curved glass that may condition the final production of the glasses or the use of these glasses. Different case studies will help illustrate the right answers and the different parameters to be considered as important keys to allow and to determine critical aspects when complex geometries are included in 3D designed façades as for e.g. thermal performance, loads, assembly systems, etc

Through different chapters, it is explained the factors that are vital to hot bending manufacturing techniques related to the specifics of real case study buildings and decisions and solutions taken to implement the intended designs and modifications that needed to be discussed and agreed with the design teams.

KEYWORDS

Double curved glass, complex geometries, lamination, thermal break, design, oversized, 3D, bent

INTRODUCTION

GEOMETRIES / MOULDS

Free form design façades ask for slumped glass fabrication inside annealing bending furnaces on top of metallic moulds created on purpose to achieve intended geometries.

Apart from the typical cylindrical shape, many other shapes can be accomplished but will condition the structural performance of the glass and the fixing system used.

A very simple way to differentiate between shapes will be those that can be done with a paper and those that cannot.

In the first group we are basically modifying the shape of the glass in one direction introducing rigidity, that it can be used to withstand windloads and eliminate supporting structure to create large openings with self standing glass (Casa da Musica in Oporto- fig. 1 - shows how to combine opposite curves within one glass pane creating stiffness). It is important to understand that we have to avoid movement in the transition sections within a glass containing more than one curve or a curve and a flat part. For example, in a J-shape glass the flat area will allow deflection, but this allowance will end as we approach the radius, and may introduce an overstress in the transition area. Ensuring that the glass is not forced from its original shape will always be critical.



Figure. 1 *Figure. 2* *Figure. 3*

The same applies to shapes which cannot be emulated with a sheet of paper, as in this case the stiffness of the glass is even greater thanks to curves in different directions .But there are other issues to be considered. During the slumping process to make spherical or compound curved glass (Emporia Shopping Center in Malmo – fig. 2 - or FKI in Seoul –fig. 3) we are enlarging the surface of the pane, stretching the coating on the glass if any. At the same time we are slightly reducing the thickness of the glass, which may need to be taken into consideration when calculating the behaviour of this glass on the façade.

Bending glass in various directions provides the resulting geometry with higher strength against wind loads. The fact that we are stiffening the panel needs to be taken into consideration when designing the glazing system making sure the panel is not forced to any new geometry caused by movements of the structure or of the fixing elements. Ideally, rigid glasses should be structurally glazed on a frame fully respecting the 3D geometry resulting from the bending process, with its tolerances to be discussed case by case. Any allowance of movement should be balanced with the frame to the primary structure of the façade. Special attention has to be given to the design of potential mechanical fittings that by pressing the glass from outside may induce non desired stresses.

COATINGS

When glass is submitted to a bend annealing process (the most common bending method to achieve 3D glasses), the glass stays long time at high temperature (6 hours), and even longer depending on the complexity of the geometry desired. Temperable coatings have been designed thinking of flat glass tempering, which typically keeps the coating in contact with high temperatures for less than 30 minutes. Strong coatings, both pyrolytic but also some magnetronic ones, withstand an annealing process. However the most selective coatings (triple silver) will experience serious difficulties and may get damaged when doing 3D glasses which may be emphasized if the surface of the glass is increased due to the final shape. However there is a wide range of coatings which can go through annealing, and it is possible to obtain very good performances by combining 2 of these coatings in 2 surfaces (FKI in Seoul –fig. 3- and Qatar National Library in Doha – fig. 4). As the damage on the coating will depend on the geometry, radii, and the time and temperature in the oven, it will always be advisable to do a mock-up to ensure the feasibility of a bent coated glass, even in the case of previous positive experiences.

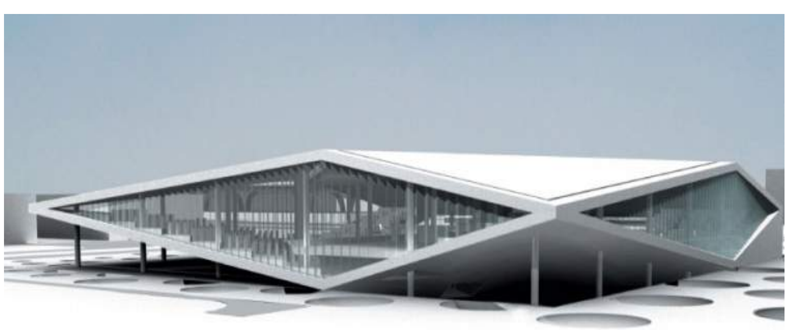


Figure 4

In façade design, it is getting more common to come across wavy surfaces creating concave and convex areas that have to be properly analysed. There is the tendency to take it for granted that all the panels can be thermally hardened (either FT or HS) while specifying the best performing coatings. However, if we have a look to the way bending ovens for tempering work, we realise soft coatings cannot be on the convex side of the panel unless we want to seriously damage them when these get in direct contact with the oven rollers. This might bring us to think it can quickly get solved by shifting the coating from one face to another in an IGU depending on whether we are on the concave or convex part of the façade. If we proceed this way, glasses will have different appearance. One solution passes for making all the panels in annealing ovens, likely using different and stronger coatings, where we can keep the coating on the same face. Another proposal could be making half of the panels in annealing ovens which would guarantee a consistent look.

IGU

While flat IGUs can balance the different isochoric pressures in the cavity by glass deflection, in the case of curved glass, due to the stiffness of the geometries themselves (similarly to what would happen in flat small IGUs), the climatic loads has a direct incidence in the primary and secondary seal. This fact obliges to analyze thoroughly every single case, engineering the proper dimensioning for both, the spacebar width and the silicone bite, as standard programs to dimension IGU will not take the rigidity of a bent glass into consideration. In extreme climates, (Qatar National Library in Doha – fig. 4, 5, 6) reducing the thickness of the cavity is a good starting point to help reducing the risk of overpressure. On the other hand, the stiffness of the geometry will also help avoiding the outboard to get in touch with the inboard by deflection.

3.2 tensile stress by isochoric pressure

3.2.1 Procedure

The isochoric pressure is calculated by the method given in [1].

By doing this the stiffness of the *curved glass* element is translated to an equivalent thickness of a *straight glass* element by comparing the existing volume of the gap of the deflected insulated glass element with the volume of the straight glass unit.

The calculation leads to the following results according to the maximum glass size and a smaller element with 50 % of the maximum height:

translation of curved element to straight element

size	**curved glass assembly**	equivalent assembly of a **straight glass** element
2400 mm x 5800 mm	LSG 2x8mm	LSG 2x**26,3**mm
	10mm LSG 2x8mm	10mm LSG 2x**26,3**mm
2400 mm x 2900 mm	LSG 2x8mm	LSG 2x**28,5**mm
	10mm LSG 2x8mm	10mm LSG 2x**28,5**mm

translation of size : 2400mm x 5800mm

curved 8mm

KNr	x	y	f	sum
1	0,2874	0	0,2874	232,17
2	0,2136	0,2723	0,34608128	
3	0,3083	0,1819	0,35796159	
4	0,1627	0,3508	0,38669359	
5	0,1382	0,374	0,39871699	
6	0,2402	0	0,2402	
7	0	0,4624	0,4624	
8	0	0,4679	0,4679	
9	0	0,4679	0,4679	
10	0	0,5115	0,5115	
11	0	0,4625	0,4625	
12	-0,3082	0,1819	0,35787547	
13	-0,1625	0,3508	0,38660948	
14	0	0,5115	0,5115	
15	-0,2136	0,2722	0,34594088	
16	-0,2873	0	0,2873	

straight 26,3

KNr	delta	x	sum
208	0	0	231,39
209	0	0,03618	
210	0	0,05585	
211	0	0,18172	
212	0	0,10432	
213	0	0	
214	0	0,06206	
215	0	0,06301	
216	0	0,24043	
217	0	0,22617	
218	0	0,06206	
219	0	0,05585	
220	0	0,18172	
221	0	0,22617	
222	0	0,03618	
223	0	0	

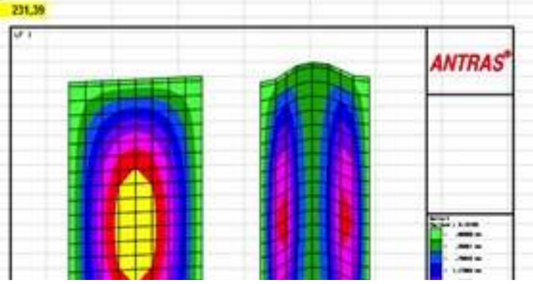
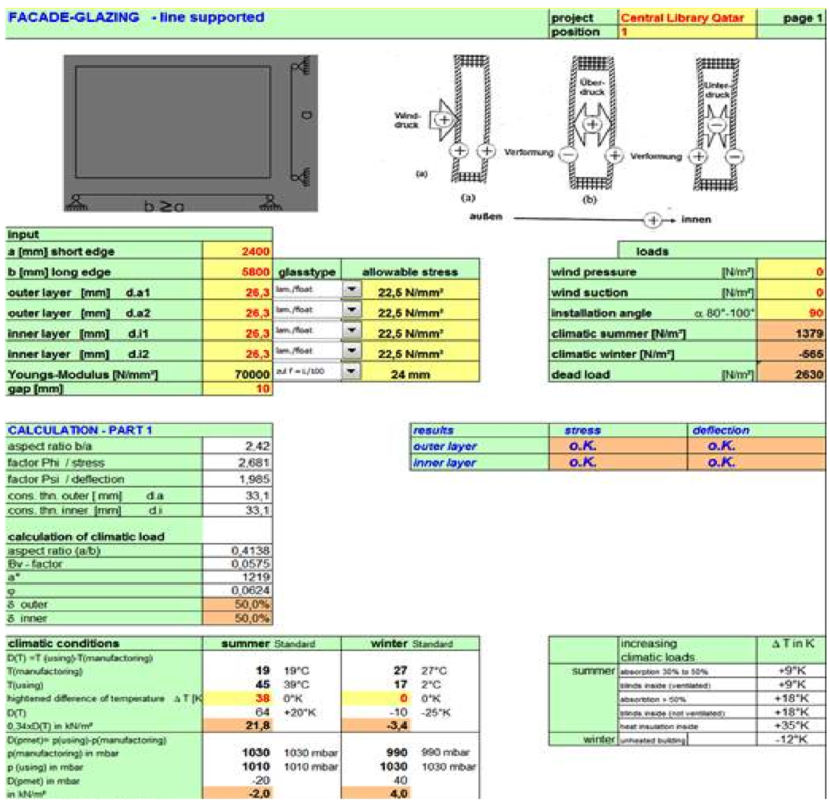


Figure. 5

The isochoric pressure then can be calculated using [1] by initially regarding a cavity of 10 mm (consideration of reducing the cavity down to 8mm see below):

size	isochoric pressure in N/m²	
	summer	winter
2400 mm x 5800 mm	**1397**	- 565
2400 mm x 2900 mm	**3349**	- 1372

isochoric pressure : 2400mm x 5800mm



FACADE-GLAZING - line supported

project	Central Library Qatar	page 1
position	1	

input		glasstype	allowable stress
a [mm] short edge	2400		
b [mm] long edge	5800		
outer layer [mm] d.a1	26,3	lam./float	22,5 N/mm²
outer layer [mm] d.a2	26,3	lam./float	22,5 N/mm²
inner layer [mm] d.i1	26,3	lam./float	22,5 N/mm²
inner layer [mm] d.i2	26,3	lam./float	22,5 N/mm²
Youngs-Modulus [N/mm²]	70000	zul f = L/100	24 mm
gap [mm]	10		

loads		
wind pressure	[N/m²]	0
wind suction	[N/m²]	0
installation angle	α 80°-100°	90
climatic summer [N/m²]		1379
climatic winter [N/m²]		-565
dead load	[N/m²]	2630

CALCULATION - PART 1	
aspect ratio b/a	2,42
factor Phi / stress	2,681
factor Psi / deflection	1,985
cons. thn. outer [mm] d.a	33,1
cons. thn. inner [mm] d.i	33,1
calculation of climatic load	
aspect ratio (a/b)	0,4138
Bv - factor	0,0575
a*	1219
φ	0,0624
δ outer	50,0%
δ inner	50,0%

results	stress	deflection
outer layer	o.K.	o.K.
inner layer	o.K.	o.K.

climatic conditions	summer	Standard	winter	Standard
D(T) =T (using)-T(manufactoring)				
T(manufactoring)	19	19°C	27	27°C
T(using)	45	39°C	17	2°C
hightened difference of temperature ΔT [K]	38	0°K	0	0°K
D(T)	64	+20°K	-10	-25°K
0,34xD(T) in kN/m²	21,8		-3,4	
D(pmet)= p(using)-p(manufactoring)				
p(manufactoring) in mbar	1030	1030 mbar	990	990 mbar
p (using) in mbar	1010	1010 mbar	1030	1030 mbar
D(pmet) in mbar	-20		40	
in kN/m²	-2,0		4,0	

	increasing climatic loads	ΔT in K
summer	absorption 30% to 50%	+9°K
	blinds inside (ventilated)	+9°K
	absorbtion > 50%	+18°K
	blinds inside (not ventilated)	+18°K
	heat insulation inside	+35°K
winter	unheated building	-12°K

Figure.6

Another issue regarding IGUs is the positioning of the butyl. As the shape gets complicated, so does the parallelism of the 2 glasses of the IGU, and we will easily find places where the butyl gets more pressed than others, creating the oozing effect (enhanced by the fact that these IGUs will be handmade). Avoiding the oozing effect could lead to lack of butyl creating other problems.

THERMAL STRESS

When there is design with curved glass, the first assumption regarding thermal stress is that it tends to have a better performance than flat glass as the stresses generated by cutting and polishing the edges disappear during the annealing process. In other words, if a thermal stress generates a breakage always starting from a microcrack at the edge, by bending that glass the flaws at the edges get softened, get annealed, and lead to less breakage. In fact, if we look 15 to 20 years back in time we realize about façades using body-tinted or dark glass were executed with flat tempered glass and annealed curved glass, as bend tempering ovens had still not been invented, and thermal breakage was not an issue whenever having proper design and engineering.

Another benefit of the shape is that typically a curved glass exposed to the sun tends to have a gradient of temperatures compared to a flat glass, as it offers different angles to the light, which helps avoiding high temperature jumps on the surface of the glass.

Very absorbing annealed curved glass has been used in numerous cases successfully (Emporia Shopping Center in Malmo – fig. 2 -, FKI in Seoul –fig. 3, Qatar National Library in Doha – fig. 4, 5, 6), however the risk of thermal stress (using conservative flat glass parameters) can be analyzed by finite elements software to ensure suitability of the composition.

WINDLOADS

The shape of a curved glass obviously affects its behavior against windloads. In fact a curved corner will tend to give better aerodynamics to a high-rise tower, and the rigidity of the shape and the dispersion of the forces will also help the glass react against a windload. In any case, it will also be an issue to be considered especially in addition to all the other stresses involved (Qatar National Library in Doha – fig. 4, 5, 6, 7).

The tensile stress by wind loads is $q = + / - 2.5\ kN/m^2$

According to the stiffness of the outer and inner glass pane the maximum part of the total wind load that one pane will have to carry is 53 %, that means **1325** N/m^2.

The finite element calculation leads to the following results of stress in outer / inner pane

σ **/** N/mm^2
12,0
<
σ **perm** **=** 22,5 x 0,8 **= 18**

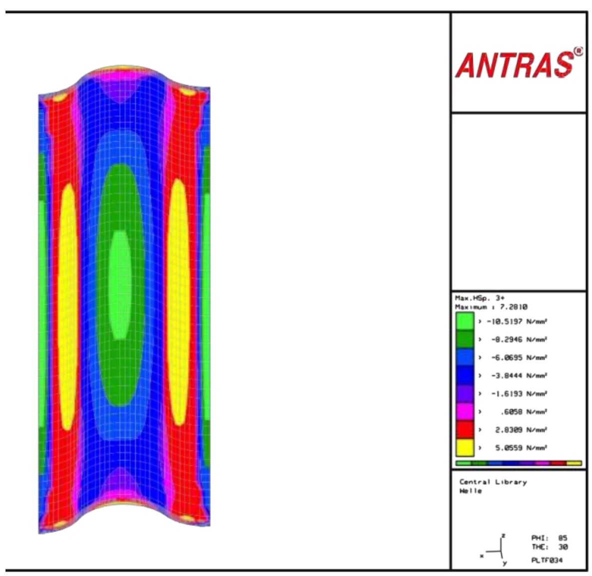


Figure. 7

FRITS

On one side a frit will add absorption coefficient to a glass and influence the risk of thermal stress, so clear or reflective colors will tend to perform better or reduce this risk. At Qatar National Library in Doha – fig. 4, 5, 6, 7 - the original grey desired color was changed to a reflective grey after the engineering of the glass composition showed too many added stresses. A similar thing occurred with Hospital King Juan Carlos in Madrid – fig. 8, 9 -, which advised a maximum 50% coverage, a good transition using dots, and even the use of clear grey silicone to fix the glass on the frame.

Figure. 8[2]

Figure.9[3]

On another side, a 3D glass comes from a flat glass, but is not a developable surface. The frit will always occur on a flat glass before the bending process, and during bending, depending of the shape the frit will get extremely distorted. For example the edges of a spherical glass will typically be curved when cutting the flat glass before bending. In such case, if we wanted horizontal parallel lines in the desired final spherical glass, we would need to design curved non parallel lines on the screen used during fritting, and we would need one screen for every shape, unless we chose a non linear design to avoid having to use too many screens. (high number of screens for FKI in Seoul fig. 3 - to ensure perfect alignment of dotted lines).

TOLERANCES

3D shapes tend to difficult the way tolerances have to be controlled, as we are considering points on the space, and sometimes they are even difficult not only to control but also to define. In most of the cases, specific tolerance criteria and ways of measuring the values will need to be stablished. In extremely complex geometries, control programs can be designed in order to ensure good tolerances. Example, scanning of the 800 moulds used for Emporia Shopping Center in Malmo – fig. 2 -, and the program to check the perimeter within a tubular tolerance of r=4mm, which ensured all the glasses produced before the first one was installed using a 3D controlling device.

Figure 10

FIXING SYSTEMS

As mentioned before, the main issue to ensure a good installation system is to allow the 3D glass to remain in its original shape. Any mechanical fixation that adds more pressure on one point than to another will be adding a constant stress that will develop a breakage due to the rigidity of the glass. The use of silicone that compensates the tolerances between the shape of the glass and the shape of the frame will always help. It is advisable not to use constant EPDM blocks to fix the glass, which will not compensate the tolerance. Side blocks and other spacers can be used to position the glass, but they should not be used to hold the 3D glass in place. Structural silicone will always be a better companion when fixing the glass. Frames or structurally bonding to sub-frames will also tend to work better than punctual fixation systems, which may introduce undesired stresses.

In addition, any system which avoids introducing stress movement or torsion to the glass, during installation (to compensate tolerances of all the curved elements) or during the use of the building, will also help. In other words, never push a 3D glass to go to a desired position, it’s much better to leave it where it wants to be.

It may be obvious, but the use of U-channels has to take into consideration that the volume of a 3D glass may make it difficult to tilt the glass when trying to introduce it into the channel as it’s typically done with flat glass. An L-frame that opens from one side will help introducing a 3D glass into its position.

OTHER ISSUES

There are other issues to be considered. For example, a very spherical glass will difficult lamination using thick and rigid ionomer interlayers. Multiple thinner interlayers will better help to adapt to a much distorted shape.

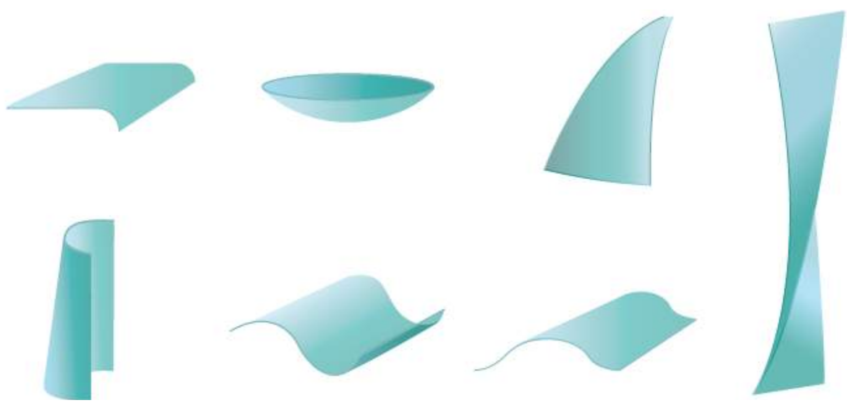


Figure. 11

Difficult shapes may also difficult transportation, and may require a special engineering of the still age.

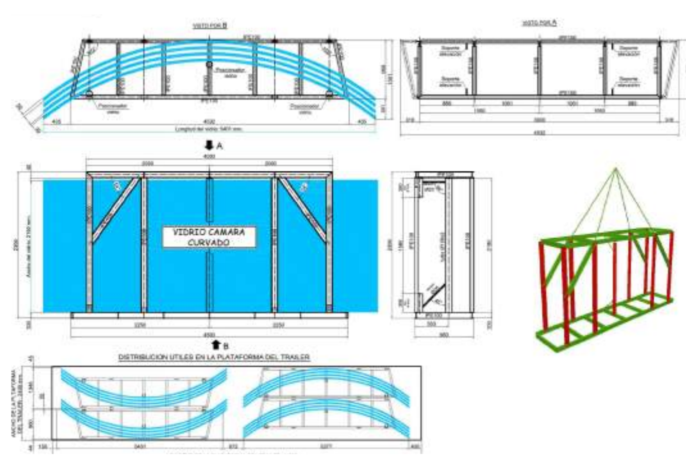


Figure 117

The same will happen with the installation equipment. Suction cups will need to adjust to the 3D shape, and in some cases they will need to allow for rotation, or for inclination from horizontal to completely vertical.

Thickness. When the surface of the final 3D glass is larger than the original cut flat piece, there will be a reduction of thickness at some point. Typically it will be quite homogeneous, and probably the stiffness of the shape will compensate the reduction, but in any case it may be something to be considered when calculating a 3D façade.

Size. Size could not to be an issue at all. In fact the shape tends to help having larger curved glasses than flat.

Figure. 13[4]

REFERENCES

Figure. 3[1]: © Adrian Smith + Gordon Gill Architecture(Photographer: Sun Namgoong)

Figure. 8[2]: © Duccio Malagamba

Figure. 9[3]: © Duccio Malagamba

Figure.13[4]: © Jeroen Verrecht

UNDERSTANDING AND ENHANCING VENTILATED FAÇADES

From the system benefits to smart sidings material

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ABSTRACT

Open joint ventilated façade (OVF) is a traditional construction method with a long history. Nevertheless, its dynamic behavior and potential benefits are still hardly known by building construction professionals.

This document is organized in three parts. First is the general demonstration of façade impact on energy savings with a real building renovation project in Italy intentionally limited to the façade. Second is the focus on impact of the naturally vented cavity with a real scale experimental comparison of ventilated and non-ventilated façades. It aims to present the influences of this construction method, validating the typical knowledge of researchers in this field. It illustrates how wall temperatures, vapor migration and heat transfer are impacted by the shading offered by the sidings and the buffer effect of the naturally vented cavity. The question of sustainability and durability of building envelope regarding climatic strain is also included. Finally, this knowledge on ventilated facades is further enhanced by energy performance simulations, where sensitivity studies helped steer the development of new sidings. The opportunity to create smart siding solutions which contribute to energy savings is illustrated by the practical example of integration of an additional functional layer to create new material: the solar reflectance technology.

KEYWORDS

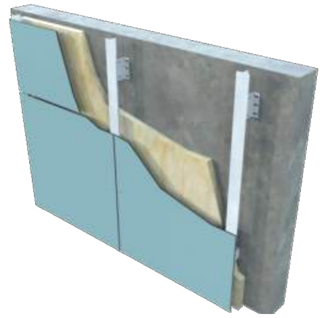
Open joints ventilated façades, energy efficiency, physical testing - mockups, durability, composites, case study, retrofit

INTRODUCTION

CONCEPT OF VENTILATED FAÇADES

Open joint ventilated façades (OVF) are multilayer envelope constructions. They consist of an external skin separated from the inner wall by an open air cavity. Several types of opaque ventilated façades exist. According to the cladding material, there are slight differences in the substructure, size of the cavity or airflow path. In this article, the studied case is a Trespa® ventilated façade with its HPL (High Pressure Laminate) Meteon® product used as siding. In this configuration, the cavity is naturally vented and there are open joints between the panels (0). With this type of material (HPL), the thickness of the cavity is at least 20mm (0,79”) and usually not above 40mm (1,57”). Thickness of the open joints is at least 10mm (0,39”).

Using separate layers was already common in Roman architecture in order to provide protection against weathering and decorative functions. Nowadays, aesthetics have become a main reason for choosing this kind of façade, conveying the idea that a ventilated façade has no impact on façade performance compared with other construction methods.



Trespa® ventilated façade with aluminum sub frame

FAÇADES CHALLENGES AND EVALUATION OF PERFORMANCES

What are and will be the challenges for façades? As the façades designed by architects have been led for a large part by the building image, as opposed to energy performance, the path toward low energy consumption buildings requires reduction and control of heat transfer through external walls. As a consequence, the recommended or mandatory insulation thicknesses for opaque walls have been increased in several countries. Energy renovation has become a fundamental issue and an opportunity to evaluate the performance of technical solutions. A partial renovation project of an office building in Italy is presented in order to give a first insight of potential for energy savings with facades in real practice. While it highlights the impact of a façade on a building, such monitoring cannot provide information on the effect of the naturally vented cavity.

The hygrothermal behavior of ventilated façades have been investigated by numerous researchers in the past decades and results were not always very conclusive (Salonvarra, 2007). Nevertheless, several publications mentioned potential energy savings related to the ventilated façade influence on thermal transfer (Naboni, 2007), (Gonzales, 2008), (Amparo López-Jiménez, P. et al, 2010). The complexity of the dynamic phenomena occurring in the naturally vented cavity, the multiple configurations corresponding to the ventilated façade concept combined with the numerous orientations, building types and climate zone, have made the clear validation of ventilated façades behavior a difficult task.

Evaluation of thermal performances through U-Value is a simple method used in many regulations to assess performances before construction. However it is a static method that does not apprehend dynamic hygrothermal behavior, the impact of siding optical properties, evolution of performances or durability of the façades.

Building Performance Simulation (BPS) gives more insights of the dynamic effects and impacts of construction choices, but they usually do not cover the behavior of open joint ventilated façades as the airflow dynamic is complex. Indeed, by design, open joint ventilated façades present local discontinuities with non-homogeneous airflow and temperature. To investigate the cavity behavior several studies used computational fluid dynamics (CFD) software successfully, sometimes combined with real scale testing for validation (Gonzales, 2008), (Amparo López-Jiménez, P. et al, 2010), (Sanjuan, 2011). Comparison with non-ventilated façades is less frequently addressed for both numerical and experimental way.

METHOD

The intention of this paper is to provide comprehensive analysis and conclusions based on empirical and numerical approaches. Three steps of investigations are presented. First is the façade impact in general. The thermal demand of Arpa headquarter (see Fig…) has been monitored one year before and after renovation. In order to focus only on impact of the façade neither the windows or the roof were changed. Building systems and their management were also not modified. This study aims to illustrate the importance of the façade on energy savings in practice

Second level is the specific effect of OVF compared to a non-ventilated façade system. Using the dedicated platform of French Institute of Technology for forest based and furniture sectors (FCBA), an experimental comparison of a typical wood construction with Trespa® ventilated façade (VF) configuration and its equivalent with Exterior Insulation Finishing System (EIFS) was realized.

Third level is the impact of cladding material thermal properties. The knowledge base confirmed by testing at FCBA was used to validate modelling processes in ESPr. Numerical sensitivity studies were performed for rapid prototyping of energy wise siding solutions. An example of product innovation with solar reflective properties is given.

EXAMPLE OF IMPACT OF FAÇADE PERFORMANCES IN RENOVATION

The whole façade of the company Arpa's headquarter (Bra, Italy) was renovated with a O?VF(0) in May 2014. Insulation was 200mm of mineral wool and fixings were made of galvanized steel. The R-Value increased from 0.9m².K/W (5.0°F.ft².hr/Btu) to 6.25m².K/W (35.5 °F.ft².hr/Btu). Additional sunblinds were added. This project represented a rare opportunity to monitor renovation impact with façade modification only without any changes to the windows.

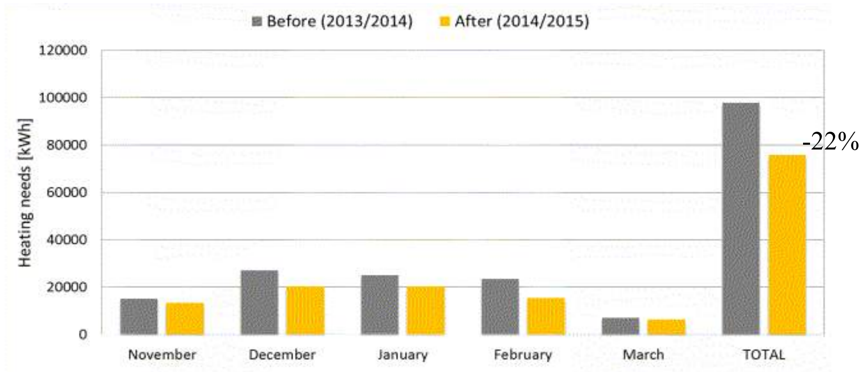
The monitoring of heat consumption was performed by measuring the flow rate of heat carrier (water), as well as its supply and return temperatures. Indoor and local outdoor temperatures were also measured. This monitoring was performed for a year prior to, and a year after the renovation. The instruments used for these measurements were as follows:

- One ultrasonic flowmeter of Endress & Hauser, type PROSONIC FLOW 91WA1, used for assessing the flow of circulating water in the heating circuits.
- Two temperature transmitters by Endress & Hauser, type TR24, used to evaluate the temperature of water supply and return within the heating circuits.
- Two temperature transmitters by Endress & Hauser, TST434 type, used to evaluate the temperature of the external environment and a typical office.

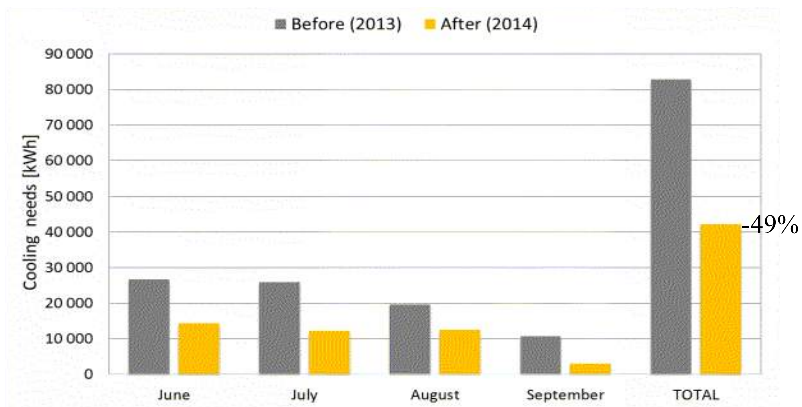
Monitored façade retrofit of ARPA headquarters in Bra, Italy

The heating demand was reduced by 22% while the cooling demand was reduced by 49% (0 and 0).The difference in savingsbetween heating and cooling demand can be explained by the addition of fixed solar protections during the renovation. The reduction of solar gains through windows increased the cooling savings of the renovation project but also had a negative effect on heating ones. In addition, artificial lighting demand should have been slightly increased but was not recorded.

As mentioned earlier, these results illustrate the importance of façade in building energy performances and demonstrate in real practice that OVF can be a reliable solution in renovation. Nevertheless, they are not detailed enough to provide comprehensive breakdowns of saving (between the insulation, the naturally vented cavity and the solar protections above windows). The impact of using OVF as opposed to other construction methods cannot be determined this way and require a dedicated experimentation.



Heating needs evolution before and after renovation in Arpa headquarters



Cooling needs evolution before and after renovation in Arpa headquarters

MEASUREMENT OF WALL DYNAMIC BEHAVIOR

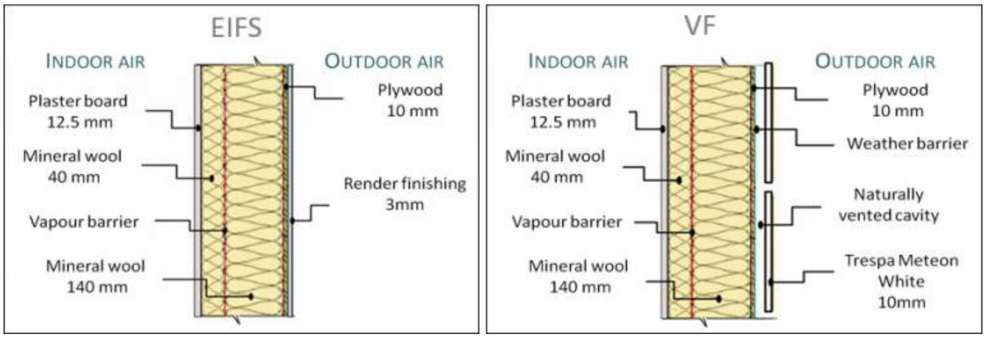
EXPERIMENTAL PLATFORM

The experimental evaluation of a Trespa® ventilated façade in comparison with an equivalent EIFS solution started in January 2014 and last for one year. The experimental platform is hosted by the French Technical Institute FCBA in Bordeaux (France). It consisted of two highly insulated testing rooms where the only external walls were the test walls (0). The orientation of test walls was South/South-West (38° from the south) and dimensions of sample walls were 2700 width by 1900mm height (8.9 by 6.2ft). Internal volume temperature of each cell was controlled during winter and allowed to fluctuate during summer. Weather conditions were measured locally and data acquisition of platform sensors was done through radiofrequencies devices. Sensors used were as follows:

- Temperature and relative humidity sensor: STH 55 (Newsteo) - sensitivity -25 to +80°C ±0,4°C and 0 to 100% ±2%
- Surface temperature: Thermocouple K - sensitivity -40 to 1100°C±0,5°C
- Heat flow sensor (Captec) - sensitivity 131 microvolt/(W/m²)
- Air velocity sensor with hot film EE660B (E+E) – sensitivity 0 to 2m/s ±0,03m/s

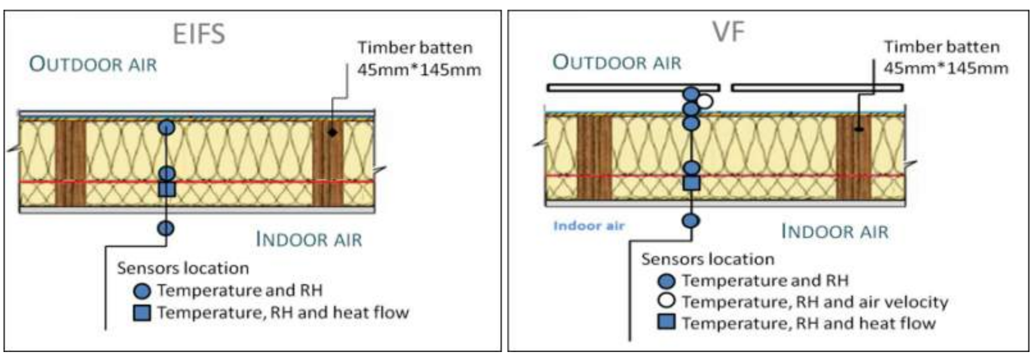
FCBA Experimental platform, empty cells and mounted walls (Trespa® ventilated façade & EIFS)

The test walls were typical wood construction. This choice was made as it avoids additional thermal bridges due to fixing substructure of the panels. Consequently, the effect of the cavity was directly measurable and isolated from parasitic effects. Furthermore, dry methods like wood construction were easier and quicker to handle, with less risk of initial moisture content difference between the two cases. Temperatures and relative humidity (RH) were measured at the interface between the different layers of the walls. Heat flow was also measured at one location within the wall. Details of the walls composition and location of sensors is given in 0 and 0. Render and Meteon® panel colors used are similar with respect to solar absorptivity (approx. 0.4).



Wall composition of EIFS and VF tested walls – Cross section

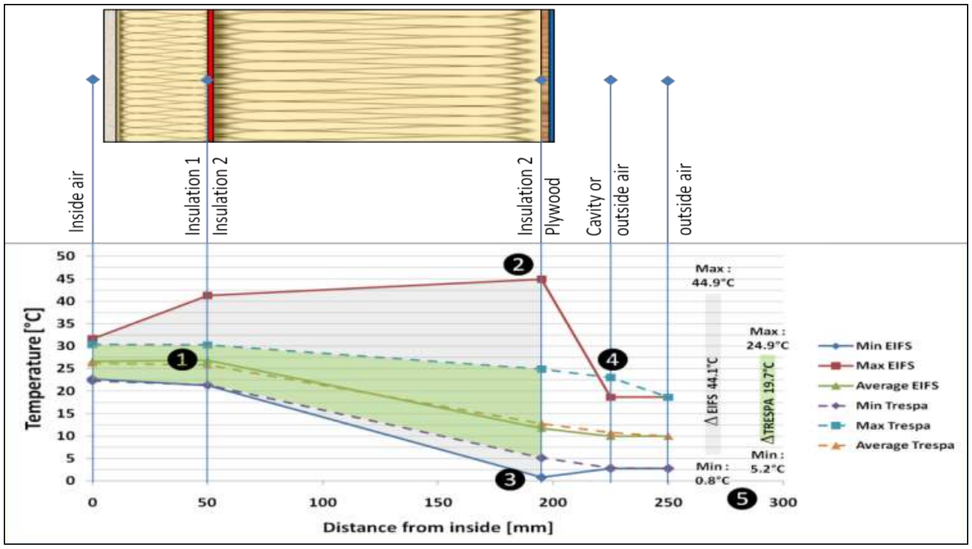
According to standards EN ISO 6946 (1996) and EN ISO 10211, the R-Values of tested walls were 4.566K.m²/W or 25.9°F.ft².hr/Btu for VF and 4.505K.m²/W or 25.6°F.ft².hr/Btu for EIFS, i.e. a difference of 1% in favor of VF. These values included the thermal bridges of the wooden batten in the structure. It also took into account the standard consideration of the cavity and the sheltering effect of the cladding with higher external surface resistance (0.13K.m²/W i.e. 0.74°F.ft².hr/Btu instead of 0.04K.m²/W i.e. 0.23°F.ft².hr/Btu).



Sensor location in tested walls – horizontal section

EXPERIMENTAL RESULTS – COLD PROTECTION EFFECT

The winter measurements have been performed during January 2014 with full heating power in both cells in order to emphasize the thermal gradient. Range of temperature variation within the walls are represented in 0.



Range of temperature variation of EIFS and VF walls in January 2014

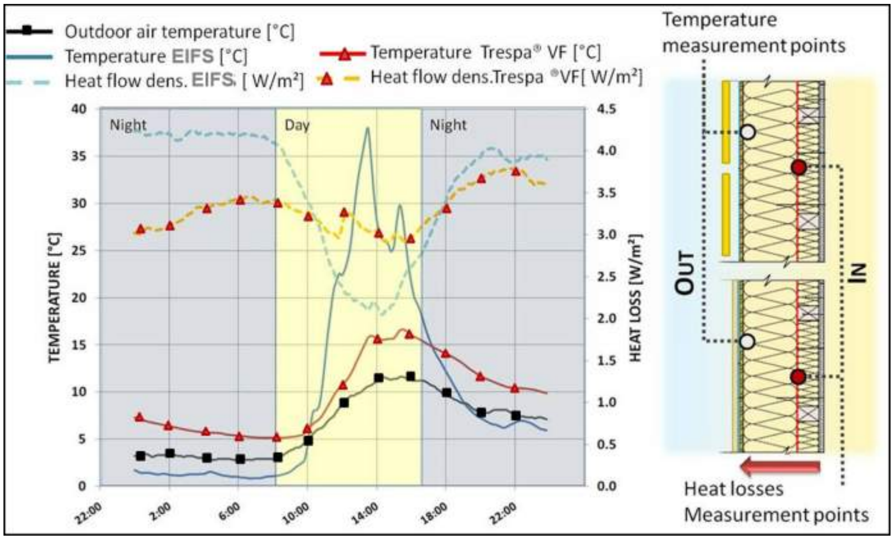
❶ Indoor temperatures of the two tested cells were very similar. The average temperature difference was inferior to 0.1% and was in the range of sensor sensitivity. Consequently, the comparison of the measurements from heat flow sensors was representative.

❷ EIFS maximum façade temperature was higher than ventilated façade one. The difference at plywood level reached 20°C (44.9°C for EIFS versus 24.9°C for ventilated façade). This high difference came from the shading effect of the Meteon® panels while at the same time the render was directly exposed to sun. The naturally vented cavity had a buffer effect that reduces the temperature variation on the external part of the wall thereby reducing the thermal stress on it.

❸ The sidings protected the rest of the façade from overcooling by night sky radiation. The external minimal temperature of EIFS was 0.8°C while outdoor air minimal temperature was 2.8°C (overcooling effect) and ventilated façade one was 5.8°C.

❹ At cavity level, the air temperature is hotter than the outside air temperature. Convection losses are thus reduced compared with EIFS. Nevertheless, this increase of air temperature resulted from the solar irradiation absorption of the panels which means that part of the free solar gains on the wall were extracted by the cavity and lost.

❺ The amplitude of temperature variation on the external part of the wall (between plywood and insulation) was minimized by the effect of the naturally vented cavity wall (19.1°C compared to 44.1°C for EIFS case, i.e. 55% reduction).



Temperature and heat flow variation in a typical sunny winter day – 21st January 2014

The dynamic evolution of heat flow and temperature on a typical day confirmed the ventilated façade acted as a thermal damper (0). It protected the wall against overcooling due to night sky radiation and wind chill, while reducing the solar gains. The global balance for this whole winter day cycle showed that the EIFS configuration was losing 7.1% more heat than the VF, which was significant comparing with the 1% R-Value difference of normative steady state approach (0).

Heat losses [Wh/m²]	Night Time	Day Time	Whole day
Trespa® VF	50,1	29,3	79,4
EIFS	58,3	26,7	85
% Diff EIFS/ VF	+16,3%	-8,7%	+7,1%

Heat flows data on 21st January 2014

EXPERIMENTAL RESULTS – HOT PROTECTION EFFECT

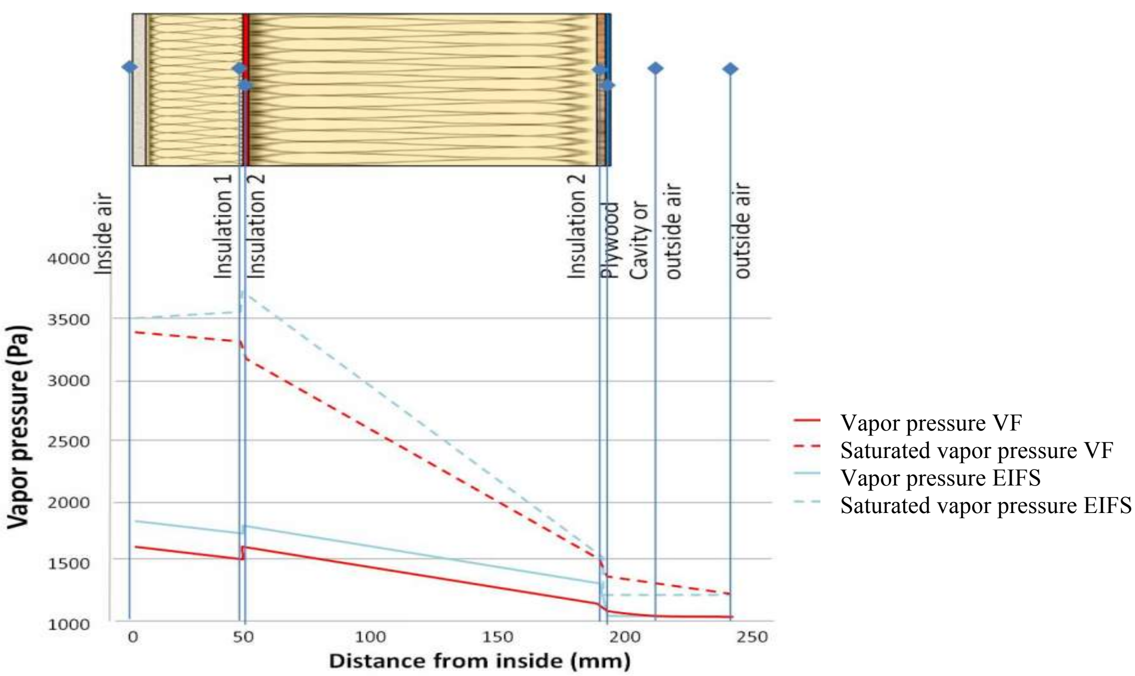
Amongst the several benefits of ventilated façades considered, protection against solar radiation is probably the most obvious and studied. The twin cells were not equipped with a cooling system. Consequently, the difference between the ventilated façade and the non-ventilated one has been measured on indoor temperature variations. The summer measurements have been performed during June and July 2014. For one of the hottest days -13th of June 2014 - the shelter effect of the panels reduces the indoor temperature peak significantly by 1.7°C and the average temperature by 1.1°C (0). Reversely, during night, the overcooling due to cold sky radiation effect is higher in the EIFS case and is beneficial for this construction case. As a consequence, the minimal temperature reached during the measurement session was lower for the EIFS (25.1°C compared to 25.6°C for VF).

Temperature [°C]	Outdoor air	EIFS	Trespa VF
Min	20.1°C	25.1°C	25.6°C
Max	31.2°C	29.0°C	27.3°C
Average	25.5°C	27.2°C	26.1°C

Temperature statistics for summer period in FCBA testing platform

BREATHABILITY

Façades need to ensure a good management of moisture migration. Moisture condensation and accumulation may degrade material performances and reduce their lifetime. According to French traditional wood constructions, vapor barrier should have an Sd value of 10m for ventilated façade and a less permeable one (Sd> 90m) for render finishing. In this experimentation, both constructions had the same vapor (Sd=10m) to be strictly equivalent and highlight the effects of the cavity. Moisture was trapped by low vapor permeability of render compared with the ventilated façade case (0). Therefore, risks of condensation appeared at the plywood level only in the EIFS case. This condensation risk would have been avoided by using the appropriate vapor barrier.



Average vapor pressure distribution in January of EIFS and VF walls

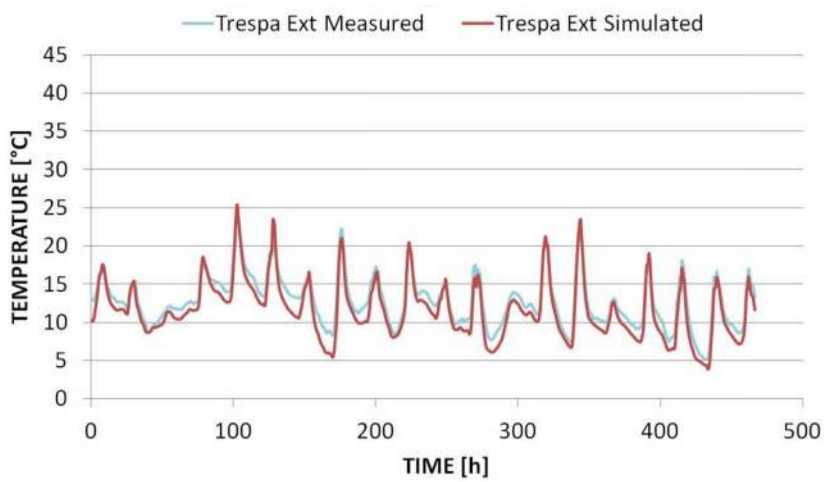
CLIMATIC STRESS REDUCTION

Separate layers allow separating functionalities. The external skin is the visible part that has to withstand the climatic strain. This implies some liberty of expansion and shrinkage while the inner wall can still ensure the air tightness. Combining climatic strain resistance, solidity and air tightness in one layer, as in the EIFS or other traditional masonry work can result in cracks. The ventilated façades protect the inner wall from rain, temperature variations and moisture accumulation, providing to the wall ideal conditions for durability. The measurements in FCBA shows that temperature variation on the external part of the wall was reduced by 55% in winter (0) for VF construction. The ventilated façade created a thermal and humidity damper effect.

BUILDING PERFORMANCE SIMULATION - ESPR

DEVELOPMENT AND VALIDATION

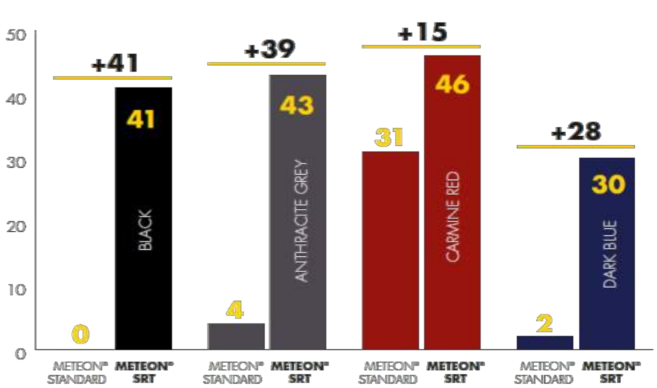
In parallel to this empirical approach, Building Performance Simulation (BPS) tool was used in collaboration with the Computational Building Performance Simulation group at Eindhoven University of Technology (Hensen et al., 2015). A naturally vented façade model was created on ESPr software. The modelling hypothesis - creation of a thermal zone with pressure airflow network to represent the cavity- was similar to those described in (Marinosci, 2011) and confirmed its conclusions. The validation process by comparison of simulation results with those obtained empirically at FCBA showed good consistency (0). Nevertheless, as mentioned in (Marinosci, 2011), the protection against overcooling due to night sky radiation was slightly underestimated by the model. This slight difference between model and measurement during night was also observed with detailed CFD model (Sanjuan, 2011). The measurements performed in FCBA are not sufficient to explain this difference as sky temperature and nebulosity were not monitored and are important inputs in these conditions. Nevertheless, with insulated façades, this lower accuracy during nights results in insignificant differences in evaluation of potential energy savings.



Comparison of measured and simulated temperatures in VF case at external insulation level (interface with cavity)

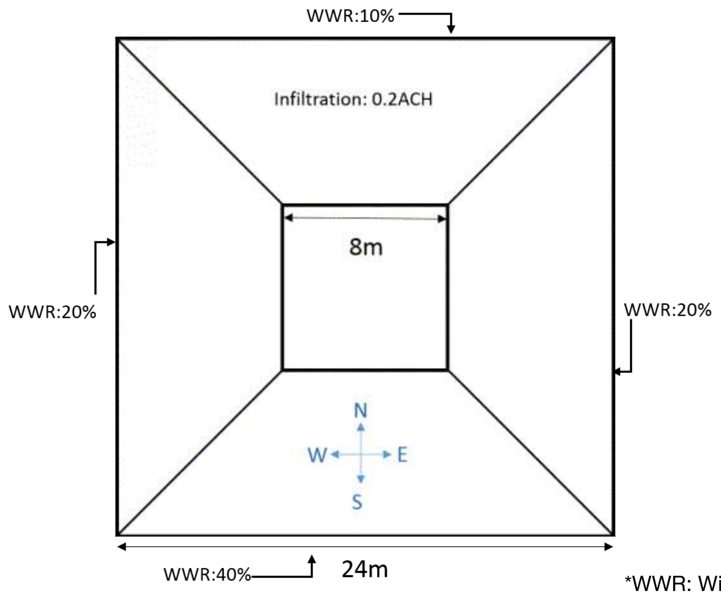
SIMULATION AND INNOVATION PROCESS – IMPACT OF CLADDING PROPERTIES

Building Performance Simulation (BPS) was used in the innovation process in early design of cladding materials . The first example of development in this field was Trespa® Meteon® SRT (Solar Reflectance Technology) launched in 2014. The near infrared absorptivity of this product was reduced in order to provide additional cooling saving. For example, the Solar Reflectance Index of black panel was increased from zero to 41% (0). Thanks to the BPS, it was possible to identify the potential gains and markets through the world, with cooling demand reduction up to 2.5%.



Solar Reflectance Index variation from standard product to SRT

In addition to this first energy oriented product development, a sensitivity study has been done to identify which thermal and optical properties of sidings should be modified to significantly influence the energy behavior of the façade. The same ventilated façade modelling was used and a simplified residential building model was developed (0).



*WWR: Windows to Wall Ratio

Occupancy profile & gains	PERIOD	Occupants	Devices	Lights
	0-6	1,3 W/m2	1,1 W/m2	0
	6-10	1,9 W/m2	5,7 W/m2	1,4 W/m2
	10-18	0	1,1 W/m2	0
	18-22	1,9 W/m2	5,7 W/m2	1,4 W/m2
	22-24	1,3 W/m2	1,1 W/m2	0
HVAC System	Unlimited capacity to meet the set -points			
	21°C set point for heating		15C setback during non occupied hours	
	24°C set point for cooling		40C over-heating protection during non occupancy	
	1ACH during occupancy hours			

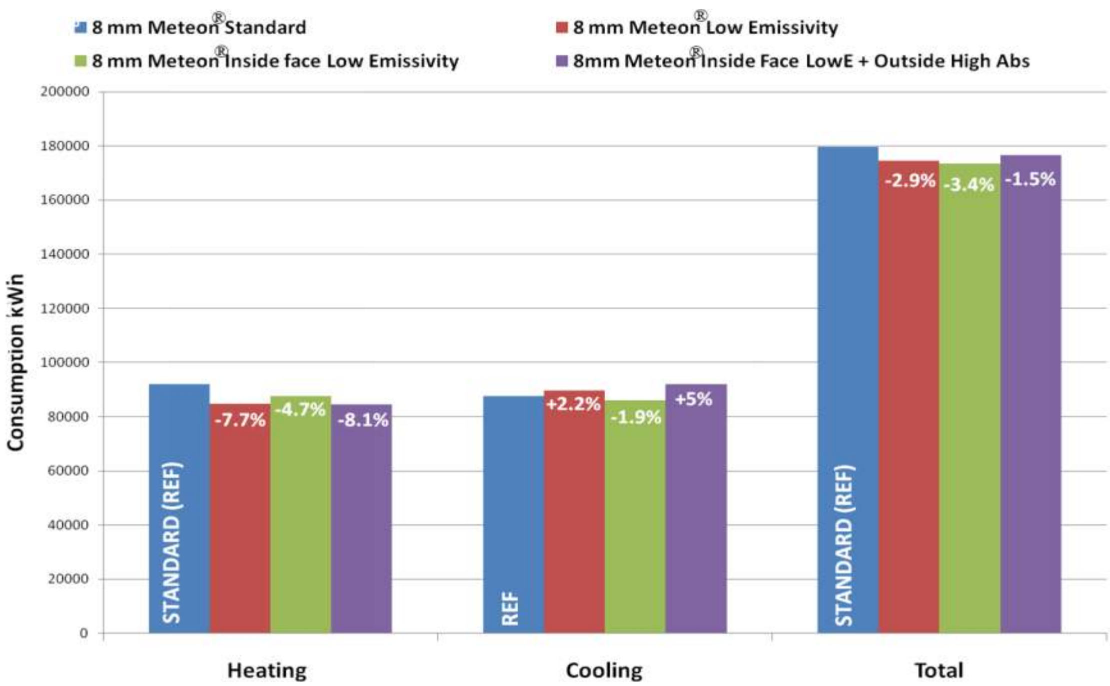
Residential model for sensitivity study. Layout, windows to wall ratio (WWR) and scenario

Two locations in Europe were simulated for a yearly period. First is oceanic climate (Köppen-Geiger classification) of Berlin (Germany), and second is the cold semi-arid climate of Madrid (Spain). The insulation thickness was adapted to the practice and requirements of each country. 120mm (4.8") of mineral wool were used in Berlin and 50mm (2") in Madrid. Simulation time step of 1min and 10min were used and compared for every orientations and climates. The difference for thermal demand was below 0.2% in all cases. Consequently the 10min simulation time step was elected to reduce computational time and memory storage. The panel thermal and optical properties and their range of variation during the simulation process was as follows (in bold is the reference case):

- Thickness in mm [8mm, 13mm]
- Thermal conductivity in $W.m^{-1}.K^{-1}$ [0.04 mineral wool, 0.3 Trespa® Meteon®, 237 aluminum)
- Heat capacity in $J.kg^{-1}.K^{-1}$ [500, 1520]
- Solar absorptivity in % [10, 41, 99] – only outside face
- Thermal emissivity in % [10, 90] – outside face, inside face, both

In a first step, every variation were tested individually for all orientations and climate. This first batch of simulations (128 in total) showed that properties with the most influence were emissivity and solar absorptivity. Heating or cooling demand was modified by 5 to 10% compared to reference. Thermal conductivity also showed some influence, albeit limited, with modification of heating or cooling demand up to 1%.

Solar absorptivity modification was addressed by SRT project. Additional studies on thermal emissivity showed that having low emissivity on inside face (facing cavity) of sidings could result in reduction of 3.4% of thermal demand (0). Low emissivity on outside face have positive impact on heating demand as the panel will release less energy through far infrared radiations and will be less impacted by cold sky radiation. Nevertheless, the same causes end up in the increase of cooling demand.



Simulation sensitivity study with Esp-r. Effect of optical properties modification in Madrid climate

The absolute value of thermal demand variations could not be generalized as it may be highly dependent of simulation conditions, but the ranking of important parameters gives valuable insights to steer innovation toward most promising developments of sidings.

CONCLUSION AND FUTURE WORK

In daily practice, the usage of ventilated façade has proven to be efficient solutions to save energy. The case study of Arpa's headquarter in Italy is a real demonstration of this efficiency. Nevertheless, it cannot describe the specific effect of the naturally vented cavity. The measurements carried out by the French Technical Institute FCBA confirmed that ventilated façades have positive influence on the thermal behavior of walls. Heat loss reductions have been observed even in the case of highly-insulated walls. Nevertheless these benefits have to be interpreted cautiously as, in this specific case; there was no additional thermal bridges due to the fixing systems of the sidings. The summer behavior confirmed common literature knowledge about the potential cooling effect of the ventilated façades. Furthermore, these measurements highlighted the thermal damper effect of the cavity, which reduces the thermal strain on the façade. Having separate layers allows separation of functionalities. The external skin is the one that has to withstand the climatic strain. This implies some liberty of expansion and shrinkage, while the inner wall can still ensure the air tightness. Combining it in one layer, as in the EIFS, can result in cracks.

Humidity analysis confirmed that the low permeability of render finishing could be a risk for condensation, as moisture could be trapped in the system. Ventilated façades, thanks to the naturally vented cavity, have a "breathable build up" and thus are a more secure option.

Finally, the knowledge confirmed empirically has been combined to a numerical approach and used in the product development process. It opened the way to an energy wise façade cladding solution with the recent market release of Trespa® Meteon® SRT. It also drives innovation towards new development of sidings like low-emissivity surfaces. Additional studies will be done to define best cases, like ideal locations, orientations, insulation thickness. The impact of optical properties variations for cladding material will increase when the amount of insulation will decrease. New model development is necessary to evaluate these solutions in specific applications were insulation thickness is minimal, such as solar protections over windows or glazed curtain walls, or singular points as windows sills.

ACKNOWLEDGMENTS

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REFERENCES

Amparo López-Jiménez, P. et al. "Model of ventilated façade in buildings by using CFD techniques", 2010 International Congress on Environmental Modelling and Software, Ottawa (2010)

Gonzales, M. "Numerical study on thermal and fluid dynamic behavior of an open joint ventilated façade." 25th Conference on Passive and Low Energy Architecture, Dublin (2008)

Hensen, J.L.M et al, "Using building simulation for moving innovations across the Valley of Death". REHVA Journal, Vol.52(2015), No. 3, p. 58-62

Marinosci, C. "*Dynamic Thermal performance of building components and application to experimental and numerical evaluation of a ventilated façades.*" Ph. D thesis, Bologna University, 2011

Naboni, E. "Ventilated opaque walls – a performance simulation method and assessment of simulated performance." Seminar Laurence Berkeley National Laboratory Environmental Energy Division, CA (2007)

Salonvarra, M. et al, "Air Cavities Behind Claddings-What Have We Learned?" Thermal Performance of the Exterior Envelopes of Buildings X, proceedings of ASHRAE THERM X, Clearwater, FL (2007)

Sanjuan, C. "Development and experimental validation of a simulation model for open join ventilated façades", Energy and buildings 43 (2011); 3446-3456

LEAF (LOW ENERGY ADAPTIVE FAÇADE)

Self-adapting micro shading façade design using responsive polymer sheets

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ABSTRACT

In a mission of producing energy-efficient buildings, building enclosures play a critical role by controlling heat gain, natural lighting, and maintaining visual comfort. All windows and glass walls have shadings and blinds to control heat gain and glare problem. However, human hands are unreliable, and recent dynamic shading systems based on mechanical hinges are expensive and consume additional energy. The Low Energy Adaptive Facade (LEAF) integrates a photochemical responsive polymer sheet into building facades through an origami inspired folding pattern. It aims to emulate the diffuse, dappled light quality created by deciduous trees in the summertime by sensitively responding to daylighting conditions. LEAF achieves the integration between the shape changing polymer sheets and parametric design for sustainability and artistry through building envelope design. The basic principle is to fabricate surface using laminated films consisting of a bilayer system: a light responsive layer and a non-responsive layer. The surface can be designed to contract during the light irradiation. This mechanism enables development of hinges that can reversibly fold with the control of mountain and valley assignments. LEAF suggests the specific folding pattern for its geometric efficiency and folding mechanism. This design frees the burden of complex construction and maintenance of mechanical dynamic façades, while it allows diffused shading with millimeter-scale panel folds, just like sunshine through leaves. This scale factor can also specifically respond to the problem of glare. The module size can be very small and LEAF's bi-directional shrinking capability also maximizes the diffusing quality. Lastly, this method can be applied to mass production of dynamic façade systems with relatively low material cost and a high degree of design flexibility. Established on well-known route of polymer synthesis, LEAF addresses the building envelope application using photochemical reaction of polymer sheets, integrating photochemical phenomenon and parametric design.

ABSTRACT

친환경 건축에 있어서 건물의 외피는 실내 온도를 유지하고 자연광을 조절하며 밖을 볼수 있게 해주는 등 중요한 역할을 하고 있다. 그래서 대부분의 유리로된 창문과 벽은 커튼, 블라인드, 차양등을 내, 외부에 설치해서 열을 차단하고 눈부심 현상을 방지하는데 손으로 조절하는 장치들은 효율적이지 않고 기계적인 모터를 이용한 장치들은 비싸고 추가적인 에너지를 필요로한다. 이에 대해 리프(LEAF, Low Energy Adaptive Façade)는 광화학적인 반응을 하는 폴리머 시트를 오리가미의 접기방식을 응용해서 건물의 입면에 적용하는 친환경적인 쉐이딩 장치이다. 형태가 변하는 폴리머 시트의 특성과 패러매트릭 다자인을 통합함으로 친환경적이면서도 미적인 건물 입면을 구현할 수 있다. 빛에 반응하는 레이어와 반응하지 않는 두 레이어로 구성된 폴리머 시트는 빛에 노출되면 한쪽 면이 수축됨으로 인해서 접히는 현상이 발생하는데 리프(LEAF)는 이를 이용해서 건물 입면에 최적화된 기하학적으로 효율적인 접기방식을 도출한다. 이는 기존의 복잡한 기계식 입면 쉐이딩 보다 적은 비용으로 만들수 있고 에너지 효율적이며 관리가 쉬운 장점이 있다. 또한 밀리미터 스케일의 작은 크기로 만들수 있기

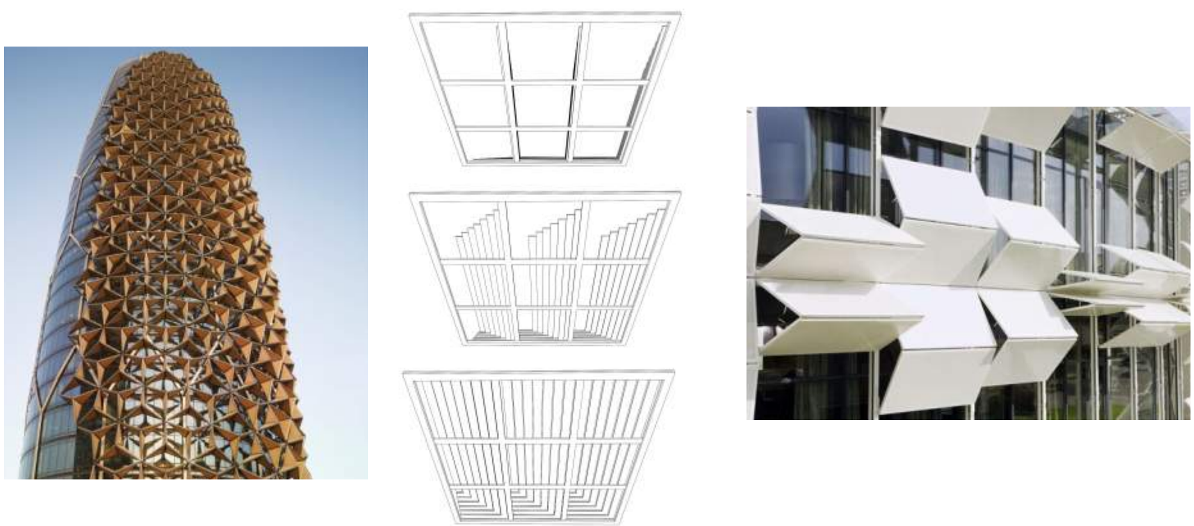
때문에 빛을 산란시킴을 통해 눈부심 현상에 효율적이며, 상대적으로 대량생산이 용이하다. 리프는 기존의 증명된 폴리머 관련 연구 성과를 통해서 광화학 작용과 패러매트릭 디자인 방법을 통합하는 건물 입면에 응용할수 있는 방법을 제안한다.

KEYWORDS

Adaptive-kinetic-dynamic, Polymers, Adaptability, Computational design, Shading, Self-folding, Aesthetics, Origami

SUSTAINABILITY AND BUILDING ENVELOPE

In the United States, buildings account for 41 % of energy use and 38 % CO_2 emission. According to U.S. Department of Energy, green buildings (designed to achieve sustainability rating) consume 25 % less energy, have 19 % lower maintenance costs and produce 34 % lower greenhouse gas emissions. Along with this great mission regarding the energy performance, in recent decades, the power of digital technology became pervasive in the building industry. Manufacturing techniques using parametric tools and robotics have opened up new ways of delivering projects. In these contexts, the design and construction of the building façade provide a direct and convenient platform for the experiments to respond to the need of energy efficient building. Recently, there are successful dynamic envelope systems developed to address this concern. Glass buildings have a mechanical folding system to shade the building (Figure 1a and 1c). Mechanical shifting and overlapping creates a ceiling shade in Abu-Dhabi (Figure 1b). In these examples, the building façade design becomes the major element embodying socio-cultural aspect of the city, client or program on top of the mission of sustainability. Despite the limitation of the mechanical actuated system such as high cost, additional energy consumption and maintenance, mechanical innovation presented in these pioneer works will continue to emphasize the role of façade design.



(a) (b) (c)

Figure 1. Built dynamic façade systems actuated by mechanical hinges/motors. (a) Abu-Dhabi Investment Council Headquarters (Photo courtesy of AHR Architects), (b) Dynamic shading at Aldar Central Market by Foster + Partners, Hoberman Associates and Adaptive Building Initiative (Diagram by author), (c) Kiefer Technic Showroom (Photo courtesy of Giselbrecht+Partner).

Advances in material science and engineering have also contributed to the mission of smarter building envelope. For instance, electrochromic glass (electronically tintable glass) uses voltage to change light transmission property (Figure 2a). Other Smart glass such as Suspended Particle Devices provides the same function (Figure 2b). Another great example is a form-changing polymer developed by Elliott Schlam of New Visual Media Group. A thin polymer sheet is wrapped and installed in the glazing unit and it rolls out to provide shading (Schlam et. al., 2014) (Figure 2c). Compared to the mechanical dynamic shading, these glass systems can efficiently provide substantial energy saving with low cost, though the façade design becomes independent gear added to the irrelevant building design.

(a) (b) (c)

Figure 2: Commercially available dynamic façade systems actuated by electro-field control. (a) Electrochromic glass by Sage Glass (Photo courtesy of Jeffrey Totaro, 2015), (b) Switchable Smartglass (Suspended Particle Devices), Photo courtesy of Smart Glass International), (c) Dynamic window by Elliott Schlam, New Visual Media Group, LLC. Photo courtesy of New Visual Media Group.

All of these cases with mechanical actuation (Figure 1) and electric actuation (Figure 2) focus on shifting the state between an opened (bright) and a closed (dark) condition providing the function of shading. However, LEAF (Low Energy Adaptive Facade) focuses on the material property of polymeric sheets and the nature of actuation (heat, light or both), which mimics the nature's subtle change in illumination and color from the sun. By designing the photochemically actuated motion with parametric folding pattern, the self-shading system based on origami and self-folding polymer sheets pursues not only a low energy actuation but also the sensation of diffused light quality smoothly responding to daylighting just like we see deciduous vegetation shade as shown in Figure 3.

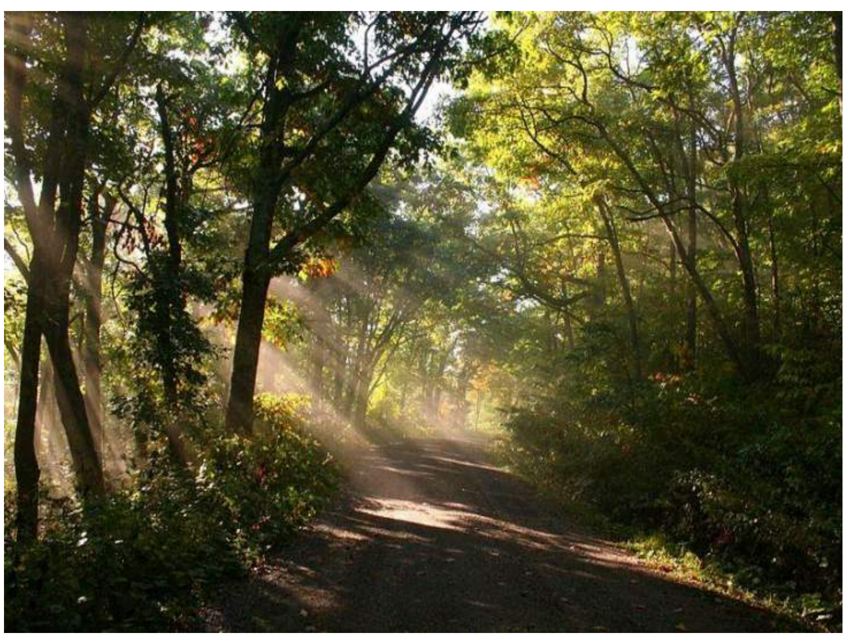


Figure 3: Shading from vegetation (Photo courtesy of Creative Commons Attribution-Share Alike 3.0 United States license.)

APPLICATION OF POLYMER SHEETS TO BUILDING FAÇADE

There is significant amount of research exploring folding or bending mechanism converting a 2-dimenional polymer sheet into a 3-dimensional shape. Thermal expansion in a bi-layer polymer sheet actuated by heat provides self-folding mechanism (Stoychev et. al., 2015). In a hydrogel, thermal actuation can program reversible origami (Na et. al., 2015). Using halftone gel lithography, the surface can generate patterned swelling, producing complex curvature (Kim et. al., 2012). Similar to the electroactive polymer which can change the form controlled by electricity shown in Fig 2c, light can actuate the shape change. Azobenzene Liquid-Crystalline can make the sheet bend responding to light exposure (Ikedaet.al., 2003). The shape programming of polymeric materials gives a great potential to building envelop applications for the following reasons. (1) Polymer sheets can be mass-produced with a relatively low cost. (2) The manufacturing process can be also simple and inexpensive due to various patterning techniques such as inkjet printing and screen printing. (3) The products can be applied to existing glass walls by simple attachment behind the façade layers. On the other hand, there are several challenges to commercialize this idea into the building envelopes. (1) Reversibility: some heat actuated polymers are not reversible. (2) Scalability (micrometer to millimeter scale): small scale must provide the functionality to the building scale. (3) Sensitivity (actuation at room temperature). Actuation in an elevated temperature makes it less applicable to the building temperature condition. Therefore, the design speculation of LEAF relies on azobenzene based polymeric materials which triggered by light (Fig 4). At the R/D level, the data show reversibility and successful movement at millimeter scale at the range of room temperature. Same speculation can be applied to hydrogel with heat actuation, containing water in the interlayer of the glass. It is also reasonable to expect further development in this technique will allow centimeter scale of operation with low cost. LEAF speculates the function of patterns, the parametric folding mechanism with the unique materiality toward leaves like shading solution.

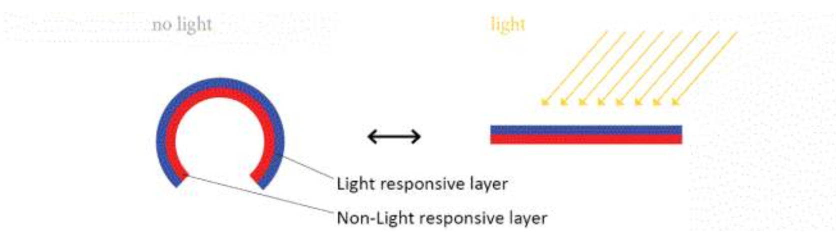


Figure 4: A schematic illustration of bending mechanism of crosslinked liquid-crystalline polymer and polyethylene bilayer films actuated by natural light (Cheng et. al., 2010).

DESIGN SPECULATION

Cheng has created hinge conditions (Fig 4) with arm, wrist and handle to bend with only light actuation. This light driven plastic micro-robot successfully demonstrated picking, lifting, moving, and placing the object in vertical and horizontal directions (Cheng et. al., 2010). To obtain the self-shading device based on origami, this daylight responsive polymer sheet of crosslinked liquid-crystalline polymers (CLCPs) provides a great potential to use natural light. Figure 5 represents the operational principle of the polymer sheet folding. Stress is developed to bilayer films from crosslinked liquid-crystalline polymer and polyethylene during the light irradiation to the polymer sheet bonded to thin stiff polymer layers. It allows the creation of hinges that can reversibly fold with control of mountain and valley assignments. This approach can provides complex folding patterns in small scales by creating mountain and valley edges in both sides with programmed folding angles based on the manufacturing property of CLCPs. This method can be applied to the mass production using a relatively inexpensive material with design flexibility.

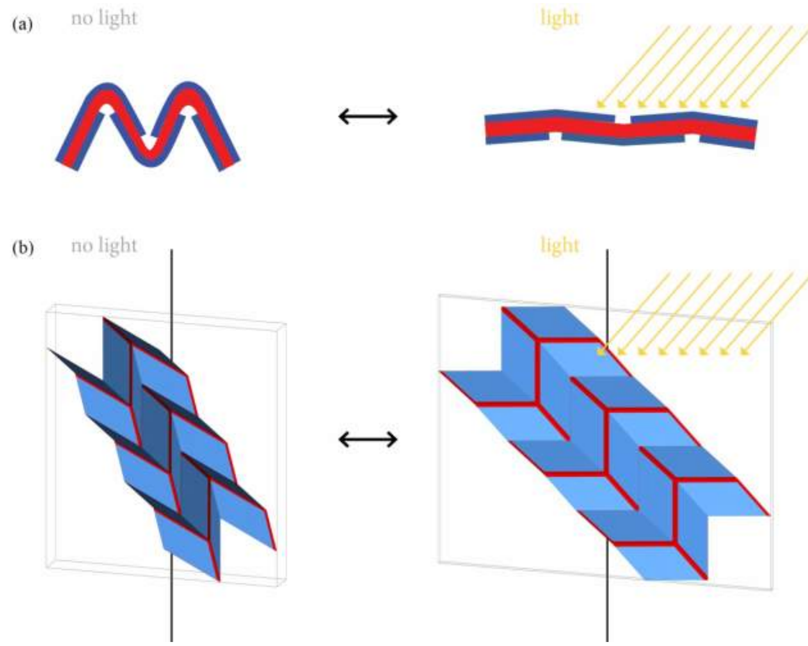


Figure 5 (a) Schematic illustration of polymer sheet folding. Blue represents stiff polymer layer which is non-responsive to light, red represents light responsive polymer film layer. When there is no light, it is folded to minimize the surface. When there is light, the photo chemical process makes it unfold to enlarge the surface. ***(b)*** *3D diagram of the LEAF's schematic film structure based on Miura-ori.*

This strategy must be for the glazing units with an efficient folding mechanism. The minimum depth with the maximum shading area is desired. Therefore, the well-studied Miura-ori (see Fig. 6), which ideally behaves as a compressible sheet with a negative in-plane Poisson's ratio. It allows us to make L/D (Length of the module / Depth of the module) value maximum. Here, D is associated with the cost and difficulty of building envelope construction while L is relating to the shading capacity. Geometrically, every folding angle of Miura-ori can be created with plane angle S, while unit plane has two vertices and each vertex consists of three mountain and one valley creases (or vice-versa) as shown in Fig 6. Since Miura-ori structure has negative in-plane Poisson's ratio, both L1 and L2 decreases while D increases during the folding process. Fig 7 presents the physical simulation of Miura folding using Shape Memory Polymer actuated by heat. Attaching the strip on either front or back side, simple hinge formation programed with folded and unfolded by temperature change defines either mountain or valley.

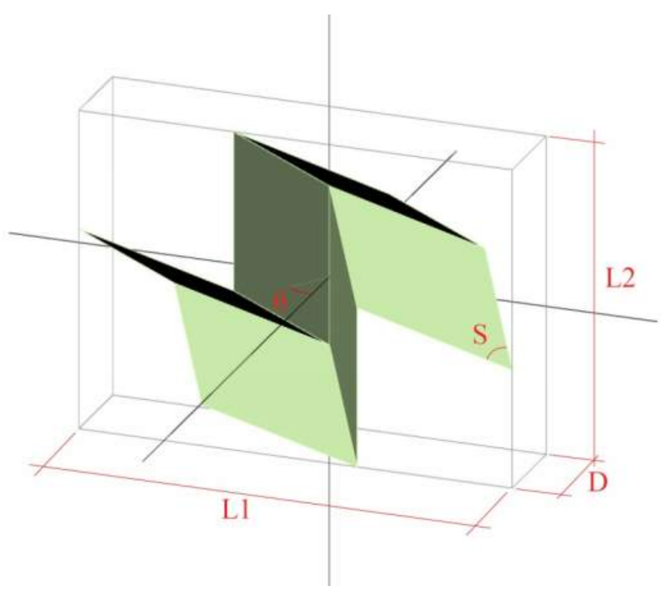


Figure 6: Schematic simulation of Origami folding. D= depth of the module, L1=horizontal length of the module. L2= vertical length of the module.

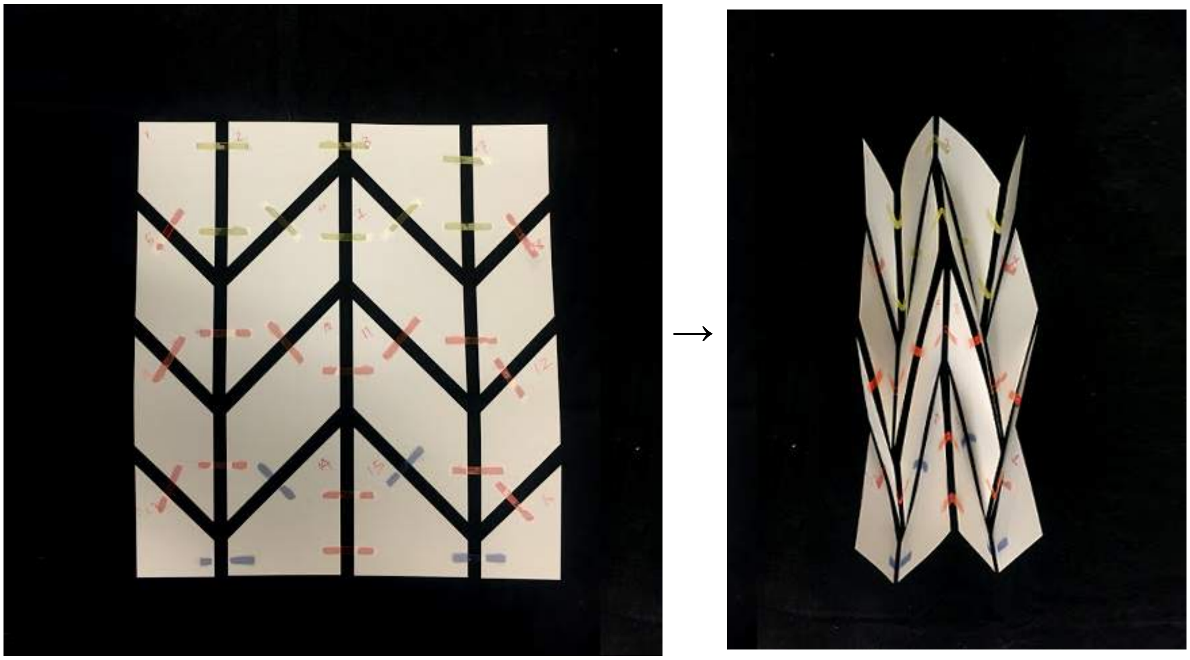
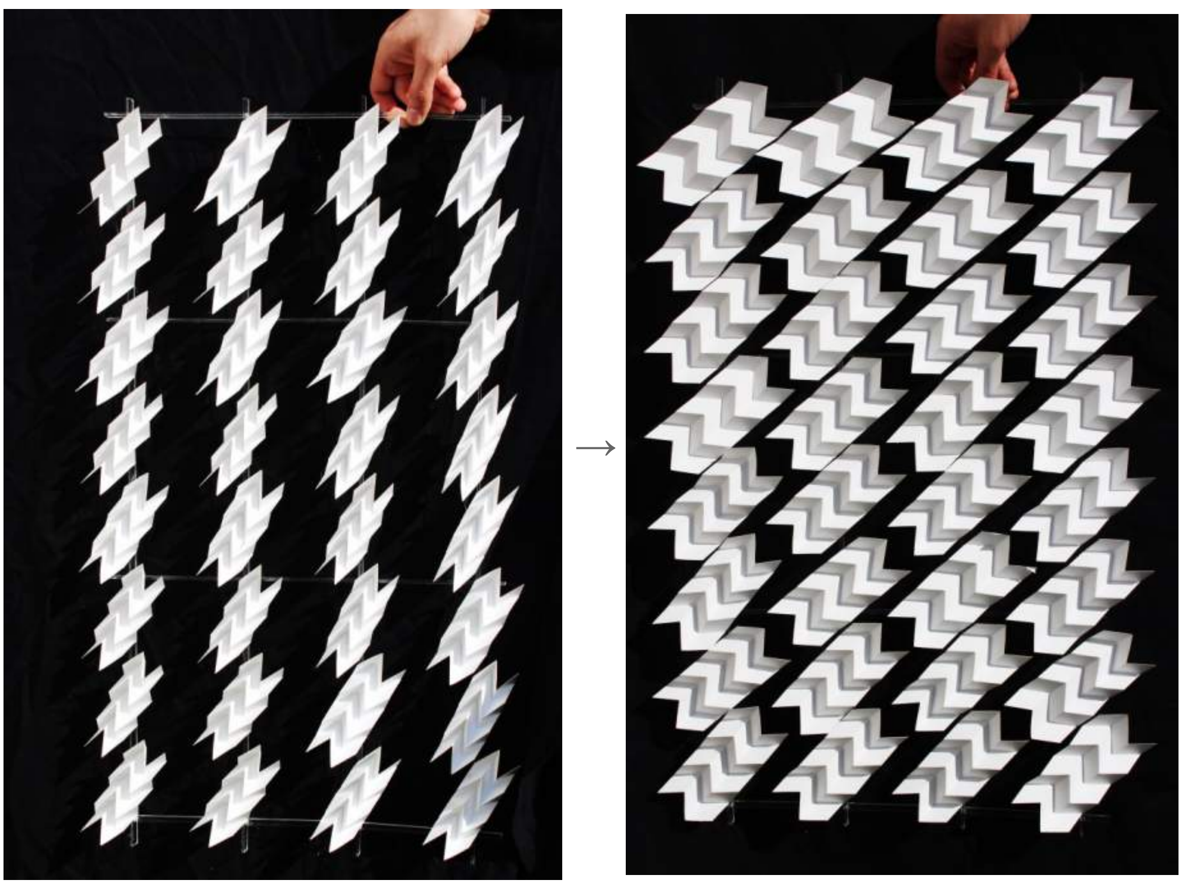


Figure 7: Hinge configuration using Shape Memory Polymer, 1/8" width 1/32" thickness strips commercially available with inexpensive cost. Despite this actuation cannot happen in the room temperature variation, it shows the potential method to overcome the size limitation of current polymeric material.



(a) *(b)*

Figure 8: Folding simulation with paper model

LEAF system is developed to repeat this base module, consisting of 18 parallelograms (Figs. 8 and 9a), each module sized by 1.28a”×7.6a”×a” (L1 × L2 × D) at its folded state (base state) and becomes 10a”×8a”×0.08a” when light hits. If the module is designed with more parallelograms, it can make L2 value bigger when unfolded. LEAF is designed to make a continuous vertical fin shape when folded so that the change of L2 value remains small. The one edge in the center of the module is anchored to the external structure (using thin wires). The effect of the plane angle S (shown in Fig 6) is studied to create an alignment to maximize the shading capacity when nearby modules are unfolded together. By nature, Miura-ori avoids collision to the next modules in x and y axis since it shrinks in both directions. Figure 8(a) shows the computational simulation of 4 modules showing a progressive transition from a folded state (base state when there is no light) to unfolded states when light hit the surface. The more unfolded LEAF is, the larger the surface faces the light source creates. This mechanism accelerates the speed of unfolding. Figure 9(b) shows opening pattern simulation in a panel condition.

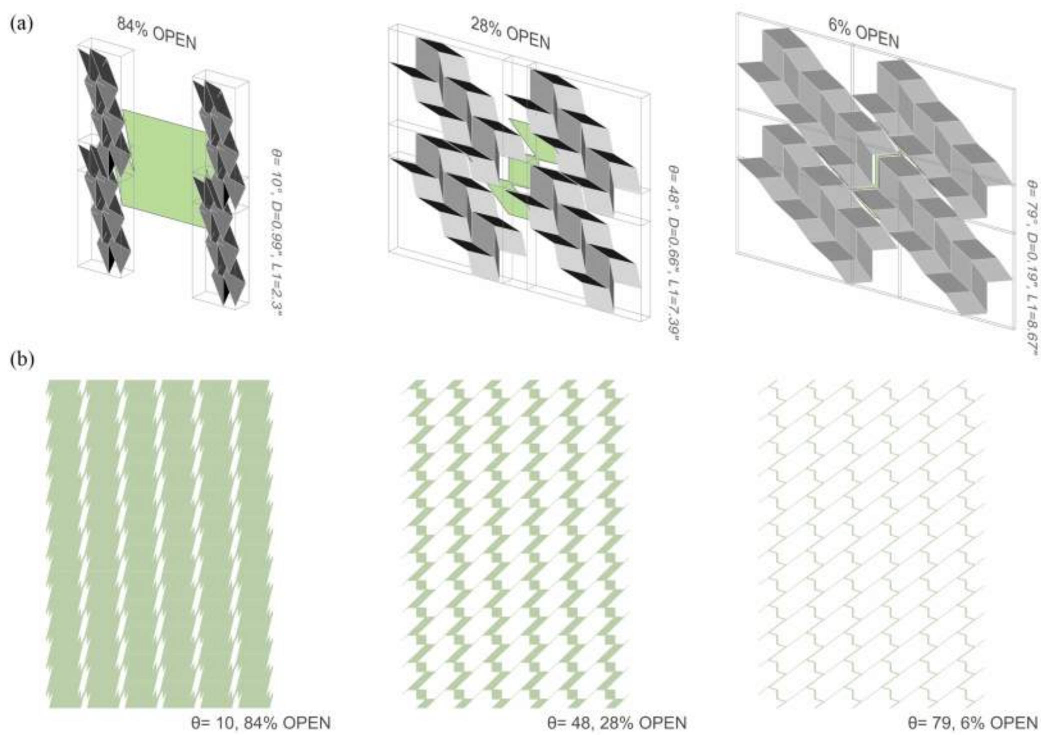


Figure 9: (a) Schematic simulation of 4 modules in LEAF system. When they are folded (basic state when there is no light), it forms vertical lines. When there is light, it unfolds to block light, (b) Projected area diagram of opening percentage change in LEAF system from folded state (10 °) to unfolded state (79 °). Green color represents the projected open area.

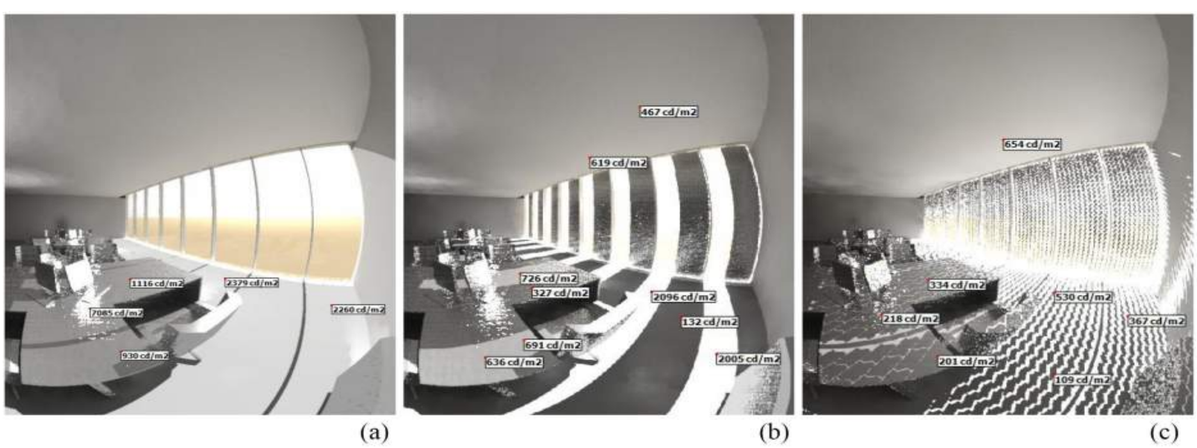
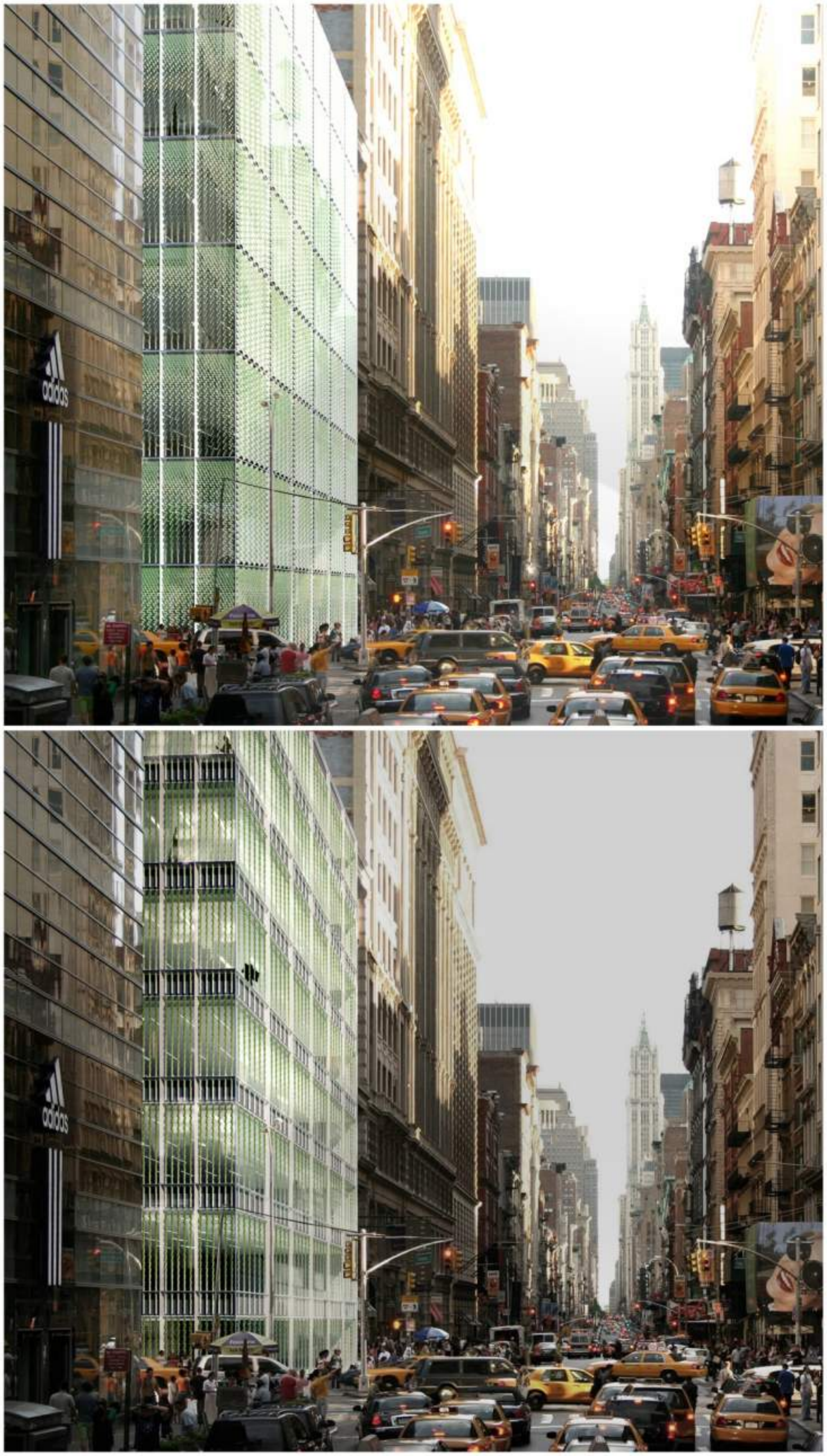


Figure 10: Lighting simulation using DIVA. (a) Typical glazing unit. (b) Generic shading device (or it can be considered as opening design) which has 57% opening. (c) LEAF with same 57 % opening.

From the standpoint of a daylighting design, LEAF can specifically respond to the glare problem. Unlike mechanical actuating shading device, LEAF's module size can be very small to produce more diffused light. In addition to the size factor, the shrinking capability in both directions also maximizes the diffusing quality. Figure 10 shows simple lighting simulation using DIVA (http://diva4rhino.com/). The test site is an office facing southwest in Los Angeles, CA. The test time is summer day 4pm. Figure 9(a) shows just a typical glass facade without any shading device. The luminance level on the workstation shows 1116 lux (cd/m2). Figure 9(b) shows generic vertical shading devices - or just window openings - which allow 57 % opening ratio. In this case, the work surface has big contrast between 327 lux to 726 lux, which is still uncomfortable condition. LEAF system that has the same 57 % opening ratio will make the workstation with constant 201 lux to 334 lux. Based on this superior function and sensational quality, Figures 11 and 12 show interior and exterior renderings depending on different light conditions.



(a)

(b)

Figure 11: Renderings of LEAF building in different lighting scenario. (a) The facade on the right side of building in this rendering shows 6 % opening. Left side of facade shows 57 % opening. (b) All facades have 84 % opening since there is no direct light hitting the building.

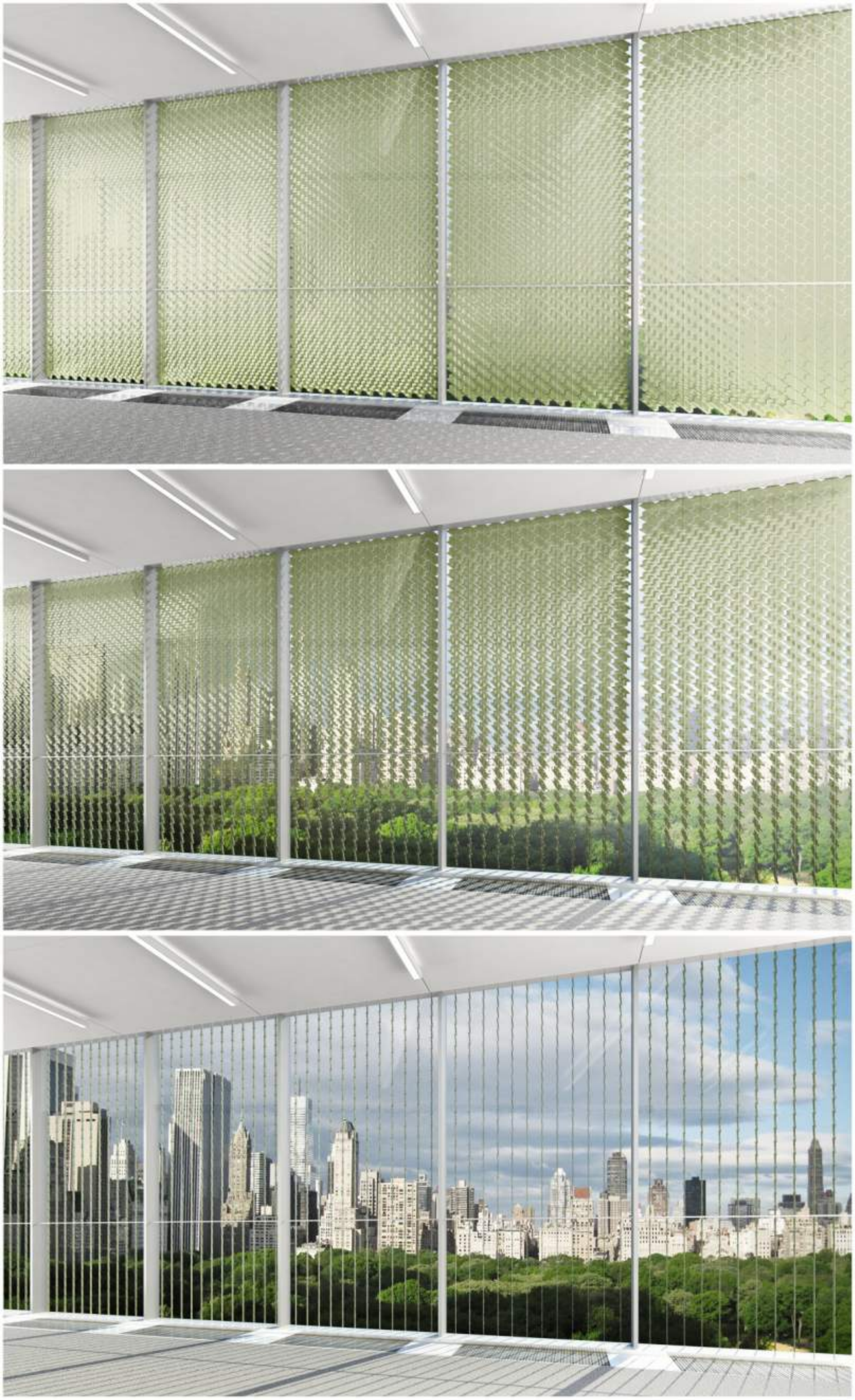

(a)
(b)
(c)

Figure 12: Interior Renderings of LEAF to show opening simulation. (a) 6 % opening. (b) 57 % opening. (c) 84 % opening.

CONCLUSION AND FUTURE WORK

Shape-programming of polymer sheets is a very attractive strategy for the building envelope design for its self-folding mechanism, low energy operation/maintenance, artistry of mechanism and noble shading effect. LEAF proposes a design speculation for the application of the emerging research emphasizing the integration of parametric design and photochemical actuation beyond a simple open and close shading system. To achieve the folding mechanism, LEAF can use alternative stimulus (e.g., heat, solvents, water with temperature change, magnetic field and pneumatics). Further progress on these polymeric materials and the performance of shape change will need to be integrated with a parametric design procedure. Despite the promising advantages, proven benefits and alternative stimulus described (Liu et. al., 2016), the current reviews of the shape programmable materials may address the size limitation. The simulation of LEAF in a more elevated temperature change (Fig. 7, pattern change simulation by author) suggests alternative hinge configuration to achieve the same performance using much smaller shape changing polymer sheet used only in the hinge definition. Therefore, in continuation of existing body of research using light actuation, the next step of the LEAF is to fabricate a light responsive polymer sheet performing the LEAF folding mechanism with size variations. In that prototype, different hinge mechanism will be explored and the optimum radius of curvature to make folding structure in the daylight condition and folding angle calibration with different mountain and valley programming need to tested. The anchor connection using the center edge of the LEAF module will be also explored with various methods in the context of glass wall to address the flexible deployment of this product to any existing building envelope condition.

ACKNOWLEDGMENTS

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REFERENCES

Cheng, Futao, Ruoyuan Yin, Yuanyuan Zhang, Chu-Chun Yen, and Yanlei Yu. "Fully plastic microrobots which manipulate objects using only visible light." *Soft Matter,* 6, no. 15 (2010): 3447-3449.

Ikeda, Tomiki, Makoto Nakano, Yanlei Yu, Osamu Tsutsumi, and Akihiko Kanazawa. "Anisotropic Bending and Unbending Behavior of Azobenzene Liquid-Crystalline Gels by Light Exposure." *Advanced Materials*, 15, no. 3 (2003): 201-205.

Kim, Jungwook, James A. Hanna, Myunghwan Byun, Christian D. Santangelo, and Ryan C. Hayward. "Designing responsive buckled surfaces by halftone gel lithography." Science, 335, no. 6073 (2012): 1201-1205.

Liu, Ying, Jan Genzer, and Michael D. Dickey. "“2D or not 2D”: Shape-programming polymer sheets." *Progress in Polymer Science*, 52 (2016): 79-106.

Na, Jun-Hee, Arthur A. Evans, Jinhye Bae, Maria C. Chiappelli, Christian D. Santangelo, Robert J. Lang, Thomas C. Hull, and Ryan C. Hayward. "Programming Reversibly Self-Folding Origami with Micropatterned Photo-Crosslinkable Polymer Trilayers." Advanced Materials, 27, no. 1 (2015): 79-85.

Schlam, Elliott, Mark S. Slater, Jeffrey P. Koskulics, and Joshua S. Finch. "Electronically controlled insulated glazing unit providing energy savings and privacy." U.S. Patent 8,736,938, issued May 27, 2014.

Stoychev, Georgi, Nikolay Puretskiy, and Leonid Ionov. "Self-folding all-polymer thermoresponsive microcapsules." Soft Matter, 7, no. 7 (2011): 3277-3279.

(All images are by the author except Figure 1, 2 and 3)

ADAPTIVE ENVELOPE

Behavior derived from climate

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ABSTRACT

Adaptive building envelopes are argued to offer significant benefits in reducing building energy use by selectively managing the interaction between the indoor and outdoor environments. These envelopes take advantage of outdoor conditions that are beneficial to indoor comfort and reduce energy loads by selectively admitting or excluding environmental variables to control the flow of energy through the envelope. Static passive energy design strategies can vary in effectiveness due to their environmental circumstances and occupant needs, while use of dynamic envelope elements, such as window shades, can enhance building performance and occupant comfort; their effectiveness is dependent on how they are used. In a similar way, the effectiveness and behavior of an adaptive envelope will be derived from its circumstances and defined by its objective functions for managing occupant comfort and energy use. Thus far, research into adaptive building envelopes has focused on energy and comfort with limited discussion on how they may behave and the possibility that some adaptive envelope response variables (changes to form, insulation, mass, porosity, and transmissivity) may complement, conflict, or result in redundant abilities under some environmental conditions.

This research examines hour-to-hour behavior of a simulated adaptive envelope for a single thermal zone under 48 unique scenarios (four climates, four orientations, and three seasons). The simulated envelope manipulated four adaptive variables (form, insulation, porosity, and transmittance) each hour to find the best solution to minimizing energy without compromising thermal comfort. Scenarios were simulated using a method that combines a building energy simulation program linked to an optimization component and together managed by a custom control script, which directs an iterative simulation process that seeks optimal envelope configurations hour by hour.

Results show that under some conditions, some adaptive envelope response variables are rarely used while others are significant contributors to achieving improved energy and comfort performance. Within the limits of this research, it is found that although some adaptive features may appear to be of limited use, they may be more significant when integrated with larger, whole building systems.

KEYWORDS

adaptive envelope, behavior, climate, energy, comfort

INTRODUCTION

Drawing parallels between human behavior and theoretical adaptive building envelopes (ABEs), human actions relating to achieving thermal comfort are generally successful (Baker, 1996) provided the appropriate adaptive opportunities are available (Humphreys and Nicol, 1998). There are behaviors that could be described as common to given environmental conditions such as wearing a jacket in cold weather or sunglasses in bright sunlight. Buildings, as with human comfort, have their own needs for maintaining desirable indoor conditions. These needs depend on an optimal energy exchange between the indoor and outdoor climates. As humans adapt to changing needs and weather conditions, buildings clad in an adaptive envelope will behave in ways specific to the prevailing weather conditions and occupant needs in order to maintain the desired internal conditions.

Building designs that depend on climatic design principles have long been shown to significantly reduce the dependence on mechanical climate control systems resulting in lower energy use while achieving quality indoor conditions for their occupants (Olgyay, 1963, Zhai and Previtali, 2010). However, this successful design approach traditionally employs relatively static responses to meet changing weather and occupant behavior and therefore is limited when confronted with extremes (Olewnik, et al., 2003). In contrast, adaptive envelopes are envisioned to respond to a broader range of weather conditions by working with changes in the weather, occupant behavior, and internal loads to exploit positive energy exchanges between the indoor and outdoor environments. Inserting an adaptive envelope between indoor and outdoor climates creates a negotiator that pursues a desirable energy transfer and seeks to satisfy objectives such as reducing energy use, controlling glare, and providing fresh air. If an ABE is designed so that its environmental barrier characteristics (e.g. properties concerned with controlling the flow of thermal energy, air, water vapor, and solar radiation) are able to respond with selective exclusion or inclusion of specific environmental variables, then it is possible to examine which adaptive responses are preferred in responding to prevailing weather conditions and occupant needs.

Although a growing number of studies investigating the potential of adaptive building envelopes have addressed many confounding issues that confront the realization of practical implementation of ABEs, there remains little information regarding how ABEs will respond across multiple scenarios (e.g. climate, urban surroundings, differences in user needs and internals loads, etc,) and how the difference in context will affect performance and behavior. Data presented here is part of a study that examined a theoretical ABE capable of modifying its form, insulation, porosity, and transmittance as needed in order to manage the exchange of energy between the indoor and outdoor environments. The results presented here examine changes in the behavior of this simulated envelope regarding climate, orientation, and season.

BACKGROUND

The concept of an ABE, initially articulated by Davies (1981) as a polyvalent wall, has captured increasing attention as advances in technologies and material science make this idea progressively more feasible. Multiple studies conducted in recent years have addressed issues relating to adaptive envelopes, establishing that this is a valuable field of research with the promise of significant benefits. Adaptive building envelopes reduce energy use for indoor climate control (de Boer, et al., 2011, Erickson, 2013, Jin, et al., 2015) in a range of climates and weather extremes (Erickson, 2016), improve indoor environmental quality (Kasinalis, et al., 2014), and offer a form of resiliency to weather and climate conditions that static structures are incapable of matching.

Only recently has simulation techniques advanced enough to be able to capture some of the significant complexities involved in modeling adaptive building envelopes (Loonen, et al., 2016, de Boer, et al., 2010). To date, most published simulation work has been confined to individual climate scenarios designed to test specific adaptive abilities of the simulated envelope such as adaptive insulation (Jin, et al., 2015) and glazing (Loonen, et al., 2010, Favoino, et al., 2015). With a more comprehensive study examining ABEs with multiple adaptive abilities in a variety of contexts (Erickson, 2013) research is beginning to examine more specific issues relating to ABEs' performance in minimizing energy use and maintaining occupant comfort as well as understanding ABE behavior and value of individual adaptive abilities due to context.

METHOD

The research objective was to mimic an ABE responding to changing weather conditions in an effort to reduce indoor energy use without compromising occupant comfort measured by Predicted Percentage Dissatisfied (PPD). A simulation program structure was created to find optimal configurations for the simulated envelope on an hourly basis, mimicking possible responses to the ABEs' changing context. Current building energy simulation (BES) software does not yet possess the ability to optimize building variables by time interval (e.g. minute, hour, day, etc.) in sequential steps requiring the creation of a composite algorithm. For this research, it was necessary to compile successive optimal envelope solutions for each hour, to form a thermal history for the simulations ($h_{0-1...n}$ where h represents a defined time interval) within the energy model that then informs the current step that is being optimized for (h_0).

To achieve this, a program structure was developed integrating a BES program (EnergyPlus (LBNL (Lawrence Berkeley National Laboratory), 2010)) for calculating energy and comfort, with an optimization tool to guide the search to minimize an objective function (GenOpt (Wetter, 2009)). Using a custom PHP script, this process was repeated for each time interval (hourly), advancing the simulation process through sequential steps and writing the optimal solutions into the thermal history of each new iteration (Figure 18). This results in an idf file with hourly-optimized configurations for the desired envelope responsive variables (ERV) which describe a continuous operation schedule for the envelope's dynamic behavior. More recent work has replicated this, and portions of this methodology, by taking advantage of EnergyPlus's evolving Energy

Management System (EMS) and MatLab for simulation management to evaluate single variable adaptive behavior of glazing technologies (Favoino, et al., 2015) and opaque adaptive façades (Jin, et al., 2015) among other experiments.

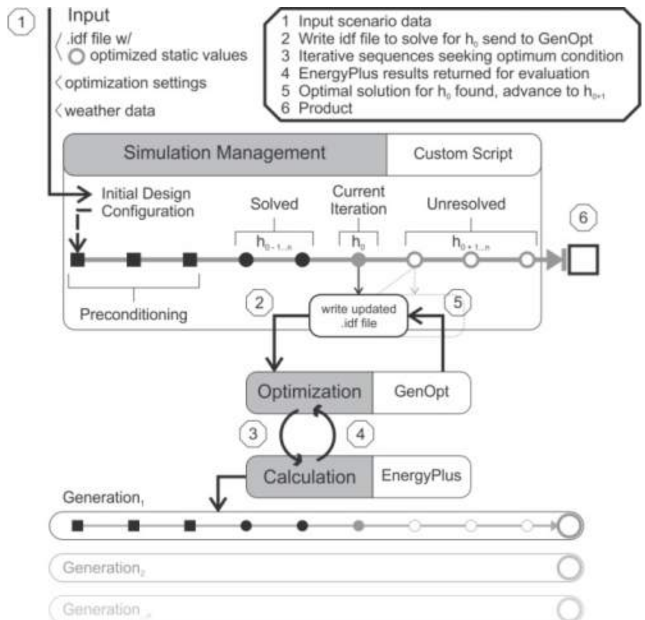

Figure 18: Adaptable optimization program structure. After Erickson (2007)

Table 1: Relationships Between Environmental, Independent Adaptable Response, and Dependent Variables

Envelope Response Variables	**Environmental Stimuli**				**Envelope Response Values**		
	Air Movement (m/s)	Air Temperature (°C)	Solar Thermal (W/m²)	Solar Visual (lux)	**Variable**	**Constraints** *Variable Type*	**Values** Range
Form *extrusions from envelope*			envelope shading from external shade depth (m)	envelope shading from external shade depth (m)	shade depth Horizontal (F_{hi}) Vertical (F_{vi})	$F_{min} \leq F \leq F_{max}$ *Continuous*	depth (m) [0, 2]
Insulation *opaque envelope*			modification of U-value though glazing to wall ratio (*A*)	glazing to wall ratio	glazing to wall ratio area (A_{wi})	$A_{i\ min}$ or $A_{i\ max}$ *Discrete*	On / Off
Porosity *void envelope*	change to air velocity from void area (m²)	envelope void to solid ratio (ach)			air changes per hour (ach/h)	$ach/h_{min} \leq ach/h \leq ach/h_{max}$ *Continuous*	window area (%) [0, 0.9]
Transmissivity *transparent envelope*		solar gain (SHGC)	transmissivity values (SHGC) affecting solar gain	glazing visual transmittance (VT)	glazing transmissivity (*VT*)	$VT_{min} \leq VT \leq VT_{max}$ *Continuous*	[0.12, 0.84]
					SHGC	$SHGC_{min} \leq SHGC \leq SHGC_{max}$ *Continuous*	[0.22, 0.70]

Building envelopes control energy flow by modifying five properties: Form (e.g. external shading), Insulation (e.g. moveable insulation), Mass (e.g. phase change materials), Porosity (e.g. operable windows), and Transmissivity (e.g. electrochromic glazing) (Erickson, 2013). At the time of this research, BES software is unable to adequately account for changes to a zone's heat balance that may occur when the envelope changes configurations that results in a discrepancy in thermal energy from one time step to the next. Such a change may affect thermal capacity and lag time resulting in "missing energy". In order to avoid this, the mass variable was excluded from this experiment and thermal mass within the test model was minimized. The result limits the magnitude of any heat balance discrepancies that could occur between steps and by minimizing thermal mass, the immediate effect of the envelope's ability to adapt to changing environmental stimuli is more apparent. The four ERVs included in the simulations affect thermal energy flow directly and indirectly by moderating temperature, airflow, and solar energy (Table 1). Each variable is able to change state between steps to values within bounds determined by existing technology limits with their initial starting values based on a previously optimized static configuration.

An objective function was defined to minimize total energy use (Q_t) without compromising thermal comfort, measured here with the PPD method already integrated into EnergyPlus. Imposing a penalty function against the cost function when PPD ≥ 10% restricts the optimization search to finding a global optimal value for Q_t without the need to decide between equal solutions along a Pareto front. The resulting equation takes the form of:

$$\min F_p(Q_t) = f(x) + \mu \sum_{i=1}^{n} \max(0, c_i\ (x))^2$$

Where $F_p(Q_t)$ is the penalized objective function; μ represents the penalty weighting factors, and $max(0, c_i\ (x))^2$ is the penalty function. For finding a global optimum, the Generalized Pattern Search implementation of the Hooke-Jeeves algorithm was used (Wetter, 2009) taking advantage of a computing cluster's multiple CPUs which facilitated the generalized pattern search phase to quickly find a global optimum before initializing a Hooke and Jeeves (Hooke and Jeeves, 1961) direct search method to find the local optimal solution.

METHOD - MODEL FORM

The basic thermal zone used in this study is derived from the US Department of Energy's Commercial Reference Buildings small, single-story office model (Deru, et al., 2011). At the time these simulations were run, ASHRAE Standard 90.1-2013 models were not yet released and as this paper addresses the behavior of the adaptable envelope, these models are included only to serve as a reference for energy and comfort performance in contrast to the adaptive model. The test office zone measures 6m deep, 3m high and 10m wide with two daylighting reference points set at 2m and 5m from the windows (Figure 19a). Adiabatic properties were assigned to five of the six surfaces restricting energy flow between indoor and outdoor environments so as to occur exclusively through the ABE surface.

Three models were built from this basic model: the first is a benchmark model, created to comply with ASHRAE Standard 90.1-2007 and referred to as the DOE Benchmark Model (DOE-BM); the second is an optimized version of the DOE-BM for minimizing annual energy use in each climate and orientation and is referred to as the Optimized Benchmark Model (OBM); and the third model, referred to as the Adaptable Envelope Model (AEM), is modified from the DOE-BM with an ABE, capable of modifying its form, insulation, porosity, and transmissivity between steps (Figure 19b) with values found in Table 1.

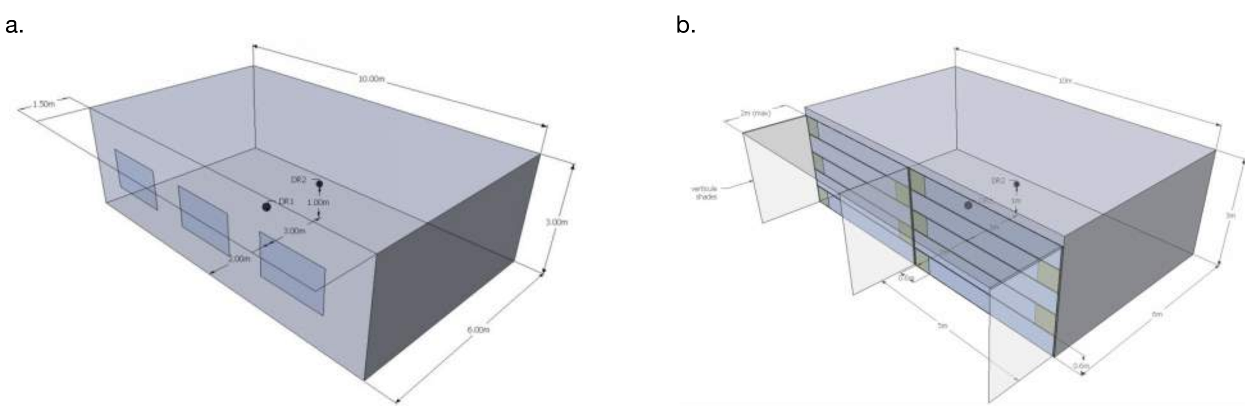

Figure 19: Static envelope single-zone DOE benchmark model (a) and single zone adaptable envelope model (b) showing window partitions and external shades at maximum depth. Daylighting reference points RD1 and RD2 marked.

METHOD - CLIMATE AND ORIENTATION SCENARIOS

Reasoning, that if an adaptable envelope could reduce energy use while maintaining occupant comfort under extreme weather conditions, then an ABE theoretically would be able to perform under "typical" weather conditions without fault, and any performance limits under these extremes would be more apparent. Therefore, four distinct climates were referenced in order to evaluate the ABEs model performance; each simulated with the model oriented at 0º, 90º, 180º, and 270º from north. Each orientation was simulated during one extreme summer and one extreme winter week and a typical autumn week (Table 2). This provided 48 unique scenarios with 2640 occupied hours for evaluating the theoretical ABEs' performance which was compared against the baseline DOE-BM and OBM models.

Table 2: Selected Weather File Locations and TMY3 File Dates Used for Simulation Scenario Weeks

Climate Zone	Climate Type	TMY3 Weather file location	Winter extreme	Summer extreme	Autumn
2B	Hot-arid	Phoenix, Arizona	8-Dec to 14-Dec	3-Aug to 9-Aug	20-Oct to 26-Oct
2A	Hot-humid	Houston, Texas	15-Jan to 21-Jan	29-Jul to 4-Aug	26-Nov to 2-Dec
4C	Mixed–marine	Seattle, Washington	13-Jan to 19-Jan	24-Aug to 30-Aug	20-Oct to 26-Oct
5B	Cool-dry	Boulder, Colorado	8-Dec to 14-Dec	6-Jul to 12-Jul	29-Sep to 5-Oct

Climates and classifications from ASHRAE 90.1 Non-residential Building Standard (2007).

METHOD - DATA ANALYSIS

To identify each ERV variable's importance (VI) relative to energy use and occupant PPD values, a modified random forest (RF) algorithm, cforest (Hothorn, et al., 2012), was used that relies on unbiased conditional inference trees that allow for unbiased results compared to the CART trees initially used by Breiman and Cutler (Hothorn, et al., 2006, Strobl, et al., 2008, Strobl, et al., 2007). Use of RF analysis provided the means to identify each predictor variable's (p) importance on the tested dependent variables.

The RF regression method enables the identification of important variables that are highly related to the dependent variable for interpretation purposes. The original RF algorithm is a number, or 'forest', of binary CART decision trees that report the mode for the permuted data output by the trees, which then "vote" for the most popular class. These votes are then used to identify which variables are most significant within the data, given the dependent and independent variables used.

The following results were created using cforest in the 'party' package v1.0.2 (Hothorn, et al., 2012), an implementation of Breiman's random forest algorithm for the statistical program R v2.15.1 (R Development Core Team, 2012). Input values for the algorithm are based on recommended settings described by (Liaw and Wiener, 2002) where mtry = 5, trees = 500, and a random seed value = 8296 was used for the final data.

Not all scenarios provide sufficient population sizes for producing reliable mean square error (MSE) or R^2 values -- much less VI rankings. In larger populations, where multiple climates, orientations, or seasons are combined (n = 165), more reliable MSE or R^2 values are observed; whereas individual zones (n = 55) show significant MSE, R^2 variance, and VI rankings, and sometimes producing only random variation around zero. In addition, Variable Importance does change depending on the population the RF analysis has to draw from. With smaller data sets (e.g. individual occupied hour data), one dynamic variable may play a significant role under that particular simulation; however, within a larger dataset, that unique relationship may be of less importance than other relationships that are more consistent between simulation scenarios.

Because of the limited amount of simulated data, VI ranks that fell within 20% of the top ranking VI (VImax) are reported to identify larger relationships between the Adaptive, Environmental, and Energy Use variables, subject to the variable falling outside of the range considered as random fluctuation around zero bounded by |VImin|. VI variables discussed in the following sections meet the following criteria:

$$VI_n \geq Z - (Z \cdot 0.2)$$

Subject to:

$$|X| < VI_n \leq Z$$

Where:
VI_n = Variable of Importance ≥ the value of $Z - (Z \cdot 0.2)$
X = Value of the smallest Variable of Importance in a set
Z = Maximum Variable of Importance value in a set subject to the value $>|X|$

The VI values that are reported only suggest a strong relationship between the independent and dependent variable. Variable of Importance with a low, or no VI value, does not necessarily mean that a given independent variable does not have a measurable influence, rather that there are other independent valuables reporting stronger relationships with the dependent variable. The VI values are reported as a percentage (%) of the total VIs identified by the above equation.

DATA

Resulting energy performance in relationship to temperatures and the reference OBM and DOE models provide context for data that begins to depict the behavior of these adaptive envelope scenarios. Energy savings observed between the OBM and AEM scenarios vary in relation to weekly mean outdoor temperatures (Figure 20).

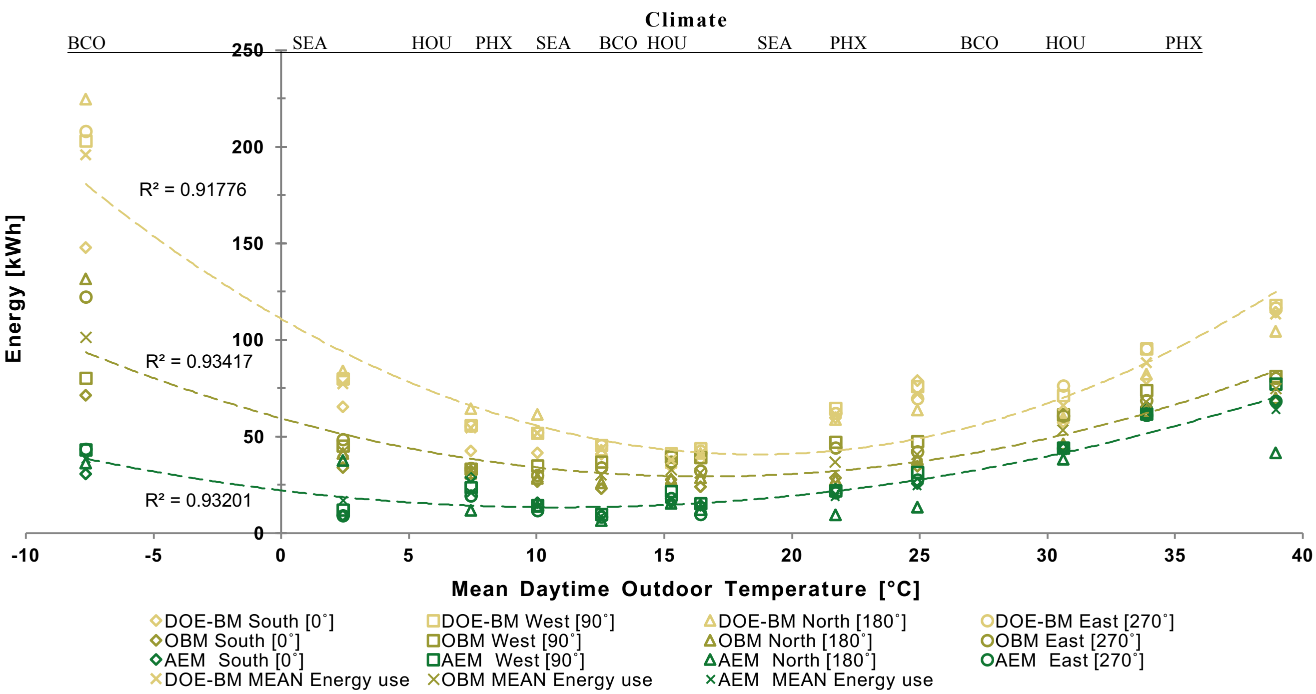

Figure 20: Total energy use during occupied hours separated by orientation. R2 values are calculated from the mean of the means.

Results from the RF analysis are displayed using radar graphs to illustrate the influence environmental stimuli VIs (temperature, solar, wind, etc.) have on the ERVs. Environmental stimuli VIs with greater influence on ERVs have greater values. From the RF analysis, data showing specific environmental stimuli are more likely to correspond to a reaction/adaptation by the adaptive envelope than others (Figure 21).

Using the full data set of occupied hours (n = 2460 hours), analysis indicates that direct solar radiation followed by outdoor temperature most often influence responses by the adaptive envelope. To some degree, these may be confounding variables as solar radiation does affect outdoor temperature, however direct solar gain can have significant energy input to a building while a low ambient outdoor temperature is present. Outdoor temperature appears to correspond with ABE behavior twice as often as indoor temperature. Solar altitude and azimuth are also confounding but inseparable at this level of analysis, reporting with equal VI values, but become independent of each other in later analysis. Wind speed and wind direction reporting as low VIs may be a result of the TMY3 weather data used since only individual weeks that captured extreme summer and winter and typical autumn temperatures were used for simulation so that it may not capture a complete picture of a region's climate.

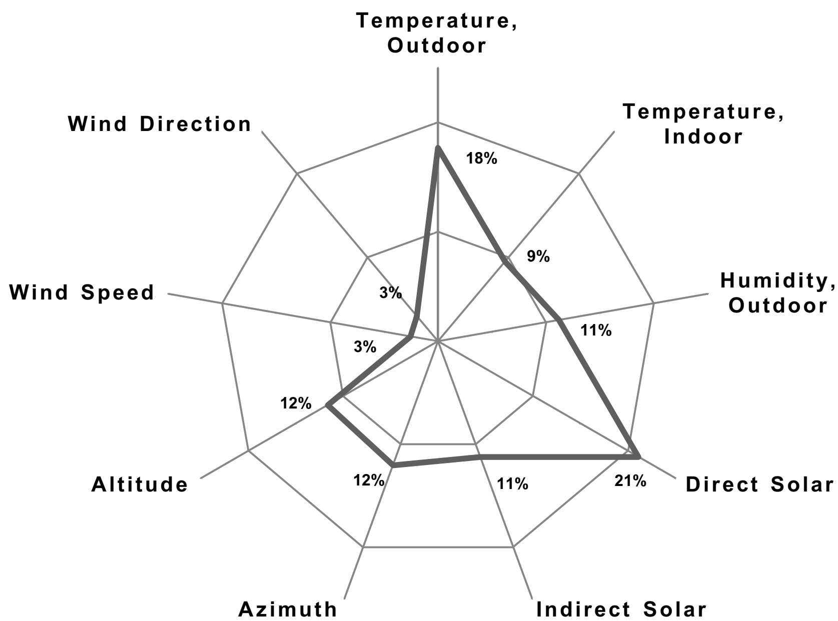

Figure 21: Distribution of environmental stimuli variables of importance reported for all adaptive responses during occupied hours.

When examining each ERV independently against environmental stimuli, changes made to Insulation and Form ERVs appear to be equally common in response to direct solar and outdoor temperature while changes in translucence are more likely to be due to the position of the sun and indirect solar (Figure 22). Climate specific adaptation behavior can be observed when ERVs are separated by climate (Figure 23). Climates with a greater diurnal swing tend to respond more to outdoor temperature (Phoenix, mean = 7°C swing; Boulder, mean= 11°C; Houston, mean= 9.3°C) in contrast to Seattle's moderate swing of 4.5°C (mean).

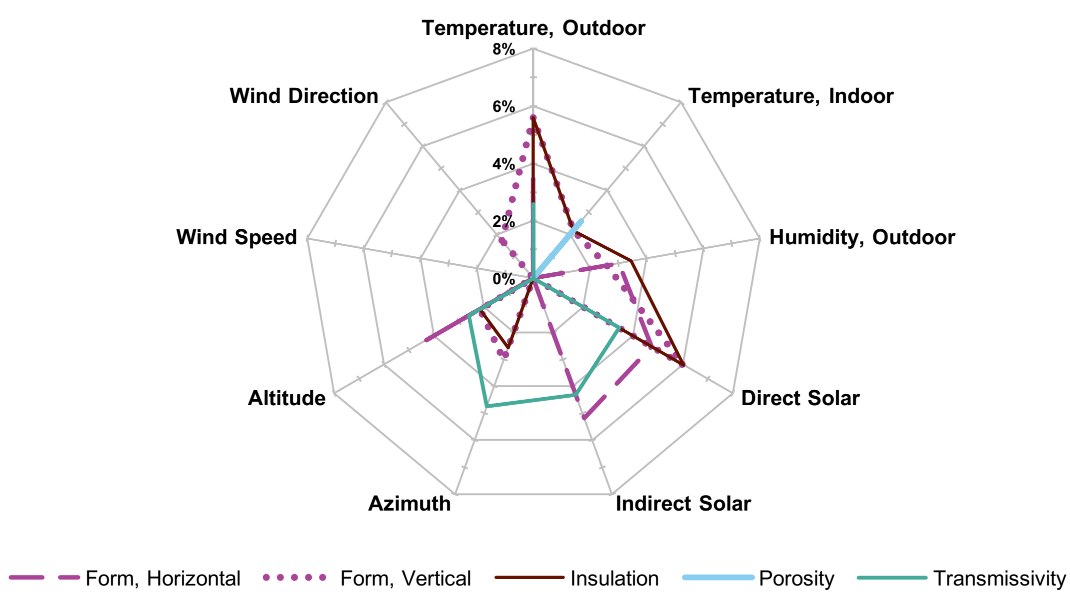

Figure 22: Percent of reporting variables of importance between adaptive responses and environmental stimuli sorted by adaptive response.

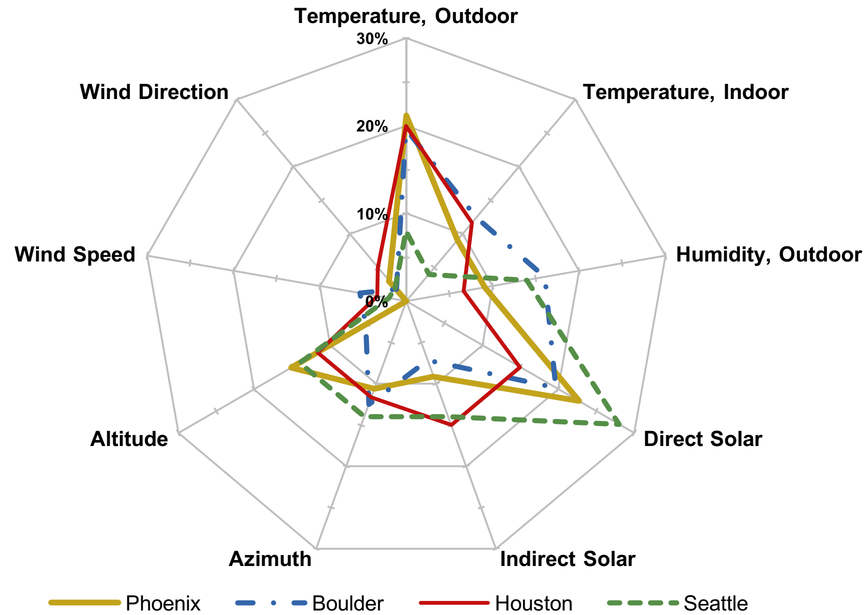

Figure 23: Percent of reporting variables of importance between adaptive responses and environmental stimuli sorted by climate.

Where the data is categorized by ERV and climate against environmental stimuli, the patterns are relatively similar in VI values (Figure 21, Figure 22, and Figure 23). However, significant differences in VI values are observed when data for the RF analysis is categorized by orientation (Figure 24) and by seasons (Figure 25). Although outdoor temperature and direct solar remain significant VIs, solar altitude and azimuth are seen to be independent in this organization of the data, revealing east and west orientations responding to solar azimuth as a significant VI while solar altitude is seen as a VI for south-facing, and to a lesser extent west-facing ABS (Figure 25).

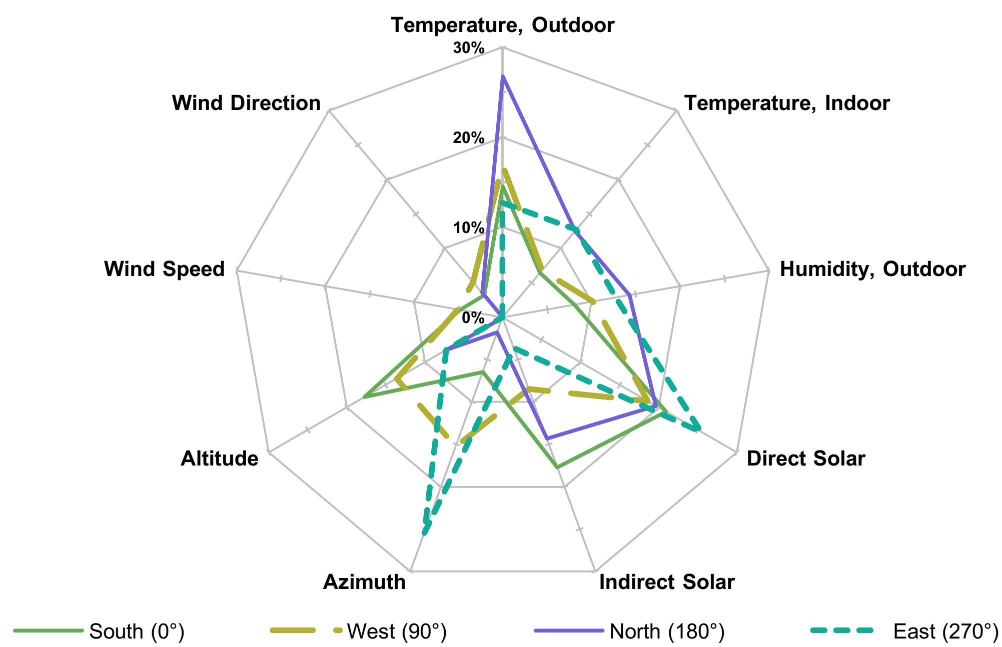

Figure 24: Percent of reporting variables of importance between adaptive responses and environmental stimuli sorted by orientation.

With data categorized by season, extreme VI relationships emerge; extreme summer week scenarios tend towards the outdoor temperatures and solar altitude VIs. Typical autumn week's ERVs tend to respond equally to changes in outdoor temperature, humidity and indoor temperature VIs (Figure 25). While direct solar remains a significant VI for all orientations (refer to Figure 24), winter week scenarios see a significant jump in VI for direct solar, suggesting that the ABE models winter behavior is significantly tied to availability and intensity of direct solar-- much more than any other single stimuli. This behavior can be observed in the Boulder Colorado winter extreme week scenario, where hours with direct solar are available see an immediate response by four of the five ERVs (Figure 26). As the outdoor temperature rises later in the week, more activity is observed corresponding with changes in the outdoor weather, most notably when direct solar is available and passive heating is possible.

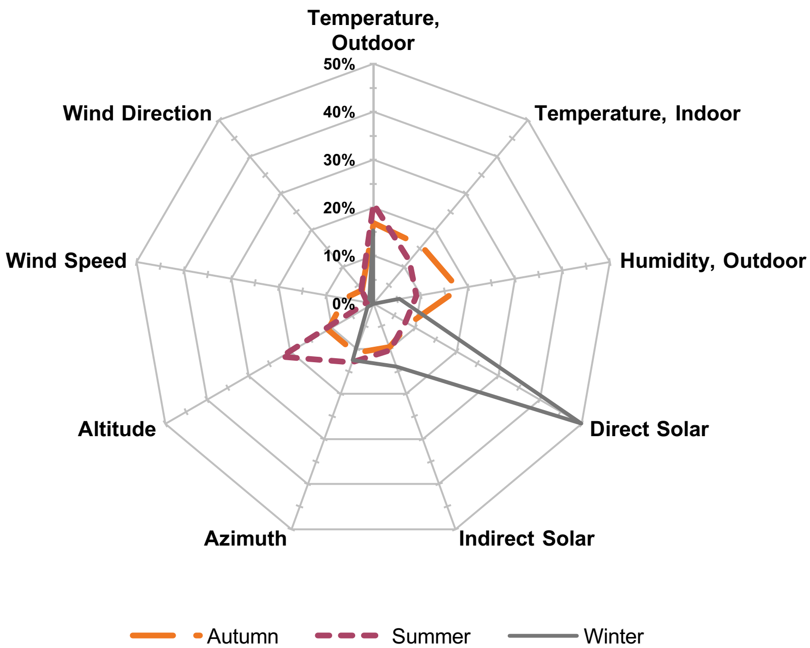

Figure 25: Percent of reporting variables of importance between adaptive responses and environmental stimuli sorted by season.

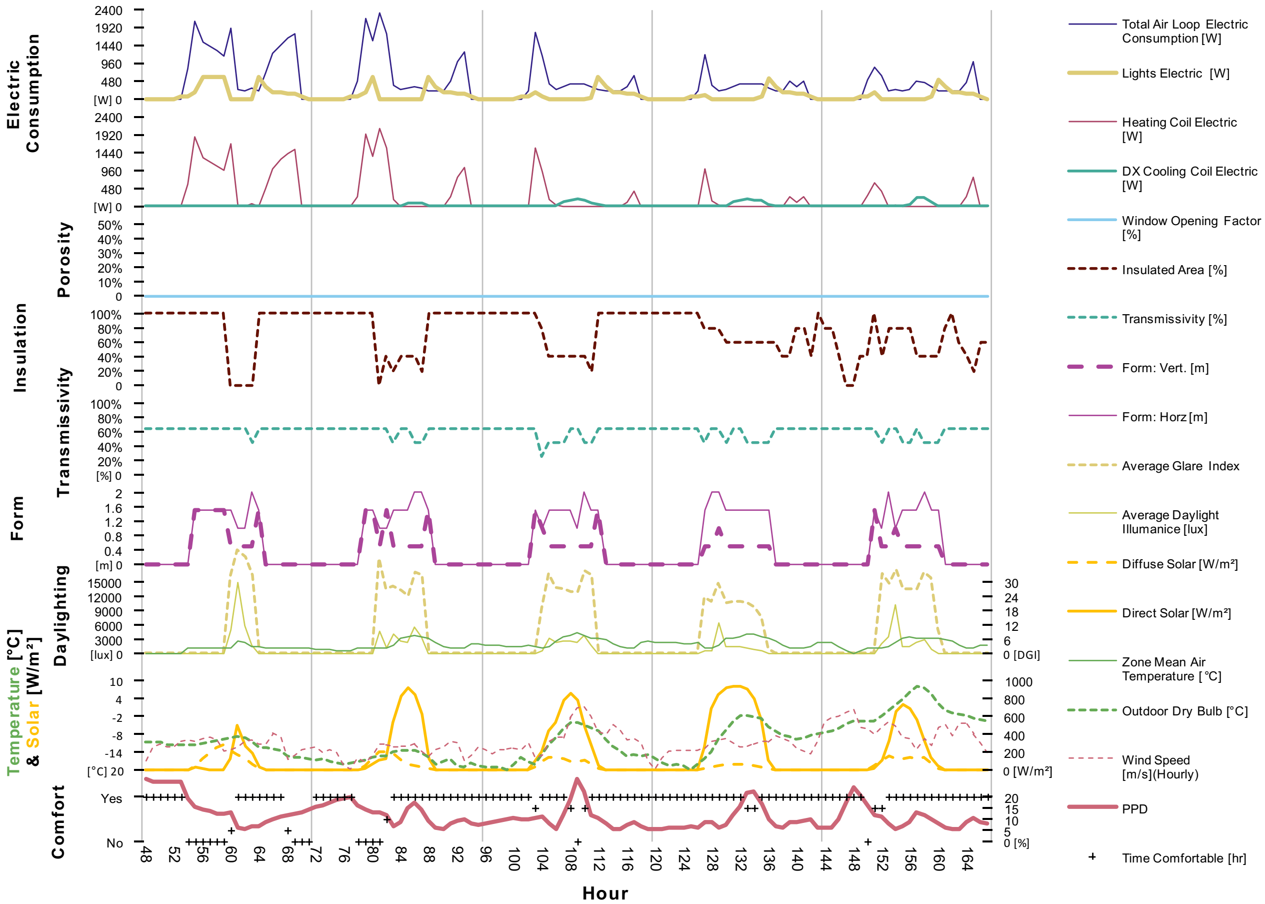

Figure 26: Hourly ABE performance illustrating energy use and occupant thermal comfort in relation to outdoor weather conditions. Data from Boulder, Colorado winter extreme week scenario.

EXPLANATION

Within the context of this study, the data describes behavior of an adaptable building envelope using adaptations to respond to environmental stimuli. In a given context, the ABE models may depend on certain environmental response variables more than others (Figure 22); that these adaptive responses cannot be generalized without considering climate, season, or orientation (Figure 23, Figure 24, and Figure 25); and that of the environmental stimuli examined, direct solar and outdoor temperature have the most significant impact on influencing the envelope's behavior.

This data, although not conclusive due to the limits of the study, suggest that some ERVs are more valuable in creating a desired energy flow through the building envelope than other adaptive responses under specific conditions, while other ERVs' effectiveness may vary significantly between scenarios or be very specific in their application as is observed with porosity in relation to indoor temperature (Figure 22). Of the environmental stimuli examined, direct solar and outdoor temperatures tend to have the strongest influence on ABEs' behavior; while individually, this relationship between environmental stimuli and adaptive response variables can differ significantly between climate, orientation, and season, characterizing unique behavior for each scenario. Other common envelope behavior reveals wind as a weak VI while relatively equal ERV are observed relating to solar geometry, humidity and indoor temperatures.

From these simulation scenarios, a one-size-fits-all adaptive envelope design appears impractical. Logically, these findings will vary between the effectiveness of the ERV materials used, actual building geometry, occupant behavior and needs, and internal loads. If such an approach were executed in construction, the typical ABE would possess rarely used adaptive responses under some climate conditions, which could translate into increased construction costs with a long payback period. While in contrast, another ABE design that possesses a selective set of effective adaptive responses would conceivably result in a better cost-to-payback ratio.

CONCLUSION AND FUTURE WORK

This study explored the behavior of a theoretical adaptive envelope capability to reduce energy use of a small office thermal zone by means of modifying its form, insulation, porosity, and transmittance to adapt to hourly changes in the weather, and how this behavior differs between climate, orientation, and season. Resulting data demonstrates that the simulated adaptive envelope behavior varies, at times significantly, between climates, orientations, and seasons, and that the preferred adaptive response differs between scenarios. Although this evidence suggests that a single adaptive envelope design would not likely be a cost effective response for all buildings in the near future, understanding how the envelope's behavior changes between seasons and building orientation can guide designers towards finding the best adaptive envelope solution for a given project.

This interesting but incomplete image of adaptive envelope behavior needs to be expanded with additional work examining insulation technologies and materials, such as dynamic heat flux and thermal storage, alternative ventilation strategies, changes in occupant behavior and needs, and internal loads. Future work will need to address multi-zonal scenarios and exploration of how such envelopes may work when simultaneously dealing with multiple orientations and objective functions. Eventually, this line of research will need to manifest as built experimental systems reacting to real world conditions to refine predictions regarding system installation, performance, and maintenance costs.

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REFERENCES

Baker, Nick. "The Irritable Occupant: Recent Developments in Thermal Comfort Theory." *Architectural Research Quarterly* 2, no. 2 (1996): 84-90.

Davies, M. "A Wall for All Seasons." *RIBA Journal* 88, no. 2 (1981): 4.

de Boer, Bart, G. J. an Ruijg, L. Bakker, W. Kornaat, L. Zonneveldt, S. Kurvers, N. Alders, A. Raue, J. L. M. Hensen, R. G. C. M. Loonen, and M. Trcka. "Energy Saving Potential of Climate Adaptive Building Shells - Inverse Modelling of Optimal Thermal and Visual Behaviour." In *International Adaptive Architecture Conference*. London, 2011.

de Boer, Bart, Gerrit Jan Ruijg, Roel Loonen, Marija Trčka, Jan Hensen, and Wim Kornaat. "Climate Adaptive Building Shells for the Future – Optimization with an Inverse Modelling Approach." In *ECEEE 2011 Summer Study, Energy efficiency first: The foundation of a low-carbon society*, edited by Therese Lindström and Lisa Nilsson, 1413–22. Belambra Presqu'île de Giens, France: ABA Intercopy, Stockholm, Sweden, 2010.

Deru, M., K. Field, D. Studer, K. Benne, B. Griffith, P. Torcellini, M. Halverson, D. Winiarski, B. Liu, M. Rosenberg, J. Huang, M. Yazdanian, and Drury Crawley. "U.S. Department of Energy Commercial Reference Building Models of the National Building Stock." 118. Golden, CO: National Renewable Energy Laboratory, 2011.

Erickson, James. "Adaptive Envelope: Reducing Energy without Sacrificing Comfort " In *PLEA 2016 - Cities, Buildings, People: Towards Regenerative Environments, Proceedings of the 32nd International Conference on Passive and Low Energy Architecture*, edited by Pablo La Roche and Marc Schiler, 35 - 43. Los Angeles, California: PLEA 2016 Los Angeles, 2016.

Erickson, James. "Envelope as Climate Negotiator: Evaluating Adaptive Building Envelope's Capacity to Moderate Indoor Climate and Energy." Doctoral Dissertation, Arizona State University, 2013.

Erickson, James. "Reactive Building Envelopes: Optimizing Indoor Comfort through Adaptable Architecture." In *EDRA38*, edited by Janice M. Bissell, 194. Sacramento, California, 2007.

Favoino, Fabio, Mauro Overend, and Qian Jin. "The Optimal Thermo-Optical Properties and Energy Saving Potential of Adaptive Glazing Technologies." *Applied Energy* 156 (2015): 1-15.

Hooke, Robert, and T. A. Jeeves. "'Direct Search' Solution of Numerical and Statistical Problems." *Journal of the Association for Computing Machinery* 8, no. 2 (1961): 212-29.

A Laboratory for Recursive Partytioning Version 1.0-2. CRAN (http://cran.r-project.org/).

Hothorn, Torsten, Peter Bühlmann, Sandrine Dudoit, Annette Molinaro, and Mark J. Van Der Laan. "Survival Ensembles." *Biostatistics* 7, no. 3 (2006): 355-73.

Humphreys, M.A., and J.F. Nicol. "Understanding the Adaptive Approach to Thermal Comfort." *ASHRAE Transactions* 104 (1998).

Jin, Qian, Fabio Favoino, and Mauro Overend. "The Potential Opaque Adaptive Façades for Office Buildings in a Temperate Climate." In *Proceedings of BS2015: 14th Conference of International Building Performance Simulation Association*, 98 - 105. Hyderabad, India, 2015.

Kasinalis, C., R. Loonen, D. Cóstola, and J. L. M. Hensen. "Framework for Assessing the Performance Potential of Seasonally

Adaptable Facades Using Multi-Objective Optimization." *Energy and Buildings* 79 (2014): 106-13.
LBNL (Lawrence Berkeley National Laboratory). "Energyplus V6.0." U.S. Department of Energy, 2010.
Liaw, Andy, and Matthew Wiener. "Classification and Regression by Randomforest." *R News* 2, no. 3 (2002): 5.
Loonen, R., M. Trčka, D. Cóstola, and J. Hensen. "Performance Simulation of Climate Adaptive Building Shells - Smart Energy Glass as a Case Study." In *Proceedings of the 8th International conference on System Simulation in Buildings*, edited by V. Lemort, P. André and S. Bertagnolio, 1-19. Liege, Belgium, 2010.
Loonen, Roel C.G.M., Fabio Favoino, Jan L.M. Hensen, and Mauro Overen. "Review of Current Status, Requirements and Opportunities for Building Performance Simulationof Adaptive Facades." *Journal of Building Performance Simulation* (2016).
Olewnik, Andrew, Trevor Brauen, Scott Ferguson, and Kemper Lewis. "A Framework for Flexible Systems and Its Implementation in Multiattribute Decision Making." *Journal of Mechanical Design* 126, no. 3 (2003): 412-19.
Olgyay, Victor. *Design with Climate : Bioclimatic Approach to Architectural Regionalism*. Princeton, New Jersey: Princeton University Press, 1963.
R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. http://www.R-project.org/, Vienna, Austria.
Strobl, Carolin, Anne-Laure Boulesteix, Thomas Kneib, Thomas Augustin, and Achim Zeileis. "Conditional Variable Importance for Random Forests." *BMC Bioinformatics* 9, no. 1 (2008): 307.
Strobl, Carolin, Anne-Laure Boulesteix, Achim Zeileis, and Torsten Hothorn. "Bias in Random Forest Variable Importance Measures: Illustrations, Sources and a Solution." *BMC Bioinformatics* 8, no. 1 (2007): 25.
Wetter, Michael. "Genopt, Generic Optimization Program." Berkeley, CA: Lawrence Berkeley National Laboratory, 2009.
Wetter, Michael. *Genopt, Generic Optimization Program, User Manual, Version 3.0.0*. Berkeley, CA: Lawrence Berkeley National Laboratory, 2009.
Zhai, Zhiqiang, and Jonathan M. Previtali. "Ancient Vernacular Architecture: Characteristics Categorization and Energy Performance Evaluation." *Energy and Buildings* 42, no. 3 (2010): 357-65.

ADAPTABLE FAÇADE

A case study of high performance system in relation to the human condition

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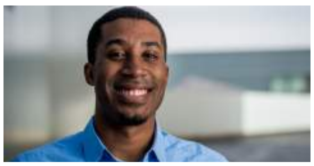

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ABSTRACT

The speculative nature of a downtown developer project presented an opportunity to explore how dynamic building components help maximize marketability through performance. The spec building utilizes active façade elements that adapt to a wide range of future tenants' personal comfort levels; while optimizing energy performance based on real-time environmental conditions. The imperative elements consist of a motorized shading system that protects the curtain walls and glass garage doors that facilitate natural cross-ventilation. The doors are arranged in pairs on the East and West Facades and open to exterior walkways and balconies. The sunshades are tied to the BMS system and automatically adjust during different times of the day/year to optimize solar performance. A few scenarios are described to illustrate the principal methods of the active systems. A Tech company occupies a suit and takes full advantage of the garage doors and operable windows to promote cross ventilation and connect employees to the energy of the bustling street, fostering creativity. They have user control to override the building automation to harvest more daylight throughout the day. The building controls optimize performance each evening to purge the space with cool outside air and recharge the thermal mass. A tenant suite on the southwest corner applies a more traditional office layout and relies on the mechanically operated exterior shades to provide optimal daylight while eliminating glare and balancing heat gain. In the next 10 years, the tech company grows and occupies the entire building due to the success of their façade optimization app. This presentation will show how the app was able to balance daylight with heat gain for different tasks, light levels, and cooling conditions by using dynamic shading. The spec building influences future developments of its urban context. This exploration demonstrates that considering facades as stagnate structures limits potential. Recognizing them as an extension of the user and dynamically integrated

with the environment, provides us with buildings that have a long life and a loose fit. This reinforces the importance of human centered design and how adaptable facades can help address the complexities of human nature.

KEYWORDS

Adaptive, Responsive, Double-Skin, Dual-Purpose, Dynamic, Smart, Daylighting

INTRODUCTION

The speculative office building will be the first completed of a 5 building, 1,000,000+ sf development. It's located in the East Village of downtown San Diego, the development will serve as a tech employment hub that strives to create a sustainable place that connects the downtown district and urban neighborhood, while fostering walkable and healthy lifestyles. The speculative office building has been designed to achieve a LEED Platinum certification and Net Zero office space. The site, however, introduced challenges in realizing the building's sustainable goals:

- Massing - the site is located on a partial city block that is oriented North/South, maximizing the East and West facades (rather than the North and South facades) to solar exposure.
- Mid-city block façade constraints – the urban environment created situations where sets back from adjacent property lines needed to be minimized in order to maximize rentable square footage. California Building Code puts restrictions on allowable open area for glazing according to set back distance. The 150' long East façade (3' set back) was restricted to 15% allowable open area, see table below in Figure 1. Daylight and natural ventilation strategies would need additional open area to be effective.

TABLE 705.8
MAXIMUM AREA OF EXTERIOR WALL OPENINGS BASED ON FIRE SEPARATION DISTANCE AND DEGREE OF OPENING PROTECTION

FIRE SEPARATION DISTANCE (feet)	DEGREE OF OPENING PROTECTION	ALLOWABLE AREA[a]
0 to less than 3[b, c]	Unprotected, Nonsprinklered (UP, NS)	Not Permitted
	Unprotected, Sprinklered (UP, S)[i]	Not Permitted
	Protected (P)	Not Permitted
3 to less than 5[d, e]	Unprotected, Nonsprinklered (UP, NS)	Not Permitted
	Unprotected, Sprinklered (UP, S)[i]	15%
	Protected (P)	15%
5 to less than 10[e, f, j]	Unprotected, Nonsprinklered (UP, NS)	10%[h]
	Unprotected, Sprinklered (UP, S)[i]	25%
	Protected (P)	25%
10 to less than 15[e, f, g]	Unprotected, Nonsprinklered (UP, NS)	15%[h]
	Unprotected, Sprinklered (UP, S)[i]	45%
	Protected (P)	45%
15 to less than 20[f, g]	Unprotected, Nonsprinklered (UP, NS)	25%
	Unprotected, Sprinklered (UP, S)[i]	75%
	Protected (P)	75%
20 to less than 25[f, g]	Unprotected, Nonsprinklered (UP, NS)	45%
	Unprotected, Sprinklered (UP, S)[i]	No Limit
	Protected (P)	No Limit
25 to less than 30[f, g]	Unprotected, Nonsprinklered (UP, NS)	70%
	Unprotected, Sprinklered (UP, S)[i]	No Limit
	Protected (P)	No Limit
30 or greater	Unprotected, Nonsprinklered (UP, NS)	No Limit
	Unprotected, Sprinklered (UP, S)[i]	Not Required
	Protected (P)	Not Required

Figure 1 is a table from California Building Code for reference 705.8.1 Allowable area of opening. per Table 705.8

How can these limitations be addressed with integrated solutions that create opportunities for sustainability and enhance human experience? Additional challenges are presented by the nature of the project. For a 6 story speculative office building, this means designing for an undefined end user. When high performance is a goal, how can a façade be optimized if it is unclear how the space will be utilized? Basic principles of optimizing high performing spaces for natural ventilation or daylight for instance, start with an understanding of the occupancy, use, and hours of operation. When these factors are unknown and possibly change multiple times over the buildings life span, a certain amount of flexibility must be incorporated to achieve this. How can this type of flexibility be planned for in the building skin? The fact that this is a developer driven project adds a layer of complication and poses more questions on how sustainable strategies can be implemented when the client doesn't see a direct return in their investment from energy savings. Can sustainability be leveraged as a marketing tool to assist a developer in maximizing their return? These are questions that most architects and engineers have been faced with, and this case study will demonstrate how one project addressed them.

BACKGROUND

The relationship between exterior glazing and shading has been a widely studied topic in relation to high performance design. Full height curtain wall systems are desired by owners and architects for aesthetic and performance purposes. It allows for deep penetration of daylight into interior spaces and unobstructed views out, however, this also creates increased opportunity for solar heat gain. Solar heat gain creates an uncomfortable interior environment, increased cooling loads and reduces the effectiveness of any natural ventilation strategies that have been implemented. An efficient shading strategy strives to minimize solar heat gain while maintaining significant natural daylight in the space. San Diego's low latitude makes it difficult to accommodate shading for the low winter sun angles without negatively impacting the daylight during the summer when the sun angles are extremely high. In past studies, the South and West glazing were analyzed for façade optimization, it was concluded that a combination of fixed horizontal and vertical fins block direct sun for the greatest amount of time throughout the year. The shading system was only effective about 70% of the time. The South façade experienced glare in the winter months while the West façade's vertical fins proved to be less effective during the summer. Other shading strategies, such as roller shades, have been studies and proven to eliminate glare and prevent solar heat gain 100% of the time depending on the fabric selection. However, the daylight was reduced to the point where artificial lighting was required to provide adequate light levels to the space.

Light levels as they relate to space type and regulatory requirements were important to understand as a part of this case study. The Illuminating Engineering Society recommends average maintained foot-candles depending on the use of the space. For example, a break room requires an average of 15 FC while an open office requires an average of 30 FC. At the same time, the break room will also be more forgiving to the occasional glare on the glazing than the open office with a primarily computer based workflow, where glare could impair the users' ability to view their screens. An adaptable façade seemed to be a viable option and serve a dual purpose; responding to environmental constraints while providing flexibility for a wide variety of programmatic possibilities.

METHOD

THE DOUBLE SKIN, SUSTAINABLE DESIGN COMPONETS AND PERFORMANCE

The facades were broken down to address 5 conditions:

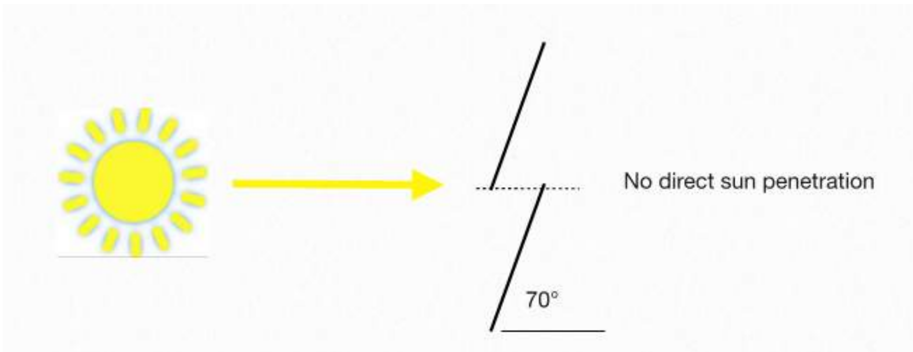
- South – Street front façade required maximum views out. The full height glazing that was implemented on this façade required shading to achieve its performance goals
- West – Street front façade required maximum views out. The full height glazing is protected by 80" horizontal protrusion that also serves as an exterior corridor. Additional shading is need for afternoon solar mitigation.
- North – Property line façade. Outdoor balcony space was programed to allow for appropriate setback dimension for maximum glazing
- East – Property line façade. A "light well" strategy was implemented to allow for more glazing and operable components to create cross-natural ventilation and even distribution of daylight
- Roof – Reflective roof to reduce heat gain with photovoltaic panels to offset office energy consumption to reach net zero goal

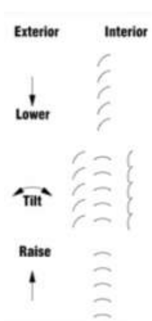
It was important to maximize view out on the street front façades. This resulted in full height curtain wall systems on the majority of the South and West facades.

Figure 2 shows a view of the speculative office building from the northwest (top) and the Southwest (bottom). This view shows the sliding operable panels and the exterior venetian blinds. (Drawing by Christianne Jordan)

An effective shading system was needed to protect the glazing from solar heat gain. The south shading method selected on the South and small portion of the West façade was exterior venetian blinds. These two facades will face the most extreme seasonal conditions, and the advantage the operable slats have over other shading systems is their responsiveness to changing solar conditions. The smart shading system is motorized, automated, and tied to the building management system. The sun tracking control system on the roof constantly surveys the position of the sun and adjusts the angle of the slat to prevent direct sunlight from hitting the glazing. This aspect is key in its ability to protect against solar heat gain and will protect the glass 100% of the time year round.

Each slat is made of perforated aluminum, so even in the closed position, views out can still be achieved. Figure 3 shows the various position of the slat and the horizontal cut off design that eliminates direct sun penetration, but also never completely closes which allows diffused light into the space.





Blind position	March 21	June 21	December 21
Retracted	Sunrise	Sunrise	Sunrise
Slats horizontal	10.15am	11.15am	8.45am
Slats @ 17.5°	2.00pm	4.45pm	11.15am
Slats @ 35.0°	2.30pm	6.00pm	12.00pm
Slats @ 52.5°	3.00pm	7.00pm	12.30pm
Slats @ 70.0°	3.30pm	7.15pm	1.30pm

Figure 3 shows the horizontal cut off design of the venetian blinds (Top) and the various positions of the slat to optimize shading and daylight (Bottom). (Diagram by Richard Wilson with Draper Inc)

The remainder of the West façade glazing implements an alternative active shading strategy. The glazing is already partially protected by an exterior walkway that extends 80” past the face of the glass on each level. The overhang provides adequate shading until the afternoon, when the direct western sunlight hits the glazing. Additional shading was required to mitigate glare and solar heat gain.

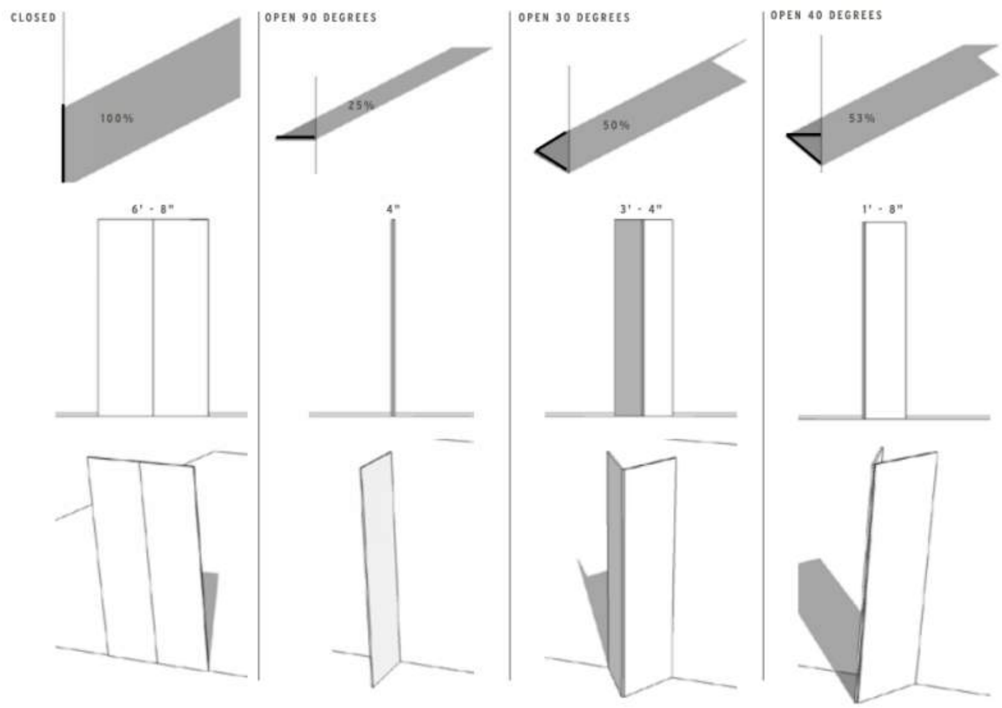


Figure 4 shows a series of panel iterations studied for west façade shading. (Diagram by Christianne Jordan)

Figure 4 shows a number of shading iterations that were tested to find the balance between performance and feasibility for the client. Bi-folding panels that are flat when opened and create a vertical fin when closed provided sufficient protection, but exceeded the client's budget. Fixed vertical fins were also examined as a more feasible option. Ultimately, the interdisciplinary team determined that the most feasible system would be a series of sliding perforated aluminum panels mounted to the edge of the slab along each exterior walkway shown below in Figure 5. The panels will operate manually and the users can slide them along a continuous 80' track that extends the length of the west glazing. Locating them to shade spaces that best fit their use.

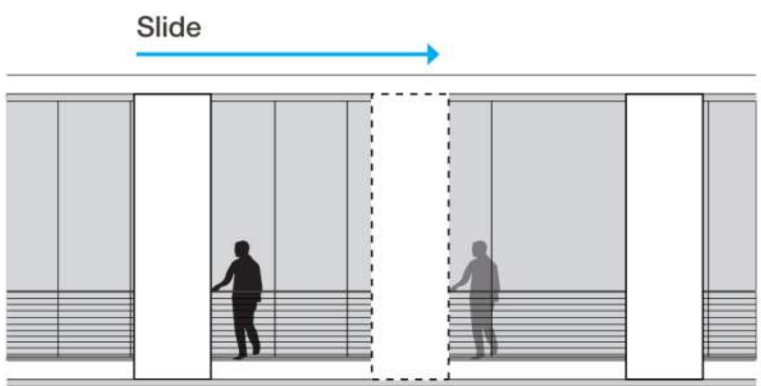


Figure 5 shows a series of panel iterations studied for west façade shading. (Diagram by Christianne Jordan)

The façades along the mid-city block property line faced a different challenge. California Building Code, shown in Figure 1, has stringent requirements for exterior wall's percentage of openness and fire rating depending on their distance from the property line. It was important to maximize the floor plate square footage, to maximize the owners return. This can be a challenge in an urban context and with dense city blocks, where setting back from a property line may be ideal to allow for relief from a monolithically solid wall with glazing and windows, but not ideal for its impact on rentable square footage.

The East façade had to address this issue. The strategy was to set the wall back 3’ from the property line for constructability purposes, but also to allow for glazing to turn the Southeast corner 14’. This provided adequate daylight for the southeast corner of the building, but how will daylight be distributed along the 150’ long façade that had 0% allowable open area? This was achieved by creating a 10’ wide “light well” for each potential office suite. The light wells protrude out from the exterior wall to the property line and are protected with a fire-rated wall with a glass sectional overhead door directly behind it, shown in Figure 6. The sides of the light wells are open to air, allowing north and south sunlight enter and bounce into the space. The light well strategy allowed for a balance of day light distribution through the space but also enable for cross-natural ventilation.

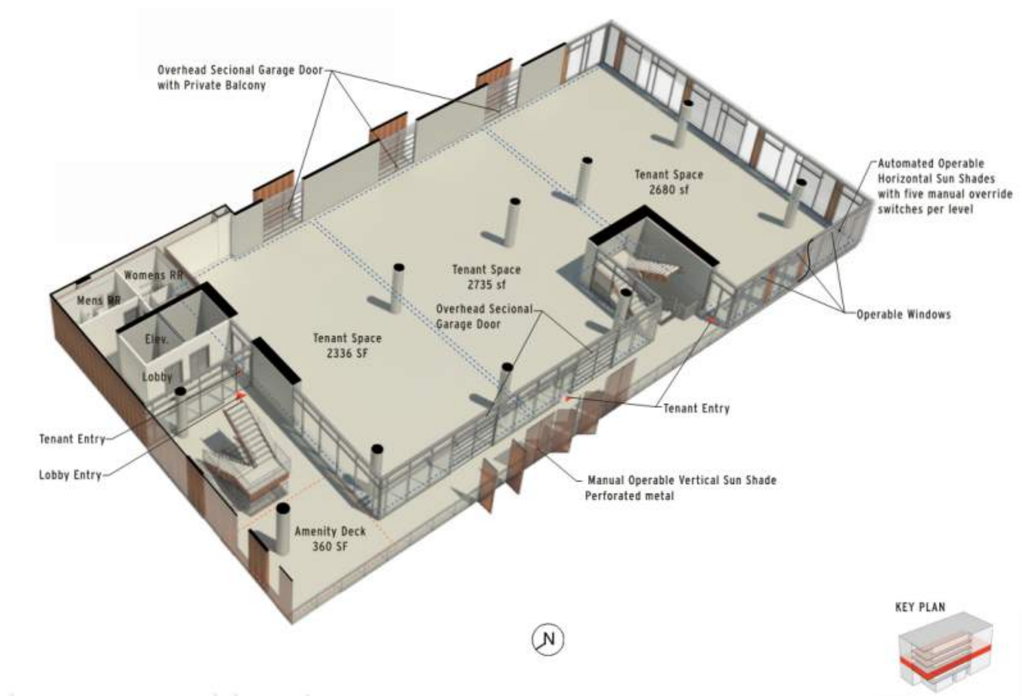


Figure 6 shows a sectional plan taken at the 3rd level with all sustainable components called out. (Diagram by Christianne Jordan)

The inner layer of the adaptable, double façade consists of an insulated tempered glazing systems that incorporates a series of operable windows and sectional overhead doors to facilitate cross-natural ventilation. These operable portions of the glazing system were designed to provide natural ventilation for each potential division of office suite. San Diego’s west prevailing winds bring air in through the west façade’s operable windows and doors and out through the east façade’s light well assembly. The operable openings at opposite sides of the building induced cross ventilation (Figure 7). When the building in not in natural ventilation mode, it uses a Variable Refrigerant Flow (VRF) mechanical system, which utilize efficient, inverter-driven compressors that rival the efficiency of chilled water systems while being a more economical approach for smaller projects. They distribute heating and cooling to local fan coil units (FCUs) through refrigerant, and can even trade heat between zones when the heat recovery option is specified. When coupled with a dedicated outside air system (DOAS), pre-conditioned ventilation air is provided to FCUs by exchanging heat with the code-required exhaust before it leaves the building. This allows the heating and cooling load of this ventilation air to be removed from the FCU itself, further saving energy use compared to traditional HVAC systems. The building automation system (BAS) allows the control of mixed-mode ventilation. The system monitors heating and cooling load within the building and compares with real-time outside air conditions to decide between mechanical or natural ventilation modes. When a zone is in cooling mode and outside air temperature is cool enough, natural ventilation mode is enabled which allows windows to open and mechanical systems to be turned off. When in heating mode or when outside air temperatures are too high for passive cooling, the mechanical systems provide heating or cooling and ventilation through the DOAS system.

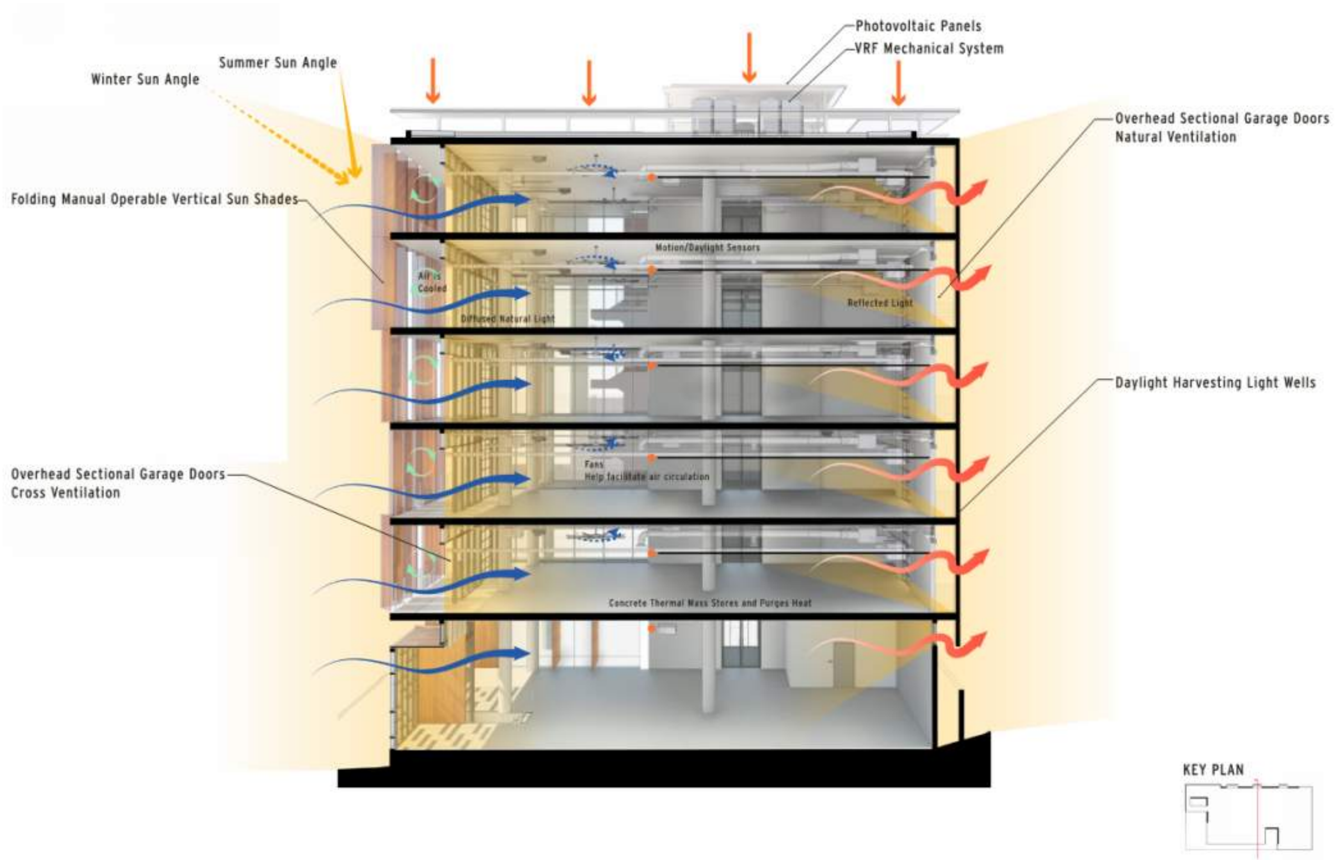


Figure 7 demonstrates how cross ventilation and daylight will penetrate the space. (Diagram by Christianne Jordan)

ADAPTABILITY AND DUAL-PURPOSED

Incorporating adaptability into the façade's sustainable components means it can respond to the most extreme cases throughout the year, making each strategy even more impactful to the building performance. The components of the skin were design with dual purposes and adaptability to give them ultimate value. The smart shading systems provide adaptable protection to adjust to the seasonal differences of summer and winter sun angles, but also offers flexibility to the users, giving them the ability to control the amount of daylight let into their space. On a summer day when the sun angle is high, the exterior venetian blinds adjust to the flat position, vs in the winter when the blades will tilt to a suitable degree to block direct sunlight on the glass. The occupants have user control and can override the system to adapt to their specific needs. When tenants change over the buildings life span, the shades will still be effective and efficient since they can adjust to the amount of light levels let in a space depending on the tenant. This is also true for the manually operable sliding panels on the West façade. They cover about 60% of the exposed west glazing along the exterior walkway and can be arranged by the users to provide shading where it best suits them. For instance, the panels can be arranged to shade an area that has work stations and pushed aside in areas that would function better with higher daylight levels (such as artist studios or breakrooms).

The East light wells also serve a dual purpose. They bring in natural daylight and facilitate cross ventilation, but also can be populated by the users as a private balcony. The private balconies were created as a result of optimizing the light wells. Daylight studies proved that extending the slabs out to support the firewall panel provided deeper penetration of light into the space, as opposed to supporting them with steel tubes. The concrete floor acts as a light shelf in this scenario and also provided the benefit of adding rentable space to the building.

DATA

DAYLIGHTING

The building has a high window-to-wall ratio of 55% and glazing with a high visible lighting transmittance (VLT) value of 70% and 62% on the west and south façades respectively. The smart-shading system provides sufficient daylighting to the space while maintaining visual comfort for the occupants. The lighting control system which is comprised of a photo sensor placed inside the space. This will measure the amount of daylight entering the space. The control system compares the measured light to a light setpoint (based on the IES recommendations described above) and decides if the natural daylight is sufficient or if more light is needed. If more light is needed, the electric lighting system will provide supplemental lighting to meet the setpoint. This reduces lighting energy consumption, especially during peak hours shown in figure 9. To evaluate the daylighting performance, IES VE was used to simulate the proposed design compared against the ASHRAE 90.1 baseline design. As shown in figure 8, the proposed design allows daylight to penetrate the office space on all side and with fewer areas of low light levels. The daylight is adequately distributed so that each tenant space will receive natural daylight on at least two exterior faces.

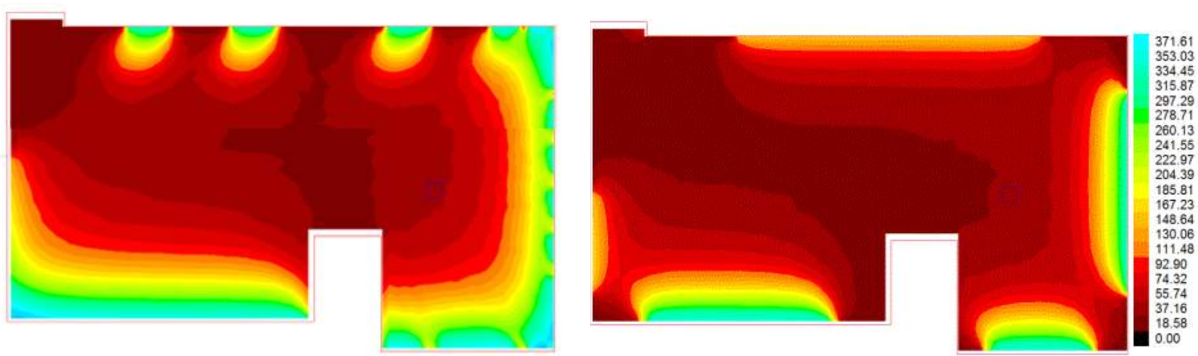


Figure 8: Daylighting performance; Left: Proposed, Right: Baseline (Diagram by Greg Collins).

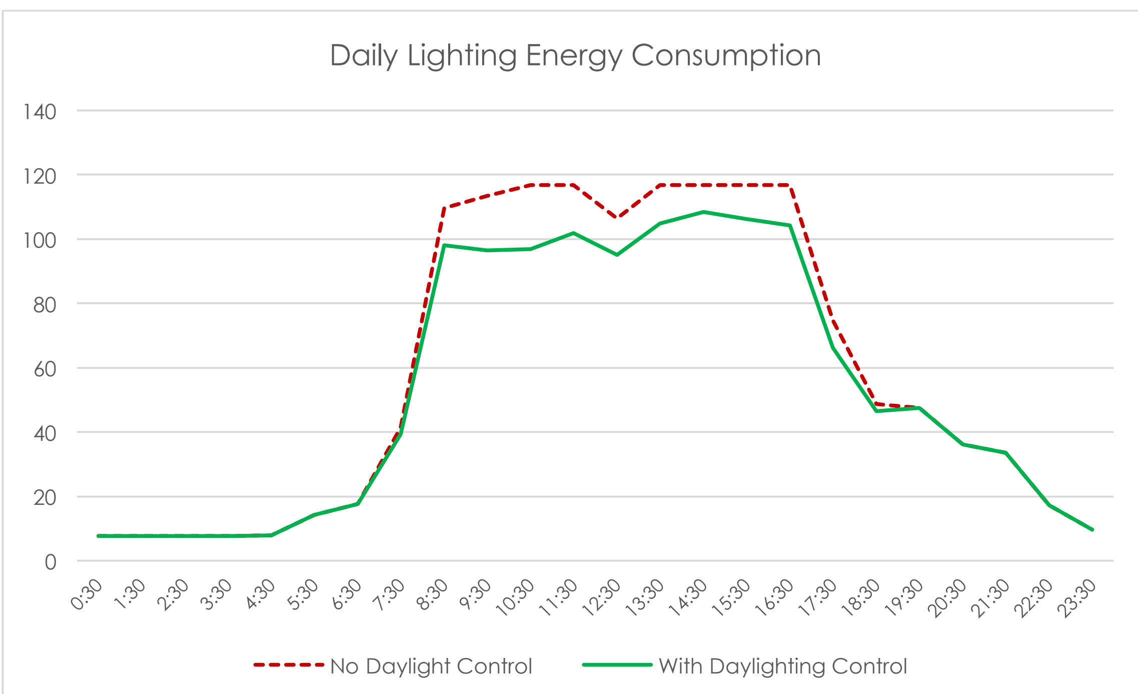


Figure 9: Lighting and energy reduction due to Daylighting (Diagram by Greg Collins)

NATURAL VENTILATION

The smart-shading system, consisting of perforated shading devices on the west façade and automatically controlled blinds on the south, mitigates the high window-to-wall ratio and helps reduce the solar heat gain. It also precools outside air before entering the building through natural ventilation. This means natural ventilation can be implemented more often and maintain thermal comfort for the occupants. Figure 10 shows interior room temperature with the recommended thermal comfort zone and illustrates when it is achieved with and without natural ventilation. Figure 11 illustrates annual cooling load demands with natural ventilation and without natural ventilation. Cooling requirements are reduced by nearly 60% with natural ventilation

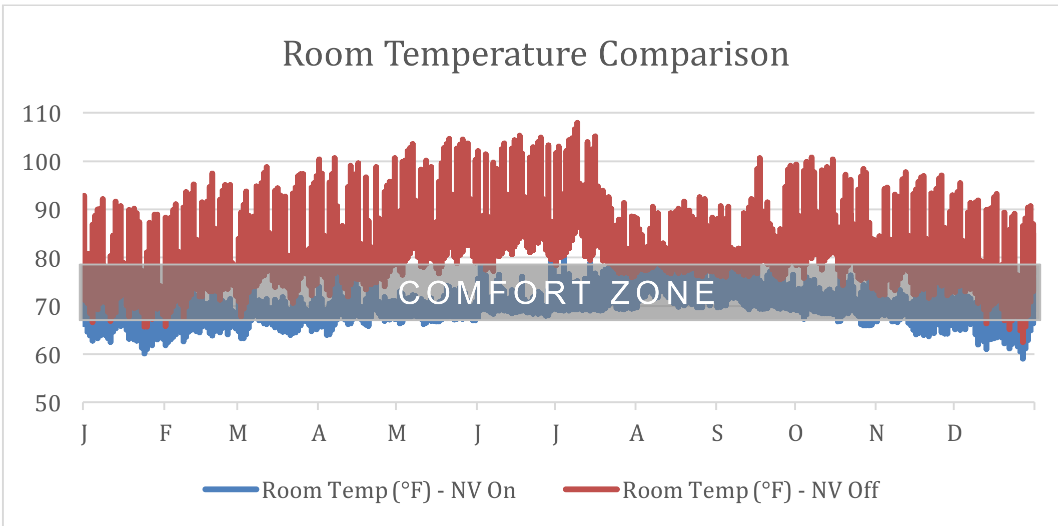


Figure 10: Thermal comfort zones reached with natural ventilation on and off (Diagram By Greg Collins)

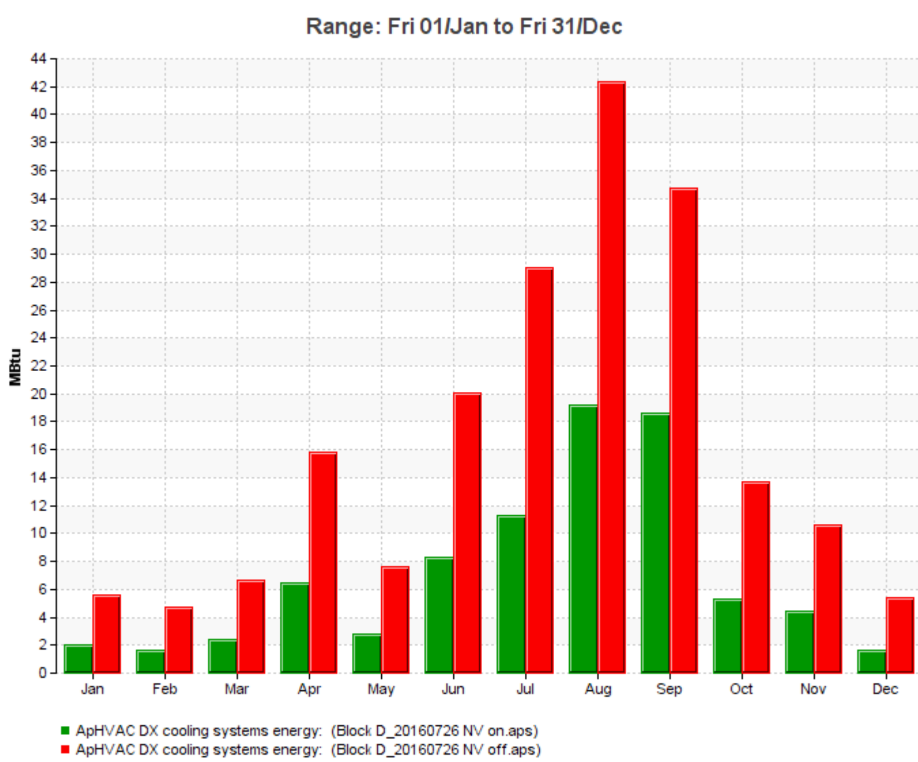


Figure 11: Cooling loads in Mbrus with natural ventilation on and off (Diagram by Greg Collins)

EXPLANATION

DAYLIGHTING

The proposed model outperforms the baseline model in daylighting performance. The illuminance reaches about 400 fc at the south and west perimeters, and between 50 fc to 150 fc in the interior space. For the ASHRAE baseline, only the spaces near the glazing have high illuminance, and the daylighting level is only between 30 fc to 100 fc in the interior space.

As shown in Figure 8, for the proposed design, 81% of the office floor area has an illuminance level higher than 20 fc, 80% of the space has an illuminance level higher than 20 fc. For the baseline model, only 69% of the space has an illuminance level higher than 20 fc.

NATURAL VENTILATION

Natural ventilation results in 11% energy cost savings as compared to a design relying on mechanical cooling. As shown in Figure 10 and 11, natural ventilation works well for more than 70% of the occupied time from June to July and 87% of the occupied time in August. This strategy provides the major savings for this sustainable façade design. Natural ventilation also works well from April to November for more than 50% of the occupied hours in those months.

Coupled with ceiling fans, this strategy also improves the occupants' comfort level, as the adaptive thermal comfort method allows occupants to achieve optimal comfort levels

CONCLUSION AND FUTURE WORK

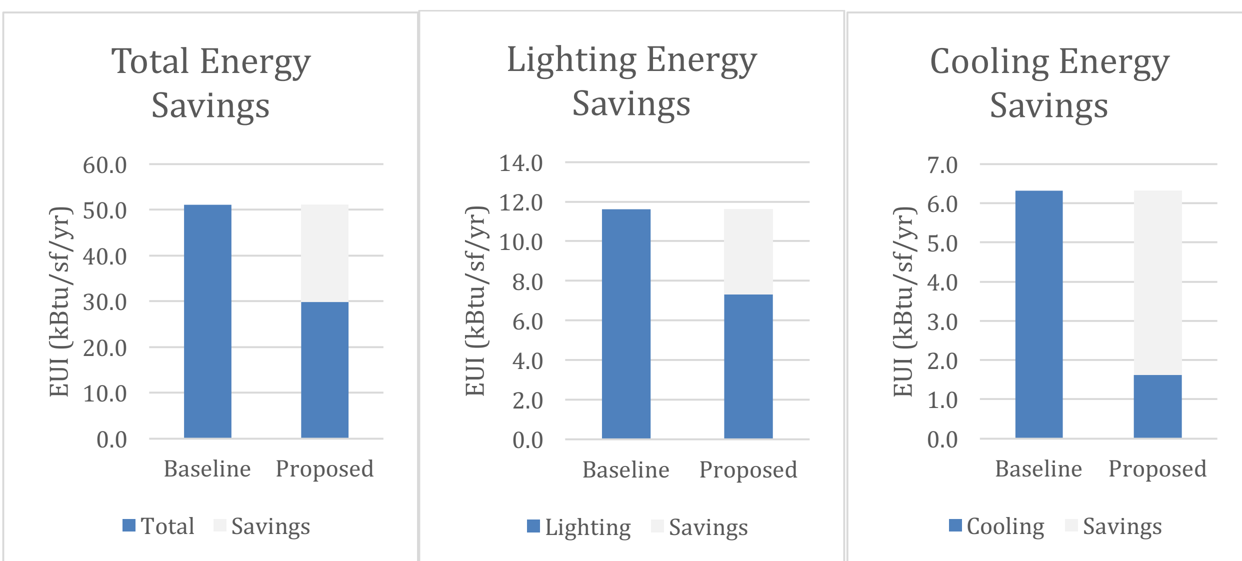


Figure 12 shows total energy savings, lighting energy savings, cooling energy savings (Diagram by Greg Collins)

The adaptable features of the façade have impressive projected performance numbers. The total energy savings compared to ASHRE baseline is 42%. The major areas contributing to these savings is shown in figure 12, the use of artificial lighting is reduced by 30% and cooling loads are reduced by 60% due to the reduction of heat gain from the smart shading system and natural ventilation.

The speculative office building will complete construction in June 2017. The operable components and sustainability features are already attracting future tenants and the client has been able to prelease the building. The sustainable components have become a selling point for the realtors and they have found that people are interested in occupying a sustainable workplace for its environmental benefits, wellness benefits from daylight and natural ventilation, and energy cost savings. Something even more interesting is the interest in the adaptability of the sustainable components of the façade.

Early on in the value engineering process of the project, the operable shades were exempted from elimination due to feedback from potential tenants.

This spec office building will be the first building complete of a 5 building development in downtown San Diego. The client intends for it to serve as a proof of concept for the remaining 4 city blocks. Meaning if the sustainable and innovative strategies implemented prove successful and feasible, the client will implement similar strategies on the rest of the development. Concept studies for two of the other blocks are underway and already incorporate high performing components to the façade. To build on this research, it’s important to validate the projected performance of the design decisions with post occupancy studies after the building is fully occupied. These studies will include, frequency of overriding controls on the venetian blinds, the position and frequency of the use of manual operation of sliding panels, occupant testimonies, and study and identification of (if any) shading failures. This research will be imperative to the implementation of an active façade on a larger scale to prove its effectiveness.

REFERENCES

Christianne Jordan. Illuminating Engineering Society. “Footcandle Lighting Guide.” https://www.lightingdesignlab.com/sites/default/files/ (accessed June 25, 2016).

Christianne Jordan. *California Building Code, Vol 1 of 2 2013* California Building Standards Commission, 2013.

Richard Wilson. “A Guide to Solar Control and Exterior Shading” Draper Solar Control Shading System (2014)

FACADES WITH GILLS

Advanced technology in hybrid breathing façade systems

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ABSTRACT

Considerable energy savings in building air conditioning systems could be gained with higher performance energy recovery ventilator (ERV) heat and moisture exchangers. Higher performance ERV's remain uncommon in part due to their large size, a function of the quantity of polymer membrane surface area required for high rates of heat and moisture exchange. A hybrid building enclosure panel containing an integral, air-to-air energy recovery ventilator has been developed, experimentally validated, and detailed to integrate within standard enclosure systems. Using space available within the depth of spandrel or rainscreen panel assemblies, a polymer membrane exchanger is created with substantial surface area in the plane parallel to the wall. The exchanger depth is sized to fit within the available space. The required quantity of fresh air is supplied through a series of modular panels distributed throughout the building enclosure.

Experimental validation of this hybrid envelope component at multiple scales demonstrated its performance and unique value proposition. The effective R-value of the panel is dynamic and varies with the temperature differential between building interior and exterior. The sensitivity of the R value change is greater at lower rates supply and exhaust airflow through the panel. Due to its large size, the integral ERV pre-conditions the air sufficiently under most conditions to enable its direct introduction to the building interior. ERV systems are typically directly coupled to a centralized HVAC system. By contrast, a decoupled approach is enabled, with the panels providing preconditioned outdoor air and an HVAC system providing fully conditioned recalculated air. Substantial savings in space used by ductwork and ventilation shafts are enabled by this "smart" enclosure system.

The hybrid component, which emulates membrane transfer systems found in human lungs, green plants, and fish gills, represents a large step forward in the integration of multiple functions into the envelope and offers the potential of substantially more energy-and space-efficient buildings.

KEYWORDS

curtainwall; rainscreen; energy efficiency; health - comfort- IEQ performance; ventilated; new, innovation; bio-mimicry

INTRODUCTION

"Facades, like words, simultaneously link and separate inside from outside."
- Colin Rowe

The role of the façade in building performance is multi-faceted and complex. Nevertheless, the basic functions required of the building façade, with a few notable exceptions such as integrated power generation, are still largely the same is those used in earliest of buildings; shelter from the elements, insulation from fluctuating exterior conditions, and basic comfort for the occupants.

Operable windows and vents have traditionally acted as the primary form of linkage between ambient outdoor air and the enclosed interior, enabling natural ventilation during those hours when the ambient exterior condition is within a suitable temperature and humidity range. Conditioning of the interior space beyond these limits has typically been the purview of heating, ventilating and air conditioning systems (HVAC).

The increasing incorporation of Energy Recovery Ventilation (ERV) technologies into air conditioning systems in the past decade has shown potential to reduce building air conditioning energy significantly. (Zhang, 2000) Traditionally an air conditioning system add-on, an ERV is a heat and moisture exchanger that captures the residual heating or cooling benefit that would be lost in the building exhaust airstream and uses it to pre-condition the incoming fresh air stream. By making this exhaust waste product do one final piece of preconditioning work before it is lost, the energy burden on the HVAC system is reduced. This "energy recycling" process is analogous to the reclamation process used in the regenerative braking systems of a Toyota Prius and other hybrid vehicles. ERV's on the market today are typically made of parallel layers of paper or polymer membrane stacked within a box-like steel housing installed in mechanical equipment or penthouse. With a latent effectiveness (a measure of the moisture transfer efficiency) in the range of 55%, conventional ERV's typically perform only a fraction of the required dehumidification and, therefore, are installed directly upstream of the conventional HVAC, which is used to complete the conditioning before the ventilation air is delivered. (Deikmann, 2008)

An ERV with a higher latent effectiveness could condition the ventilation air sufficiently to allow it to be introduced directly into the room without the need for direct coupling to the HVAC system. Such an ERV, however, would be inordinately large in order to provide the requisite membrane surface area, resulting in a large space penalty in the buildings.

A hybrid concept was developed to create an ultra-high efficiency ERV by creating an exchanger that is large in two dimensions but smaller in the third, creating a panelized form. These exchangers are then integrated into modular envelope units that occupy unused depth within commercial curtain wall and rain screen systems. With the addition of small supply and exhaust fans, these panels create a façade element supplying clean, decentralized and preconditioned fresh air requiring less energy and less space than conventional alternatives. (Franzke et. al., 2003)

A series of critical development steps were taken to move the system from a concept through a laboratory bench-scale validation to three full-scale operational systems. In addition to considerable HVAC energy savings, the technology presents improvements to indoor air quality and occupant health, better leasable floor area, a dynamic insulation quality, and enhanced building control. This paper summarizes a five-year product development effort, culminating in a new, hybrid building envelope/HVAC product – The AirFlow™ Panel – that is just emerging onto the market.

BACKGROUND

The concept of a single, hybrid building component simultaneously performing a façade function- acting as an element of the building enclosure – and an air conditioning function – recapturing air conditioning energy already invested in the interior environment –presented a series of complex design challenges. The investigation set out to develop, demonstrate and, ultimately, to commercialize a hybrid façade panel with an integral ERV in a progression of physical demonstrations and validations increasing both in scale and severity of climate. In order to meet this challenge, the Architectural Applications (a2) created a team of world-class collaborators that included i) Lawrence Berkeley National Lab (LBL) with deep experience in building science, ii) a Membrane Technology & Research, Inc.(MTR), who is versed in producing tailor-made products, iii) Arup, a global building engineering firm with expertise in both façade systems and HVAC design, and iv) the ETH-Zurich (ETH), a major European Technical University with expertise and facilities to test novel building technologies in the harsh subtropical climate of Singapore.

METHOD AND RESULTS

The heat and moisture exchange function was initially addressed with mathematical simulation and analysis work by the LBL team and the development polymer membranes with custom-tailored water vapor permeability properties by MTR. (Figure 1) Small acrylic prototypes of façade panels containing exchangers made of the new membranes were tested in the laboratory for their efficiency at transferring heat and moisture between air streams flowing through them. Their performance results, when extrapolated to the scale of a commercial building, were sufficiently promising to warrant continued development of the project.

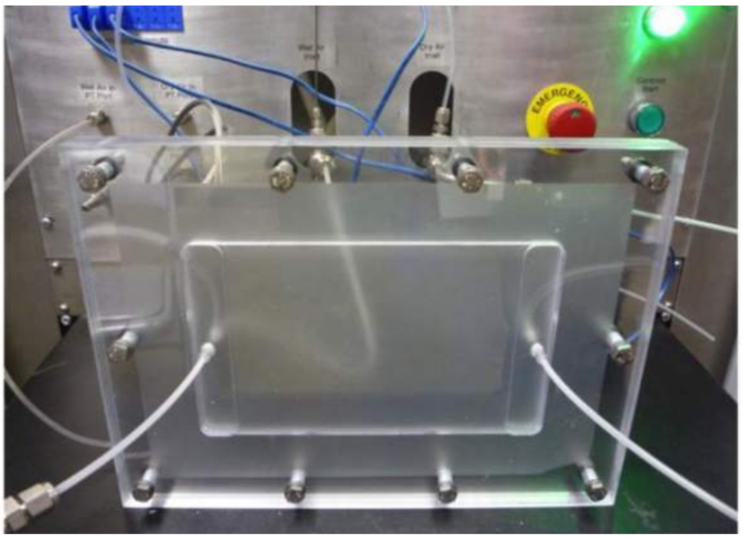


Figure 1: Lab-bench validation of a façade-integrated membrane-based recovery exchanger. Images courtesy of Architectural Applications.

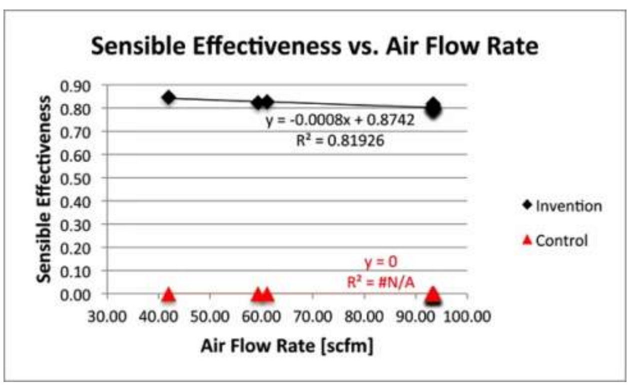
The primary objective of the next stage of development was to assess the simultaneous performance of the component in both its functions as an envelope element and an HVAC element. The primary metric of envelope performance is effective thermal resistance ($R_{effective}$), or the net resistance of heat flowing from one side of component to other between the chamber interior and exterior. The metric of HVAC performance in this case is effectiveness, or the amount of heat (sensible effectiveness) or moisture (latent effectiveness) transferred between airstreams within the component as a percentage of the total possible transfer in an idealized case. The two primary energy transfers are interdependent within the hybrid component, and the experiment was structured to gauge the effect of changes in one of the performance metrics on the other.

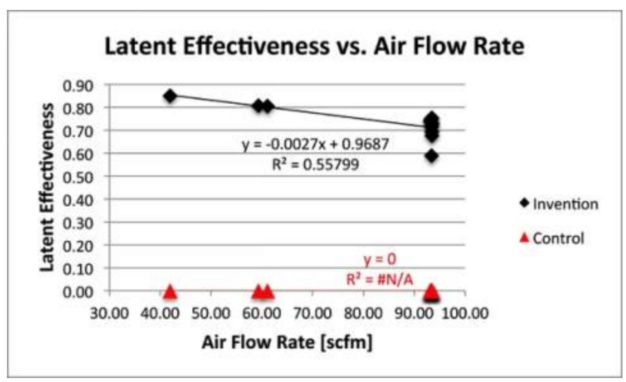
A medium-scale panel (approximately 3'x 4') and an identically-sized, inert control unit were installed in wall apertures within side-by-side calorimetric climate chambers at LBL so that they formed a part of the enclosures of the chambers. (Figure 2) The control unit comprised a build up, from interior to exterior of painted ½" plywood/ 1" expanded polystyrene rigid insulation/ 7 ¼" dead air space/ 1" expanded polystyrene rigid insulation / ½" painted plywood, yielding a net total R-value (excluding film coefficients) of R14 (U = 0.071 BTU/h-ft2-°F). Measurements of the ventilation air flow rates, temperatures and humidity levels as well as precise metering of the net heat transfer through the panels provided a first test of the panel's combined function in situ. Each device was installed into the aperture in one of the two Climate Chambers, calibrated to known airflow rates, and instrumented to measure temperature and relative humidity levels of the external environment, the chamber interior, the incoming air stream at its point of entry into the chamber, and the exhaust airstream at its point of exiting the exchanger housing. Additionally, the paired temperature measurements were made on the inner and outer faces of the insulation layer disposed toward the exterior of the chamber. The paired temperature measurements were evenly spaced grid of nine points arrayed over insulation surface.

Figure 2: Medium-scale experimental and control units installed in calorimetric chambers Image courtesy of Architectural Applications.

Data was collected under a variety of conditions over between July 25th and August 18th, 2013. Supply and exhaust air flow rates were maintained at equal rates in both devices and ranged between 45 and 100 cfm. The temperature difference between chamber interior and exterior was controlled between 0 and 33° F. Fifteen individual, steady-state data points were measured, each consisting of average of five-minute interval values over a 30-minute period with the lowest standard deviations in the data set.

Figures 3a & b display the measured sensible and latent effectiveness respectively plotted against the air flow rate over a range of operating conditions. The data show trends consistent with conventional heat exchanger theory, in which both sensible and latent effectiveness decrease with increasing airflow rates. To within experimental uncertainty, the device performs its HVAC function at levels of performance commensurate with a comparable non-façade-integrated device. The effectiveness of the control device was zero under all conditions, as expected given that no heat and moisture exchanger is included in this system.





Figures 3a&b: Experimental results from medium-scale chamber measurements. Image courtesy of Architectural Applications.

Figure 4 displays the measured thermal resistance (R-value) of the panel versus measured under a range of conditions. The inert Control unit displays a relatively constant R-value across all conditions as would be expected from a static, insulating envelope component. The experimental device, however, displays a dynamic R-value that varies fairly linearly with the overall temperature differential between chamber interior and exterior. The rate of this change varies with the supply and exhaust air flow rates moving through the panel. The R-value changes more rapidly with the temperature differential at lower airflow rates than at higher. Within the overall energy balance of the panel, variations in the effective R-value can be attributed to the portion of the total heat flux transferred through the panel form interior face to exterior (or vice versa) compared to the portion that is convected into the air streams flowing through the panel interior. At lower flow rates, the lower internal air velocity results in a smaller convective fraction. Under this condition, more of the net heat flux through the system is transferred as conduction from panel interior to exterior. As the internal air velocities increase, the convective fraction increases, reducing the conductive fraction and, thus, raising the effective R-value.

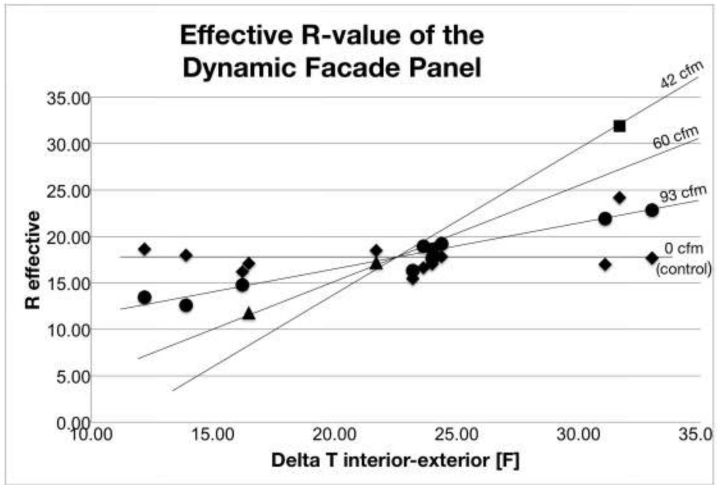


Figure 4: Experimental results from medium-scale chamber measurements. Image courtesy of Architectural Applications.

In a subsequent phase of work, a full-scale demonstration was developed for installation in a sophisticated and well-instrumented building system test facility at LBL. The primary objective of this phase of work was to explore aspects of envelope integration. In this case, the test chamber, sized to emulate a single office, had one fully glazed façade that utilized a standard extruded aluminum storefront system with pressure bars and snap covers supplied by a major North American manufacturer. A panel component was fabricated to fit the opening dimensions of the existing glazing system (approximately 5' x 12'). The existing IGU's were removed, and the new panel was installed in their place using the original pressure plate and snap-cover assembly. The entire process, including the electrical connections required to power the panel's internal fans, was completed by a crew of four people in under two hours

Figures 5a & b: Full-scale envelope-integrated exchanger unit installed in test facility- Exterior view / Interior view. Image courtesy of Lawrence Berkeley National Laboratory.

The panel was designed and detailed to match the depth of the aluminum framing system so that the interior face of the panel was flush with the rear face of the mullion. (Figure 6) The body of the panel is held ¾" inside the storefront framing bay, creating a continuous shadow gap around the panel from the interior and creating a location for the necessary power and control wire terminations. The airflow capacity and the effective R-value of the panel are related to its overall depth. As such, matching the panel depth of the overall envelope system framing depth may not yield the ideal result in all situations.

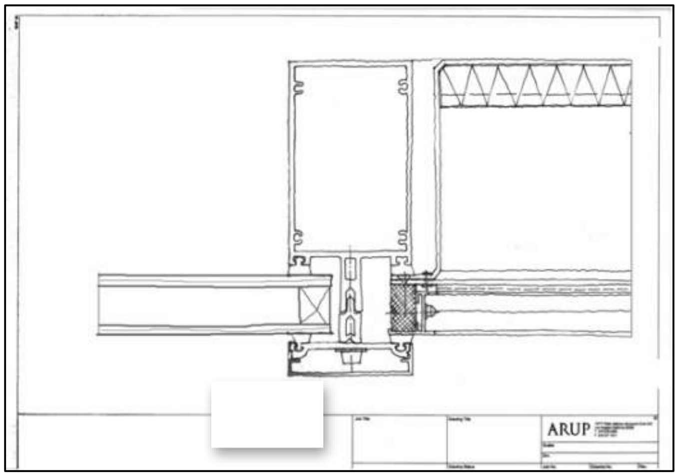
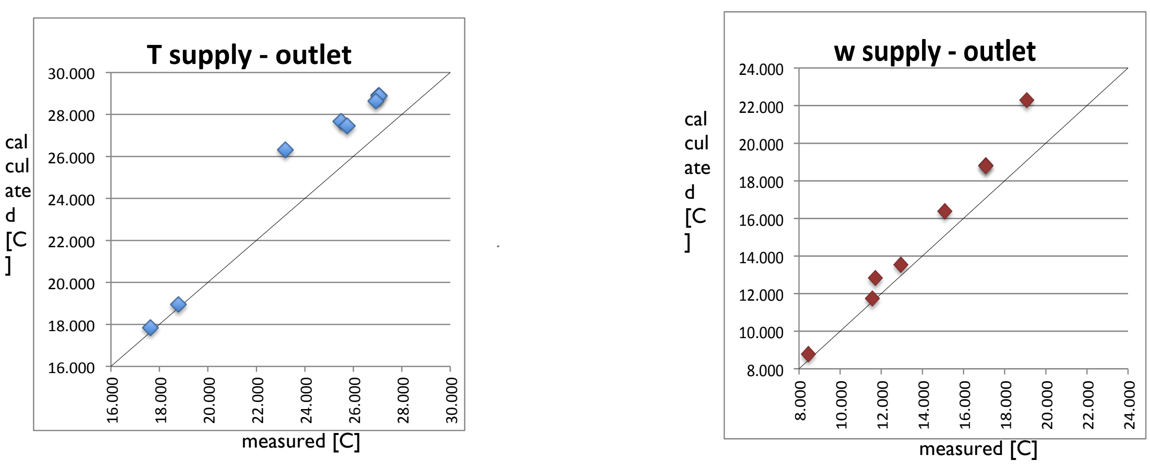


Figure 6: Plan detail sketch for integral heat & moisture exchange panel as part of a curtainwall enclosure system. Image courtesy of Arup.

With the device integrated into the test cell exterior envelope, the system was operated as two decoupled ventilation air streams: a 100% outdoor airstream was brought through the wall panel and preconditioned via the integral exchanger prior to entering the room. A 100% re-circulated air stream was simultaneously drawn from the room, through a fan coil located above the chamber ceiling, and reintroduced into the room via the ceiling diffuser seen in Figure 8. In this arrangement, the room itself acts as a mixing plenum for the two airstreams, and careful design is required to ensure sufficiently uniform air distribution is achieved.

Eight data points were measured at steady-state conditions under a range of temperature- and humidity-gradients induced between chamber interior and exterior. Analytical models developed to assess the panel performance were benchmarked against the measured data points. The modeled results showed agreement with the measured data to within 7% (Figures 7a & b)



Figures 7a & b: Comparison of measured vs. predicted results of supply air conditions. Image courtesy of Architectural Applications

A simple, single-zone whole-building energy model using EnergyPlus v8.1 software was constructed comprising a 2,400 ft2 single story, one zone model with a Slab-on-grade floor and one Double LowE (40% WWR) south-facing window. (Figure 8) All schedules, internal loads, wall constructions per climate, and outdoor air requirements from the DOE EnergyPlus Commercial Prototypical Building models, 90.1-2010 version, (www.energycodes.gov/development/commercial/90.1_models) with three versions of HVAC system: i) fancoil unit with a dedicated outdoor system, ii) the system in item i with the addition of a rotary desiccant energy recovery ventilator operating at the system level (i.e. directly coupled to the DX

VAV unit), and iii) a decoupled ventilation system comprising an envelope-integrated ERV panel as described previously operating in parallel with a fully recirculating in-zone fan coil unit. (Figures 9-11)

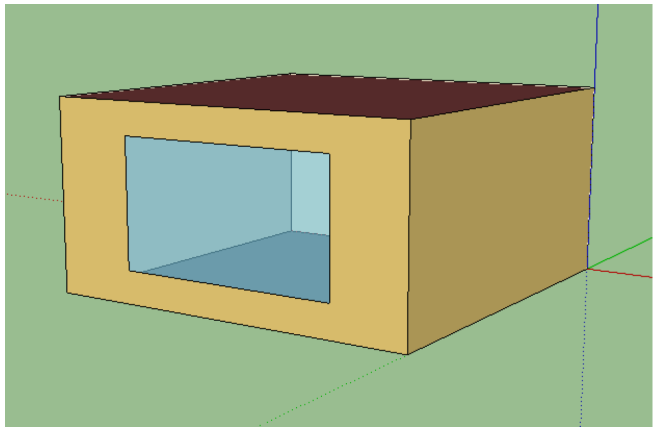


Figure 8: EnergyPlus single zone model

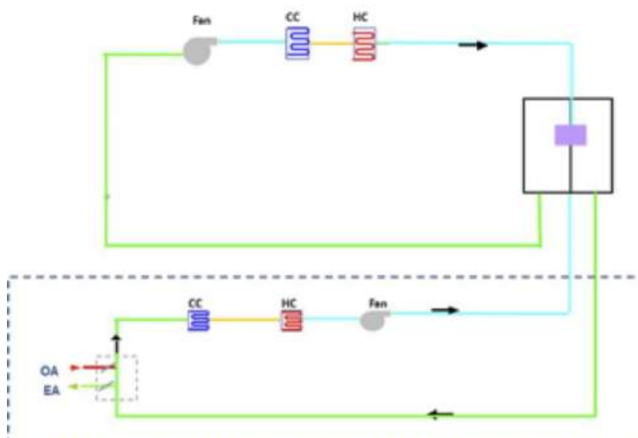


Figure 9: Schematic diagram for Base Case System, a FanCoil with a dedicated outdoor air system, OA-outdoor air, EA-exhaust air, CC-cooling coil, HC-heating coil. Image courtesy of Lawrence Berkeley National Laboratory

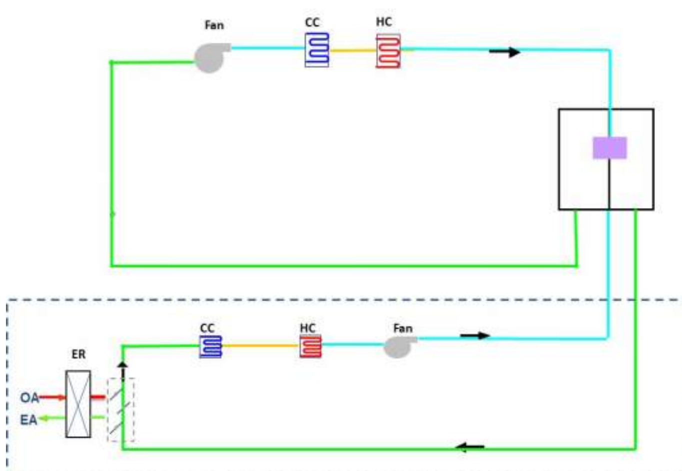


Figure 10: Schematic diagram for Base Case System, a Fan Coil with a dedicated outdoor air system and a system level ERV, OA-outdoor air, EA-exhaust air, CC-cooling coil, HC-heating coil

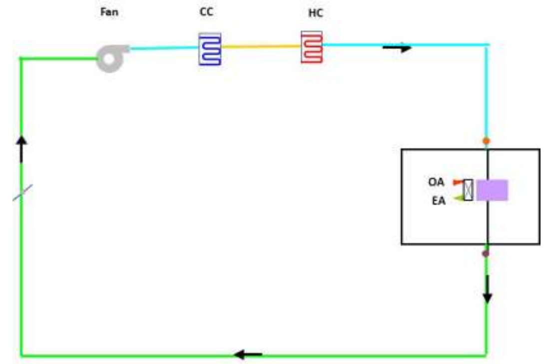


Figure 11: Schematic diagram for Fan Coil system with an Energy Recovery unit integrated at zone level, OA-outdoor air, EA-exhaust air, CC-cooling coil, HC-heating c

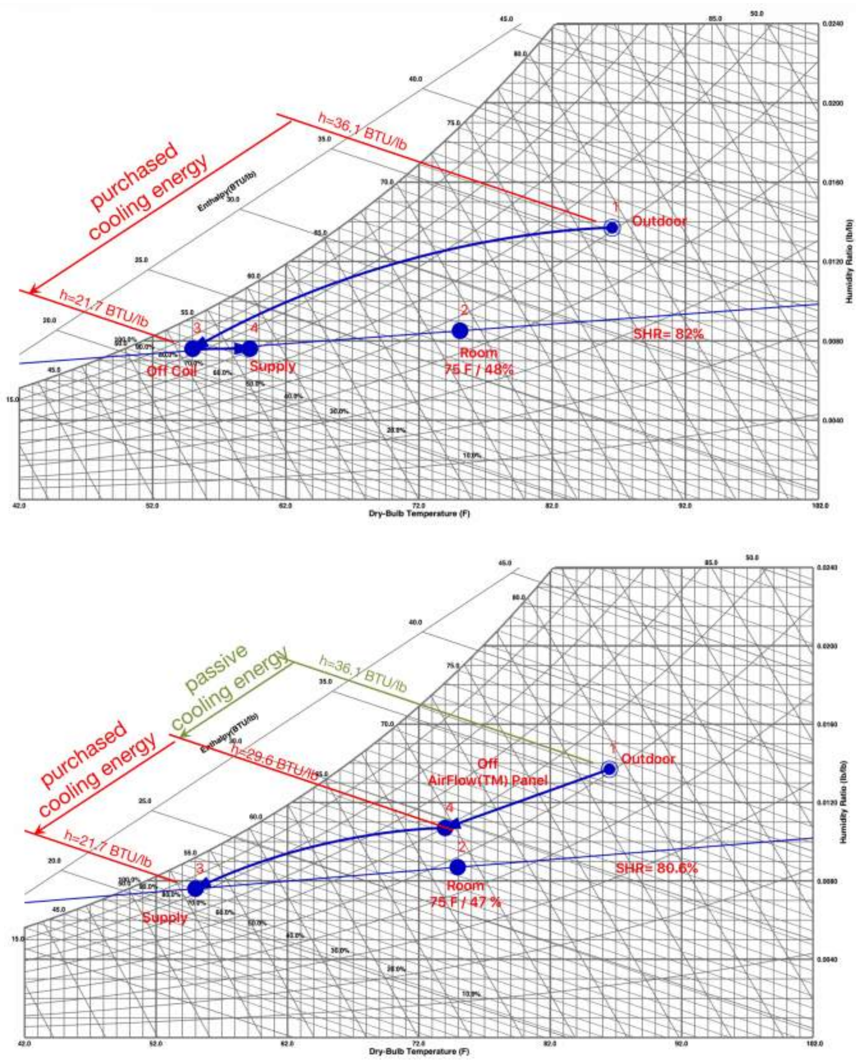
The three system type models were evaluated with loads and occupancy schedules corresponding to four building types: an office, a school, a hospital, and a residence. Four climate zones were chosen to represent a range of conditions found in North America, represented by North (Minneapolis), Central (Atlanta, Washington DC), and South (Phoenix). For all cases, a minimum outdoor air flow rate was provided to maintain acceptable indoor air quality. The amount of air flow, based on DOE Commercial Building Prototypes, was different for each building type. The air flow rate schedule followed the occupancy schedule. The membrane separating the air streams within the exchanger has been found to be very resistant to transfer of certain strains of virus as well as other pollutants such as formaldehyde. While this is promising for the system's use in applications with high risk of cross contamination such as labs and hospitals, further testing will be necessary to ensure standard are met.

The results of these parametric runs are shown in Table 1. In all four climates evaluated, there is energy savings due to the addition of the Energy Recovery unit. The savings is significantly higher for an AirFlow Panel, connected at the zone level. Building types requiring higher ventilation rates also see more savings, as would be expected (i.e. school and hospital).

		1. Fan Coil Unit with DOAS				2. Fan Coil Unit with DOAS + Enthalpy Wheel				3. Fan Coil Unit with **AirFlow™ Panels**			
[KBTU/sq. ft. per year]		Heating	Cooling	Fan	Total	Heating	Cooling	Fan	Total	Heating	Cooling	Fan	Total
ATLANTA	Office	6.99	16.54	1.35	24.88	5.24 -25%	16.40 -1%	1.35 0%	22.98 -8%	4.10 -41%	9.60 -42%	1.30 -4%	15.00 -40%
ATLANTA	School	8.34	27.49	2.75	38.58	3.72 -55%	25.19 -8%	2.75 0%	31.66 -18%	1.80 -78%	14.43 -48%	2.61 -5%	18.84 -51%
ATLANTA	Hospital	22.68	41.70	4.34	68.72	14.83 -35%	37.30 -11%	4.34 0%	56.47 -18%	7.44 -67%	17.16 -59%	4.10 -5%	28.70 -58%
ATLANTA	Residence	22.25	18.01	1.63	41.89	20.07 -10%	18.08 0%	1.63 0%	39.78 -5%	17.32 -22%	10.19 -43%	1.59 -3%	29.10 -31%
MIAMI	Office	0.38	31.25	1.61	33.24	0.36 -6%	29.88 -4%	1.61 0%	31.85 -4%	0.28 -25%	21.04 -33%	1.56 -3%	22.89 -31%
MIAMI	School	0.45	43.98	2.72	47.15	0.45 0%	36.80 -16%	2.72 0%	39.97 -15%	0.21 -53%	24.67 -44%	2.56 -6%	27.44 -42%
MIAMI	Hospital	1.49	82.34	4.76	88.60	1.45 -3%	69.40 -16%	4.76 0%	75.61 -15%	0.54 -63%	40.16 -51%	4.53 -5%	45.23 -49%
MIAMI	Residence	2.87	29.90	1.61	34.38	2.84 -1%	29.10 -3%	1.61 0%	33.55 -2%	2.23 -22%	20.12 -33%	1.56 -3%	23.91 -30%
MINN.	Office	23.29	11.11	1.42	35.83	16.21 -30%	11.26 1%	1.42 0%	28.88 -19%	13.13 -44%	6.68 -40%	1.37 -3%	21.18 -41%
MINN.	School	35.59	17.30	2.82	55.71	12.32 -65%	16.73 -3%	2.82 0%	31.87 -43%	6.21 -83%	8.96 -48%	2.65 -6%	17.82 -68%
MINN.	Hospital	73.69	24.22	4.48	102.39	39.52 -46%	22.94 -5%	4.48 0%	66.94 -35%	23.86 -68%	10.97 -55%	4.24 -5%	39.07 -62%
MINN.	Residence	60.94	12.06	1.85	74.85	52.89 -13%	12.35 2%	1.85 0%	67.08 -10%	47.86 -21%	6.66 -45%	1.80 -3%	56.32 -25%
WASH. DC	Office	12.25	13.93	1.40	27.58	8.44 -31%	13.98 0%	1.40 0%	23.81 -14%	6.73 -45%	8.32 -40%	1.35 -3%	16.40 -41%
WASH. DC	School	16.85	23.20	2.77	42.82	5.85 -65%	21.75 -6%	2.77 0%	30.38 -29%	2.58 -85%	12.11 -48%	2.63 -5%	17.32 -60%
WASH. DC	Hospital	40.54	33.43	4.41	78.38	23.55 -42%	30.59 -9%	4.41 0%	58.55 -25%	12.51 -69%	14.03 -58%	4.17 -5%	30.71 -61%
WASH. DC	Residence	32.87	14.74	1.75	49.36	28.27 -14%	15.09 2%	1.75 0%	45.12 -9%	24.41 -26%	8.46 -43%	1.71 -3%	34.57 -30%

Table 1: Results of EnergyPlus single-zone models showing change from baseline system

The high effectiveness of the exchanger within the integrated panel enables it to deliver preconditioned fresh air to the room at temperatures and humidity levels only marginally above the room conditions. Under most conditions, this high heat and moisture exchange rate enables the 'decoupled' operation of two parallel ventilation air streams as described previously. (Figures 12a & b)



Figures12a & b: Psychometric chart for air conditioning via a centralized condensing coil at the ASHRAE 1% cooling condition, New York, NY.

Mixed room condition : T = 75° F, RH = 47%

Off-panel fresh air supply: T = 74.5° F , RH = 59%

Mixed room condition : T = 75° F, RH = 48%

Image courtesy of Architectural Applications

DISCUSSION

The true advantage of the system described here is in its decoupled operation. Energy recovery ventilation components typical in the industry today achieve only a portion of the required outdoor air conditioning. They are, therefore, directly coupled in sequence to a mechanical HVAC system to complete the conditioning before the air is introduced into the room. The decoupled operation of the panel described here is enabled by its hybrid design as both envelope and HVAC component. The large exchanger surface area required to achieve high levels of heat and moisture exchange is accommodated – at least in two dimensions – by integration within an envelope panel. The resulting high exchange levels enable the preconditioned outdoor air to be delivered directly to the space without first passing through a cooling coil to control the final temperature and humidity levels.

An additional benefit of the product is that the portion of the humidity removed from ventilation airstream is accomplished by permeation in vapor form, without condensing it into liquid as is common in conventional dehumidification technologies. Numerous studies have shown that the presence of moisture within the building envelope, particularly coupled with higher temperatures, tends to increase the production of mold, microbes and other biological agents that can be harmful to building occupants. (World Health Organization, 2009) From the laboratory measured performance described above, the reduction in condensate production in the ventilation air stream for each of the test cases was calculated in each of the four test case cities to be 50-55%. This reduction in condensate production, therefore, may reduce the risk of occurrence of these agents in buildings using the AirFlowTM Panel.

A standard panel has been brought to market with an outdoor air capacity of 200 cfm available in a wide range of face dimensions and finishes to match project-specific envelope constraints. A single 200 cfm exchanger can be accommodated in a panel nominally five feet wide with height ranging from 3-14 feet, enabling it to be installed in floor-to-floor, floor to sill, or spandrel zone configurations. As an example, an office building with a 20' deep perimeter zone and an occupant density of 100 sq. ft. /person designed to current California Title 24 ventilation standards would require a single panel every 65 lineal feet along the façade perimeter. The ventilation requirements of a 40-student classroom could be met satisfied with three panels in any of the configurations described above.

CONCLUSION AND FUTURE WORK

A variation of the technology is being developed to integrated within conventional rain screen systems. (Figure 13)

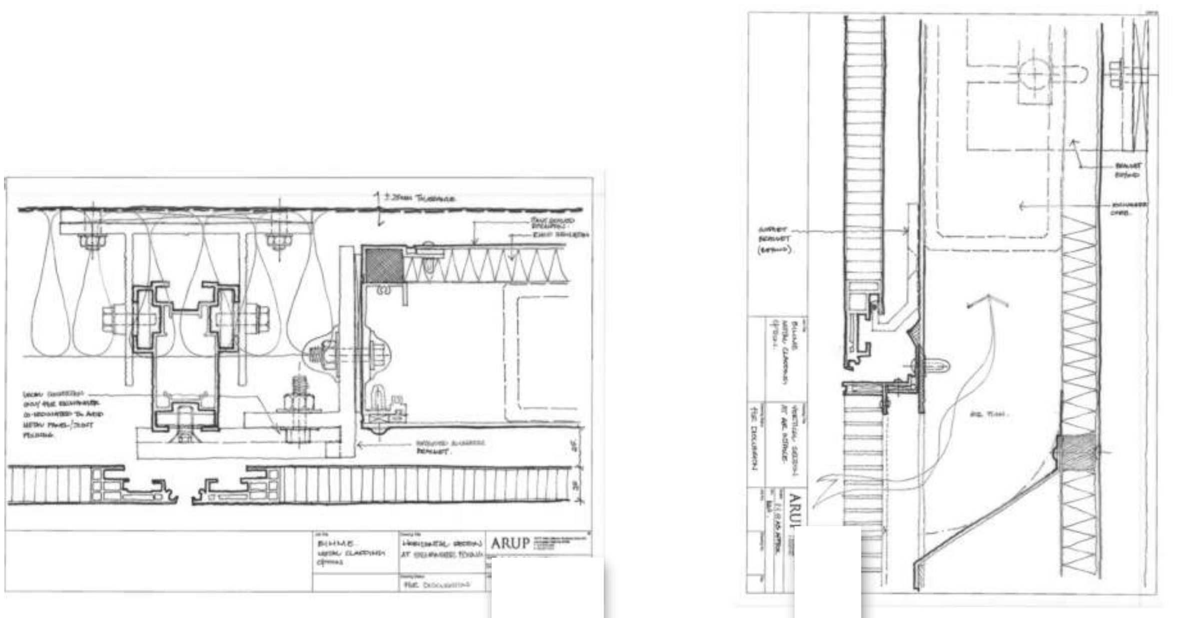


Figure 13: Plan & section sketch details for a rain screen-integrated heat and moisture exchanger preconditoner.

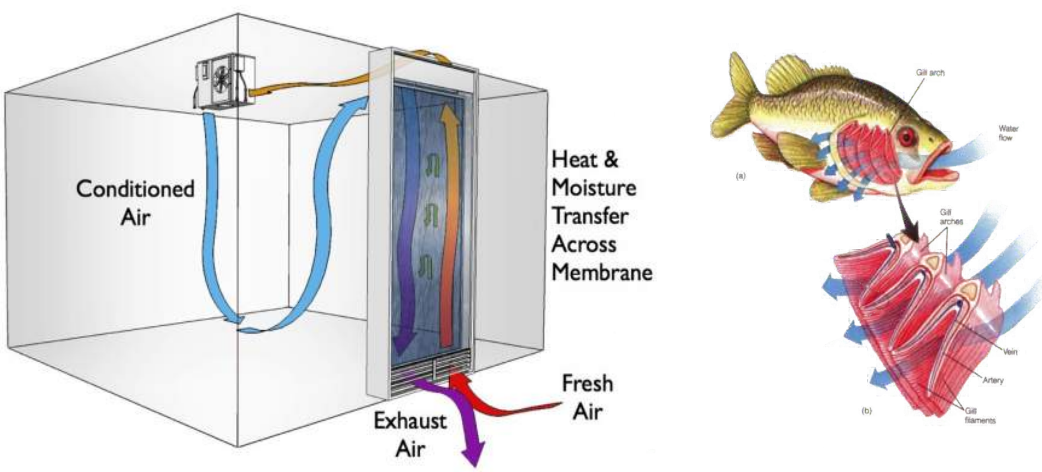


Figure 14: Biological analogs to a membrane-based exchanger for efficient pre-conditioning of building ventilation air. Images courtesy of Architectural Applications.

The idea of an ultra-efficient heat and moisture exchanger integrated into the building fabric led initially to investigations of the architecture of human lungs. It eventually became clear that the gills of fish were a better model for this challenge given that water holds only 1/5 the concentration of oxygen as air. Gills, therefore, need to do their job in an environment of oxygen scarcity, requiring them to operate at higher efficiency. The mathematics of fish gills was studied during the design and optimization of the membrane exchanger. (Parka, 2014)

We as architects and engineers are fond of referring to buildings that “breathe.” By this terminology, we refer to buildings that move volumes of fresh air into and out of them without the need for fans. We learn in middle school biology class, however, that moving air into and out of our lungs is only a means to an end and that the actual purpose of respiration is the transfer of oxygen and carbon dioxide into and out of the bloodstream via permeation across membranes that line the lungs.

It is significant that the bio-mimetic technology enabling these benefits is at heart a building enclosure technology. Like the lining of our lungs, the panel gains it efficiency of exchange by virtue of a very large membrane surface area. Like the gills of fish, these membrane exchangers are located at the interface between interior and exterior, where they can mediate the flow of air into and out of the space to best advantage. The design potential of this new technology is as rich as the technical. The panels are currently opaque (although a translucent product is anticipated for the future), and perform a function formerly unheard of in the building enclosure sector – passive dehumidification. These opaque “gills” of the building can offer infinite possibility to express in the façade design this unique function and its role in changing the way buildings use energy.

The revolutionary nature of the technology presented here is underscored by its distinction as the only building envelope technology supported by the Advanced Research Project Agency for Energy (the most elite clean tech funding program in the country, as well as the US Department of Energy’s Emerging Building Technologies Office and various private and nonprofit entities. The product has been sold in California and is currently being implemented in projects in Texas, Georgia, Hong Kong, and Vietnam.

Buildings currently use 40% of global energy and emit approximately 1/3 of all greenhouse gas emissions. With the current rates of urbanization, particularly in Southeast Asia, the problems of energy use and environmental degradation are growing rapidly. Combining multiple functions into a single, hybrid façade component to produce efficiencies and benefits greater than the traditional systems could produce on their own is truly and evolutionary step in intelligent building enclosures. With this technology we have taken a significant step closer to creating buildings that actually respire, and the benefits provided by this advance are multiple and substantial.

ACKNOWLEDGMENTS

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REFERENCES

Cherem-Pereira, G. and N. Mendes. “Room Air Conditioners: Determination of Empirical Correlations for Predicting Building Energy Consumption.” Eighth International IBPSA Conference, Eindhoven, The Netherlands. (2003).

Deikmann, John. "Improving Humidity Control with Energy Recovery Ventilation." ASHRAE Journal (2008).

Fisk, William J. and Arthur H. Rosenfeld. "Estimates of Improved Productivity and Health from Better Indoor Environments."

Indoor Air 7.3 (1997): 158-72.
Fisk, William J. “Review of Health and Productivity Gains from Better IEQ.” Proc. of Healthy Buildings 4 (2000): 23-34.
Franzke, Uwe, Ralf Heidenreich, Angelika Ehle and Falko Ziller. “Comparison Between Centralised and Decentralised Air Conditioning Systems.” Institute for Air- und Cooling Technique, Dresden, Germany. (2003). Print
Hu, H., V. Topolkaraev, A. Hiltner, and E. Baer. "Measurement of Water Vapor Transmission Rate in Highly Permeable Films." Journal of Applied Polymer Science 81 (2001): 1624-633. Print.
Narayana, G., Prakash, Karan H. Mistry, Mostafa H. Sharqawy Mostafa, Syed M. Zubair, and John H. Lienhard. "Energy Effectiveness of Simultaneous Heat and Mass Exchange Devices." Frontiers in Heat and Mass Transfer (FHMT) 1 (2010).
Nasif, Mohammad Shakir, Graham L. Morrison, and Masud Behnia. “Proc. of 6th World Conference on Experimental Heat Transfer, Fluid Mechanics, and Thermodynamics.” (2005)
Niu ,J.L. and L.Z. Zhang. “Membrane-based Enthalpy Exchanger: material considerations and clarification of moisture resistance.” Journal of Membrane Science 189 (2001): 179–191.
Parka, Keunhwan, Wonjung Kimb,, and Ho-Young Kima. “Optimal Lamellar Arrangement in Fish Gills.” Proceedings of the National Academy of Sciences,111, 22. (2014). 8067–8070.
Wijmans, J. G., and R. W. Baker. "The Solution-Diffusion Model: A Review." Journal of Membrane Science 107 (1995).
World Health Organization. (2009). “WHO Guidelines for Indoor Air Quality: Dampness and Mould.”
Zelenay, Et.al., K. "High Performance Facades-Design Strategies and Applications in North America and Europe.” Center for the Built environment, UC Berkeley (2010).
Zhang, Et.al., Y. "Analysis of Thermal Performance and Energy Savings of Membrane Based Heat Recovery Ventilator." Energy 25 (2000): 515-27. Print

MATERIAL ACTUATION IN ARCHITECTURE

Using shape memory alloy in dynamic skins

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ABSTRACT

This paper examines several distinct approaches to using shape memory alloy (SMA) in kinetic architectural surfaces/facades. It describes several different ways of utilizing SMA as a dynamic force in the deformation of a surface, material system or construct. The paper discusses the application of SMA wire as a non-mechanical actuator and examines how its capacity to change its length and shape when heated is used to explore the change in shape or change in structural and material behavior of the kinetic material system. To achieve this several projects that use SMA to dynamically activate building skin or spatial constructs are reviewed. Through these examples the value and possibilities the SMA affords in developing adaptive building skins is discussed. On a broader scale, the paper looks into concepts of using smart material technologies to construct material assemblies capable of adjusting to their constantly changing surroundings and environmental conditions. The principal argument is that these new technologies and their seamless integration into material assemblies could have a transformative effect on the built environment and on how we experience and inhabit that environment. To imbue building skins with dynamic, changing behavior, their elements need to be actuated, i.e. moved, rotated, expanded, shrunk, twisted, etc. so that the desired performance objectives are met. What differentiates these adaptive examples is not so much what is actuated (and that matters greatly), but how that actuation is produced. This paper focuses on material-based actuation using SMA.

KEYWORDS

adaptive - kinetic – dynamic, adaptability, case study, future trends, shape memory alloy (SMA)

INTRODUCTION

Buildings are assumed to be stable and inactive even thought their external and internal environments are constantly altered by change, exchange and flow of energy, matter, people and information. The way we conceptualize and build buildings today does not successfully engage these dynamics. This paper discusses a number of research and design initiatives that attempt to re-conceptualize the relationship between the dynamic and stable in architecture. In particular it discusses initiatives that use shape memory alloy and explore opportunities SMA affords in rethinking the architectural assembly as a dynamic construct. At the core of these discussions are two sets of questions. The first set is addressing the nature of the architectural assembly: How can architectural assembly be hypothesized as a dynamic and adaptive material system? Can this be achieved through material itself instead of mechanically activated components? The second set of questions frames the broader discussion of dynamic and adaptive building skins: What kind of transformative effect these dynamic surfaces could have on their users and on environment? How could that change the way we design buildings? What are the opportunities and challenges in designing responsive architectural surfaces and systems?

ARCHITECTURAL ASSEMBLY AS A DYNAMIC MATERIAL SYSTEM

Material systems in nature generate movement and force through the interaction of materials, structures, energy sources and sensors (Jeronimidis 2004). Furthermore, material systems in nature don't distinguish between structural and functional materials. Instead, information about functional and structural needs of an organism travels through integrated material layers and informs material distribution. Naturally constructed material systems have a hierarchical structure on many levels that span several orders of magnitude (Speck and Rowe 2006). Functional properties of these materials can vary and change from one structural hierarchical level to the next, producing variability that can adjust to and accommodate changes in the external and internal environment. Manmade material systems distinguish between functional and structural aspects of the material. They are constructed, assembled, and designed to respond to a specific design and performance criteria by separating functional and structural aspects of the system.

Technology transfers from fields such as material science, biomimetics, autonomous robotics, interface design and computation are not only influencing the range of the materials used in architecture but the very scale at which they are deployed. Smart materials, for example, may present an interesting opportunity to augment the capabilities of the manmade architectural assemblies. Traditionally, architectural components are assembled using several different material layers and every one of them has a particular role and specific material properties. Smart materials, on the other hand, are not artifacts; they are technologies of motion, energy, and exchange. Integrating them into an architectural assembly and utilizing their capacities and properties presents a challenge as well as an opportunity. By doing this we could begin to re-calibrate materialization of architectural components and surfaces to include functional qualities of energy and/or information transfer.

This paper reviews number of projects that have experimented with the integration of SMA into building skins or dynamic constructs. All of these projects draw on SMA's capacity to change its length when heated; they derive their dynamics from the force exerted during the shape/length change of SMA.

MATERIAL ACTUATION

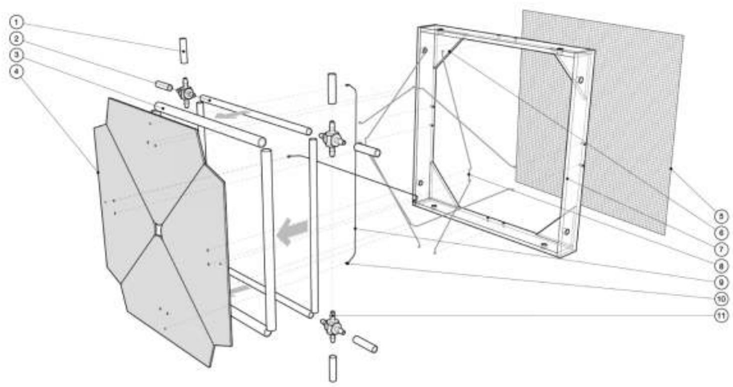
Like many other property changing smart materials, SMA can react to temperature changes in its environment with significant material response at the molecular level. This is possible due to a phase change of its internal structure. The high-temperature phase (austenite) and the low temperature phase (martensite) define the change of its crystalline structure. This enables SMA to recover its initial shape after deformation through a reversible thermo-elastic phase transformation. In other words shape memory alloys are functional materials that have the ability to change their shape without permanent deformation and can 'remember' their original geometry.

There are several types of SMAs. The most common are based on a combination of nickel and titanium (Ni-Ti) with roughly 55 to 56 per cent nickel and 44 to 45 per cent titanium. By changing this ratio the transition temperature changes. We can, therefore, have SMA that contracts at the body temperature or at much higher temperatures. The change from martensite to austenite phase causes a stress within the material that results in a 4 to 5 per cent wire contraction i.e. motion (http://www.dynalloy.com/pdfs/TCF1140.pdf). This motion is utilized in various ways in the projects discussed in this paper.

SMA is usually used as an actuator in robotics and aircraft hydraulic systems and in microcircuit breakers, temperature controls and electronic locks. It is also used in medicine as reinforcement for arteries and veins (stents) or in dental braces. Its use in architecture is relatively new. For the past ten years architects have been experimenting with SMA and its application in dynamic structures and surfaces. In the examples discussed here, the SMA is most often used as a linear actuator. The contraction of the wire activates a lever or a system of pulleys that in turn can animate the surface or construct. One of the best examples of this could be found in the work of Philip Beesley and his *Hylosoic Ground* project. SMA can also be embedded in the surface. In this situation the force of the activated wire has capacity to change the topography of the surface. David Benjamin and Soo-in Yang use this in their *Living Glass* project to open the slots cut into the silicone surface (surface gills). The force produced by the action of the SMA could (1) act indirectly by producing motion in another connected component that could then move a larger construct (2) or activate the surface directly by producing a tension within the material system. Shape memory alloy wire can also be trained to return to a specific shape after deformation. The 'trained' wire can be embedded into a surface or used to cause a specific change in the construct. This can be seen in the *SKiN* and *Lattice* projects by the author, described later in this paper.

TRANSFORMATIVE EFFECT OF DYNAMIC SURFACES: CASE STUDIES

The *Air Flow(er)* project by Andrew Payne is a thermally active ventilation device that uses shape memory alloy as a sensor, processor and actuator. The device is imagined as a component of a double-skin façade system and can be integrated to enable the thermal exchange between the perimeter zone and outside. The active component in the *Air Flow(er)* device is a custom manufactured SMA wire that opens the device when temperature rises thus enabling the air flow through the aperture. After the heat is removed, the wires begin to cool off and the elastic cords pull each panel back into its closed position. In the Air Flow(er) two SMA wires cross over the module opening. When activated the mechanical force generated as the wires shorten rotates the two opposite panels over the pivot points to open them. The system utilizes a force of the elastic cords to pull the panels back in place as the wire cools (Fig. 1). According to Andrew Payne, because of SMA's sensitivity to temperature, *Air Flow(er)* can provide automatic response during the summer to the rising temperature in the cavity between the inner and outer skin. The hot air could be vented out of the building through the *Air Flow(er)* mitigating solar gain and decreasing the cooling load on the building's mechanical equipment. In the winter, absorbed radiation can be kept within the cavity of a double-skin facade with *Air Flow(er)* acting to seal the cavity and using the absorbed radiation to minimize the façade heat loss (Payne 2011).



An exploded axon drawing of the four-leaf prototype. Key: 1) rigid connector tubes, 2) inner tubes, 3) outer tubes, 4) panels, 5) wire mesh screen, 6) gusset plates, 7) frame, 8) elastic cords tied between panels and outer frame, 9) Shape Memory Alloy wires, 10) barrel crimp, 11) four-way connectors.

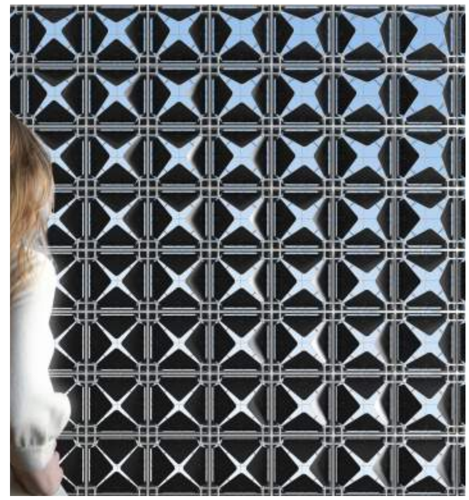


Figure 1: An exploded diagram of the four-leaf prototype assembly. Photograph of the possible module layout. Diagram and photo courtesy of Andrew Payne.

This simple materially actuated 'mechanism' is energy independent and operates silently according to the environmental heat it absorbs. It responds to the heat by gently moving panels to allow airflow from the glass cavity. But if we imagine an accumulated effect of this panels across a large glass wall – where glass cavities are of different sizes and therefore heating at different time intervals and where modules are strategically positioned to form a changing pattern across the large wall surfaces – the system could, in addition to its environmental contribution, generate dynamically changing material effects across the entire building façade.

This power of a silent dynamic environment afforded by SMA is best experienced in Philip Beesley's *Hylozoic Ground* Project. In this project a simple dimensional contraction of SMA wire is amplified and proliferated to create a rich and alluring environment that invites exploration and experiential involvement. Most of the dynamic elements in this project use a lever or a system of pulleys to amplify the effect of the SMA wire contraction. The environment includes several kinds of actuating elements: breathing pores, sensor lashes, filters, crickets and swallowing all of them actuated by SMA wires (Elsworthy 2010). The length of the SMA wire plays an important role in the amplitude of movement. The breathing pores and lashes are driven by ten-inch long Flexinol wire that is only 300 microns in diameter. The contraction of this long wire, amplified by mechanical leverage, translates into a curling motion of the mylar frond. Filters and crickets use shorter lengths of wire in series to provide more subtle kinetic responses. The wire diameter is also important since the weight the SMA wire can lift depends on its diameter. For example, an SMA "muscle" wire with a 0.004" diameter can pull 150 grams per one foot of wire while a 0.012" thick wire can pull 1,250 grams per foot of wire (Elsworthy, 2010). Figure 2 shows a breathing pore assembly diagram where the SMA wire (4) and a tensioned tendon (6), shown in color, act in unison to curl the mylar frond. (Position change of the mechanical leverage hand is also visible in the axonometric part of the diagram.)

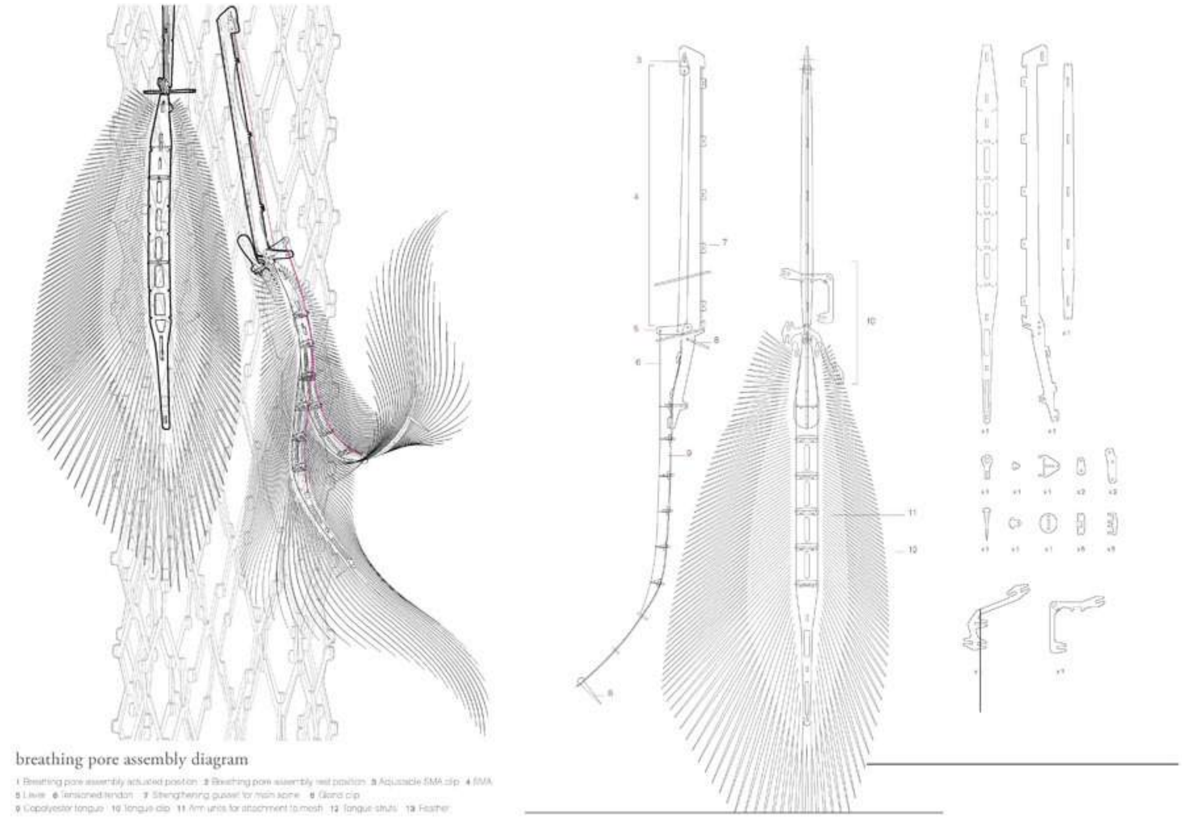


Figure 2: Hylozoic Ground project breathing pore assembly diagram. Drawing made by Eric Bury and Philip Beesley, courtesy of Philip Beesley.

In this project SMA wire is used mostly as an actuator; it is not used as a sensor, processor and actuator as in the Air Flow(er) project. Even though the use of SMA is a focus of this paper it is important to mention that other means of actuation are used in the *Hylozoic Ground* project, such as small direct-current motors, SMA powered pneumathic valves, and custom air muscles (Gorbet, 2010). The network of analog and capacitance-based sensors in communication with Arduino processors facilitate the response of the environment to the occupants. The complexity of this interactive environment lies in the orchestration and coordination of many dynamic regions. Over the years of development the *Hylozoic Ground* evolved into an immersive architectural environment " that behaves like a highly mobile crowd of interlinked individuals acting in chorus." (Gorbet, 2010). The *Hylozoic Ground* project hints at what future responsive environments could be. Its performance and contribution are in the exploration of the responsiveness and interaction, creating different experiences that proliferate as one moves through the environment. The environment touches or blows air at the visitor, its silent, animal like motion triggered by the presence of people and produced by the subtle work of SMA.

The *Living Glass* project by David Benjamin and Soo-in Yang is another project that questions the assumed inertness of architectural elements and assemblies. The main premise of the project was that an architectural element should respond to the varying conditions in its environment. To do so, the element would have to collect the information from the environment, process that information and trigger appropriate response of the surface. The resulting *Living Glass* surface is thin, transparent and light. It responds to carbon dioxide levels and opens to let in the fresh air. The surface has no motors or mechanical parts. The movement that opens and closes the surface is contained within the surface itself and is triggered by the embedded SMA wire. The rigorous studies of the relationship between the embedded wire and the surface cuts were conducted. Benjamin and Yang experimented with the variables of thickness, topography, length of surface cuts, shape of the cuts and wire placement in order to determine the most effective relationship between the cuts and the wire (Benjamin and Yang, 2006). A full-scale prototype features an array of gills linked to an array of sensors. Activation of the strategically embedded SMA wires opens and closes the gills in response to human presence (Figure 3).

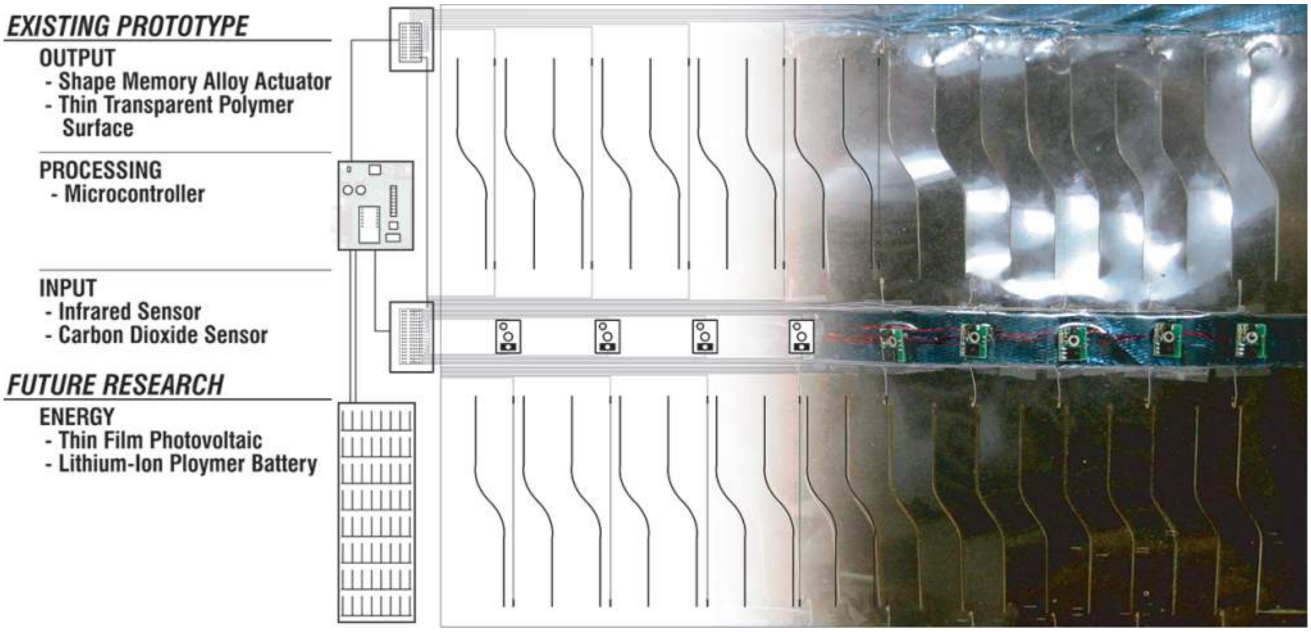


Figure 3: Lliving Glass project prototype. Courtesy of David Benjamin

Embedding the shape memory alloy wire into the surface presents another way to actuate that surface. This approach requires experimentation and studies of the surface movement caused by the wire. In the case of *Living Glass* project the relationship between the cuts and the wire was carefully studied since deformation of the surface depended on the shortening of the wire i.e. a straight movement across the surface.

The SMA wire, however, can be trained to conform to a particular shape when heated. When the previously trained wire is embedded into the surface it can alter the surface topography and produce a robust movement. This approach was taken in the *SKiN* research project developed by the author. The initial phase of the project focused on the studies of movement of the "trained" SMA wire and its effects on the silicone grid and silicone surface in which the wire was embedded. The "V" shaped memory alloy joints were inserted into the silicon tubing (Figure 4). The network joints were "programmed" to open and close and by doing so generate movement of the entire network. This experiment examined the capacity of an SMA wire joint to act as a point source of actuation within the surface. To better understand the gradient of movement the grid was restricted by anchoring joint points to a flat surface in a variety of configurations. The behavior ranged from expanding grid cells to vertical movements of the grid's regions. The vertical movement was surprisingly agile and pronounced (Figure 4).

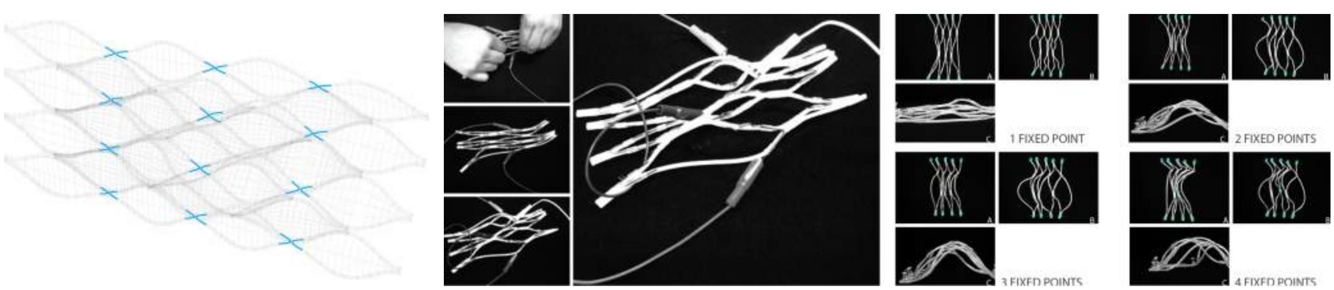


Figure 4: Point actuation using "V" joints and fixed-point test showing the grid deformation.

The second experiment examined the capacity of SMA wire to act as an embedded linear source of actuation. The 'long' (45cm) pieces of SMA wire trained/baked into large amplitude (15cm) waves was treaded through the silicone tubing grid. The silicone tubing grid was then integrated into a silicone surface. The fusion of the grid and silicone cells created a structural yet flexible surface that achieved a certain level of material equilibrium; the SMA wire pulled the surface into a particular shape dictated by the large amplitude wave shape while silicone layer pulled the material system back to its original shape, deforming the SMA wire in the process. In this experiment the accumulation of local movements resulted in a complex global movement where each shift of a cell depended on the movement of adjacent cells or regions (Figure 5).

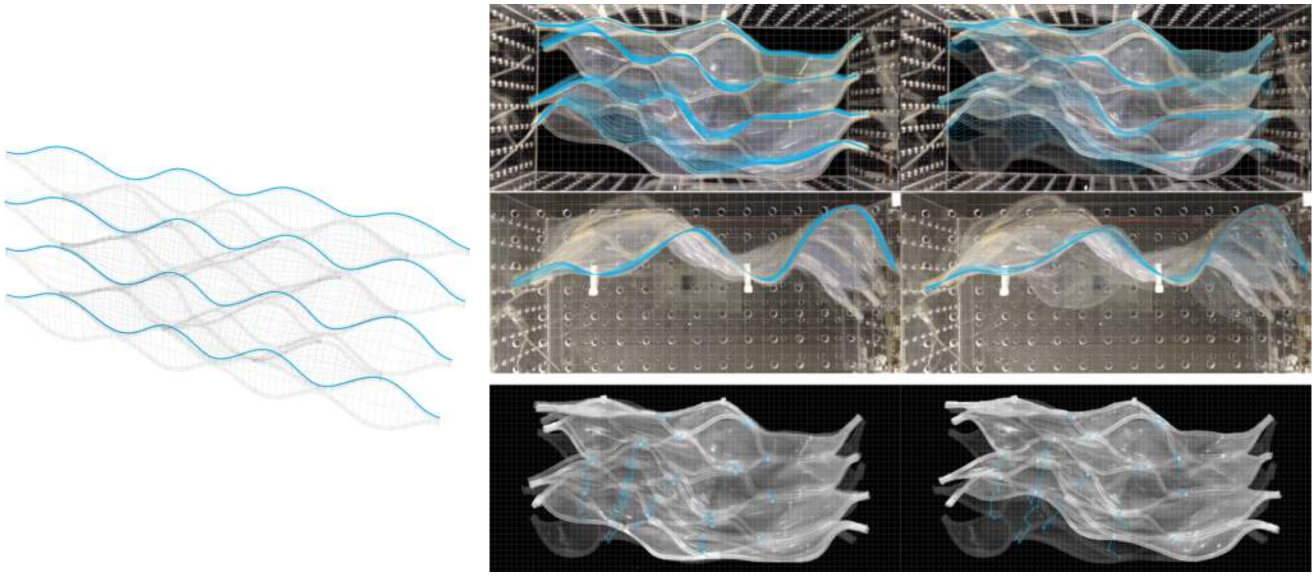


Figure 5: Using motion tracking to map the movement of the diagrid points.

Both, point and linear actuation provide a good strategy to capitalize on aggregation of local movements to produce a global dynamic surface effect. Point actuation facilitated greater variety of movement. Continually reversed joints could produce twisted movement. Linear actuation produced more dramatic movement and reduced the number of connections between the electrical wire and the SMA. Combination of these two strategies could result in a number of patterns that can produce different dynamic surface choreographies.

In contrast to the *SKiN* project, where movement of the surface was at the center of the exploration, the point of departure for the design of the *Lattice* project material system was material variability and structural hierarchy found in the naturally constructed materials. This was addressed on two levels. First, an attempt was made to distribute the structural hierarchy across several scales of the material system by using a gridshell lattice and its capacity for deformation as a basic structure of the system. Second, the material variability was explored by adding SMA actuators to the structural lattice to produce deformation (alter the cell geometry of the lattice system) and blur the boundary between functional and structural roles within the system. The gridshell lattice is designed as a uniform grid layout made from elastic members and organized into intersecting three-layered ribs. What is particularly interesting about this configuration is that, because of its connectivity, the cross-sectional local manipulation of the grid “cell” geometry enables a global change of a gridshell form. The gridshell form is altered when the distance between the peaks in the top or bottom and the middle grid layer is changed. The change in distance is achieved by strategically placing SMA springs between the gridshell layers. Their activation introduces a tension into the middle layer of the lattice. This tension causes bending of the middle layer that results in the movement of the entire lattice structure (Figure 6). Strategic placement of the actuators across the lattice produces accumulated bending effect and can deform the entire surface. SMA is here used to produce the movement of the material system by introducing tension that alters the geometry of the system causing bending and ultimately movement of the structure. This structural behaviour of the gridshell was instrumental in the development of the kinetic lattice system. Integrating SMA with the lattice enabled variation in the shape and behavior of the proposed structure. This is best described in the sectional diagram in Figure 6 that shows the sectional change of the “cell” geometry and the consequent change of position.

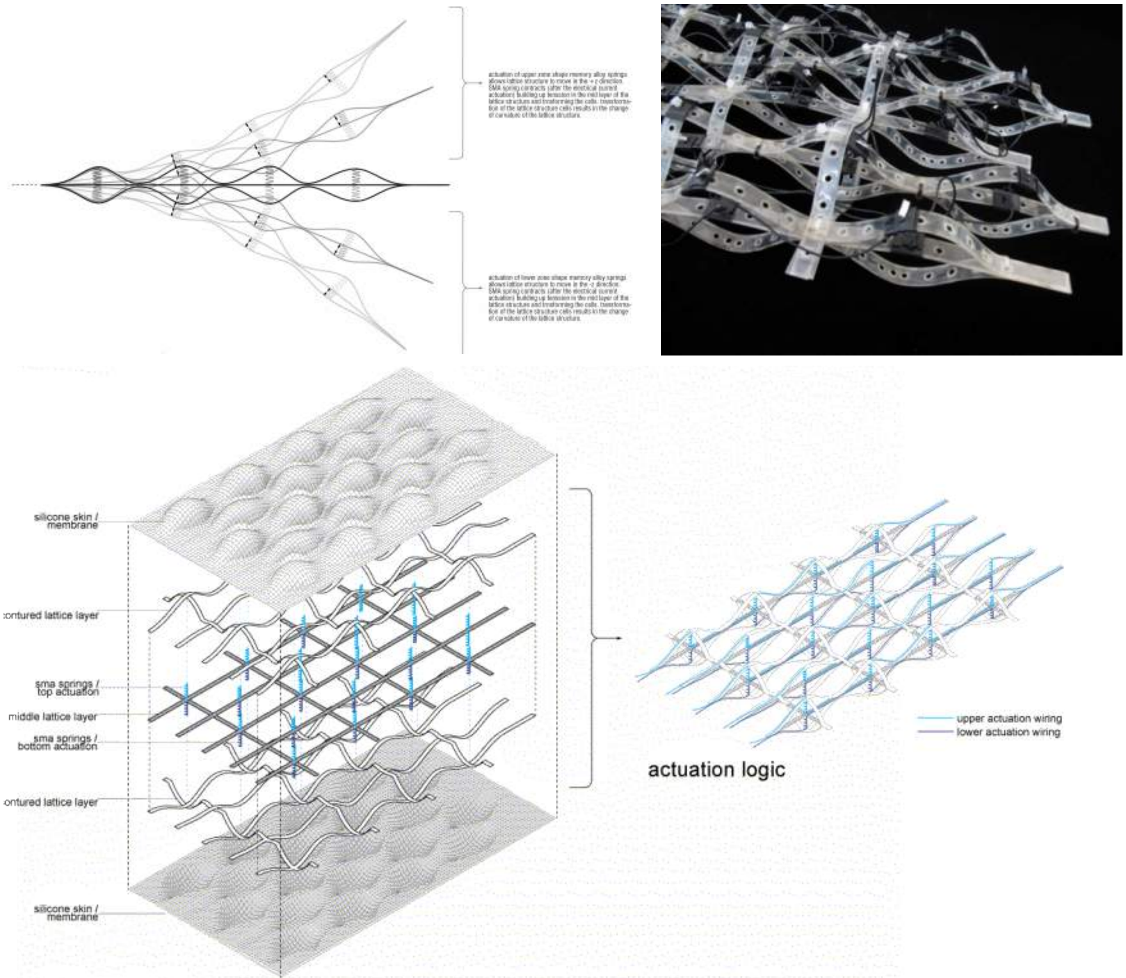


Figure 6: Amplitude of bending and cell deformation after SMA spring actuation. Lattice structure physical prototype. Lattice assembly and the actuation logic.

CONCLUSION

This paper describes concepts of using SMA as a smart material technology to construct building assemblies capable of adjusting to constantly changing surroundings and environmental conditions. Integration of these technologies into material assemblies underlines possibilities for re-thinking architectural assemblies as adaptive and dynamic material systems. Buildings that respond to change in their environment could have could a transformative effect on the built environment and on how we experience and inhabit that environment. A decade ago Mark Goulthorpe stated:

“Increasingly, I think of a project as a distribution of material in space, not as the assemblage of preformed elements. We are moving from collage to morphology, looking to deploy material as material for its spatial and surface effects …” (Goulthorpe 2005)

In other words, there is a shift in interest away from elements and towards morphology. Distributing material, and not preformed elements, suggests a different operational scale – that of material intensities. We are starting to incorporate a new series of materials with designed behaviors. Their inherent dynamic quality, that in some cases encompasses a movement (as in SMA), is beginning to undermine traditional model of material selection in architecture. The model of choosing a material for its properties is being shifted towards choosing a material for its behavior or even designing a material behavior to suit a design challenge. We see this in medicine where new materials are made (or grown) to address particular medical challenges.

Technology transfer from fields such as material science, biomimetics, autonomous robotics, interface design and computation are not only influencing the range of the materials used in architecture but also the very scale at which they are deployed. As discussed previously, the latest tendencies of integrating material design and sensing technologies are clearly favoring responsiveness and adaptation over static and inert architectural conditions.

It is still difficult to imbue synthetic matter/material with the kind of “intelligence” that would recognize changes and adapt to them in an organic way. But the shift is here. Introduction and use of this new class of materials brings into architecture a level of innovation that is changing the role of a designer. Confluence of information and matter, the rise of interactive surfaces and use of innovative materials ushers “impactful transformation of inert physical materials into connected, information-rich and increasingly lifelike objects” (Brownell, 2016). The digital and analog worlds are merging in the built environment welcoming a new class of materials and an unprecedented scale of innovation that together are changing the role of the designer. (Brownell, 2016)

The future of dynamic building skins will likely belong to low-energy systems that can harvest the heat from the sun or the kinetic energy of the wind. In many experiments described in this section, the “sensing” and “actuating” capacities were built into the material, eliminating the need for complex mechatronic assemblies. Such systems of dynamic activation that rely on innate properties of materials are perhaps the most promising direction for developing adaptive building envelopes.

REFERENCES

Benjamin, David, and Yang, Soo-in. 2006. “Flash Research 1: Living Glass.” in *Life Size*, 33-51. New York, Graduate School of Architecture, Planning and Preservation of Columbia University.

Brownell, Blane. 2016. “The Architect as the Orchestrator of Information” http://www.architectmagazine.com/technology/the-architect-as-the-orchestrator-of-information_o (accessed May 15, 2016)

Elsworthy, William. 2010. “Component Design and Actuated Devices An Evolutionary Process.” in *Hylozoic Ground: liminal responsive architecture* by Philip Beesley, 96-111. Riverside Architectural Press.

Gorbet, Rob. 2010. “Revealing the Hylozoic Ground Interaction Layer.” in *Hylozoic Ground: liminal responsive architecture* by Philip Beesley, 112-124. Riverside Architectural Press.

Goulthorpe, Mark. 2005. Matter. in *Crib Sheets: Notes on Contemporary Architectural Conversation*. ed. S. Lavin and H. Furjan, 17. New York, The Monacelli Press.

Jeronimidis, George. 2004. “Biodynamincs.” in *Emergence: Morphogenetic Design Strategies*, ed. Michael Hensel, Achim Menges and Michael Weinstock, 92-95. Chichester, Wiley-Academy Press.

Payne, Andrew. 2010. “Air Flow(er)” http://www.liftarchitects.com/#/air-flower/ (accessed May 16, 2016)

Speck, Thomas and Rowe, Nick. P. 2006. “How to become a successful climber - mechanical, anatomical, ultrastructural and biochemical variations during ontogeny in plants with different climbing strategies.” in Proceedings of the Fifth Plant Biomechanics Conference, (2006): 103-108.

“Technical Characteristics of FLEXINOL® actuator wires” About FLEXINOL® Shape Memory Alloy Wire. Dynalloy, Inc., n.d. http://www.dynalloy.com/pdfs/TCF1140.pdf (accessed May13, 2016).

MAPPING RESPONSIVE ENVELOPES

Material culture evolution and climatically responsive building facades

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ABSTRACT

This research paper proposes the transfer of biological evolutionary methods to the field of climatically responsive building facades. Through charting their trajectories and situating them across the physical and biological sciences, the paper will explore knowledge transfer, historical flows and the fate of information from a sustainable perspective.

Despite similarities to biological evolutionary processes, the application of biological methods does not directly correlate to responsive building facades. Through a database of precedents and projects, a hybridized method of mapping will be developed as a means towards understanding the genus of ideas, mutation, and selection within this process so as to establish to what degree it is similar to that of biological systems as well as Gould and Elderedge's (1972) theory of 'punctuated equilibrium'. 'Punctuated equilibrium' states that evolution within biological systems occurs in short, sharp bursts after long periods of inactivity, contradicting orthodoxy of evolution as a slow, gradual process. This theory proves correct for climatically responsive facades due to the convergence of technology with cultural awareness for environmentally conscious architecture. Temkin and Eldredge (2007), in their application of phylogenetic analysis on musical instruments, identified lateral exchange of information as the most significant factor in material culture systems.

Through developing a hybridized map of climatically responsive facades, this research will indicate characteristics, ideas, and historical flows of information as well as their subsequent fate. Within material culture there is considerable conservatism, pointing to selection by designers and manufacturers as an inhibitor of evolution. As a result, this process identifies new architectural connections and areas of focus where distinct innovation may occur.

KEYWORDS

History of facades; façade theory; material culture evolution; climatically adaptive; future trends; innovation

INTRODUCTION

Climatically responsive building facades have been well documented in recent years due to the emergence of design consciousness towards energy efficient architecture. Most sources catalogue projects according to their location, climate, or typology, like *Kinetic Architecture: Designs for Active Envelopes* by Russell Fortmeyer. However, none aims to establish their evolution or the impact of other industries on their form and function through the consideration of principles, techniques, objectives, and technologies. By defining these projects as 'material culture artifacts' and placing them in a wider context, their evolution can be charted. Material culture evolution refers to the study of tracing changes in physical form, the transmission of information, and the 'descent of modification' of cultural artifacts, or objects, over a period of time (Lycett, 2015). The process by which the evolution of climatically responsive facades is mapped will offer an insight into how designers and manufacturers borrow, share, and innovate in the digital age, with the hope of highlighting common ideas, themes, and concepts as well as patterns of innovation. Designers and makers must be aware of this network of information transmission in order to truly assess the value of current orthodoxy. In material culture, the danger exists whereby flawed concepts continue to be reproduced because of human presence within the system, despite how marketplace economics may limit the threat. In researching such evolutionary trends, and by identifying horizontal and vertical transmissions of knowledge, we become aware of the significance of inheritance in creative genus and idea**s,** which, according to some research, creates stability and conservatism in design and manufacturing. Through an overview of material culture theory, evaluating its application to contemporary, climatically responsive facades and applying a hybridized method of mapping knowledge transfer, historical flows, and the fate of information, it hopes to offer designers and makers a broad overview of this network which could lead to new and broader innovation.

BACKGROUND

The application of phylogenetic analysis to material culture artifacts has become a common theme in recent years with the aim of identifying cultural transmission and knowledge transfer. Phylogenetic analysis is the reconstruction of evolutionary history which studies the patterns of relationships in physical and genetic characteristics between organisms, generally conveyed through evolutionary trees. Previous attempts to apply this area of study to material artifacts have included cornets and Baltic psalteries (Temkin & Eldredge, 2007), ornament patterns of Turkmen textiles, (Tehrani & Collard, 2002) and skateboards (Prentiss et al., 2011) where a cultural transmission thrives. As a result of this work, key similarities and differences between material culture evolution and biological evolution have been highlighted. One of the most interesting similarities, first noted in biological systems by Eldredge and Gould (1972), explains why biological systems, and later material artifacts, experience rapid changes and development followed by long periods of dormancy and stagnation. 'Punctuated equilibrium' proposed that evolution is not a gradual process, but one which occurs in short, sharp bursts of rapid change. Despite this, obvious differences occur. Within the biological realm, lineage occurs, creating "vertical transmission of genetically-ensconced information (meaning parent to offspring)" (Temkin & Eldredge, 2007). For this reason, mapping of biological lineages develops a neatness and compartmentalization. Evolution takes place in a restricted framework dependent on adaptation and mutation if organisms are to survive in the fight for resources. In contrast, material culture artifacts can be described as networks which link historical information while indicating idea theft, 'directed variation', 'selection' and horizontal transmission of knowledge (Barnet, 2004). Arguably, these are the most important dynamics within material culture systems because networks proliferate as knowledge and technological transfer from outside industries increases. Vital to this process is the human presence – a maker or designer.

Identification of these dynamics in material culture evolution primarily considers morphology of the 'artifact' or object, as seen in the indicated studies, despite human presence within the system, which plays a critical factor. At the heart of conscious design is what Eldredge refers to as 'directed variation' (Wertheim, 2004). The maker mimics concepts, components or models because of their perceived benefits, either in manufacturing or in performance. Despite this, there is still an evident conservatism within material culture artifacts even though no genetic constraints exist. 'Selection' is the reason for this and it exists for two reasons. The role of manufacturers accounts for the first. As makers, they are aware of all possibilities within the design framework but the expense of resources to manufacture – tooling and machinery for example – restricts the design scope to a selected number, primarily based on marketability and demand. Within this framework of manufacturing and selling, as Eldredge explains, the design, or 'type', remains fundamentally similar throughout time and individual exemplars, or 'tokens', "are more-or-less faithfully rendered versions of the types" (Barnet, 2004). The second form of 'selection' is due to the demand by clients for the same 'model/type' as others while demanding uniformity and consistency in product quality and price. These restrictions in production and fabrication result in limited variation of the artifact when considering its morphology. In contrast, understanding the network of social interaction and learning provides insight into why conservatism exits in human-made objects.

The dynamics of human makers are identified as social learning mechanisms, which foster and enhance horizontal knowledge transfer, as well as 'idea theft'. Social learning can be defined as "learning that is influenced by observation of, or interaction with, another animal or its products" (Heyes, 1994). Lycett (2015) labels social learning as an umbrella term for various mechanisms through which information is inherited or shared amongst individuals. Such mechanisms can range in complexity but are generally defined by four distinct characteristics: stimulus enhancement, emulation, imitation, and teaching (Lycett, 2015). Stimulus enhancement refers to the effect one individual has on another's behavior through exposure to a particular stimulus. This takes place either through the process of making or with the material itself, not with the aim to directly copy, but to enforce behavioral adjustments (Heyes, 1994; Lycett, 2015). Emulation, as Lycett defines it, is similar to Eldgredge's term 'selection'. It refers to copying of objects formed by an individual without replicating the demonstrator's exact actions. Within the field of climatically responsive facades, this form of social learning is observed in the proliferation of shading devices through simple vertical elements copied globally, without applying the exact same mechanisms. Imitation differs from emulation as it is the 'direct copying of the precise actions of a demonstrator which could bring about the same effects or results (Lycett, 2015; Whiten et al., 2004). Architecture has been a very specific focus of material culture studies because it is rooted in location and context. It is a work of art as well as a device or machine, which adds layers of complexity. "It is both a work of art and a tool for living, combining aesthetic with utilitarian drives at a variety of conceptual levels" (Prown, 1982). All these conditions, particularly since the development of digital technologies and communications, have made social learning easier and more accessible. As a result, these mechanisms generate a significant network of information and knowledge sharing, far more complex than biological systems.

METHOD

The consequence of this complexity requires a hybridized method of analysis and interpretation when mapping contemporary responsive building envelopes by establishing a data sample of real buildings, research prototypes, and speculative designs. A descriptive process of each project was then undertaken and finally mapped through cladistic and phenetic interfaces. Firstly, this paper considers contemporary, climatically responsive facades as a starting point, but is not limited to this, and in some cases encompasses the holistic, broader interpretation of the term responsive, including media facades. A database of projects (Fig.1) was established which offers varying project 'types' in order to portray a cross-section of designs, from Jean Nouvelle's Arab Institute (9), built in Paris in 1987, to concepts, like Building Integrated Concentrating Solar Façade (44) by Centre for Architecture, Science and Ecology (CASE). As a result, the examples have been exposed to varying degrees of holistic architectural application, which include client approval, budgets and schedules.

Subsequently, the database underwent an objective analysis based on three stages - description, deduction, and speculation (Prown, 1982). All steps are vital in ensuring the perspectives and experiences of the investigator do not distort the analysis of the artifact. The description records the object itself through internal evidence – drawings, images, and models – to highlight dimensions and materiality for example. Deduction allows the investigator to engage intellectually and sensorily as well as determining an emotional response to each of the projects. Here, some allowance for interpretation exists as it contributes to alternative approaches to understanding a very specific field and set of artifacts. Speculation allows for the formulation of hypotheses aimed at exposing effects noted by the investigator. It also accommodates a 'program of research', which exposes external data and information. External evidence supports findings and allows for a continual readjustment of hypotheses and ideas, discussed through the findings. The output of these stages (Fig.1) notes the projects according to object (A), purpose (B), aim (C), technique (D), and movement (E) pattern. Unlike biological systems, which use analytics of DNA, presenting black and white information, design relies on interpretation and inference on the part of the observer. Drawings, patents and images infer connections in idea genus while designers and makers indicate human and social relationships, which affect 'selection' and social learning mechanisms as discussed earlier. The method required the development of unique approaches to 'historical interfaces' when considering the evolution of climatically responsive facades. In order to visualize the fate of information and knowledge transfer in the design of contemporary, climatically responsive facades, phyletic interfaces were used as a basis to develop two alternate network maps. Simple phyletic methods - branch structures - were used, namely phenetic and cladistics approaches, in order to initiate the mapping process. Phenetics attempts to classify organisms based on their similarities and differences without regard for evolutionary relationships. This involves the description of the organisms, qualitatively and quantitatively, the evaluation of their similarity, and the identification of clusters. Morphological similarities generate groups of organisms that form a network of relationships but do not necessarily share the same evolutionary histories (Fig. 2). On the other hand, cladistics can be defined as the study of pathways of evolution. The network created expresses ancestor-descendant relationships, which exemplifies evolutionary modifications over time. Cladistic mapping used a smaller sample set, indicated by dots (Fig. 1), and demonstrates interconnection of concepts, ideas and knowledge from one project to another over time (Fig. 3).

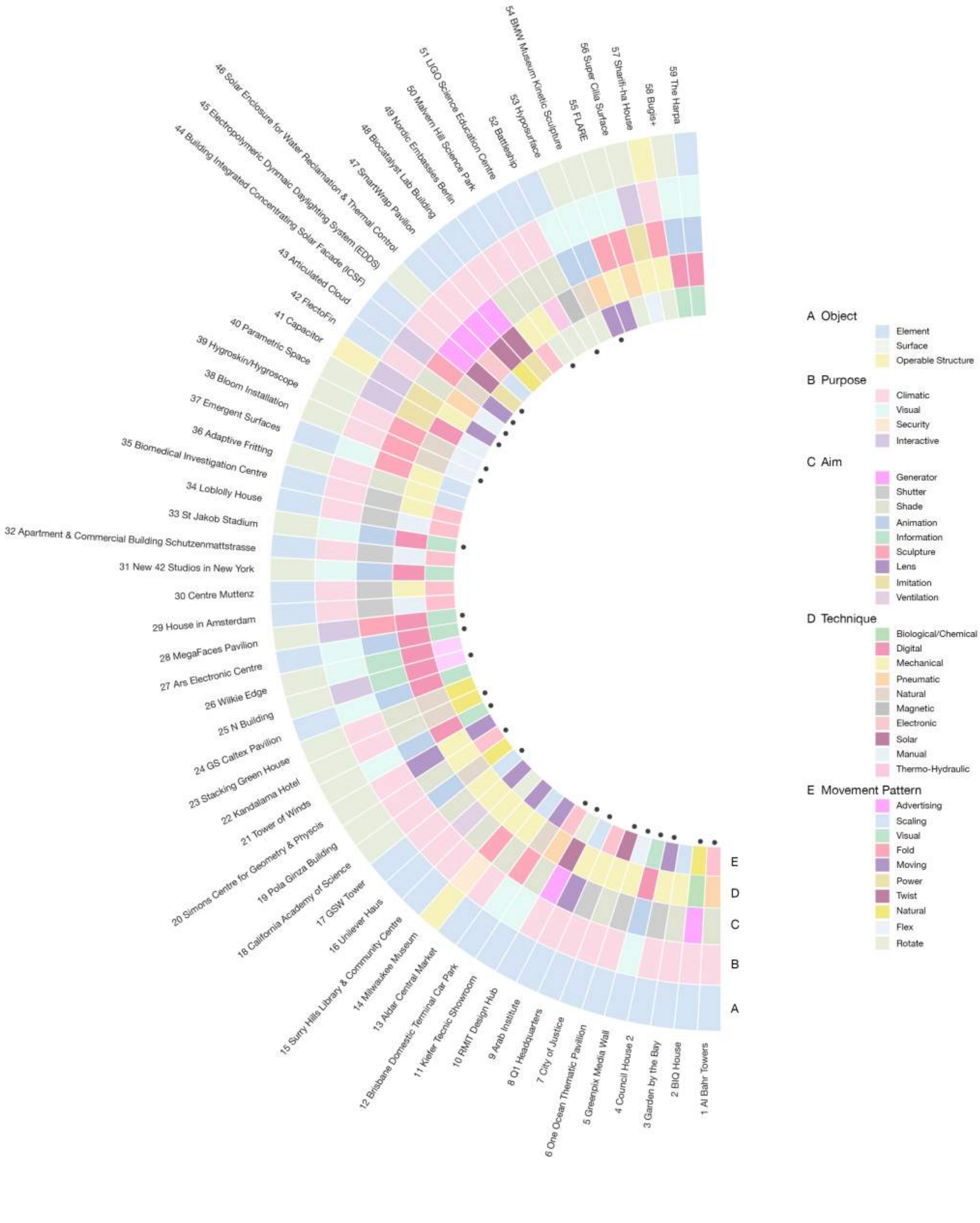
1 Al Bahr Towers
2 BIQ House
3 Garden by the Bay
4 Council House 2
5 Greenpix Media Wall
6 One Ocean Thematic Pavilion
7 City of Justice
8 Q1 Headquarters
9 Arab Institute
10 RMIT Design Hub
11 Kiefer Tecnic Showroom
12 Brisbane Domestic Terminal Car Park
13 Aldar Central Market
14 Milwaukee Museum
15 Surry Hills Library & Community Centre
16 Unilever Haus
17 GSW Tower
18 California Academy of Science
19 Pola Ginza Building
20 Simons Centre for Geometry & Physcis
21 Tower of Winds
22 Kandalama Hotel
23 Stacking Green House
24 GS Caltex Pavilion
25 N Building
26 Wilkie Edge
27 Ars Electronic Centre
28 MegaFaces Pavilion
29 House in Amsterdam
30 Centre Muttenz
31 New 42 Studios in New York
32 Apartment & Commercial Building Schutzenmattstrasse
33 St Jakob Stadium
34 Loblolly House
35 Biomedical Investigation Centre
36 Adaptive Fritting
37 Emergent Surfaces
38 Bloom Installation
39 Hygroskin/Hygroscope
40 Parametric Space
41 Capacitor
42 FlectoFin
43 Articulated Cloud
44 Building Integrated Concentrating Solar Facade (ICSF)
45 Electropolymeric Dynmaic Daylighting System (EDDS)
46 Solar Enclosure for Water Reclamation & Thermal Control
47 SmartWrap Pavilion
48 Biocatalyst Lab Building
49 Nordic Embassies Berlin
50 Malvern Hill Science Park
51 LIGO Science Education Centre
52 Battleship
53 Hyposurface
54 BMW Museum Kinetic Sculpture
55 FLARE
56 Super Cilia Surface
57 Sharifi-ha House
58 Bugis+
59 The Harpa
E
D
C
B
A
A Object
Element
Surface
Operable Structure
B Purpose
Climatic
Visual
Security
Interactive
C Aim
Generator
Shutter
Shade
Animation
Information
Sculpture
Lens
Imitation
Ventilation
D Technique
Biological/Chemical
Digital
Mechanical
Pneumatic
Natural
Magnetic
Electronic
Solar
Manual
Thermo-Hydraulic
E Movement Pattern
Advertising
Scaling
Visual
Fold
Moving
Power
Twist
Natural
Flex
Rotate

Figure 1: List of projects, precedents and prototypes used in this paper to track responsive façade design. Each was analyzed within the categories listed.

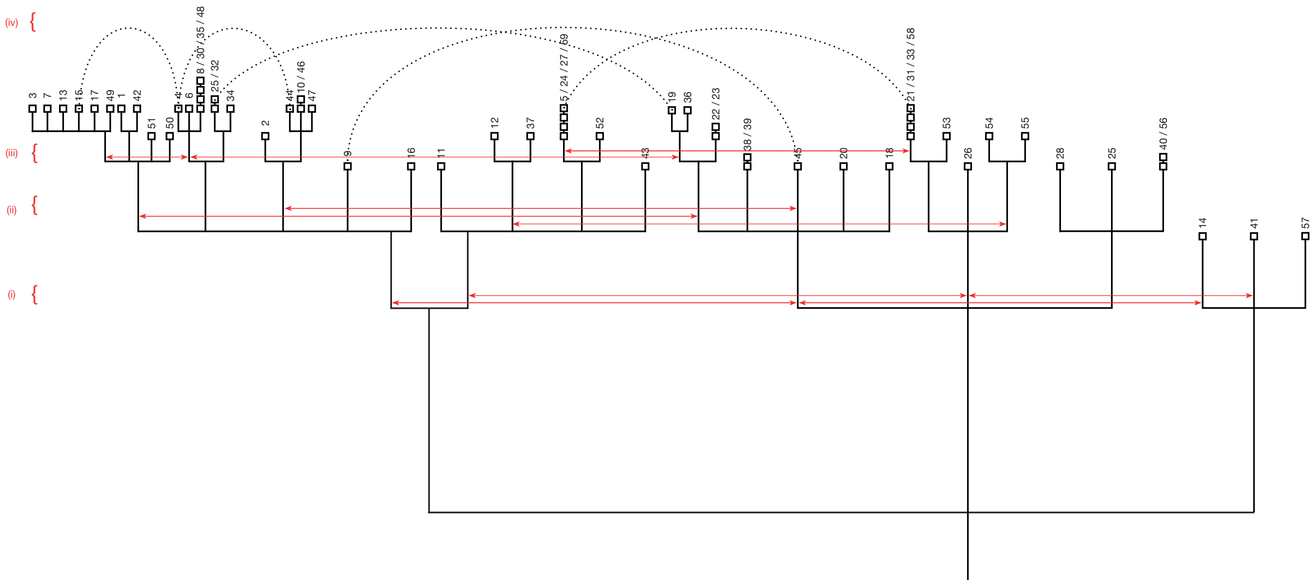

Figure 2: Interface based on a phenetic approach. Numbers correspond to projects as listed (Fig. 1). Red arrows – (i) purpose; (ii) aim; (iii) technique – and arched lines – (iv) movement pattern – indicate characteristic connection. Note groupings of projects that carry identical traits indicating areas 'selection' and conservatism.

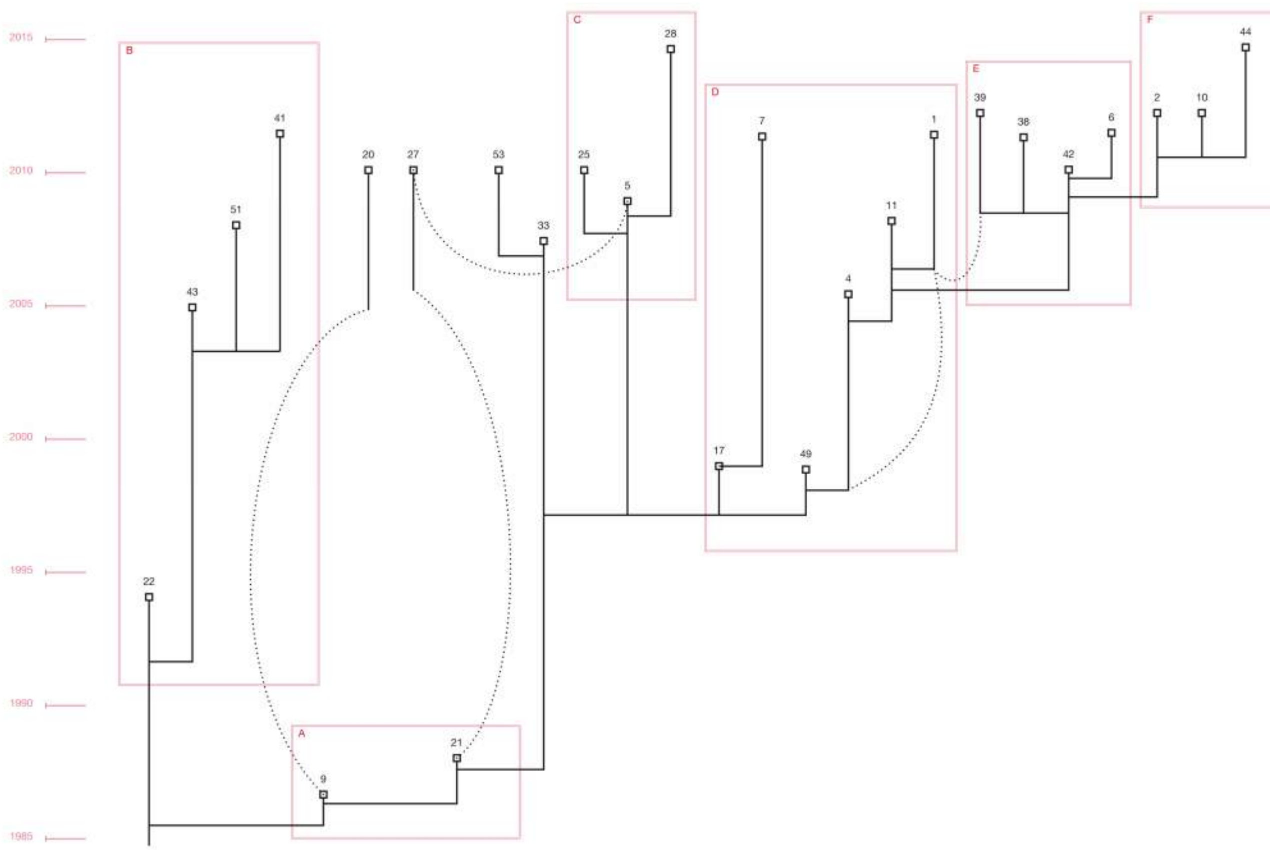

Figure 3: Network map based on cladistics interface of climatically responsive building facades. Numbers correspond to project as listed (Fig. 1). Arched lines indicate transfer of certain technological innovations, tracking the fate of information and knowledge rather than the morphological characteristics of the projects.

FINDINGS & DISCUSSION

The database and network maps identify certain characteristics while highlighting interesting aspects to the form, development, and evolution of responsive facades. The phenetic interface (Fig. 2) does not depict the morphological evolution of a certain model, but instead charts the fate of information and concepts through the development of responsive building facades. It results in projects, which, on the surface, appear completely unrelated but adopt extremely similar design principles. An example of this is the Al Bahr Tower (1), by AEDAS, and FlectoFin (42), by Institute for Building Structures and Structural Design (ITKE), which only vary in the movement pattern applied; all other principles are identical. Projects, which do appear similar, result in close proximity. Of particular note is Bloom Installation (38), by DO|SU Architects, and Hygroscope/Hygroskin (39), by Institute for Computational Design (ICD). In both cases they use material responses to climatic conditions to open and close, allowing light and ventilation. Interestingly, a number of clusters of projects occur while there is significant sharing of characteristics, despite vastly differing morphologies as indicated through various parameters shown by the red arrows - purpose (i), aim (ii), technique (iii) – and arched lines – movement pattern (iv). In contrast, the cladistics interface traces projects over time and is ancestor dependent. This is because of the obvious social learning mechanisms at work, which allows for idea theft, imitation and emulation to occur. The structure reflects ‘areas’ of conceptual understanding and implementation, identified as: (A) pioneers; (B) interpretation of nature’s role; (C) interpretation of digital and media; (D) climatic control; (E) methodological impact; and, (F) façade as producer. Arched lines indicate non-vertical instances of information transfer.

The application of material culture theory to climatically responsive building envelopes supports the concept of ‘punctuated equilibrium’, highlighted by conservatism amongst designers, makers, and clients (Fig. 2) while it also demonstrates areas of conceptual focus, exposing approaches and social networks that have the potential to encourage speciation (Fig. 3). Firstly, it is notable that the concept developed by Eldredge and Gould (1972) of ‘punctuated equilibrium’ is applicable to the case of responsive building facades. Although building facades have always acted in a responsive manner, in recent years, primarily through the rapid development of technology, the field is experiencing a period of sharp, and potentially short, burst of change. The Oil Crisis of the 1970s fostered green, energy efficient building envelopes, driving design and manufacturing towards high performance envelopes, which are intelligent and reactive to weather, climate, and use. In conjunction with the boom of digital technologies, enhanced communications, and fabrication, it has allowed for significant diversity and development in the last 25 years. This is notable in the number of projects that sit alone on strands. Increasingly, however, certain ‘types’ are becoming standard as selection and closer social learning takes place. Multiple projects along a strand indicate such ‘types’, like 8, 30, 35 and 40 representing folded mechanical shutters (Fig. 2). Stagnation and conservatism are becoming more common for various reasons. Increased connectivity through global, digital communications offers leads to more conventional designs representing ‘tokens’ of a ‘type’. The impact of closer social learning mechanisms sees slight iterations of previously established examples because there is demand from clients and it is safe for designers and contractors. As stated previously, clients generally seek products that are similar to others and demand a stable price. Projects, viewed holistically, are ‘tokens’ rather than ‘types’, where branches signify principles and concepts, which are similar, not necessarily morphologically. Therefore, it may lead to the proliferation of ‘poor’ design and idea genus. In traditional material culture artifacts, like the cornet or skateboard, ‘types’ become successful because of marketplace demand, as users appreciate their design and/or cost. This leads to famous or notable models of artifacts. With regard to façade design, ‘types’, which exist at the level of conceptual design and component specification, thrive because of their perceived success and benefits. Double skin facades and kinetic shading devices represent the ‘types’ most prevalent today. Even though some designs appear significantly different, they are merely ‘tokens’ of the ‘type’. At a more detailed level, there is a tendency for designers to select standardized components, which manufacturers produce in high quality and quantity for a considerably lower cost. This leads to vastly differing costs and quality of product and, generally speaking, distinct branching in evolutionary development. However, it is at a conceptual level, and the specific function or aim of climatically responsive facades, where stagnation and stasis occur. The ‘lock-in’ effect limits the choice for designers, manufacturers, and clients due to tooling, resources, and the costs required to break molds. On the other hand, charting these projects in a cladistics process highlights what potential future developments and evolutionary processes that encourage speciation. It allowed projects to be clustered according to similar traits despite varying evolutionary histories. Two distinct clusters are notable, indicating current research focus and drive, which break near-market products and ‘types’; methodological impact (E) and façade as producer (F). Here, conceptual applications to the design of climatically responsive facades are occurring which go beyond responding to marketplace demands – an obvious form of selection. In order to drive advancement of new approaches to climatically responsive architecture, these areas need to be exploited due to their independence from marketplace demands. Each area relies heavily on advanced social learning afforded by global, digital communications.

CONCLUSION

Through the evolutionary mapping process, it is clear that the current development of climatically responsive architecture relies on a global network of designers and makers. Information and design knowledge are shared and borrowed which, in many cases, leads to only slight iterations of an overriding concept or idea, the most obvious of which is the moveable, mechanical solar shade and the double skin façade. As a result, these concepts have created major stability and conservatism in the field. This is due to what could be considered the 'lock-in' effect, seen in various global technologies and industries, a good example of which is the car. Driven by market forces, manufacturers and designers focus on certain processes in design and production in order to function profitably – a 'selection' which inhibits innovation. Currently, major innovation occurs in research institutes, where focus is on the development of specific prototypes, technologies, and/or methodologies rather than considering a holistic view of the field, which includes marketability and wholesale manufacturing. These organizations, including CASE, ICD, ITKE and Hoberman Associates, utilize revolutionary design methodologies and manufacturing techniques. They generally apply the greatest degree of knowledge transfer from other industries but struggle to bridge the gap to full-scale application, due to economic costs, or undergo the rigor of holistic architectural application – including budgets, schedules, and building codes. However, this exemplifies the extreme potential for advancement in the evolutionary process as the use of design ideas, methodologies, and technologies from alternate industries allows for rapid change, dynamism, and, key to climatically intelligent architecture, speciation.

REFERENCES

Barnet, B., 2004. Material Culture Evolution: An Interview with Niles Eldredge. *The Fibreculture Journal*. Available at: http://three.fibreculturejournal.org/fcj-017-material-cultural-evolution-an-interview-with-niles-eldredge/.

Eldredge, N. & Gould, S.J., 1972. Punctuated Equilibria: An Alternative To Phyletic Gradualism. *Models In Paleobiology*, pp.82–115. Available at: http://www.blackwellpublishing.com/ridley/classictexts/eldredge.pdf.

Heyes, C.M., 1994. Social learning in animals: categories and mechanisms. *Biol. Rev.,* 69, pp.207-231.

Jordan P, Shennan S., 2009. Diversity in hunter–gatherer technological traditions: mapping trajectories of cultural 'descent with modification' in Northeast California. *Journal of Anthropological Archaeology*, 28, pp.342–365

Lycett, S.J., 2015. Cultural evolutionary approaches to artifact variation over time and space : basis , progress , and prospects. *Journal of Archaeological Science*, 56, pp.21–31. Available at: http://dx.doi.org/10.1016/j.jas.2015.01.004.

Moore, JH., 2004. Putting anthropology back together again: the ethnogenetic critique of cladistic theory. *American Anthropologist*, *96,* pp.925–948.

Prentiss, A.M. et al., 2011. Get Rad! The Evolution of the Skateboard Deck. *Evolution: Education and Outreach*, 4(3), pp.379–389.

Prown, J.D., 1982. Mind in Matter: An Introduction to Material Culture Theory and Method. *Winterthur Portfolio*, 17(1), pp.1–19.

Tehrani, J. & Collard, M., 2002. Investigating cultural evolution through biological phylogenetic analyses of Turkmen textiles. *Journal of Anthropological Archaeology*, 21, pp.443–463.

Tehrani J, Collard M., 2009. The evolution of material culture diversity among Iranian tribal populations. *Pattern and Process in Cultural Evolution*, pp.99–112.

Temkin, I. & Eldredge, N., 2007. Phylogenetics and Material Cultural Evolution. *Current Anthropology*, 48(1), pp.146–154.

Wertheim, M., 2004. Scientist at Work - Niles Eldredge; Bursts of Cornets and Evolution Bring Harmony to Night and Day. *The New York Times*. Available at: http://www.nytimes.com/2004/03/09/science/scientist-work-niles-eldredge-bursts-cornets-evolution-bring-harmony-night-day.html?pagewanted=all.

Whiten, A. et al., 2004. How do apes ape? *Learn. Behav*, 32, pp.36-52.

VERIFICATION OF INSULATING GLASS UNITS

A new approach for the glass design for discussion

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ABSTRACT

ASTM E1300 is the main US standard for determining the load resistance of glass in buildings. The safety concept is based on a “Failure Prediction Model (FPM)”. Depending on the application, the accepted probability of glass breakage can vary and is typically less than 0.008 for vertical glazing. Normally verification of glass is done against wind loads and for rectangular units only. In modern Curtain Walling facades, irregular shapes and the additional impact of linear or concentrated loads on the glass units are demands not yet covered by FPM of ASTM E1300. Considering relevant load sharing between inner and outer lite as well as climatic effects caused by the enclosed gas volume in hermetically sealed IG units is required for a reliable glass design. For proper verification and evaluation of various influences, use of an “Allowable Stress Design” is advisable. Taking into account the static fatigue of annealed glass the load duration is a dominant factor for determining the relevant allowable stress. Relevant load case combinations are mentioned in IBC and ASCE, but just for typical loads within the building sector. The structural analysis of insulating glass units requires taking into account probable interaction of internal and external loads. While wind loads are determined for load duration of 3s, live loads and climatic effects can act in a period of several minutes, hours or years.

This paper shows an approach of combining loads with different load durations based on the safety concept of ASTM E1300 and how to combine load types which are not explicitly mentioned in that standard. In conclusion, the proposal of appropriate load case combinations and relevant load durations leading to an “Allowable Stresses Design” is presented.

ABSTRACT

Die Norm ASTM E 1300 ist die wesentliche Richtlinie zur Festlegung der Widerstandsfähigkeit von Glas für das Bauwesen. Das Sicherheitskonzept basiert auf dem Modell der Ausfallwahrscheinlichkeit. In Abhängigkeit der Anwendung kann die Wahrscheinlichkeit des Glasbruchs variieren und ist typischerweise für Vertikalverglasungen kleiner 0.008. Normalerweise wird der Nachweis der Glasdicken für Windlasten und rechteckige Scheiben geführt. In modernen Vorhangfassaden werden aber auch die Verwendung von Modellscheiben und die Beachtung anderen Lasten, Linienlasten oder Punktlasten, gefordert. Diese werden aber Bemessungskonzept der ASTM E 1300 derzeit nicht berücksichtigt. Sowohl die Beachtung der erforderlichen Lastaufteilung zwischen der Innen- und Außenscheibe als auch die Klimalasten, die durch das hermetisch abgeschlossene Gasvolumen bei Mehrscheiben-Isoliergläsern verursacht werden, werden für ein verlässliches Glasdesign gefordert. Für einen geeigneten Nachweis sowie die Beachtung verschiedener Einflüsse, wird das Konzept basierend auf „zulässigen Spannungen“ empfohlen. Wesentliche Lastfallkombinationen werden im IBC und ASCE genannt, aber nur für typische Lasten im Bereich des Hochbaus. Die statische Bemessung von MIG fordert die Berücksichtigung der wahrscheinlich gleichzeitig auftretenden internen und externen Lasten. Während Windlasten für eine Lastdauer von 3s bestimmt werden, können Eigengewicht und Klimalasten mehrere Minuten, Stunden oder Jahre wirken. Der Aufsatz soll

einen Ansatz beschreiben, der die Kombination von Lasten mit unterschiedlichen Lastdauern auf Basis des Sicherheitskonzeptes der ASTM E 1300 ermöglicht und darstellen, wie Lasten miteinander kombiniert werden, die nicht ausdrücklich in dieser Norm genannt werden. Zusammenfassend wird vorgeschlagen, welche Lastkombinationen und Lastdauern in einem Konzept der „zulässigen Spannungen" kombiniert werden können.

KEYWORDS

unitized curtainwall, finite element analysis (FEA), insulating glass, case study, climatic loads, ASTM E1300, load sharing

INTRODUCTION

Standard practice for determining the existing load resistance of specific glass units used in buildings, especially in windows, is found in ASTM E1300 [2]. Procedures described in [2] also cover determination of load resistance and maximum lateral deflection for glass types combined in sealed insulating glass units. Focusing on common practice, the procedures of [2] are applicable for rectangular insulating glass units, simply supported on four sides and exposed to uniform lateral loads of short and long duration. An approximation of the behavior and probability of fracture of various types of glass combined in sealed IG units as well as a proportional assumption of load sharing between inner and outer lite of double glazed IG units is stated in appendixes X2 and X3 of [2], which is sometimes a conservative approach but not in any case. Appendix X5 provides an approximate technique to combine various lateral uniform loads of different load duration. However, all assumptions given by [2] are very limited in terms of shape, edge support, load effects and sufficient evaluation of combined types of glass.

State-of-the-art applications of insulating glass in Unitized Curtain Walling and Structural Sealant Glazing require effective evaluation methods of special shapes, loads and boundary conditions along with a reliable combination of various loads acting concurrently but in different directions, with different load durations and concentrated on different areas of a glass unit. For these cases more accurate calculation methods are needed as internal loads have to be taken into account for an IG unit and capable procedures for evaluating separated and combined effects have to be discussed.

DESIGN LOADS AND LOAD SHARING

Various types of loads and combinations of loads have to be taken into account for the design of architectural glass in facades according to [1]. Most relevant are those like:

- Wind loads (3s gust), both acting positive (inward) and negative (outward)
- Dead load components of inclined (inward or outward sloped) IG units
- Barrier loads (horizontal line load, concentrated load and uniform load representing human impact)

In practice there are additional internal load effects existing if insulating glass units are used. ASTM E1300 is using a load share factor between the lites of an IG unit, but does not address the internal "climatic effect", deeper described in the next section. Within this section, the rules of load sharing between inner and outer glass shall be presented, first.

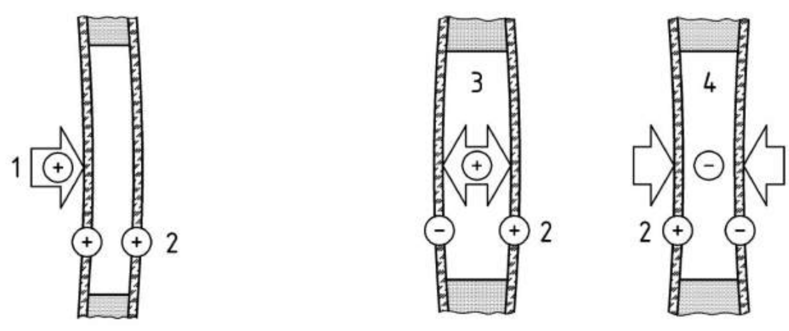

Figure 1: Sharing of external loads and acting of internal loads according to[3].

Lites of an IG unit are not only linearly bonded around the perimeter. They are also connected by the gas volume enclosed in the hermetically sealed cavity. This coupling effect causes load sharing between the connected lites. A simplified approach widely used in engineering practice and mentioned in [2], appendix X3 is determining the correct proportional stiffness of inner and outer glass. Actually, an accurate approach of load sharing (ref. to Table 2) has to respect the shape and the dimension of the IG unit and the direction of the relevant loading as stated in [3] and [5], too. Covering all the relevant influences Prof. Feldmeier introduced an insulating glass factor φ which depends on the length of the shorter glass edge a and the characteristic length a*. a* is representing characteristic properties of the IG unit like aspect ratio B_v (ref. to Table 1), dimension of the hermetically sealed cavity t_{cavity} and stiffness of the two lites (outer lite t_1, inner lite t_2). The equations to determine these factors are shown in (1).

E	- Young's modulus glass	- 71 700 MPa
p_B	- barometric pressure	- 100 kPa

$$\varphi = \frac{1}{1+\left(a/a^*\right)^4}; \quad a^* = \sqrt[4]{\frac{E}{p_B} \times \frac{t_1^3 \times t_2^3 \times t_{cavity}}{\left(t_1^3 + t_2^3\right) \times B_v}}; \quad \delta_1 = \frac{t_1^3}{t_1^3 + t_2^3}; \quad \delta_2 = \frac{t_2^3}{t_1^3 + t_2^3}. \tag{1}$$

Table 1. Coefficient Bv according to [3] and [5].

a / b	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
B_v	0.0194	0.0237	0.0288	0.0350	0.0421	0.0501	0.0587	0.0676	0.0767	0.0857

a – length of the shorter glass edge, b – length of the longer glass edge

Table 2. Load components bases on load sharing according to [3] and [5].

Loading	Load direction	Load component taken by the outer lite	Load component taken by the inner lite
Negative wind pressure	Pressure onto the inner lite	$w_{n,1} = \left(1-\varphi\right) \times \delta_1 \times w_{n,total}$	$w_{n,2} = \left(\varphi\delta_1 + \delta_2\right) \times w_{n,total}$
Positive wind pressure	Pressure onto the outer lite	$w_{p,1} = \left(\delta_1 + \varphi\delta_2\right) \times w_{p,total}$	$w_{p,2} = \left(1-\varphi\right) \times \delta_2 \times w_{p,total}$

CLIMATIC EFFECTS IN HERMETICALLY SEALED UNITS

Insulating glass units are hermetically sealed systems. This means that gas (air or inert gases like argon and krypton) is enclosed in the space between at least two or more lites. It is an isochoric condition. This means that the volume is remaining constant, as shown in (2).

$$\frac{p}{T} = const. \tag{2}$$

Climatic effects imply internal load effects caused by the expansion of the gas volume. The expansion of the enclosed volume is confined by the inner and the outer lite. Due to the fact that the lites are not absolutely rigid, the actual state is balanced between an isochoric and an isobaric limit state. The individual loading depends on the external conditions and the geometrical properties. Geometrical properties are the dimension of the cavity, the dimension of the IG unit and the thickness of the inner and the outer lite. External conditions include

- Variation of atmospheric pressure patm,
- Variation of temperature of the enclosed gas ΔT and
- Variation of elevation ΔH, which can result an increasing pressure in the cavity.

Variations acting on the glass and the edge seal are also related to changed conditions between production of the IG unit just as the edge seal and conditions after installation or during service life. The relevant isochoric limit state p_0 can be determined according to (3). The geometrical properties are embedded into the insulating glass factor φ determined in (1). The product of isochoric pressure and insulating glass factor in (4) results in the internal load $P_{climatic}$ acting as the maximum climatic load effect on the inner and the outer lite as well as on the edge seal of the IG unit.

$$p_0 = (\Delta T \times 0.34 kPa/K) + \Delta p_{atm} + (\Delta H \times 0.012 kPa/m). \quad (3)$$

$$P_{climatic} = \varphi \times p_0. \quad (4)$$

While larger IG units are mainly affected by wind loads or other externally imposed loads the impact of climatic effects becomes more and more decisive for smaller and narrow units. In some cases, climatic load effects for the smaller IG units are much higher than wind load impacts relevant for the larger units. That makes it important to not just consider the largest IG units for a proper glass and secondary seal design. Taking into account climatic load effects and considering smaller IG units is significantly important for the entire glass design, a durable edge sealing system and a final IG configuration which meets all demands on safety and life expectancy.

ALLOWABLE SURFACE STRESS IN ACCORDANCE WITH ASTM E1300

The glass failure prediction model (FPM) that serves as a basis for the non-factored load (NFL) charts of ASTM E1300 [2] assumes that the probability of glass breakage is a function of the distribution and severity of stress-raising surface discontinuities and the distribution of surface tensile stresses over the glass area. If the maximum stress levels on two lites with different dimensions and thicknesses are the same, the lite with the maximum stress distributed over the bigger area is more likely to fail. It is not appropriate to base the structural adequacy of glass used in buildings solely on its modulus of rupture as determined through the testing of small-scale laboratory specimens. The verification approach of [2] is based on the load resistance (LR) determined as a uniform lateral load. LR is composed of a non-factored load (NFL) representing a maximum applicable load (3-seconds duration, probability of breakage ≤ 0.008, monolithic annealed glass) taking into account surface conditions, glass thickness as well as glass dimensions and of the glass type factor (GTF) representing the appropriate glass type and the relevant load duration. This procedure becomes more complex if laminated glass (LG), insulating glass (IG) or even the combination of more than one load acting concurrently with different load durations, has to be considered. Depending on the specific case, additional load sharing factors (LS), lite probability factors (p) and combination of load effects and load duration according to [2], X5.1 have to be respected. LR is going to be determined for each lite, while the lower of all load resistance values is decisive. In case of combined loads q and LR are determined for an equivalent 3-seconds duration, shown in (5).

$$LR_i = NFL_i \times GTF_i \times LS_i; \quad q \leq LR_i. \quad (5)$$

More and more there is demand for designing and verifying glass units of irregular shape or composition, not 4-sided simply supported or even exposed to non-uniform load impacts and load combinations. In these cases, more flexible and accurate calculation techniques such as finite element, finite difference or standard engineering mechanics formulas have to be used to determine maximum surface stress and deflection taking into account specific boundary conditions. Different from FPM used in [2] most common engineering practices and tools are based on allowable stress design (ASD). Covering design of special glass shapes and loads on an adequate level of safety and confidence ASTM E1300 gives some indications for the approximate maximum surface stress to be used with an independent stress analysis in appendix X6. Mostly conservative allowable surface stress values for a 3-seconds duration load and a probability of breakage ≤ 0.008 are mentioned in [2], X6.2 with 23.3 MPa (3 380 psi) for annealed float glass, 46.6 MPa (6 750 psi) for heat-strengthened glass and 93.1 MPa (13 500 psi) for fully-tempered glass. X6.3 requires calculating the maximum surface stress in a glass lite using rigorous engineering analysis, which takes into account large defections, like non-linear finite element analysis. In general, non-linear effects get more significant for the verification of continuously supported glass units the bigger the glass deflection in relation to the glass thickness and the closeness of the aspect ratio to quadratic shape. The calculated surface stress has to be less than the maximum allowable stress.

The maximum allowable surface stress is a function of area (A), load duration in seconds (d), surface flaw parameter (k), probability of breakage (Pb) and an exponent that characterizes the weakening effect due to sub-critical crack growth (n). All of these parameters can be considered as properly represented by the allowable surface stress according to [2], X6.2. The equation mentioned in X6.2 must be verified in each individual case or within a proper structural design considering different loads and their combination factors. Parameters, which still could be adapted to the specific cases and glass types are the load duration (d) and the exponent n differentiated in [8], Note 2 for different glass types, using n = 16 for annealed float glass, n = 32 for heat-strengthened glass and n = 48 for fully-tempered glass. Another important point is a suitable evaluation of fritted glass. [8], Note 1 gives a general recommendation for disruptive surface treatments stating an allowable stress reduction factor of 0.5 but with a remarks to consult the glass manufacturer. [9] summarizes a useful study. Based on its conclusions an allowable stress reduction factor of 0.6 is sufficient and reliable.

$$\sigma_{allowable}[d,n] = \frac{\sigma_{allowable,[2],X6.2}}{\sqrt[n]{d/3}} \quad (6)$$

Representing the effective conditions, always the minimum glass thickness in accordance with ASTM C1036 is relevant. In case of a European glass manufacturer or float glass supplier the minimum glass thickness according to EN 572 should be taken into account. For annealed glass, the assumed values for Young´s modulus and Poisson's ratio are 71.7 GPa (10.4e6 psi) and 0.22, respectively. Based on [2] the PVB interlayer is allowed to be considered with a shear modulus of 0.40 MPa at temperatures up to +50 °C (122 °F) and for 3-seconds load duration.

Table 3. Allowable surface stress for different load duration and glass types based on (6).

Load Duration	3 s		60 s		600 s (10 min)		43 200 s (12 hours)		473 040 000 s (>> 1 year)	
	[MPa]	[psi]	[MPa]	[psi]	[MPa]	[psi]	[MPa]	[psi]	[MPa]	[psi]
AN	23.30	3 380	19.32	2 803	16.73	2 427	12.81	1 858	7.16	1 039
HS	46.60	6 750	42.44	6 147	39.49	5 720	34.55	5 004	25.84	3 742
HS, fritted	28.00	4 050	25.46	3 688	23.69	3 432	20.73	3 003	15.50	2 245
FT	93.20	13 500	87.54	12 683	83.46	12 089	76.35	11 059	62.90	9 111
FT, fritted	55.90	8 100	52.52	7 610	50.08	7 254	45.81	6 635	37.74	5 466

Table 4. Nominal and minimum glass thicknesses according to ASTM and EN standard.

Nominal Thickness or Designation		Minimum (calculation) Thickness acc. to ASTM C1036		Minimum (calculation) Thickness acc. to EN 572	
[mm]	[in.]	[mm]	[in.]	[mm]	[in.]
4.0	1/8	3.78	0.149	3.8	0.150
5.0	5/32	4.57	0.180	4.8	0.189
6.0	3/16	5.56	0.219	5.8	0.228
8.0	1/4	7.42	0.292	7.7	0.303
10.0	5/16	9.02	0.355	9.7	0.382
12.0	1/2	11.91	0.469	11.7	0.461

COMBINATION OF RELEVANT LOADS

ASCE Code 07 [4] is the basic rule for minimum design loads and relevant load combinations in buildings and other structures. The challenge is to define an approach for a proper IG unit design respecting these rules and basic design principles as well as recognizing that both wind loads and climatic effects are leading impacts for capable dimensioning of glass thickness and secondary seal bite. Actually, climatic conditions, alternating temperatures and different elevations of production site and installation site create expansion or contraction of the enclosed gas space, an effect that is not specifically described in [4]. But assuming that [4] is defining the combination of permanent loads (named as dead load), variable loads (mainly wind load) and self-straining loads (put as system-implemented load, like climatic effects, only affecting the IG unit itself), we can split the climatic effect summarized in equation (3) into different components differentiated regarding load duration and combined action. While effects caused by the difference of elevation H separately create a permanent impact, the combined action of H, temperature difference T and difference of atmospheric pressure patm is an effect alternating during the course of a day or the combination of climatic effect and wind is in total a short-term combination. Furthermore, [4], section 2.4.4 states that it's unlikely that the maximum effect of self-straining loads occurs simultaneously with the maximum effect of other variable loads. A combination with 0.75 of the maximum effects is recommended. Table 5 takes into account all summarized aspects for a proper combination of wind load and climatic effects in vertically installed IG units.

Table 5. Load combinations representative for proper design of vertical insulating glass units

LC	Combination	Load Duration
1	1.0 negative wind pressure + 1.0 effect of maximum difference of elevation between installation and production (ΔH)	3 sec
2	1.0 negative wind pressure + 1.0 effect of minimum difference of elevation between installation and production (ΔH)	3 sec
3	1.0 positive wind pressure + 1.0 effect of maximum difference of elevation between installation and production (ΔH)	3 sec
4	1.0 positive wind pressure + 1.0 effect of minimum difference of elevation between installation and production (ΔH)	3 sec
5	0.75 negative wind pressure + 0.75 climatic effects at "summer conditions" (difference of atmospheric pressure (Δp_{atm}) and difference of gas space temperature between service and production (ΔT)) + 1.0 effect of relevant difference of elevation between installation and production (ΔH)	3 sec
6	0.75 negative wind pressure + 0.75 climatic effects at "winter conditions" (difference of atmospheric pressure (Δp_{atm}) and difference of gas space temperature between service and production (ΔT)) + 1.0 effect of relevant difference of elevation between installation and production (ΔH)	3 sec
7	0.75 positive wind pressure + 0.75 climatic effects at "summer conditions" (difference of atmospheric pressure (Δp_{atm}) and difference of gas space temperature between service and production (ΔT)) + 1.0 effect of relevant difference of elevation between installation and production (ΔH)	3 sec
8	0.75 positive wind pressure + 0.75 climatic effects at "winter conditions" (difference of atmospheric pressure (Δp_{atm}) and difference of gas space temperature between service and production (ΔT)) + 1.0 effect of relevant difference of elevation between installation and production (ΔH)	3 sec
9	1.0 climatic effects at "summer conditions" (difference of atmospheric pressure (Δp_{atm}) and difference of gas space temperature between service and production (ΔT)) + 1.0 effect of relevant difference of elevation between installation and production (ΔH)	12 hours
10	1.0 climatic effects at "winter conditions" (difference of atmospheric pressure (Δp_{atm}) and difference of gas space temperature between service and production (ΔT)) + 1.0 effect of relevant difference of elevation between installation and production (ΔH)	12 hours
11	1.0 effect of maximum difference of elevation between installation and production (ΔH)	>> 1 year
12	1.0 effect of minimum difference of elevation between installation and production (ΔH)	>> 1 year

CASE STUDY: 33 TEHAMA, SAN FRANCISCO, CA, USA

The approach described above has been used for verification of glass design in several projects in the US. The following project helps to compare the normal procedure of ASTM E1300 [2] and an allowable stress design including combined action of wind load and climatic effects. Relevant for the glass design of the project was not just the estimation of wind loads expected for different zones of the building façade but also a comprehensive thermal analysis including thermal glass stress analysis, calculation of the maximum temperatures of glass components and primary seal as well as the minimum and maximum temperature of the enclosed gas space. These temperatures are basically needed for calculating expected climatic effects.

33 Tehama Tower in San Francisco is a 35-story apartment high-rise building under construction. Its completion is expected

in 2017. Due the thermal requirements, the spandrel units were identified as IG units with very high air space temperatures. As mentioned above, small and narrow units can create very high climatic effects. For typical spandrel units one has the accumulation of both extraordinary high temperature and inappropriate small glass dimensions. The units of GD-6, as a best practice example, were considered in a smaller dimension 100% utilized by climatic effects and in a maximum dimension showing 27% utilization due to the impact of negative wind pressure or even 42% utilization caused by positive wind pressure creating the maximum surface stress on the fitted (disruptively treated) surface of the inner lite. While bigger units are mainly restricted by limitation of deflection, the huge utilization of smaller units caused by climatic effects isn't recognized by the standard procedure of [2].

Boundary conditions taken into account for glass verification of the spandrel units GD-6:

- Production site (Lauenfoerde, Germany): 97 m [318 ft] a.s.l.
- Installation site (San Francisco, CA, US): 5 m [16 ft] a.s.l.
- Installation height: 123 m [420 ft]
- GD-6: Spandrel unit, insulating glass make-up
  - Outer lite: 6 mm [1/4 in.] Planibel Clearlite ipasol Neutral 48/27 # 2, fully tempered & heat soaked
  - Space: 20 mm [3/4 in.] air, aluminum spacer, black
  - Inner lite: 6 mm [1/4 in.] Planibel Clearlite, fritted, RAL 7035 # 4, fully tempered & heat soaked
- Dimensions (width x height)
  - Smaller span: 997 mm x 391 mm [39.3 in. x 15.4 in.]
  - Maximum span: 1505 mm x 3452 mm [59.3 in. x 135.9 in.]
- Wind load (3 sec): -2.155 kPa / +1.915 kPa [-45 psf / +40 psf]
- Continuously simply supported
- Internal shadow box make up
  - Internal backup: 63 mm [2 ½ in.] distance, air, not ventilated
  - Insulation: 50 mm [2 in.], R = 1,43 m^2K/W
  - Steel back pan: 1 mm [1/32 in.]
  - 200 mm [7 7/8 in.] air, not ventilated, R = 0.18 m^2K/W acc. to ISO 6946
  - 20 mm [3/4 in.] sub ceiling or floor, R = 0.1 m^2K/W
- Isochoric pressure
  - Climatic effects, summer ($\Delta T_{cavity} \leq 80K$; $\Delta p_{atm} \geq -2kPa$; $\Delta H_{altitude} \leq 30m$): +29.6 kPa [+618 psf]
  - Climatic effects, winter ($\Delta T_{cavity} \geq -24K$; $\Delta p_{atm} \leq 4kPa$; $\Delta H_{altitude} \geq 15m$): -12.0 kPa [-251 psf]

Table 6. Maximum surface stress and deflection for load cases of Table 5. The first table shows the results for a linear calculation and the second one for a non-linear calculation based on a Finite Element Analysis. Grey mark indicates the decisive load case.

GD-06: Spandrel, Maximum Span

Glass dimension: 1505mm x 3452mm; Glass make-up: 6mm FT & HST / 20mm Air / 6mm FT & HST, fritted on #4

Wind load (ULS, 3sec): -2.155 / +1.915 kPa — Climatic effects, summer: 29.6 kPa; Climatic effects, winter: -12.0 kPa

Load case	Outer glass						Inner glass					
	principle stress [MPa]	allowable stress [MPa]	utilization [%]	deflection [mm]	allowable deflection [mm]	limitation ratio [%]	principle stress [MPa]	allowable stress [MPa]	utilization [%]	deflection [mm]	allowable deflection [mm]	limitation ratio [%]
LC1*	24.8	93.20	27	-24.8	25.4	98	25.2	93.20	27	-25.1	25.4	99
LC2*	24.7	93.20	27	-24.7	25.4	97	25.2	93.20	27	-25.2	25.4	99
LC3*	23.5	93.20	25	22.7	25.4	89	23.5	55.90	42	22.7	25.4	89
LC4*	23.5	93.20	25	22.8	25.4	90	23.5	55.90	42	22.6	25.4	89
LC5*	24.4	93.20	26	-24.8	25.4	98	17.8	93.20	19	-16.1	25.4	63
LC6*	19.8	93.20	21	-18.8	25.4	74	22.9	93.20	25	-22.7	25.4	89
LC7*	16.0	93.20	17	13.7	25.4	54	23.3	55.90	42	22.8	25.4	90
LC8*	21.4	93.20	23	20.5	25.4	81	18.6	55.90	33	16.9	25.4	67
LC9	6.3	76.35	8	-6.6	25.4	26	6.3	45.81	14	6.6	25.4	26
LC10	2.6	76.35	3	2.7	25.4	11	2.6	76.35	3	-2.7	25.4	11
LC11	0.1	62.90	0	-0.1	25.4	0	0.1	37.74	0	0.1	25.4	0
LC12	0.0	62.90	0	0.0	25.4	0	0.0	37.74	0	0.0	25.4	0

* non-linear FE Analysis

GD-06: Spandrel, Smaller Span

Glass dimension: 997mm x 391mm; Glass make-up: 6mm FT & HST / 20mm Air / 6mm FT & HST, fritted on #4

Wind load (ULS, 3sec): -2.155 / +1.915 kPa — Climatic effects, summer: 29.6 kPa; Climatic effects, winter: -12.0 kPa

Load case	Outer glass						Inner glass					
	principle stress [MPa]	allowable stress [MPa]	utilization [%]	deflection [mm]	allowable deflection [mm]	limitation ratio [%]	principle stress [MPa]	allowable stress [MPa]	utilization [%]	deflection [mm]	allowable deflection [mm]	limitation ratio [%]
LC1	2.2	93.20	2	-0.2	7.8	2	4.4	93.20	5	-0.3	7.8	4
LC2	1.6	93.20	2	-0.1	7.8	2	5.0	93.20	5	-0.4	7.8	5
LC3	3.9	93.20	4	0.3	7.8	4	2.0	55.90	4	0.1	7.8	2
LC4	4.4	93.20	5	0.3	7.8	4	1.5	55.90	3	0.1	7.8	1
LC5	35.7	93.20	38	-2.5	7.8	33	30.7	55.90	55	2.2	7.8	28
LC6	12.6	93.20	14	0.9	7.8	12	17.6	93.20	19	-1.3	7.8	16
LC7	31.1	93.20	33	-2.2	7.8	28	35.6	55.90	64	2.5	7.8	32
LC8	17.2	93.20	18	1.2	7.8	16	12.7	93.20	14	-0.9	7.8	12
LC9	45.8	76.35	60	-3.3	7.8	42	45.8	45.81	100	3.3	7.8	42
LC10	18.5	76.35	24	1.3	7.8	17	18.5	76.35	24	-1.3	7.8	17
LC11	0.6	62.90	1	0.0	7.8	1	0.6	37.74	1	0.0	7.8	1
LC12	0.0	62.90	0	0.0	7.8	0	0.0	37.74	0	0.0	7.8	0

ASTM E1300 [2] is a simplified concept. Direct comparison of values determined according to [2] with values from a non-linear finite elements analysis is not reliable. Producing a direct comparison between failure prediction model FPM and allowable stress design ASD the type factors for insulating glass stated in [2], X2.2 were neglected. Furthermore, any disruptive effect of the ceramic frit was not taken into account, as Table 7 is a comparison of concepts but does not represent any verification. Wind pressure and climatic effects were evaluated separately. In step 1 maximum surface stress of the glass units was calculated on a single glass unit respecting the load sharing factors of [2]. In step 2 the more accurate load sharing concept of Table 2 was applied to the determination of load resistance LR according to [2]. Based on this modification a comparison with the simulation of a full IG model was more feasible. Additionally, only minimum glass thickness according to ASTM C1036 was used for comparing the results at similar conditions.

Table 7. Comparison of FPM concept of ASTM E1300 [2] and ASD concept based on a non-linear finite elements analysis for wind load.

<table>
<tr><th>Glass Type</th><th>Step of Comparison</th><th>Failure Prediction Model FPM</th><th>Allowable Stress Design ASD</th></tr>
<tr><td rowspan="6">Smaller Span
997 mm x 391 mm [39.3 in. x 15.4 in.]
6 mm [1/4 in.] FT & HST
20 mm [3/4 in.] air
6 mm [1/4 in.] FT & HST</td><td>Step 1
Load sharing acc. to [2]
Negative wind load:
-2.155 kPa [-45 psf]</td><td>LSF1 = LSF2 = 2.00
NFL = 11.1 kPa
GTF1 = GTF2 = 36
LR = 11.1 kPa x 3.6 x 2.00
LR = 79.92 kPa</td><td>LSF1 = LSF2 = 2.00
σ_{max} = 3.62 MPa
$\sigma_{allow,1} = \sigma_{allow,2}$ = 93.2 MPa *
$\sigma_{allow,A,1} = \sigma_{allow,A,2}$ = 118.8 MPa **</td></tr>
<tr><td rowspan="2">Utilization step1</td><td rowspan="2">2.155 / 79.92 = 2.7 %</td><td>3.62 / 93.2 = 3.9 % *</td></tr>
<tr><td>3.62 / 118.8 = 3.1 % **</td></tr>
<tr><td>Step 2
Load sharing acc. to Table 2
Negative wind load:
-2.155 kPa [-45 psf]</td><td>LSF1 = 3.78
LSF2 = 1.36
NFL = 11.1 kPa
GTF1 = GTF2 = 3.6
LR = 11.1 kPa x 3.6 x 1.36
LR = 54.35 kPa</td><td>Full IG model
$\sigma_{max,1}$ = 1.96 MPa
$\sigma_{max,2}$ = 5.28 MPa
$\sigma_{allow,1} = \sigma_{allow,2}$ = 93.2 MPa *
$\sigma_{allow,A,1} = \sigma_{allow,A,2}$ = 118.8 MPa **</td></tr>
<tr><td rowspan="2">Utilization step 2</td><td rowspan="2">2.155 / 54.35 = 4 %</td><td>5.28 / 93.2 = 5.7 % *</td></tr>
<tr><td>5.28 / 118.8 = 4.4 % **</td></tr>
<tr><td rowspan="6">Bigger Span
1500 mm x 3450 mm [59.1 in. x 135.8 in.]
6 mm [1/4 in.] FT & HST
20 mm [3/4 in.] air
6 mm [1/4 in.] FT & HST</td><td>Step 1
Load sharing according to [2]
Negative wind load:
-2.155 kPa [-45 psf]</td><td>LSF1 = LSF2 = 2.00
NFL = 0.89 kPa
GTF1 = GTF2 = 3.6
LR = 0.89 kPa x 3.6 x 2.00
LR = 6.41 kPa</td><td>LSF1 = LSF2 = 2.00
σ_{max} = 24.83 MPa
$\sigma_{allow,1} = \sigma_{allow,2}$ = 93.2 MPa *
$\sigma_{allow,A,1} = \sigma_{allow,A,2}$ = 80.9 MPa **</td></tr>
<tr><td rowspan="2">Utilization step 1</td><td rowspan="2">2.155 / 6.41 = 33.62 %</td><td>24.83 / 93.2 = 26.7 % *</td></tr>
<tr><td>24.83 / 80.9 = 30.7 % **</td></tr>
<tr><td>Step 2
Load sharing according to Table 2
Negative wind load:
-2.155 kPa [-45 psf]</td><td>LSF1 = 2.01
LSF2 = 1.99
NFL = 0.89 kPa
GTF1 = GTF2 = 3.6
LR = 0.89 kPa x 3.6 x 1.99
LR = 6.38 kPa</td><td>Full IG model
$\sigma_{max,1}$ = 24.85 MPa
$\sigma_{max,2}$ = 25.13 MPa
$\sigma_{allow,1} = \sigma_{allow,2}$ = 93.2 MPa *
$\sigma_{allow,A,1} = \sigma_{allow,A,2}$ = 80.9 MPa **</td></tr>
<tr><td rowspan="2">Utilization step 2</td><td rowspan="2">2.155 / 7.08 = 30.4 %</td><td>24.97 / 93.2 = 26.8 % *</td></tr>
<tr><td>24.97 / 80.9 = 30.9 % **</td></tr>
</table>

* Conservative allowable surface stress values for a 3s duration load stated and probability of breakage ≤ 0.008 in [2], X6.2.

** Specific allowable surface stress values acc. to [2], equation X6.1, additionally considering influences of glass dimension, glass thickness, aspect ratio and stress distribution on the probability of breakage.

Table 7 shows a good approximation of utilization determined according to FPM and ASD. In general, a more accurate concept of load sharing factors, as given in Table 2 and shown in step 2, is advisable for smaller units. For bigger units a significant influence of surface area on the load resistance is considered in the FPM of [2] but neglected for the allowable surface stress values according to [2], X6.2. This could have an impact on design and resistance of larger annealed glass lites. For commercial façade units and SSG application it is common to use tempered or heat-strengthened glass so glass dimensions or accepted loads are mainly limited by allowable deflection and the utilization of allowable surface stress and usually far away from 100 %. In conclusion, allowable surface stress values defined in [8], X6.2 are conservative for smaller IG units and sufficient for larger ones. But a suitable and appropriate limitation of glass deflection is an important design condition, too.

Figure 2: Project renderings (© Hines Constructions & Invesco)

CONCLUSION

The above-discussed concept and the presented project example show that “Allowable Stress Design” is a useful and suitable practice for finding and verifying a capable glass design as well as including much more significant boundary conditions than provided by the standard procedure used in ASTM E1300 [2]. Important considerations for proper design are not just a suitable link between FPM and ASD, but also a reliable concept of combining different loads with different load durations. The draft given in Table 5 is specifically considering load effects on vertical IG units. Essential for proper and sustainable design of IG units is an appropriate concept for determining climatic effects caused by the interaction of the enclosed gas space and external environment as well as respecting effective load sharing between inner and outer lites of a double glazed unit. Here, ASTM E1300 [2] shows some inadequacy, especially regarding smaller and midsize glass dimensions, which can be heavily affected by climatic effects and which clearly show a load sharing behavior different from the simplified approach of [2]. For larger glass units, especially those composed of tempered and heat-strengthened glass, the verification based on ASD should be completed by evaluation and limitation of maximum glass deflection.

It should be mentioned that in the European design codes are based on the principle of partial safety specific combination factors. The limit state design approach requires taking into account safety and combination factors for the values of applied stress as well as for the resistance value of the glass product. Both safety factors for the stress and resistance value are separated and represent the specific statistical deviation for loading and material.

Regardless from other international glass codes, this paper describes an approach keeping the systematic of the existing North American standards ASTM E1300 and ASCE 07. Thanks also to Permasteelisa North America regarding their expert support and their support regarding the case study, as they have done the curtain wall cladding.

REFERENCES

Glazing-Manual-50th-Anniversary-Edition, Glazing Association North America (GANA), 2009.

ASTM E1300 – 12a: Standard Practice for Determining Load Resistance of Glass in Buildings, 2012.

DIN 18008-2: Glass in Building – Design and Construction Rules, Part 2: Linearly Supported Glazings, 2010.

ASCE/SEI 7-10: Minimum Design Loads for Buildings and other Structures, American Society of Civil Engineers, Structural Engineering Institute, 2010.

Feldmeier, F.: Insulating Units Exposed to Wind and Weather – Load Sharing and Internal Loads, GPD Glass Processing Days, Tampere, pp. 633-636, 2003.

Morse, S. M.; ASCE; A. M.; Norville, H. S.: Relationship between Probability of Breakage to Maximum Principles Stress in Window Glass, Journal of Architectural Engineering, ASCE, March 2010.

Haldimann, M.; Luible, A.; Overend, M.: Structural Engineering Documents 10, Structural Use of Glass, International Association for Bridge and Structural Engineering, 2008.

ASTM E2751/E2751M – 13: Standard Practice for Design and Performance of Supported Laminated Glass Walkways, 2013.

Maniatis, I.; Elstner, M.: Investigations on mechanical strength of enameled glass, Challenging Glass Conference 5, International Conference on the Architectural and Structural Application of Glass, Delft, 2016.

Doebbel, F.; Elstner, M.; Patterson, M.; Davis, W.: Optimized Secondary Seal of Insulating Glass Units for Structural Sealant Glazing Application, GlassCon Global Conference Proceedings 2014, Philadelphia 2014.

Process <> Delivery

ENVELOPE LONGEVITY

The benefits of the building enclosure commissioning process

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ABSTRACT

Longevity, as defined by something that has a long existence or service, is critical for Building Envelopes. As technology advances, and methods of construction change, the increased longevity of envelope components must continue to be challenged by the industry. While the tendency of the industry is focused on ensuring system performance is met, one of the less discussed, but perhaps equally important aspects of the process are ensuring that the envelope systems installed will stand the test of time. The architectural glazing community accepts the fact that an Insulated Glazing Unit (IGU) on a building should last for 25 years. This still falls well short of the goals that many owners have for their buildings, which is an expected lifespan of 50, 75, or even potentially 100 years.

The purpose of this paper will be to identify critical factors, which have a direct relationship to the potential longevity for envelope systems, identify and propose enhanced performance criteria to meet these longevity goals, and to reset the discussion with the Building Envelope Industry as it relates to the design, engineering, fabrication, and installation of lasting Building Exterior Envelope Systems. The paper also hopes to start a dialog into what an acceptable longevity of an envelope should be industry wide.

KEYWORDS

Commissioning, durability, energy efficiency, obsolescence, exterior envelope, facades

INTRODUCTION

The growing popularity and acceptance of the Building Envelope Commissioning (BECx) process, which now allows for the building's exterior envelope performance to be validated from design through construction, is quickly changing the industry and opening up the importance of the exterior wall performance to a much broader audience. While green building standards, like LEED V.4 offer additional credits for involving a BECx Authority on a project, the benefits over and above the typical air infiltration/exfiltration and water infiltration performance criteria are not being discussed by the industry. One of these less spoken about benefits is the potential for enhanced envelope longevity. Longevity, as it relates to building envelope, is not limited to only meeting owner system warranty requirements; but, also to ensuring materials and components integral to the envelope assembly are manufactured, assembled, and installed in a way that ensures that they exceed their typical industry expected lifespans. Aside from the primary building functions, the façade is essentially the identity of a building. A long lasting façade is able to sustain a buildings core architectural identity throughout the course of potentially many different uses of its interior.

BACKGROUND

In the United States, the current BECx scope and process is defined by ASTM E2813: Standard Practice for Building Enclosure Commissioning, which is based on the National Institute of Building Standards (NIBS) Guideline 3-2012 “Building Enclosure Commissioning Process BECx”. Currently, the ASTM E2813 standard provides and defines minimum scope requirements for the responsibilities of the BECx Agent. The standard includes, but is not limited to, the following types of building envelope systems that are to be commissioned:

- Air barriers, thermal barriers, vapor barriers, and moisture barriers integral to the exterior envelope
- Roofing systems with associated flashing and trims
- Below grade and above grade waterproofing system, including any slab on grade conditions with associated flashing and trims
- Fenestration systems including curtain walls, windows, storefronts, and glazed openings
- Exterior wall cladding systems, inclusive of terra cotta rain screen cladding and aluminum rain screen cladding Systems with associated insulation, support systems, and air and vapor barriers.
- Exterior louvers
- Stone cladding
- Sealant joints, expansion joints and control joints related to the exterior envelope

Within the standard, there is also a scope of services. The scope of services is broken down by project phases, from pre-design through post occupancy and includes the following key steps throughout the project duration:

- Development of Owner Project Requirements (OPR) and assist in the development of the project’s Basis of Design (BoD)
- Provide technical design reviews of the project’s Contract Documents
- Develop BECx specification section
- Develop BECx testing matrix and Cx plan
- Attend Pre-Construction/Pre-Installation meetings
- Provide review of project submittals related to the exterior envelope
- Conduct regular BECx meetings with the design and construction team
- Provide regular site inspections to witness exterior envelope component installation
- Verify system performance through the witnessing of on-site testing
- Provide final BECx Report at substantial completion
- Attend a lessons learned meeting with the owner/facilities staff
- Provide post occupancy support to assist in issues that arise through the warranty period

While these minimum standards and processes may be suitable for a wide range of projects, there are several major items which are currently not addressed by all BECx Agents. This includes the offsite verification of material / component fabrication and the BECx Agents involvement with the procurement strategy or bidding process. These two items, together with site installation and detailing, are most critical to ensuring a long lasting and successful project. BECx agents aren’t intended to take on the role of the owner’s/contractor’s QC agent, rather they are there to ensure that the contractors are following all of the proper steps to ensure that systems are being properly installed. The ultimate end product still relies on the contractors performing the work.

SYSTEM LONGEVITY

System longevity is directly tied to the architectural design, systems selected, and the quality of material fabrication, assembly, and installation onsite. While proper detailing is required to ensure both the continuity of the building’s air and vapor barriers and flashing systems, much attention needs to be paid to the specification and manufacturing of the components utilized within the envelope systems. The materials, and their quality of fabrication, are what will ensure the building maintains its Day 1 performance throughout its expected lifespan.

It has become common place for people in the Architectural Glazing community to accept the fact that an Insulated Glazing Unit (IGU) on a building should last for 25 years; but, this is still far less than the expected lifespan of 50, 75, or even potentially 100 years that many owners envision having their buildings last. As architectural trends have changed, from more solid masonry construction with limited areas of glazing to, in many cases, fully glazed facades with different infill materials at opaque zones, there have been limited examples of all modern glass buildings which have been in service for more than 50 years. Many of these buildings are located in our populous urban centers, such as New York City, Chicago, and Los Angeles, and are at or past their useful lifespan.

As next generation materials have generally resulted in advancements in their performance, the technologies have not always addressed the need for greater longevity of the modern materials. One example of this can be seen in the Insulated Glazing fabrication process. Trends have moved to having flush glazed appearances on many curtain wall projects. This requires the use of structural silicone edge seal constructions. As known throughout the industry, a silicone edge seal in an IGU is susceptible to vapor migration and puts most of the effort on sealing the IG unit on the primary polyisobutylene (PIB) sealant. We also know that other sealants, like urethane based sealants, when utilized in edge seal construction of IG units, are much less permeable to moisture. However, given their compatibility issues, cannot be utilized in applications where glazing is held in place with structural silicone.

Additionally, when using more complex high performance low-e coatings, the importance of fully edge deleting the coating to protect it from vapor migration is key in ensuring that no advanced corrosion will occur of the coating itself. Similar and when applicable, attention must be paid to the quality of the lamination processes to ensure proper adhesion and protection of edges, which depending upon the interlayer material, may result in visually unacceptable conditions after a period of time.

The focus on the fabrication of these IG units should be paramount to the BECx process, as minor defects in the IG unit, or glass product fabrication, can result in accelerated aging and a shortened lifespan of the material. In many cases, the inspection of IG units, which are still performing over and past their 25 year life expectancy, are found to have limited deficiencies in their edge seal construction.

Figure 1: View of a skip or discontinuity between the primary and secondary seal of the IGU

Advancements have been made concerning the metal finishing process; with liquid applied finishes or powder coated extruded or sheet aluminum products. With advancements in the use of high-performance 70% polyvinylidene fluoride (PVDF) based liquid and powder finishes for exterior aluminum components, longevity of the finishes aluminum components, over their historic anodized predecessors, allow for aluminum products to remain exposed to the elements with little or no performance degradation for a significant period of time. Extruded aluminum appears to remain the material of choice. Especially, for the curtain wall and façade industries and as metal finishing processes become more environmentally friendly. The industry also has a strict set of QA/QC procedures to ensure that materials perform in accordance with project specifications through years of harsh environmental exposures.

Lasting materials like stainless steel (if proper alloys are specified) together with masonry type cladding materials will still remain superior in terms of their potential for lasting on buildings for many decades. This is evident throughout our existing building stock. These materials, however, are only as good as their adjacent or related construction components. And with more buildings following a cavity wall type construction, the quality of the air barriers and associated workmanship with the detailing of anchorages and brackets become paramount over the material exposed to view.

The design review process helps to reaffirm that the details of the design and following steps make sense in the context of the building and are carried out properly.

- Schematic design - Rough concepts of building massing, appearance, and materials are developed and tested against the OPR to arrive at a solution that best fulfills all criteria. The Basis of Design (BoD) is created and clearly conveys the assumptions made in developing a design solution that fulfills the intent and criteria in the OPR document. The OPR is evaluated and updated to balance scope, budget, and quality. Descriptions of building exterior enclosure systems are developed and included in the BoD and the commissioning plan is expanded.
- Design development- More detailed drawings, typically large scale wall sections, elevations and plan details, and preliminary specifications for the exterior enclosure systems are developed. Commissioning procedures are established (National Institute of Building Sciences 2004-2006).

This process ensures that the details are technically sound and provides a maintainable system for the owner.

Figure 2: View of a poorly attached insulation in a wall cavity with missing seals at anchors.

Material and system performance needs to be validated in the field as well; either through laboratory mock-up testing or through the use of onsite testing methods. This will ensure Day 1 operation and set a benchmark for how the building should perform; minus any potential from material degradation. Post occupancy testing is something that requires more research. Working together with key industry partners to perform accelerated weather testing on typical systems may start to provide insight as to how materials are performing throughout their lifespan.

OBSOLESCENCE

- The condition of being antiquated, old fashioned, or out of date.

A building can effectively last over 100 years and be efficient past its predicted service life, but a well-functioning envelope will not always tame an owners desire for a new look. While countless measures can be taken to ensure the envelope stands the test of time, obsolescence is much less easily accommodated. Whether it is brought on by new technology, neighborhood deterioration, or a shift in public demand, buildings and their systems are bound to become obsolete. To combat this issue and keep costs of renovations to a minimum, changes to the façade and included systems must be anticipated as much as possible. In the scope of building enclosure, this is relevant because as materials (such as gaskets and sealants) fail and new technology improves efficiency ratings of envelope systems, the rate that energy escapes the building and is wasted becomes less and less acceptable.

Facilities can be programmed, designed, and operated to be able to accommodate change without significant loss of performance capability. Because some form of obsolescence is eminent when it comes to buildings, there are a few ways to attempt to avoid it as much as possible:

- Review new developments for trends that may stimulate obsolescence
- Conduct facilities programming to address the possibilities of future functional change
- Assure that design guidelines and criteria are based on the latest available information and provide for future change
- Make flexibility an explicit design goal
- Unconstrained interior, modular components, shell space, interstitial space, ensure structural and utilities do not prevent expansion
- Assure quality in construction and maintenance to avoid declination of performance
- When obsolescence does occur, acknowledge it and retrofit or reuse the space or materials to limit the amount of money lost
-

A common approach is to build excess unfinished space in new construction to allow for a significantly greater amount of freedom and flexibility as technology and design ideas advance. It is important to start early in the design process and continue to address the possible methods of preventing obsolescence throughout the service life of the building (Donald G. Iselin and Andrew C. Lemer 1993).

Figure 3: View of a field hose water test onsite

Resiliency is defined as the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events. It is a necessary trait for buildings in wake of man-made or natural disasters such as a terror attack, hurricane, earthquake, flood, etc. A resilient design helps to address the building and building system vulnerabilities when facing shocks and stresses during and following an emergency spectrum of man -made and natural disasters (Patterson 2014). The BECx process can aid in implementing this design through the constant assistance it offers. When dealing with façade systems that have to resist seismic events, storm surges, extreme temperatures and winds, fire, and even blasts/ballistics, it is imperative that the proper care is taken to install everything properly. This will not only promote the longevity of the façade and building, but can also have a valuable economic impact in the form of future savings.

The BECx agent should work closely together with the building owners and design teams to ensure that all of these longevity goals, just like what is done for thermal performance and air infiltration requirements, be set forth early in the design phase. Close attention is to be paid to the specification language development and testing criteria. Additionally, budgets should be reviewed to ensure that the goals and the material specifications fall within the established project budgets.

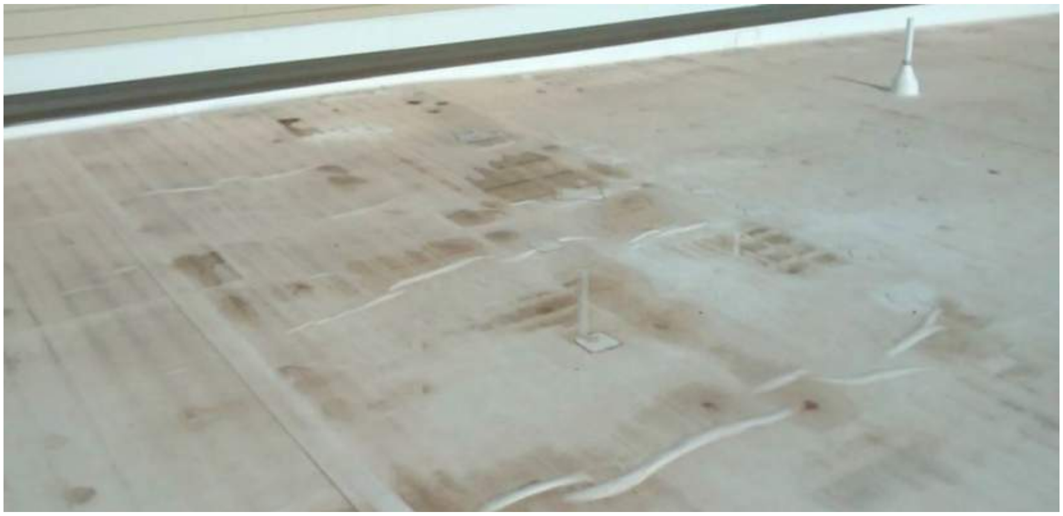


Figure 4: View of a poorly installed waterproofing membrane.

WHERE SHOULD WE BE GOING AND HOW

It is not uncommon to hear a director of facilities at a healthcare institution say that they intend to build 100 year buildings, and then get into value engineering discussions about reduced warranties on certain systems or materials as a cost savings measure. In addition, the design team typically does not include such criteria within their project specifications or Basis of Design Documents. The BECx Agent involved in the project must become the vocal party of the collective design and construction team to bring a level of realism to what can be expected early in the design phase. As an example, if they are serious in their intent to construct a 100-year building, do they want to utilize a curtain wall system with IG units around the building? With current technology, this would be difficult to achieve as we have yet to utilize this type of construction. Should we be looking back in history at more lasting construction types of materials, which will result in a much different architecture, as well as, cost? Not to mention the lack of skilled labor, which would be required, in many cases, to construct such building types?

A BECx Agent, in the opinion of this Author, should bring to the table a level of reasonable expectations, provide recommendations and provide specific Quality Assurance and Quality Control requirements to ensure that the materials being designed and ultimately installed on the building are used in a way which they will meet or exceed their typical service life. The material and system suppliers are key players to ensure they are providing sufficient test data to support their claims. In addition, key partners must be identified which can start to provide real data and metrics to the BECx Agents, allowing them to make informed decisions back to their teams.

While the content and processes noted herein are not to be construed as new ideas, what requires more attention, especially in the BECx process, is how we begin to define and establish Owner Project Requirement's over and above the typical baseline criteria and standards defined by ASTM. The area that needs the most research is the process of trying to re-baseline what should be an acceptable and achievable lifespan of a certain building type. We should remain cognizant that certain building types. Residential housing for instance, may have a higher turnover rate than a healthcare facility or an institutional client, or even an owner occupied commercial office building.

Similar to what the industry has done in the United Kingdom, Europe, and Asia, to define expected material lifespans, the BECx Agents operating in the United States should begin to interrogate these expectations and include them in their project's specifications. Educating architects, owners, and contractors not familiar with such requirements will require time, but also the support of the industry to ensure that initial goals are achievable.

As more projects continue to be completed, with well documented reporting by the BECx Agents, a body of work will start to be developed, which can form the basis for ensuring that we return to the trend of building 100-year buildings with the types of materials and technologies currently in favor by the architectural community.

CONCLUSION AND FUTURE WORK

Much research has been conducted in the realm of energy savings related to reduction of whole building air infiltration rates, which are more and more commonly being validated through the BECx process. Additional research must be made public from key material and system manufacturers, as it relates to their internal life cycle testing programs. While many fabricators will be hesitant to share information, as it may be seen as a request to increase typical warranty durations, the conversation should continue industry wide with the focus on ensuring that materials are designed and installed to meet their maximum possible service life on the buildings.

There remains the need for continuous discussion between BECx Agents to ensure that similar scopes of work are being proposed to building owners. Additionally, the importance of the longevity of the exterior envelope systems must be on par with the water and airtightness of the building. Similar methods for the evaluation of the payback on the initial investment, similar to what can be done for air infiltration rates effect on energy usage, must be evaluated by the industry to start to generate metrics to understand the payback of ensuring the longevity of materials onsite .

By utilizing the established BECx Process, BECx Agents need to continue to exploit and further define the process to ensure that longevity of systems becomes to cornerstone for all building envelope projects, regardless of size, cost, and/or complexity.

ACKNOWLEDGMENTS

Much of the knowledge and experiences exploited in this paper have been built upon the tutelage of my previous colleagues of Heintges & Associates and Skidmore, Owings & Merrill. Additionally, many thanks have to be given to my colleagues at Horizon Engineering Associates, LLP for giving me the insight into the history and development of the Building Commissioning Process especially as it relates to how the process can be utilized to holistically advance the exterior envelope industry. Also special thanks to Iris Greges, who without her this paper would have not been possible.

REFERENCES

All images by Author.

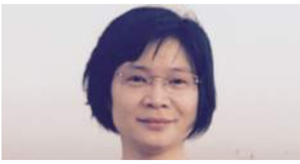
Donald G. Iselin Andrew C. Lemer. 1993. Fourth Dimension in Building: Strategies for Avoiding Obsolescence. Washington D.C.. National Academy Press.

National Institute of Building Sciences. 2004-2006. Exterior Enclosure Technical Requirements For the Commissioning Process.

Patterson, Mic. 2014. Resilience and the Building Façade Part One.

3D GLASS FACADE DESIGN APP

Design, development, and evaluation



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ABSTRACT

Compared to the traditional software solutions, mobile apps have advantages of increased flexibility, efficiency, and mobility for the AEC (architecture, engineering and construction) industry. However, to the best of our knowledge, no mobile apps were directed at facilitating the early design process in façade engineering for architects. In the paper, the design ,development and evaluation of a three-dimensional (3D) glass façade design app is presented .The goal is to provide architects a user friendly tool in a simplistic format that can assist them in the preliminary façade design process and help them maintain aesthetic control over the design based on the instant façade function analysis results. The main modules of the current release are Façade Design, Façade Analysis, Façade Material, and Façade Information. The app has been extensively evaluated for its usability and the preliminary results are promising.

相比传统的软件解决方案，移动端应用有更大的灵活性，效率高和互动性强等优点，并已经被AEC行业广泛采用。然而，据我们所知，还没有移动应用程序被开发用来辅助建筑师进行幕墙初步设计。本文介绍了一款针对建筑师的3D玻璃幕墙设计的移动端应用工具的设计与评估过程。该工具能够让建筑师在进行幕墙初步设计的同时得到幕墙性能分析结果，建筑师保证幕墙外观效果，提高工作效率。当前版本的主要模块是：幕墙设计，幕墙分析，幕墙材料和幕墙资讯。该应用程序已被广泛评估其可用性，初步结果是令人满意的。

KEYWORDS

Glass façade,3D,mobile app, structural analysis, generative design

INTRODUCTION

Mobile apps provide a huge potential for increased flexibility and efficiency. The trend indicates that mobile apps users are increasing and statistic shows the number of mobile downloads are expected to reach 268.69 billion in 2017 (Statista 2016). Compared to desktop applications, mobile apps offer new opportunities for working process optimization for three reasons: anywhere and anytime characteristics, easy-to use touchscreen-based handling, and task-oriented and context-aware design (Eva al.2015). From condensed versions of large scale software packages to blank canvases to scratch ideas, mobile technology has also provided the AEC (architecture, engineering, and construction) industry with some innovative solutions that increase productivity at their fingertips (Gabrielle 2015) and help the AEC industry save valuable time and resources by streamlining communication and providing shared resources.

Despite the apparent popularity of AEC apps, no previous app has been directed at exploring the 3D design in façade engineering. As a separate specialized discipline in AEC industry, façade engineering is an integrated knowledge of engineering, building physics, and advanced modeling techniques that is closely related to other disciplines. Architects and façade subcontractors need make the right choice of façade system and specifications and apply their experience to develop the solution into practical working details later (Kazmierczak, n.d.). A general lack of knowledge of façade functions among architects could lead to the confusion and eventual failure of a project as the understanding of information generated in the design process is very important.

An easy-to-use and interactive 3D façade design mobile app has been developed that has the potential to assist architects understand the early design implication and facilitate the façade design process. The app is called Mini Façade which can be run on both Android and iOS system. The challenges faced by architects inherent in the current facade design process are first identified. The concept and prototyping process of Mini Façade is then discussed along with its modules and functions; an extensive evaluation process and results are discussed and analyzed; and a conclusion is given that highlights future work.

THE CURRENT FACADE DESIGN PROCESS

Façade design is a highly professional engineering task which requires a distinguished appearance, technical functionality and significant investment in installation. (3ds.2016). Many factors have to be evaluated and balanced to ensure the desired level of structural ,thermal, acoustic and visual comfort together with safety, accessibility and aesthetic excellence in façade design. The impact of building façade has become more important than ever in determining the operational and economic performance of construction projects.

In the most typical scenario, a façade is delivered on a Design-Bid-Build project delivery process(Kazmierczak, n.d.). In the standard Design-Bid-Build project delivery process, an architect develops the design before sending it out to bid and the input of experts tends to be incorporated very late in the process.

CHALLENGES INHERENT IN THE CURRENT FACADE DESIGN PROCESS

To obtain a thorough understanding of the challenges faced by architects in the current façade design process, an industry survey, followed by a structured questionnaire with industry experts was used. Ten architects with more than 5 years of work experience in the sector were selected.

The questions asked and answers obtained are summarized in Table1.The results of the survey shows that many architects only have very limited knowledge of façade system and functions which accounts for their lack of confidence of the performance of the façade in early design stage.

When asked what could improve the façade design process and enable them to understand the implication of the early design decision, the selected experts gave the following suggestions:

- A user friendly tool in a simplistic format that can assist architects in the façade design process.
- Appointment of façade consultants and subcontractors early in the design process.
- A better understanding of façade system and functions.

Table1: Industry Survey and Answers

Do you think you have adequate knowledge about façade system and the related functions of the façade system?			
VERY WELL (0%)	QUITE WELL (30%)	NOT QUITE WELL (70%)	NOT AT ALL (0%)
When selecting a façade system and the related characteristics, do you have confidence that it will meet the engineering requirements?			
VERY CONFIDENT (0%)	CONFIDENT (10%)	FAIRLY CONFIDENT (30%)	NOT CONFIDENT (60%)
Have you ever had experience of the selected façade system and characteristics being changed due to their incapability of meeting engineering and technical requirements?			
QUITE OFTEN(0)	OFTEN (10%)	SOMETIMES (60%)	NEVER (30%)

CONCEPT OF MINI FACADE

Mobile Apps are evolving rapidly and making ubiquitous information access at any time anywhere a true reality. The users can carry out a variety of activities through mobile devices. In considering the challenges the architects are facing in façade design process, the author proposed a glass façade design app named Mini Façade which intends to assist architects in the preliminary glass façade design process. In comparison with the desktop façade design software, the following features of mobile apps pose challenges in developing a 3D glass façade design mobile app(Zhang and Boonlit 2005).

- Connectivity: the slow and unreliable wireless network connection.
- Small screen size: physical constrains of mobile devices, especially small screen size, can significantly affect the usability of mobile applications.
- Different display solutions: the display capability of mobile devices supports much less display resolution in comparison with desktops.
- Limited processing capacity and power: computational power and memory capacity of mobile devices lag far behind desktop computers.
- Data entry methods: providing input to small devices is difficult and requires a certain level of proficiency.

In considering these issues, the app is not intended to substitute the desktop design software and is formalized to achieve four main goals:

- To provide architects with a user friendly tool in a simplistic format that can assist them in the
- preliminary façade design process.
- To help architects maintain aesthetic control over the design based on the instant façade function
- analysis results such as structural analysis, thermal analysis ,cost estimation etc.(Structural analysis is included in the prototype, thermal analysis and cost estimation module is under development.)
- To generate a performance report with quantified specification and performance levels.
- To provide a brief, up-to-date and informative resource that covers general and specific topics in façade
- industry.

DEVELOPMENT CYCLE OF MINI FACADE

Development process of Mini Façade is shown in Fig.1 and different interface solutions have been proposed to ensure the usability of the app such as automated 3D model generation and automated function analysis process, efficient input mechanisms and local stored database.

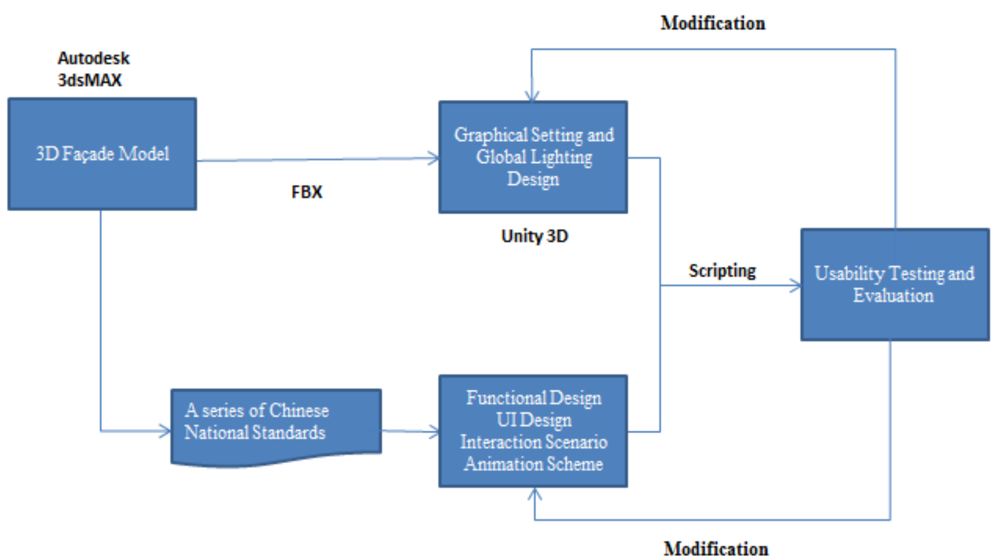


Figure 1.“Mini Façade” Development Process

TECHNOLOGY SELECTION

Factors that affect the selection of technology are multifaceted. The selection of the development engine is the key in achieving the goal of the project. Several criteria were set for candidate development engines such as capacities of 3D, cross platform, supporting different operating systems, open source, and affordability.

Finally, Unity 3D, Autodesk 3ds Max, Javascript, and Adobe Photoshop were selected to create the proposed Mini Façade. Several types of glass s façade models were first created in Autodesk 3ds Max and exported as FBX file to Unity 3D as a new asset. Major scripting efforts took place after the comprehensive scenarios and functional analysis, which dictated the animation scheme and graphical user interface design.

SOFTWARE ARCHITECTURE

A multilayered software architecture model provides a logical way to separate the different responsibilities of software applications(Sana et al. 2013). The multilayered software architecture of Mini Façade is illustrated in Fig.2.

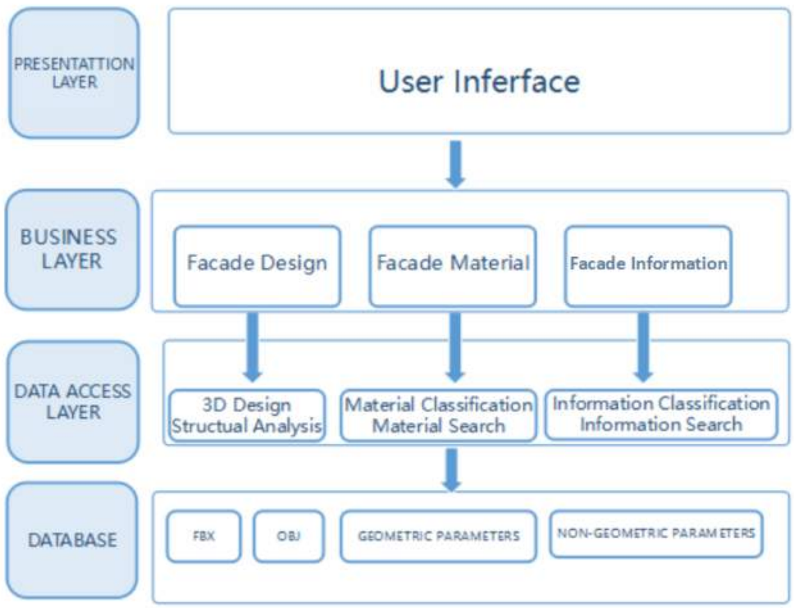


Figure 2."Mini Façade" Software Structure

FUNCTIONAL DESIGN

Functional design is the process of responding to the needs or desires of the people who will use an item (Dustin 2008). The following categories of desirable features were selected in the prototype(Table2): Façade Design, Façade Material, and Façade Information. The function buttons are located on the left side of the interface which can be hidden or revealed by sliding the screen to the left and right (Fig. 3).

Table2: "Mini Façade" Functions

Category	**Content**
1.Façade Design Module	Size selection：surface geometry and glazing grid Structural Analysis 3D Visualization Project Saving Data Export
2.Façade Material Module	Material database for the façade Suppliers
3.Façade Information Module	Façade news and resources

Figure 3.“Mini Façade” Functions User Interface

FAÇADE DESIGN MODULE

Façade Design features a simplified 3D interactive façade model generation tool and integrated facade function analysis tool. The prototype supports the following types of glass structure façades (Table 3)and the following systems: hidden frame system, vertically exposed mullion system, horizontally exposed mullion system, exposed frame system, point supported glass system(Fig. 4).

Table 3:Glass Structure Facade Types Supported by Mini Façade

Types	Details
Façade System Type	Hidden Frame System ,Vertically Exposed Mullion System ,Horizontally Exposed Mullion System , Exposed Frame System, Point Supported Glass System
Glass Type	Simple Glass, Float Glass, Tempered Glass, Semi Tempered Glass, Wired Glass
Glass Thickness	6mm,8mm,10mm,12mm
Mullion Type	6061-T4, 6063-T5,6063-T6, Q235,Q345
Mullion Cross Section	60/80, 60/100, 60/125,60/150, 60/200
Beam Type	6061-T4, 6063-T5,6063-T6, Q235,Q345
Beam Cross Section	6061-T4, 6063-T5,6063-T6, Q235,Q345
Mechanical Type	Simply Supported Beam

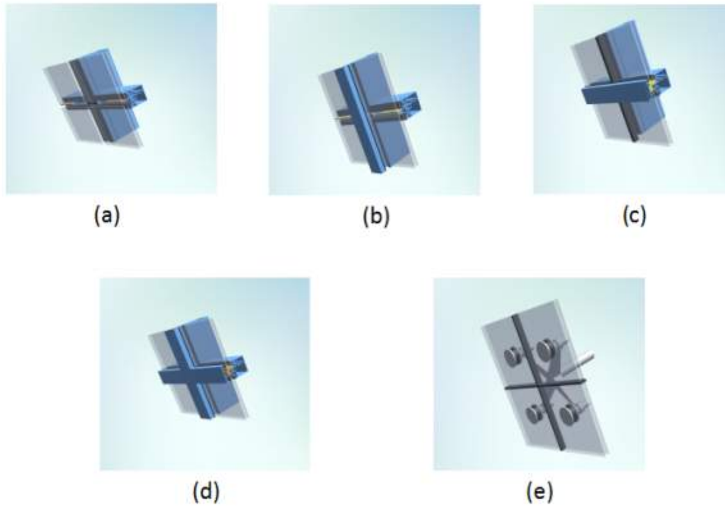


Figure 4. Five Systems Supported by Mini Façade:

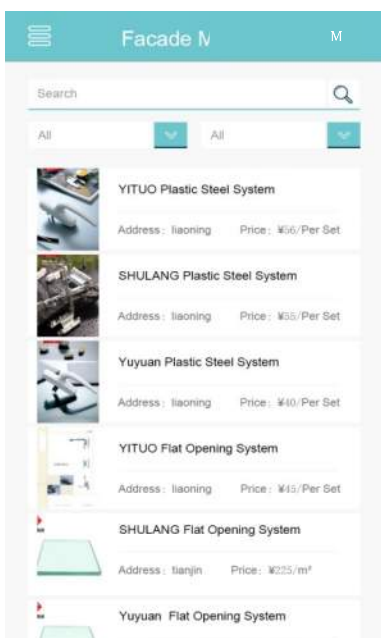
(a) Hidden Frame System, (b) Vertically Exposed Mullion System, (c) Horizontally Exposed Mullion System, (d) Exposed Frame System, (e) Point Supported Glass System

FAÇADE MATERIAL MODULE

Façade Material is an online façade material catalogue resource and search engine (Fig. 5).The user can browse across images of the façade material catalogue by scrolling up and down the screen. When the image is selected, a more detailed description will be shown on the screen. The information is extracted from relevant websites which is classified and can be searched by keywords.

FAÇADE INFORMATION MODULE

Façade Information aims to bring together the world's most productive building professionals and leading researches to share the industry trends and insights on how façade ideas are brought to life (Fig.6). The content covers from industry news to events and industry innovations.



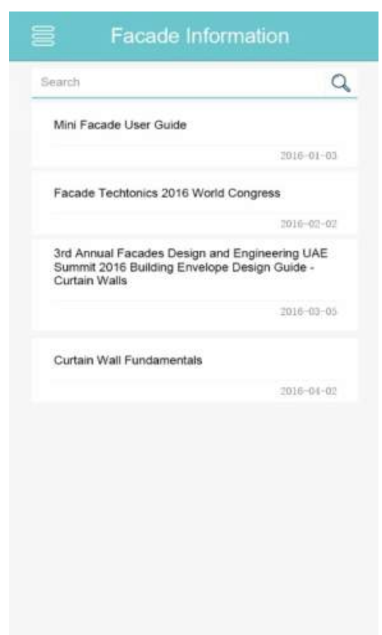


Figure 5. Façade Material UI *Figure 6. Façade Information UI*

FACADE DESIGN WITH MINI FACADE

The user can initiate the design by clicking "New Design" button or retrieve the previous projects by clicking "My Projects" button (Fig. 7). If the "New Design" button is selected, the user can choose from several facade systems which are shown in 3D models (Fig. 8).

Figure 7. Façade Design UI

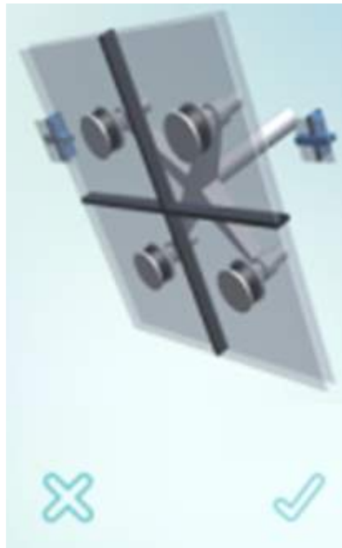


Figure 8. Façade System Selection UI

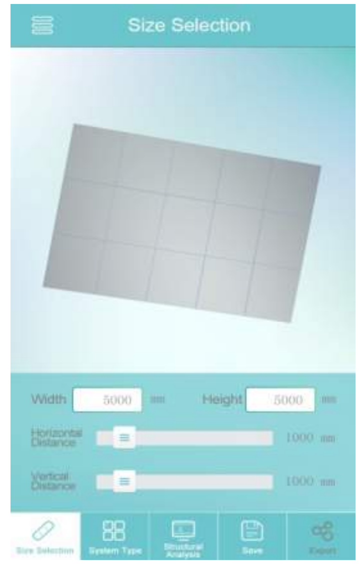


Figure 9. *Size Selection UI*

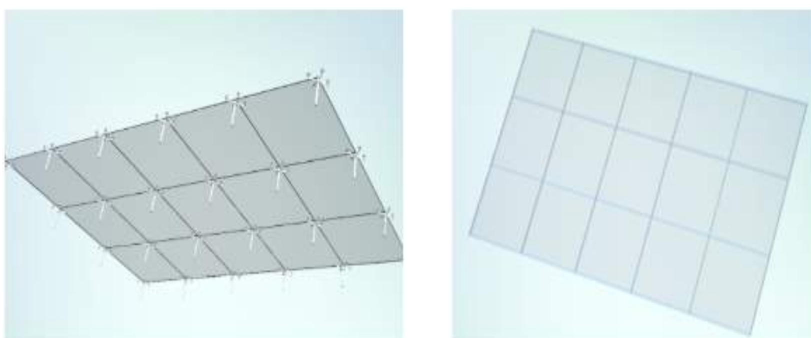


Figure 10. *3D View of the generated façade model*

When the facade system is determined, the user will enter the size selection user interface to input the width and height of the facade together with the horizontal distance and vertical distance of the grid module (Fig.9). In accordance with the parameters, a 3D model of the facade will appear on top of the screen which enables the user to interact with it (Fig.10).

The automated structural analysis can be carried out after the size selection. The user can initiate the analysis by selecting the predefined parameters and instant structural analysis results will be generated (Fig.11). For users' convenience, the parameters for structural analysis are classified into the following 4 sections: Project Parameters, Mullion Parameters, Beam Parameters, Glass Parameters (Table 3) .The result of the analysis is classified into the following sections: Mullion Calculation, Beam Calculation, Glass Calculation(Fig.11). Depending on the result of the structural analysis, the user can modify the parameters of the facade and initiate a new analysis, repeating the process until a satisfactory solution is determined (Fig.12). The calculation sheet can be exported by clicking the export button by the users for guidance.

Table 3:

Classification of Parameters	**Parameters**
Project Parameters	Elevation, Ground Type, Porosity, Shape Factor, Region, Recurrence Interval
Mullion Parameters	Mullion Selection, Mullion Material Selection, Mullion Span, Distance Between Mullions(Right),Distance Between Mullions(Left)
Beam Parameters	Beam Selection, Beam Material Selection, Distance Between Beams（Up）,Distance Between Beams(Down)
Glass Parameters	Outer Glass Thickness, Outer Glass Type, Inner Glass Thickness, Inner Glass Type

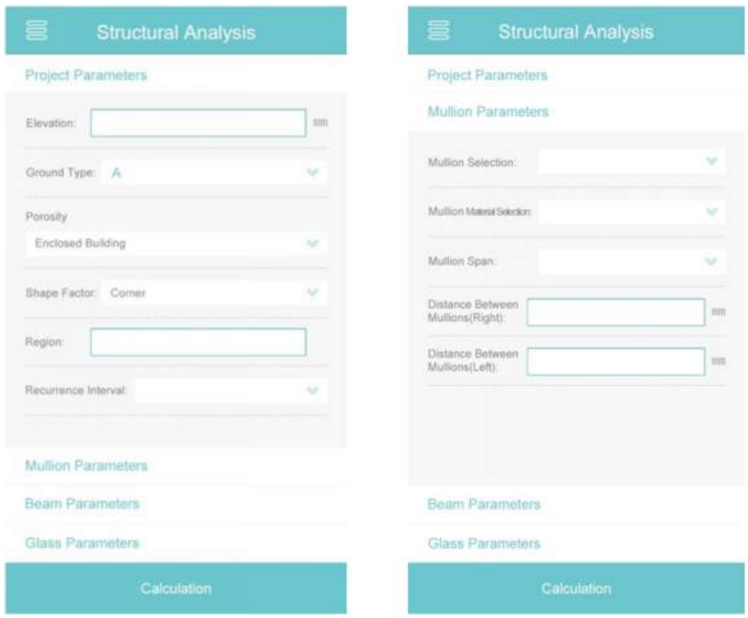


Figure 11.Structural Analysis UI

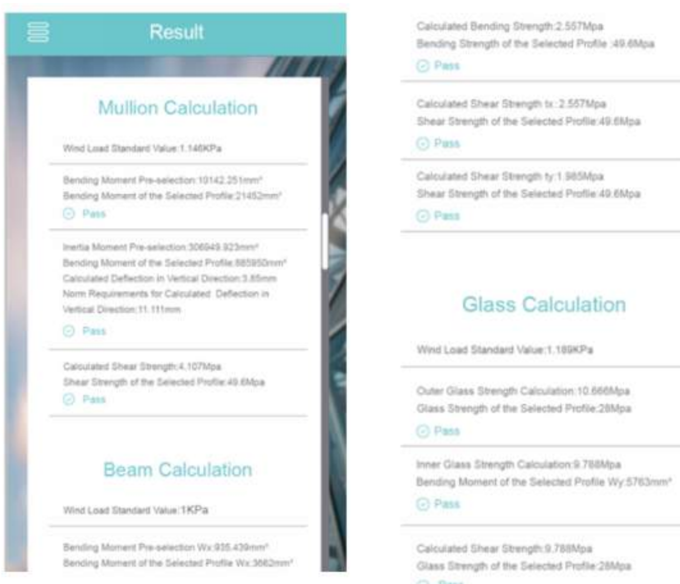


Figure 12: Calculation Result (note: the user need scroll down the screen to browse the result)

USABILITY ASSESSMENT OF MINI FACADE

After the release of the prototype, the app underwent a usability evaluation to reveal its strength and weaknesses. The evaluation employed a group of architects to take the usability test and comment on the features. Ten architects are selected according to criteria, including a basic understanding of façade engineering along with at least five years of experience in AEC industry.

The questionnaire used is the System Usability Scale (SUS), which is one of the most widely employed usability questionnaires. It consists of 10 items designed to measure users' perceived usability of a software system. The resulting score of the SUS was a single composite measure of the overall system usability. Scoring involved calculating the mean of test item responses on a normalized 100-point instrument scale. Negatively formulated items (2,4,6,8,10)underwent a transformation prior to calculation (Usability.2016). The resulting score was then multiplied by 2.5 to obtain the overall value. A generally acceptable cutoff score for the instrument is 68. Any SUS score above this cutoff is considered greater than average. In addition to the numeric data, experts also filled out a comments section at the bottom of the SUS regarding overall apps function . The mean score for each test item is in Table 4.

Table 4: Descriptive statistics for the SUS scores of the apps.

Item	M	SD
1. I think that I would like to use this system frequently.	3.1	.44
2. I found the system unnecessarily complex.	2.4	.80
3. I thought the system was easy to use.	3.1	1.34
4. I think that I would need the support of a technical person to be able to use this system	3.0	.40
5. I found the various functions in this system were well integrated.	3.4	.40
6. I thought there was too much inconsistency in this system.	2.3	.90
7. I would imagine that most people would learn to use this system very quickly.	3.4	.80
8. I found the system very cumbersome to use.	2.5	.90
9. I felt very confident using the system.	3.3	1.20
10. I needed to learn a lot of things before I could get going with this system.	3.1	.30

Note. All scores from n=5 raters.

The lowest scored items included:

2. I found the system unnecessarily complex. (Reverse -scored).
6. I thought there was too much consistency in this system. (Reverse -scored).

The highest were:

5. I found the various functions in this system were well integrated.
7. I would imagine that most people would learn to use this system very quickly.

The lowest rated items are both reverse –scored indicating the consistency and simplicity of the apps. The highest rated items indicate the integrity of the system. Regarding the combined items, the mean score for the 10 participants was 74 which was greater than the average score .In addition to the numerical data, the expert reviewers commented on the features of the app. The comments revealed the following:

- The app can assist architects in making more realistic decisions quickly in the early façade design process.
- The app expands the understanding the fundamentals of façade engineering among AEC industry.
- The app should be developed to support more system types and glass types.
- The app should improve interoperability with the desktop software.
- The visual effects of 3D model should be optimized.

CONCLUSION AND FUTURE WORK

This paper outlined the design, development and evaluation of a 3D glass façade design app called Mini Facade which has the potential to facilitate the design process for architects and improve their efficiency. The app can also act as a collaborative facade knowledge and technology exchange online forum for the AEC industry. The prototype only supports a limited selection of façade systems and materials now and can only generate instant feedback of structural analysis results. The app is also lack of the interoperability with desktop software. In the future, the app will support more systems and materials. Instant thermal performance analysis and cost estimation analysis will be encompassed. A new API will be developed to export the model information to desktop façade design software. The façade material catalogue and façade information will be updated on a regular basis.

ACKNOWLEDGEMENTS

All images by the author.

REFERENCES

3ds.2016."Curtain Wall Industry: History And Challenges Of Façade Design | 3D PERSPECTIVES". 2016. http://perspectives.3ds.com/architecture-engineering-construction/the-curtain-wall-industry-history-current-state-and-challenges-of-façade-design/(assessed May 24,2016).

Dustin,W., 2008. "7 Essential Guidelines For Functional Design". https://www.smashingmagazine.com/2008/08/7-essential-guidelines-for-functional-design/(accessed April 25, 2016).

Eva,H, Gröger C, and Mitschang B., 2015. “Mobile Apps in Engineering : A Process-Driven Analysis of Business Potentials and Technical Challenges.” Procedia CIRP 33. Elsevier B.V.: 17–22. doi:10.1016/j.procir.2015.06.005.

Gabrielle, B., 2015. "Top ten apps for construction professionals". http://www.benazziengineering.com/blog/2015/7/31/top-ten-apps-for-construction-professionals/(accessed April 25, 2016).

Kazmierczak,K., n.d. "Review of Curtain Walls , Focusing on Design Problems and Solutions" no.786: 1–20Sana,B., Guetat,A., Ben S., and Dakhli D., 2013. "A Multi-Layered Software Architecture Model for Building Software Solutions in an Urbanized Information System" 1 (1): 19–34. doi:10.12821/ijispm010102.

Statist.2016."Number of Mobile App Downloads 2009-2017 | Statistic". http://www.Statista.com/statistics/266488/forecast-of-mobile-app-downloads/(accessed April 25, 2016).

Usability.2016."System Usability Scale (SUS)".http://www.usability.gov/how-to-and-tools/methods/system-usability-scale.html/(accessed April 25, 2016).

Zhang, D., and Boonlit,A. 2005. “Challenges, Methodologies, and Issues in the Usability Testing of Mobile Applications.” International Journal of Human-Computer Interaction 18 (3): 293–308. doi:10.1207/s15327590ijhc1803_3.

MANAGING COMPLEXITY

Implementing parametric tools in project management: a case study

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ABSTRACT

Recently the construction industry has seen a rise in the implementation of parametric tools in the design and fabrication process, but there has been less emphasis on the application of these processes on the production and installation phases of a project. There is often a dramatic disconnect between the technologies and precision used in the design phase of the process and what happens in the shop and field during the construction of a complex project.

This paper documents an example of a residential building in New York City where the complexity of the geometry created a challenging task for the façade installation team. Our team of designers and industrial engineers came in to help. We merged the parametric models used for design with excel spreadsheets used by the project management to create a new set of tools that were better able to help our team coordinate material delivery and handling, workforce management and track the progress of the work. This allowed installation to become a controllable and predictable process.

We automatically generated bi-weekly reports that were very clear and concise. These reports allowed us to distribute visual maps to each of the subcontracts that contained only the information pertinent to them. The visual maps were linked parametrically to both the building model and smart excel tracking spreadsheets. We were able to use these updates to help direct the field crews and report on progress of the project.

This paper presents a real world approach that linked a 3D model with a schedule and smart tracking worksheets, in order to provide a more sophisticated and accurate method of managing a project. Further, it shows the possibilities and needs of using this approach to create a true 5D model in which the entire project can be tracked and managed better from design to closeout.

KEYWORDS

case study, design processes, project management, construction management, parametric workflow, means and methods, curtainwall

INTRODUCTION

This paper describes a case study that examines a real world example of integrating parametric tools, typically used in architectural design and fabrication, into the project management workflow in order to improve the construction process.

It examines the current practices and trends in both design and project management, then gives a specific example of how advanced tools and processes were utilized to improve the execution of a complex construction project. Finally, this paper explains how our team aims to further develop these tools in order to advance the execution of an entire construction project.

BACKGROUND

DESIGN VS. PROJECT MANAGEMENT

In recent years, the architectural industry has largely benefited from advances in technology. This is particularly evident on the design side: a growing number of projects over the last decade have shown increased geometric complexity. Thanks to the advancement and democratization of 3D modelling tools and parametric design, architects are able to control, rationalize and optimize previously unmanageable geometries so that these projects can leave the drawing board and turn into real buildings (see Figure 1).

Figure 1: SFMOMA, an example of complex geometry realized using prefabricated panels, recently completed in San Francisco. Photo courtesy of Enclos.

Project management, on the other hand, has not greatly adjusted its approach in quite some time. Although there have been advancements in several tools to help manage construction documents or create comprehensive schedules, the underlying process has remained relatively stagnant and an Excel spreadsheet is still the tool of choice. However, with the increasing complexity of construction projects, the amount of information and coordination required to manage them is growing exponentially. Furthermore, most projects utilize trade labor that is not always technologically proficient or trained to handle complex construction details. There is an opportunity to utilize some of the advanced tools used in design and the amount of information that they contain to help advance the process of project management.

CASE STUDY: VIA 57 WEST

The case study presented in this paper is portion of VIA 57 WEST, a unique residential building recently completed in New York City. (See Figure 2). This project is a perfect example of the growing complexity within the construction industry; its most prominent façade is a shiny double-curved slope that opens towards the south into a courtyard surrounded by apartments and amenities.

Figure 2: VIA 57 WEST, designed by BIG, Bjarke Ingels Group. Photo courtesy of Tom Dobbins.

The building's envelope consists of four major façade wall types: a somewhat traditional curtain-wall runs in a saw-tooth fashion along the north and east elevations; a curtain-wall and window-wall hybrid wraps the courtyard; prefabricated mega-panels compose the hyperbolic paraboloid geometry of the slope; a stick built system closes the punctured balconies, referred to herein as cockpits. (See Figure 3)

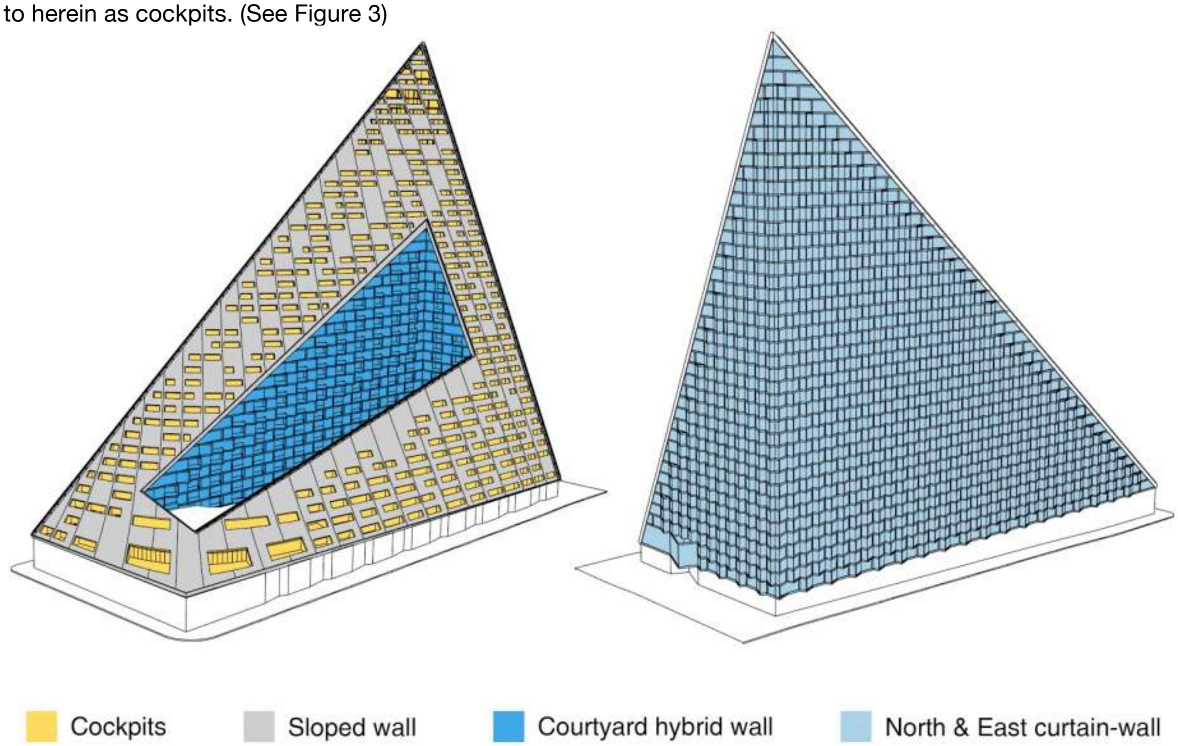

Figure 3: VIA 57 WEST wall types. Image by the authors.

The company we represent worked on the engineering, fabrication and installation of all these wall types. We treated the management of the façades of this project as two separate projects: one for the sloped wall and cockpits, and another for the curtain-wall and window-wall. Each one of these projects was engineered and manufactured in a different location by a different group, creating a significant number of suppliers to manage throughout the production phase.
The part that turned out to be the most challenging to manage was the in-field construction of the cockpits. Each of them required different materials from several suppliers installed by an even larger number of subcontractors alternating daily at each location. The case study in this paper focuses on the procurement, installation, and management of the cockpit system.

METHOD

COCKPITS - DESCRIBING THE CHALLENGES

Traditionally, balcony units stand out beyond the watertight curtain-wall. The cockpits of VIA 57 WEST instead are sunken into the weather barrier of the sloped wall and as water flows down the slope, it pours into the cockpit cavity. Therefore extra care had to be taken to ensure that the cockpits, and especially at the connections with the sloped wall, were waterproof and that water could properly drain through and out of the system.
As mentioned earlier adding to the complexity was the fact that this work required the coordination of several different suppliers and several different sub-contractors alternating in and out of each cockpit.

COCKPITS - DESIGN ELEMENTS

All the apartments designed under the sloped roof have their own private cockpit offering terrific views towards midtown Manhattan and the Hudson River. The connection and the views between the interior and the exterior are guaranteed by a continuous window-wall that runs along the entire width of each cockpit. The remaining three sides are framed with ½” thick GFRC (Glass-fiber Reinforced Concrete) panels mounted on a drywall system. (See Figure 4)

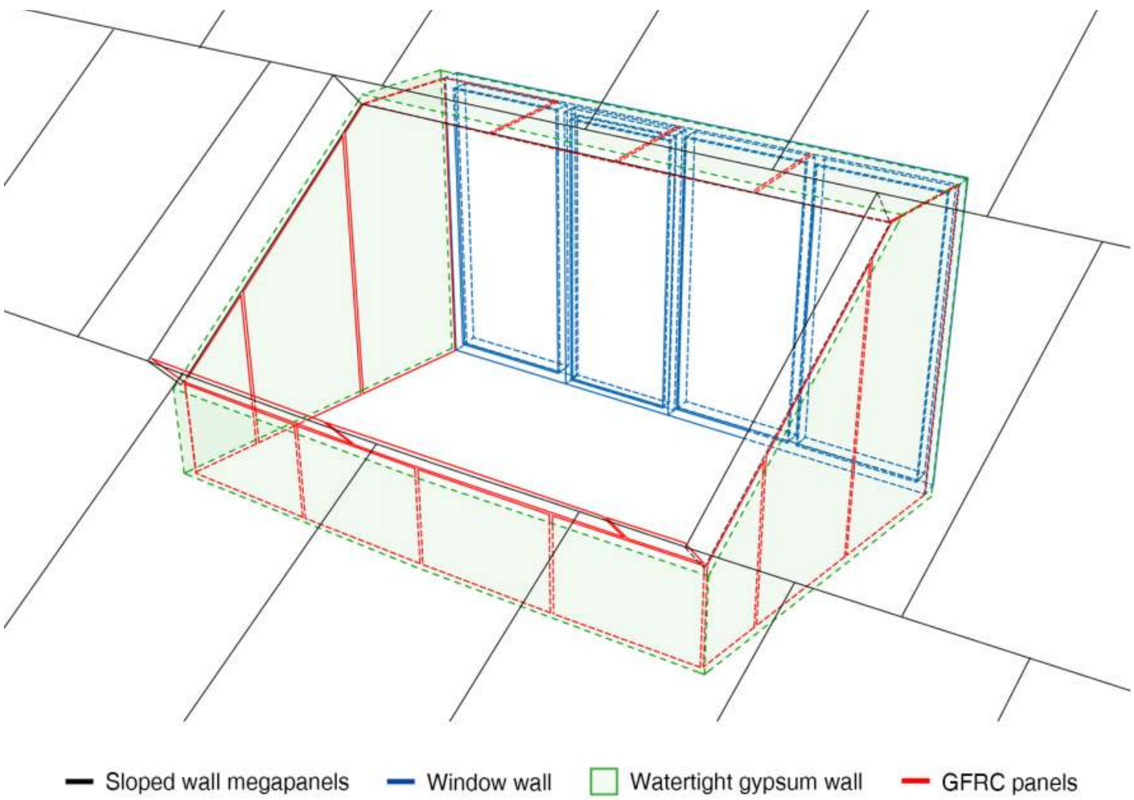

Figure 4: Cockpit layers. Image by the authors.

Because of the geometry of the building, each one of these 279 cockpits is different in shape, therefore every drywall is unique in its geometry and in the angle it forms with the window wall. Similarly, every single GFRC panel profile is different, adapting to an ever-changing angle of the slope.

COCKPITS - INSTALLATION FLOW

The section below outlines the 15 distinct steps that had to be completed at each cockpit. Our organization's field crew, the project consultant, five (5) different subcontractors, and three (3) different material vendors performed the combination of steps described below. See Figure 5 for a graphical representation of the workflow.

- Cockpit Window Wall
  - The window wall did not have any major predecessors preventing progress, other than installation of the sloped-wall anchoring system.
  - The sloped wall anchoring system was installed far enough in advance that the vertical window walls of the cockpits could be installed well ahead of the completion of the sloped wall mega-panels.
- Sloped Wall Completion
  - The sloped-wall mega-panels must be installed and adjusted before any of the other finish work can be done to tie the sloped wall to the window wall.
  - Since each mega-panel is unique and the double curved geometry is so complex, there was a significant amount of final adjustment that had to take place.
  - Finally, at the transitions between the N/E and courtyard facades, the geometry was even more difficult, adding to the complexity.
- Sloped Wall Inspection & Sign Off
  - Prior to moving on to the cockpit finish work, the consultant was required to inspect the sloped wall for conformance to the specifications and geometry.
- Caulking
  - Subcontractor #1: A caulking and sealant subcontractor was utilized to seal the joints between the sloped wall and the structure.
- Insulation & Fireproofing
  - Subcontractor #2: Another subcontractor installed insulation and sprayed fireproofing prior to any finish material being installed.
- Inspection & Signoff #2
  - Here another inspection was required prior to moving onto finish materials, in order to ensure the system was properly insulated and fireproofed.
- Install Formed Aluminum
  - Subcontractor #3: another subcontractor performed the Installation of formed aluminum angles and support components.
  - This material had to be coordinated from a vendor located in Chester, VA.
- Install DensGlass
  - Subcontractor #4: After the formed aluminum was installed, yet another contractor came in behind to install DensGlass fiberboards for extra weather protection.
- Install Blueskin
  - Subcontractor #5: The fifth and final subcontractor then installed an air and vapor barrier membrane (Blueskin) on top of the DensGlass. This acts as the primary weather barrier for the cockpit walls.
- Booting & Final Sealing
  - Subcontractor #1: Here the sealant contractor returned to the cockpit in order to install the final boots and sealant.
- Inspection & Signoff #3
  - Since the blue skin acts as the primary weather barrier, another inspection is required, prior to performing the required water testing.
- Water Testing
  - Once the primary weather barrier is in place and signed off on, we were required to perform a water test to verify compliance.
- Install Stainless Steel Trim
  - Subcontractor #3: After the weatherproofing was verified, subcontractor 3 returns to the cockpit to install the stainless steel trim.
  - Stainless steel trim had to be procured from and coordinated with another outside vendor.
- Install GFRC
  - Subcontractor #4: Finally, subcontractor 4 returns to the cockpit to install the final finished Glass Fiber Reinforced Concrete (GFRC) panels.
  - The GFRC panels were procured and coordinated from yet another outside vendor.
- Final Inspection & Signoff

- A 4th and final inspection was required after the GFRC was installed to finalize and turn over the cockpit to the customer.

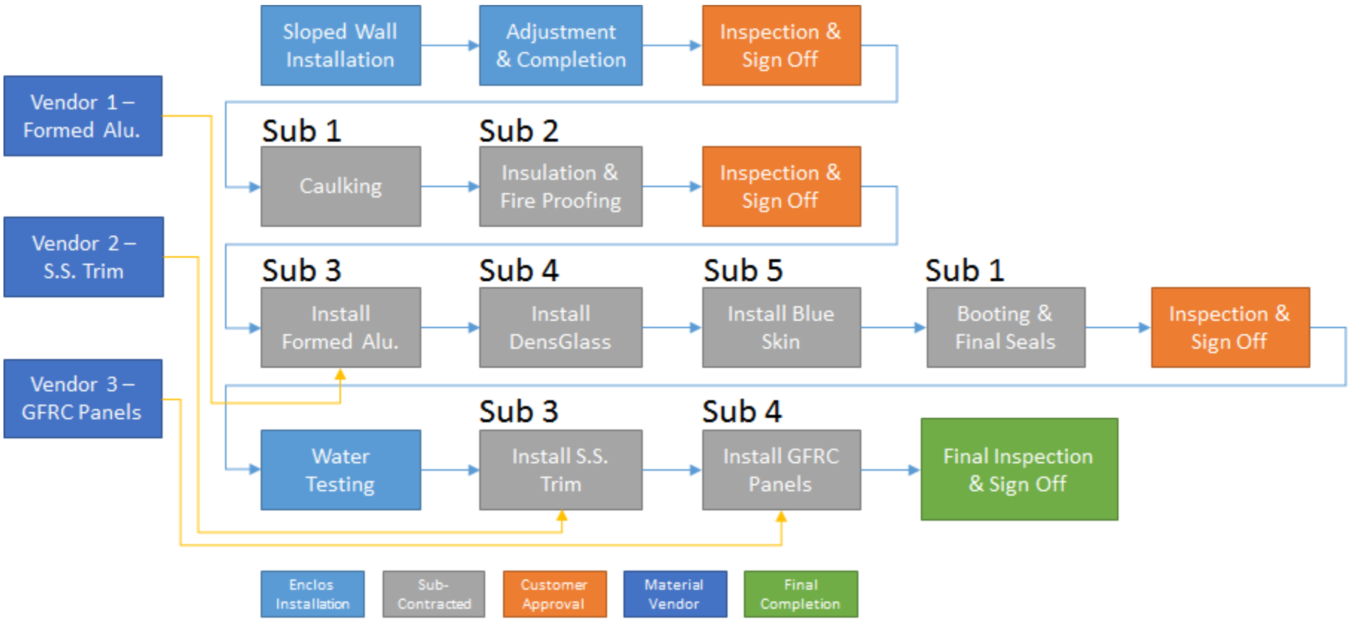

Figure 5: Cockpit installation workflow. Image by the authors.

COCKPITS - EARLY INSTALLATION

As described in the section above, in order to install and complete the cockpits, there were a significant number of different activities, done by different work crews and utilizing material coming from different vendors. Initially the coordination was a nightmare. It was impossible to group the work into different releases and track a group of cockpits in sequence. Just too many activities had to be performed. The schedule did not allow us to complete a certain activity on a particular floor prior to moving onto the next activity.

All of the subcontractors knew what specific activities they were responsible for, but they did not know at any given time, which cockpits were completed up to their scope of work. Subcontractor would carry their tools and materials up to a certain floor and literally look into each cockpit to see if it was ready for them. If the cockpit was ready, they would do the work; if not, they would go see if the next cockpit was ready.

COCKPITS - A NEW METHOD

At the beginning, the cockpit installation was slow and grueling. Work could not have continued in that manner or the job would never have been completed, and costs would have soared through the roof. Furthermore, as the building installation neared the later part of the project, cockpit completion became a priority. It became more and more essential to complete cockpits and turn over entire floors to the customer. A new method to manage the vendors, subcontractors, and internal labor had to be developed.

After the design was completed, the vendors and subcontractors were selected for the various components of the system. Initial sequencing and flow was understood but not well documented and connected. The first step in formalizing this process was to document the workflow as laid out in Figure 5. Once the ideal workflow was defined and agreed upon, we could begin to determine how to monitor, manage, and direct.

In typical construction projects, management tends to group activities into blocks: per floor, per 5 floors, etc. Then they can manage each major step to completion, prior to moving onto the next activity. For example, engineering might be completed for levels 5-10 prior to sending to assembly, which cannot start until after engineering is completed. However, due to the high number of individual activities for the cockpits, this approach was not feasible. For that reason, it was decided to monitor each cockpit individually. This presented quite a challenge. We were now committing to managing 279 cockpits, each with 15 distinct activities that were all occurring simultaneously. If we were to represent this is a traditional schedule, we would

need 4185 individual tasks. Again, this was impractical.
Instead, we utilized a smart spreadsheet in order to track and sequence the activities. The spreadsheet was set up with rows that represented each cockpit and columns that represented the different activities. The cells in each column contained equations that would mark them as available when all of the predecessor work was complete. For example, Cockpit X would be marked available for stainless steel trim installation if water testing had passed, inspection #2 was complete, and stainless steel material for Cockpit X was onsite. Since S.S. trim installation belongs to Subcontractor #3, Cockpit X would now be marked as available for work.
The smart spreadsheet acted as the primary document to understand status for the project manager. They would walk the site twice per day to update status for every cockpit on the job and updated completion status in the spreadsheet. It would automatically update and show the next available activity for any given cockpit. In addition, it would identify activities that were approaching in the near future. Since the PM was the one coordinating material delivery to site, they would also know when they had to ensure material availability for any given cockpit. See Figure 6 below for a small excerpt of the utilized spreadsheet.

Figure 6: Cockpit tracking spreadsheet. Image by the authors.

The spreadsheet worked very well for the project managers to update status and understand where we needed to go next; however, it was not ideal for communicating back to the subcontractors where there was work available.
To solve this problem we decided to link the data from the spreadsheet to one of the 3D models we used for the fabrication of the cockpit parts. Twice a week we examined the work of each trade, updated the spreadsheet and used Grasshopper for Rhino to link this information to a 3D model and generate clear maps of the work in progress (See figure 7).
We soon realize that in order to make these operations as efficient and precise as possible we had to write a routine that would have avoided any human error in picking the right map, data and recipient.

With the push of a button in the master Excel file, we activated a script that opened Rhino and loaded the Grasshopper definition. This definition would then look for the updated information on the spreadsheet itself, color each subcontractor’s map accordingly and export the result as .jpg images. These images were automatically linked into different Word template files able to collect additional information and completion tables from the Excel spreadsheet.

Once these files were completed, the same script exported them to PDF automatically titled with the contractor’s name and ready to be emailed directly.

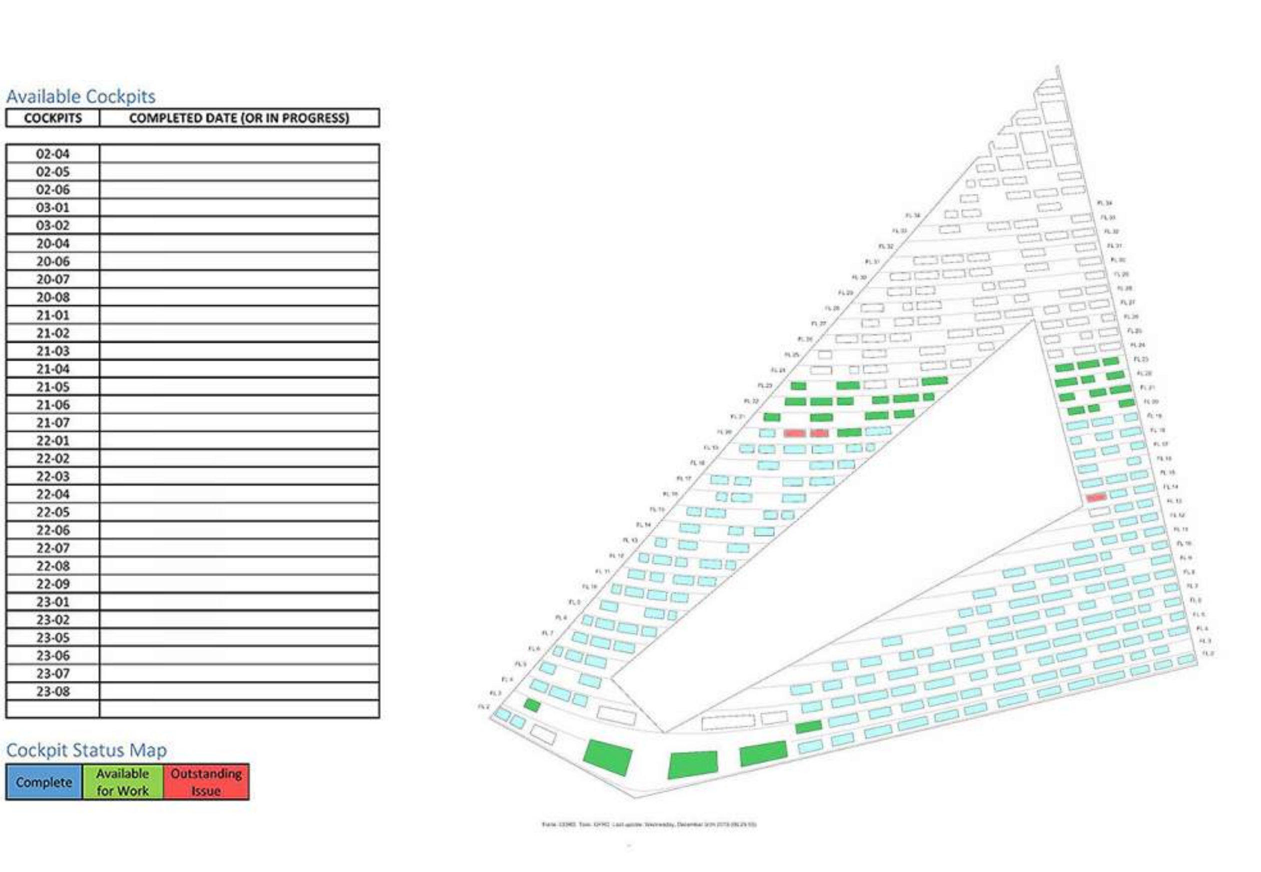

Figure 7: Subcontractor map, on the left the list of work to do, on the right the relative image showing completed, in progress and deficient work. Image by the authors.

DATA AND FEEDBACK

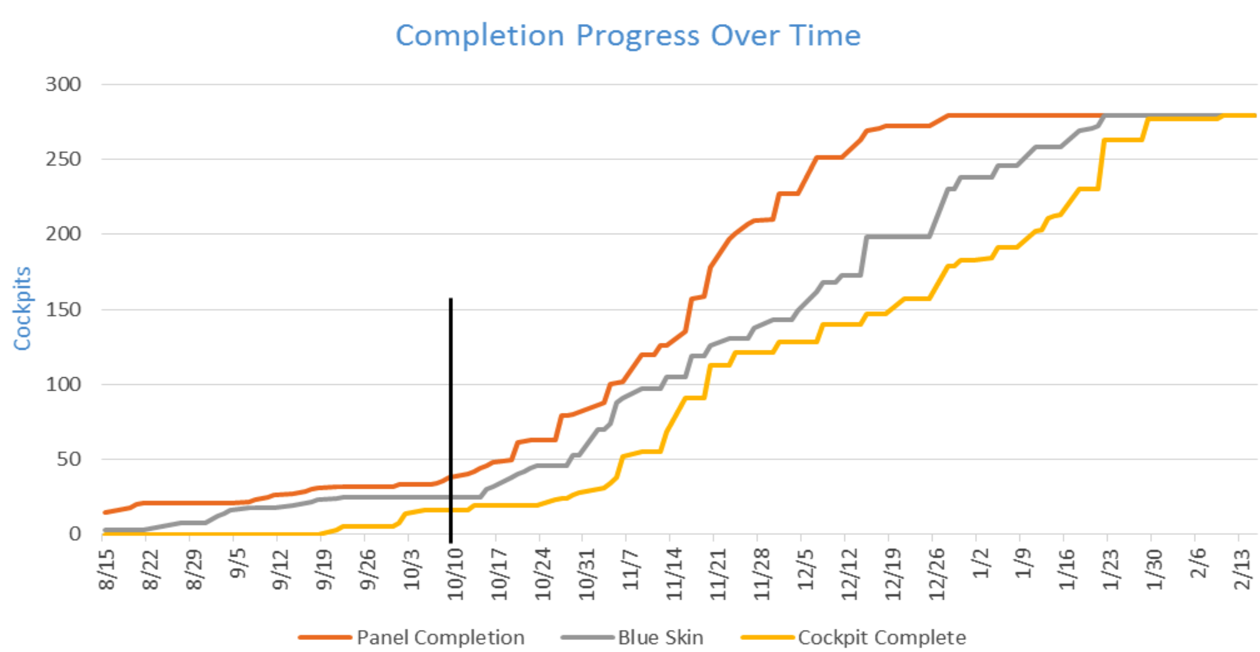

Figure 8: Cockpit completion rate, October 10th marks the beginning of the use of the new managing system. Image by the authors.

Prior to implementing the method described, only 5-6 cockpits were completed each week. From the day we introduced the new tool to the project management team and the subcontractors the production quickly grew; after only 4 weeks we reached a pace of over 20 cockpits completed each week, an average better than any of our previous estimates.
The subcontractor's foremen received these maps with great enthusiasm; seeing the completed and the expected work in a clear and universally understandable way was extremely helpful to communicate with their different crews in the field and with our project manager to schedule efficiently the delivery of materials. Keeping a constant track of work and responsibilities also allowed us to pinpoint immediately the responsibility in case of mistakes and therefore to have a better handle of all the parties involved in the construction.
Finally yet importantly, the client was pleased to receive weekly reports showing the constant and accelerating progress of the work and to be able to track the progress of it in a clear and efficient way.

CONCLUSION AND FUTURE WORK

Although this methodology was applied only to the 279 cockpits we should not forget that the completion process involved 5 different material suppliers and 15 steps per each, unique, cockpit. Such a process is by far more complicated than the installation of most curtain-walls, usually requiring only one supplier and much fewer steps to be completed.
The success of this operation has already lead us to apply this method to another project our company is working on, also in New York City. In this case, we would track the entire facade, more than 10,000 curtain-wall units divided in 10 different wall types. Recognizing and keeping track of the installation of units is still a progress involving project manager consulting plans and elevation but our intent is to introduce technologies currently available to make the work in the field smooth and error proof. Using technologies currently available we want to assign a scannable code to every units so that everybody in the field could not only recognize immediately the unit they are about to install, but also recall from the cloud its exact location and any standard or particular detail that applies to it.

Similarly, once the work is completed the information can be immediately uploaded to the cloud and the next crew can come in without any waste of time and energies.

Project managers, ironworkers, subcontractors and consultant would be able to inform and be informed in real time of completed and inspected work, reducing dramatically the time spent in writing reports at the end of each day and providing a precise and incontestable tracking of the work.

ANALOG ANALOGUES

Reconstructing “play” in the exploration of building façade strategies

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ABSTRACT

This paper explores the use of games and “play” in architectural education and describes some tactics used in an academic setting to engage students in lessons about facade design and wall construction. The paper also details examples from studio design exercises that address the use of analogues and games to help students become more aware of fundamental issues in construction like materiality, tolerances and constructability.

KEYWORDS

case study, design processes, masonry façade, precast façade, masonry, generative design, lego, brick, play




Figure 1: Student Yukie Takeshi on a field trip to Lego Store Burbank for 2011’s The Brick Studio, Cal Poly Pomona. Figure 2: A demonstration of self directed play in studio by students using the materials at hand. Figure 3: First year students who began a self directed assembly inspired by Tara Donovan’s 2012 piece “Styrofoam Cups” Figure 4: First year undergraduate students collaborating, evaluating, and modeling a group “street” and landscape design.

INTRODUCTION

“Play cannot be denied. You can deny, if you like, nearly all abstractions: justice, beauty, truth, goodness, mind, God. You can deny seriousness, but not play. (Huizinga, Homo Ludens, 1950)

“Play” or “playing”, like in all other manner of cultural production (Huizinga, 1955), is a critical part of architectural design. This paper explores some consequences and outcomes of five years of material based studio design explorations that have used “play”, “playing” and “games” to a curriculum for understanding and designing walls and facades. In the series of exercises that are highlighted in this paper, permission and encouragement was given for participants to “play” in an academic studio environment, setting aside time for students to think, evaluate on their own, and to make productive time of that which might appear “’merely’ a game” (Huizinga, 1955). Whether the studio’s focus was the design of facades in brick, precast concrete or other type of walls, the engagement in play at all scales of design was found to be a useful way to quickly instigate some novel design approaches, help students to identify architectural concepts and initiate discussions and reflections of both analog and digital work.

BACKGROUND

“Play” is embedded in most of the traditions and practices of the architectural design studio. It is an educational model that utilizes make-believe, games and role-play to touch on many lessons and practices that designers may face in their professional lives. Studio instructors and design faculty propose an agenda for fictitious building projects or programs and students are then encouraged to react as an architect would, working on designs that respond to this prompt. Architecture studios, despite where they may sit on the academic spectrum of “practical” constraints or supposedly “theoretical” ones, all begin with an invitation to explore playing the role of an architect. Many scholars, educators and psychologists have made attempts to codify and define play and playing. For the purposes of the explanations and observations discussed in this paper, the elements of productive childhood play can be defined in the following way (Isenberg, 1988):

- Play is *symbolic*, in that it can represent “a” reality that taps into the participants imagination.

- Play is *pleasurable* to the participant, even when the activity is serious, the intensity of involvement can create a focus that reinforces the idea that enjoyment can enhance one’s work.

- Play is *meaningful* in that it connects or relates an individual’s personal experience.

- Play is *active* in that individuals are doing things and not watching passively.

- Play is *episodic* in that its goals can shift, be flexible, and develop throughout the experience.

- Play is voluntarily entered into by the participant and although contrary to common misconception usually *governed by a set of rules* that are either imposed by or are the result of some type of self governance.

While studying technical aspects of architecture such as the design of façades or wall systems, exercises like the ones described below attempt to further expand a students knowledge base and use tactics that challenge notions that they have previously built up over several years of architectural education. One of the goals of the exercises was to engage students to address and evaluate their projects at multiple scales so that they would not lose sight of broader design goals in their projects. In developing an agility to balance between the assemblies of components, their materiality, of tolerances, and the design of buildings as a whole, students are confronted with an essential part of design practice where the outcome is frequently the execution of envelopes, facades and other tectonic issues related to wall construction. Another goal was to postpone the kind of seduction that students can be prone to by the exclusive use of digital tools that, as Robert Somol has said can, “provide answers before the significance of the questions can be formulated” (Somol, 2003). Again the goal in the approach of the exercises described below was to ask students to “toggle” as Stan Allen says “between the actual and the virtual” in using both digital and analog tools to evaluate form and its material manifestation in both environments. By letting students create analogues and to “play” with complex ideas “Games can address such issues directly” without a student’s lack of facility stifling their impulse to create or participate (Radford 2000).

Games and play techniques in architecture studio achieve many of the same outcomes that psychologists have observed when children play with blocks. This is a time when both students of architecture and young children may be juggling and exploring many new concepts at once, for instance how to collaborate, how to identify patterns, how to evaluate the interactions of systems, how to communicate concepts, or how to incorporate their previous academic and life experiences into their present coursework (Piaget, 1962) (Moffitt, 1974). Using games and play in the exploration of façade design specifically has the potential to awaken students’ memories of discovery, and evoke a sense of fun and anticipation at the prospect of exploration and can be an opportunity for students to reevaluate their assumptions of what they have previously learned through the course of their schooling. This reevaluation also can come at a time while they are still forming the infrastructure and knowledge base for their future development (Jabr, 2012).

With these issues in mind, an organized design studio play session can have the potential, depending on the engagement of the students, to draw out the best attributes of the studio/project based educational system. Obviously student participation, their receptivity to new ideas and their ability to explore is crucial in every design studio, but to make the most of the opportunities afforded by time that is set aside to play, students must feel that they have agency and are entering into it voluntarily. This idea is complicated by the fact that students are required to participate in studio course work for the completion of their degree. Entering into the exercises described in this paper *was* voluntary for the students in that they chose to participate in these studios from others that were offered and although many of the exercises described had an assigned set of guidelines, they were left open ended enough to insure the students had agency over the design decisions they were making without direct guidance or critique.

METHODS

STUDYING THE SHAPES OF STACKING:

As part of a studio dedicated that was to brick construction in 2011, students working in teams of two were asked to simultaneously research and draw common objects whose shapes were designed both to operate as independent units (such as a Styrofoam cup) and also to aggregate to form something larger (such as a Lego brick to a structure, or designs that nest to form a column like egg crates, shipping containers, or Aalto stools). Embedded into the diversity of the research subjects was the variety of their scales. Through drawing, making diagrams and photographs students found that objects that were designed to stack like the ones mentioned previously must be shaped, detailed and executed out of different materials depending on their size.

While students explored the histories of these objects they also drew their components, details, and the shapes that allowed for their stacking and storage. They then described the original uses of these objects, their intended functions and other novel uses and unintended works that were created and may not have been predicted by the designers (Fig. 3,5). In the second portion of the studio research, students drew and built models of masonry structures, both contemporary and historical. This included making silicone molds and producing the bricks of their case studies being careful to accurately depict the proportions and dimensions of the units in the original buildings. They then stacked them in the method that they had observed in their research, acting as the masons on the construction site (Fig. 6,7).

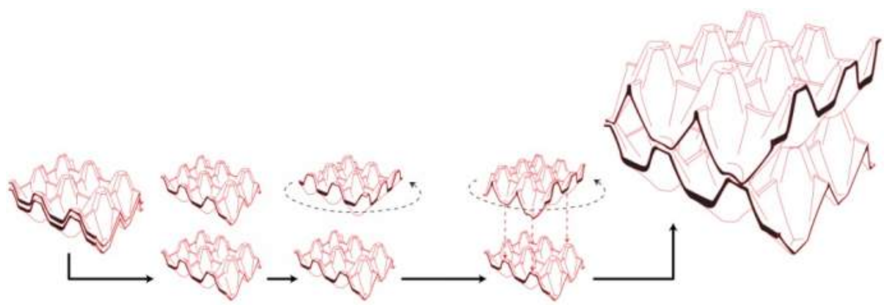

Figure 5: Diagrams of stackable everyday objects drawn by student Yukie Takeshi. Figure 6: A model of a section of the brick construction of Eladio Dleste's Church at Atlantida by Jeremy Schmidt and Katelynn Rodgers.

OUTCOMES:

A discovery of these exercises, both in terms of pedagogy and design research, was the impact that scale had on the students' work. As a means of creating a comparable taxonomy of different brick constructions, the scale of the exercise was held to ½"=1' so that students could adequately handle making large batches of units to assemble (fig.7). This meant that in some cases, while this restriction served to help the students to understand the sectional quality and proportions of a given wall construction, it may not, for example have been possible to accurately construct a complete dome or full portion of a selected project. That is something that could be remedied in future explorations by adjusting the student team sizes or selecting fewer projects and concentrating resources to make larger models. Scale was also a key component of the stackable object exercise as it revealed the ability of many of the smaller objects that were studied to have a broad array of formal possibilities when they were aggregated in a way that they were not designed to. This was the case with the Tara Donovan artwork "Styrofoam Cups" that the students studied, as well as other examples including those built of shipping containers or Lego (fig.3).

Another valuable teaching tool for students that was identified through the course of these exercises was to engage them in creating units of varying materials, scales, and different manufacturing techniques. For example most of the students in the brick studio began making their model brick units by hand, as most were simple repetitive shapes. All of the students experimented with using various mediums to act as a substitute for mortar at the scale they were working in. The best material proved to be silicone in that it had a slow enough drying time so the bricks could be worked into place in the same way a mason would build a brick wall. It was a group of students studying the construction of Frank Lloyd Wright's SC Johnson Wax Building (1939) that realized the project's variety of shapes and sizes would make it impossible in the given time of the exercise to complete the project. They found that by using CAD to recreate the varied types of semi circular bricks found in the building they could achieve a high degree of accuracy and produce the bricks much faster than if they were to form and mould the variations by hand. They laser cut the patterns for the moulds and then poured in the plaster that they were using to make the model bricks (Fig. 7). This technique led to other experiments in the studio and later material based and foundational studios that used 3d printing and laser cutting to make plaster moulds and bricks, combining the analog and the digital to help the students continue their engagement with materiality (Fig. 8).

The ability for students to understand the design challenges and issues with tolerances between machine made parts and those made by hand has been an invaluable tool, especially in foundational studios, to teach the concept of construction tolerances and the interaction of materials that have different properties and technical considerations. When learning and studying façade or wall constructions in a studio setting where more impactful full scale student constructions may not be possible, large scale models in these cases brought about unforeseen lessons about tectonics, tolerances and techniques.

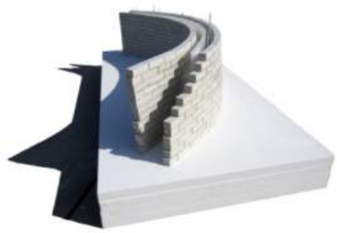

Figure 7: A model of a section of the brick construction of Frank Lloyd Wright's Johnson Wax Building by Yukie Takeshi and Amanda Woo made from molds that were laser cut . Figure 8: 3d printed molds and plaster wall models of James Stirling's Andrew Melville Hall made by Necils Lopez, Yanelli Monjaras, and Pedro Cuin-Molinero,Pedro.

PATTERNS 1:THE ROLE OF GAMES IN DESIGN: USING LEGO AS A TOOL NOT A TOY.

In the same brick studio of 2011, as a final warm up exercise before a building program was given, students were taken to the Lego Store in Burbank where they were invited to pick from a predetermined selection of Lego Bricks (Fig. 1). While the role of the first exercise was to challenge the students' ideas about materiality, scale, and tolerances, this exercise was specifically meant to challenge the students ability to interweave two differing logics together and make systematic decisions about the compromises between the objectives of their designs (in this case replicating a given pattern) and the logic of the building component (a Lego Brick). Despite the experience of 1st or 4th year or even a graduating student has, their ability to identify patterns as a language in architecture and find systems and rules for resolving inconsistencies between the parts of a façade or wall and the whole building can be a lifetime pursuit. This became an analogue of the type of negotiation that is commonly found in architecture: when the logic of the unit and the logic of the design intent are in contradiction and a resolution must be found that accommodates a unified whole.

Once at the "play session" location, which was away from campus, a large collection of Lego bricks was scattered onto a communal work table. Students were then given several patterns from nature or textiles and asked to replicate the patterns with the Lego bricks that they had in front of them. The goal for this exercise was for students to make choices about how they would interpret the patterns. Once the directions were given, students were left without any further instruction or coaching to perform the task. They were allowed a specific time for this activity that was protected from outside interruptions by removing all phones and other devices. In the second part of the exercise students were then asked to merge their two pattern interpretations into one wall system, synthesizing their designs together and reconfiguring the originals as needed. (Fig. 9,10,12,13).

The follow up exercise to the original pattern explorations executed in Lego created a unique opportunity for students to collaborate on creating a single project from two previous models. The students were asked to adapt and change their own rules about how they made their original design decisions so that they could move forward to create a new project. They were players now in a different game, or as Adrian Snodgrass and Richard Coyne write in *Interpretation in Architecture,* “the players begin by playing, but are caught up in the game and lose themselves in what is happening”, just “as the act of designing draws in the designer : the process ‘takes over’”(Snodgrass, Coyne, 2006)



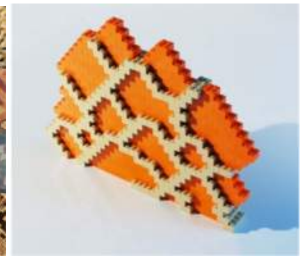


Figure 9: Fourth and fifth year undergrad architecture students engaged in a Lego play session without the use of their phones. Figure 10: Patterns that served as the basis for students Lego pattern explorations. Figure 12 and 13: Giraffe Pattern Lego model by Anabelle Rigg with the following collaborative transitional model of Annabelle Rigg and Garrett Wehan.

OUTCOMES:

The unexpected benefits of this exercise staged over two class meetings, was that in both environments, students that were caught up in the rules that they had created, began making “side” projects or “Lego doodles” out of the scope of the task that was given to them. Was it the inviting and provocative nature of the Lego itself? Was it the controlled environment without phones or devices to intrude on the students pay time? There is no real way of knowing as no attempt was made to create an equal session that allowed student to have phones or devices on hand and this maybe an interesting avenue for future inquiry to see what impact this may have on the play and the work of the sessions. The resulting “side” models that were produced, although often times not resembling the required patterns were often times more developed than those were the result of the assignment (Fig. 14). In the exploration of façade design in this studio a premium was placed on investigation that did not have a specific starting point or may have wandered from the students’ initial goal. The ability for students to work outside of the programmed activity of certain tasks fed an environment where one could look outside of a given architectural problem to explore outcomes at different scales and with different outcomes in the final design. (Fig. 2,3)


Figure 14 and 15 : A” Lego Doodle” outside of the assigned task that became the basis for Chelsea Woodard’s final studio wall prototype in 2011’s The Brick Studio.

PATTERNS 2 STUDIES: 2D TO 3D (IMMATERIAL TO MATERIAL)

As a result of the previous studio exercises with Lego building and pattern identification in the 2011 brick studio, subsequent studio explorations were broadened to include materials chosen by the students to explore the development of 2d patterns to a 3d representational model. The students in these exercises developed their own criteria from observations, sketches, and photographs of their assigned project sites. The expansion of the “input” material for the exercise offered students more choices than the Lego brick’s construction system had and gave students the opportunity to create more idiosyncratic and layered study models. It also asked them to create their own systems for identifying a “constructive logic” in the abstract patterns and drawings that they had made. Some students chose to serialize their patterns into modules, some chose to combine and compact their patterns using various methods, and some chose to extrude their patterns directly form the drawings resulting in prototype wall constructions that could be then explored at various architectural scales later in the quarter (Fig. 16,17,18,19). As the projects were created without a scale and as students pursued a variety of potential architectural outcomes from their initial studies it was determined by some that their models should become a smaller unit of a larger system. In other cases the initial concept was expanded to become the shape of the overall project.

Figure 16,17,18 and 19: Student façade explorations that were made with two dimensional patterns as their basis. From Left to right the students were Sebastian Greider, Beatriz Coronado, Julie Stenger-Smith with Leo Rodriguez and Julie Stenger-Smith with Stephanie Yoo.

OUTCOMES:

An aspect of this exercise that fed future design studio exercises was that students could create an initial pattern drawing and then be asked at every new stage of development to move between hand made to digital 3d models and then back to drawing, again either by digital or analog means. This set up an expectation and rhythm in the studio as students explored their projects at various scales in both three dimensions and as a two dimensional drawing. The goal was to build a multifaceted understanding of the projects they were conceiving by drawing on both analog and digital model making and analog and digital representation. This meant engaging in all of the attributes and limitations of both of these methods, be it the precision of digital technology or the intuition and imagination necessary in using some of the analog techniques. In the creation and understanding of façade systems in practice, the ability to be able to explore element and tectonics multi dimensionally, both physically and digitally is an important aspect of the integration of envelope design with the rest of an architectural project. Hopefully by engaging with these faculties these exercises or similar exercises can begin to address the process of linking materiality, construction systems and technical considerations with a students future explorations.

Figure 20, 21: Mayrelis Perez's exploration of the stacking and design of plastic dosage cups, Jaehyun Cho's exploration of the stacking and design of crayons. Figure 22 and 23: First year undergraduate students evaluating and modeling a group "street" and landscape design made from laser cut modules, hand milled elements and pour plaster elements.

MADE BY HAND VS MADE BY MACHINE.

Another outcome of Brick Studio's 2011 exercises was that they instigated a reevaluation of studio exercises in the foundational courses at Cal Poly Pomona. It was observed from working with advanced students that they may have been better equipped to make decisions in studio if they had had more experience with working with materials and systems that focused on issues such as the impact of scale on materiality or the interaction and consequences of construction tolerances earlier in their design education. A key aspect to this approach was to have the students integrate elements and materials into their projects that were made by machine and those that had been made by hand. By replicating a relationship that is commonly seen in the field- the role of field construction and their accommodation ad fit with prefabricated or manufactured components- students would be able to see the impact of the tolerances or the lack of tolerances that they had created in their own projects (Fig.20,21). The goal of taking a playful approach to materials and creating analogous relationships to the ones they will encounter is that there will be less of an opportunity for students to take architectural precedents and their tectonics that they have seen in practice for granted when it is applied to their own explorations. As defined above, one aspect of play is that it must be meaningful in order to connect to a participant's individual experience. With this in mind creating analogues to construction and letting students play with them encourages students to evaluate their relative usefulness in achieving their own design goals.

This exercise, like it had in the previous advanced studios, challenged students who are beginning to form ideas about space to evaluate the usefulness and opportunities in the selection of appropriate materials in their projects. In subsequent years, this exercise also asked individual students to create spaces whose walls had to meet a specific performance criteria by assigning varying opacities from 25 to 75 percent to different aspects of their constructions. They achieved this with a specified number and size of modules that were laser cut and more that were milled by hand (Fig.22,23). To introduce team dynamics, cooperation and group work students were also asked to break into teams to make the base for their projects as a collective unified design from four individual pieces. The goal of this was again to replicate a professional environment where some degree of negotiation, cooperation, precision and tolerances were all factored into the final grades.

CONCLUSION

Analogues and the games that designers are afforded by scaled mimicry or by the behavior of materials at different scales can be an extremely useful tool for both students and professionals. The making and understanding of architecture through small scale representation or as the product of a play session, or a design "birdwalk", or a doodle should not be discounted as a valid form of discovery in the office or the classroom/studio. Playing in architecture, whether through the games designers consciously or unconsciously play or the use of scale models to replicate material or site conditions will always be a part of our educational and professional lives as designers. It is in fact necessary for the development of architecture as a cultural production.

ACKNOWLEDGMENTS

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REFERENCES

Borden, Gail Peter and Meredith Michael. "Matter: Material Practices in Architectural Production", Routledge, 2012

Fromberg, Doris and Bergen , Doris. Play from Birth to Twelve and Beyond: Contexts, Perspectives, and Meanings, Garland Publishing, 1998

Huizinga, Johan. "Homo Ludens: A Study of the Play Element in Culture, The Beacon Press, 1955

Isenberg, Joan."Play: A Necessity for all Children." Childhood Education Volume 64, Issue 3, 1988

Jabr, Ferris. "The Neuroscience of 20-Somethings" http://blogs.scientificamerican.com/brainwaves/the-neuroscience-of-twenty-somethings/ (accessed May 18th, 2016).

Moffitt, Mary. "Children Learn about Science through Block Play " in The Block Book. ed. Elizabeth Hirsch, The National Association for the Education of Young Children, 1974

Piaget, Jean. Play, dreams and imitation in childhood; translated by C. Gattegno and F.M. Hodgson., Routledge and Kegan Paul Ltd, 1962

Radford, Anthony. "Games and Learning about Form in Architecture." Automation in Construction 9, (2000): 379-385.

Snodgrass, Adrian and Coyne Richard. Interpretation in Architecture: Design as a Way of Thinking "Playing by the Rules". Routledge, 2006: 65-67

Somol, Robert. "Operation Architecture" in Inchoate: An Experiment in Architectural Education .ed. Marc Angelil, ETH/ACTAR, 2003: 11-17

TIMBER FACADES

A conversation about the engineering process

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ABSTRACT

The availability of timber made it an obvious resource for civilization throughout history. Collected by small teams with available tools, one of its primary use was for construction. When used for construction, timber can be used for the base skeleton through to the skin and internal linings of structures. As a structural element timber is an attractive prospect due to its ease of workability and strength to weight ratios, as a façade or lining timber provides an aesthetic and connection to the natural environment that can promote comfort levels and productivity. As a resource timber can be sustainably produced and procured.

When construction advanced and the design of modern buildings called for larger projects, other materials such as steel and concrete has taken the place of the primary structure, glass and aluminum has become the dominant facade materials. The use of timber is still widely used but generally limited to small dwellings.

More recently the use of timber as both a building and façade material has made a resurgence as the built environment searches for more efficient, healthier and low embodied carbon buildings.

This paper will present timber selection processes and discuss the pros and cons of timber within facades. It will discuss timber's potential as a surface finish in relation to comfort and human response, the performance parameters that need to be considered in design such as durability, material and mechanical properties, fire resistance properties will also be briefly discussed. It will present guidance for the design process and finally pose questions for further consideration and study.

KEYWORDS

timber, performance, sustainability, health, design processes, verification, validation

INTRODUCTION

While timber as a façade material offers significant thermal resistance and improved occupant health through a greater connectedness and affiliation with nature, it is not without its shortcomings; including combustibility, durability and susceptibility to biodegradation. This paper will discuss the selection and engineering process for timber used in facades and provide guidance for this process. This paper is aimed at assisting building owners and designers when considering timber for facades.

There are many timber products available in the market. This paper does not intend to list and describe them all. Products are generally defined according to their species (including hardwoods and softwoods) and treatments or constructions such as laminates, heat treatments, chemical treatments and composites. Each product will have its own defining qualities and aesthetic. Timber products considered in this paper include Glulam, cross laminated, LVL, thermal and heat treated wood, chemically treated timbers such as Acetylated. Other composites also exist products such as 'Prodema', 'Modwood' etc. Often the makeup and recipe of composite products is protected and commercially sensitive. Bamboo has also been referenced as a potential alternative.

ENGINEERING DESIGN APPROACH AND PROCESS

Timber has been used for centuries as a building material and surface finish, however there is still limited guidance on selection process for façades. Timber elements can be considered for use in external sunshades, blinds, fixed cladding and window frames (as shown in the images in Figure 1). The key considerations to be investigated for any design are Architecture (geometry, aesthetic, and finishes options), material properties (for example compatibility, durability, fire resistance), mechanical properties (structural capacity, impact resistance and the like), construction (detailing, connections and sealing of joints), cost, availability and procurement. Guidance on aesthetics, durability, design, advanced structural engineering and detailing, testing and verifications is usually limited to experience and industry availability.

Figure 1: University of Sydney Law School, automated timber ply shading device within double skin façade (top left); Brisbane Supreme Court and District Court, Timber clad mullions within double skin façade (top middle); Peter Doherty Institute in Melbourne, fixed timber slats within double glazed units (top right); Darling Walk Sydney, operable timber blinds and timber clad mullions (bottom left); 200 George Street in Sydney, operable timber blinds and timber clad mullions within closed cavity façade and timber clad external sunshades (bottom middle); Canberra National Arboretum Visitors Centre, timber fixed cladding and glulam structural beams.

Typically, the requirements for these performance parameters are described and nominated by design guides, codes and standards, (as is common for other materials such as glass, aluminum or steel). This is not necessarily the case for timber façade elements.

There is some industry standard guidance for timber on mechanical and material properties (for example in Australia AS1720, SA 108 HB 2013, in Europe the Eurocode 5). These codes include references to standardized tests to determine properties of the materials.

Guidance on architectural durability is sparse and requires further development, documentation and standardization. This paper will discuss various durability concerns, possible verification techniques such as accelerated weathering tests and management strategy for design.

Design for detailing and connections requires experienced designers and fabricators to accommodate the properties of wooden products. Several guidelines exist for standard structural connections, however custom designs for facades, often seen in modern architecture, requires non-standard connection details with relevant consideration and verifications through specific and focused engineering and testing.

It is critical that designers carefully research and understand the procurement process for wooden products. Locally sourced timbers are often restricted to certain species and products. Products such as laminated (Glulam, LVL), chemically treated (acetylated), and composite products are often specialist products made by certain suppliers and each supplier's product will vary.

Procurement of sustainable timber can be quantified through authorities such as Forest Stewardship Council (FSC) and Program for the Endorsement of Forest Certification (PEFC) who offer independent certification of sustainably sourced timber products and responsible forest management.

WHY USE TIMBER IN BUILDINGS AND WHAT RISKS NEED TO BE MANAGED?

In this discussion it is important to consider what the key advantages are to architectural design and the built environment. In general, timber is considered a more sustainable option compared to aluminum (for example). Using timber within a façade can also improve thermal performance due to its material properties (including reducing energy usage of a building). Timber surfaces can provide a sense of affiliation to nature that can improve productiveness within spaces such as offices and it can also improve comfort and healing abilities within health facilities. Timber is typically easy to work with and can provide aesthetic architectural results. Timber has certain properties that are required to be managed within a holistic design.

As a natural material wooden products are prone to deterioration when exposed to heat, moisture and light. Given this susceptibility it is the general consensus that timber requires regular maintenance, re-coating or early replacement to achieve the relevant design life of modern buildings. Additionally, protective barriers can be considered in façade designs to protect the timber and extend its expected life.

Timber and the timber composites considered are combustible materials and require relevant management strategies and authority approval in order to be installed on modern buildings.

SUSTAINABILITY

Designers, fabricators and constructors are striving for greener and healthier solutions. As a natural resource, it is well documented that a well-managed source of trees and timber provides low embodied energy solutions and ultimately provides a suitable and acceptable material when considered in a whole of life cycle (cradle to grave) situation (Robertson, A. B., Lam, F. C. F. & Cole, R. J. A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office Building Construction Alternatives:Laminated Timber or Reinforced Concrete.).

There are a number of key points to consider in the design of timber façade elements including,

- Where should timber be sourced from?
- Are local sources viable?
- Is shipping logical?
- Do the market drivers influence the source (that is, for example if the timber product needs to be integrated into a Curtain Wall should this be done in the factory or should and could it be installed locally at a later stage, or in a staging facility near the project?).

These questions have significant impacts on life cycle and embodied energy calculations and should therefore be considered early in the project phase in order to determine the suitability of timber material selection.

Additionally, it is important when selecting engineered wood products (including particleboard, plywood, MDF, LVL, HPL, compact laminates and decorative overlaid panels) to consider the levels of formaldehyde emissions associated with these products. Building certification schemes place heavy emphasis in the reduction of volatile substances including formaldehyde. When selecting engineered wood products, designers should obtain relevant test certificates and datasheets to ensure formaldehyde emissions limits are not exceeded.

AFFILIATION WITH NATURE

Each timber element has its own unique appearance; this is a natural fingerprint of the tree. The use of timber can impact and benefit occupant health through a greater connectedness and affiliation with nature through this aesthetic. Designing buildings with this in mind can be referred to as biophilic design:

“Biophilic design and architecture aims at creating strong connections between nature and man-made environments, and has proven benefits, including helping office workers be more productive, encouraging children to learn and helping hospital patients get better.

Says Biophilic designer Oliver Heath: 'Biophilic design is more than just bringing the outside in, it's about making and strengthening a connection with many aspects of nature. It's about natural light, views on nature, plants, natural materials, textures and patterns.'” (Quote http://www.designcurial.com/news/biophilic-design-and-architecture---10-of-the-best-biophilic-buildings-4527750/)

Given that on average people spend 80-90% of their time indoors, it is critical that the indoor environment quality of today’s buildings is designed to support occupant physical and mental health. The emphasis on wellness in buildings is further gaining traction through numerous building certification schemes including Australia’s Green Star and internationally recognized LEED and WELL building standards.

HEALTH AND WELL BEING

There exists evidence that timber has a beneficial effect on occupant well-being (Anme, T. Behaviour Changes in Older Persons Caused by Using Wood Products in Assisted Living.). The use of wood in hospital aged care facilities has been shown to have positive psychological effects on the elderly through greater interaction between residents and increased awareness. A similar effect has been observed in the shortening of hospital stays through reduced recovery times through the introduction of wood in interior environments (Augustine, S.; Fell, D. Wood as a restorative material in healthcare environments)

The natural warmth, connectedness and comfort that wood creates a calming effect for occupants. In some studies, it has been observed that stress levels and heart rates of pupils decreased through the introduction of wood in classrooms. (Planet Ark. "Wood Housing Health Humanity.").

VISUAL COMFORT

The use of wood in interiors and facades may have visual comfort benefits through more evenly distributed and higher quality of light. Warmer atmospheres and a more equal balance of lighting are created through the use of light wood panels through the characteristics of wood surfaces. This can be especially important during overcast days where gloomy or dull skies have been shown to affect occupant’s moods. Figure 2 indicates the diffuse nature of light with timber blinds. Further studies and occupant surveys are required in order to quantify this effect.

Figure 2: Darling Walk in Sydney with the blinds in three separate degrees of closing, note the nature of the lighting caused by the properties of the timber blind.

MATERIAL AND MECHANICAL PROPERTIES

The physical properties and test methods to verify them are generally well documented in industry standards. Detailed design of elements must consider the specific properties of the products under consideration.

THERMAL PERFORMANCE

Timber is an insulative material and compared to metals such as aluminum provides greater thermal resistance and ultimately better thermally performing facades if used as framing elements. The thermal conductance of timber varies between species and compositions, grain direction, moisture content and temperature. Typical results show figures in the range of 0.1-0.3 W/m.K. When compared to metals such as aluminum, which have thermal conductance in the order of 1000 times higher than timber, this demonstrates the advantages in adopting timber frames in facades to reduce thermal bridging and providing more comfortable surfaces and spaces.

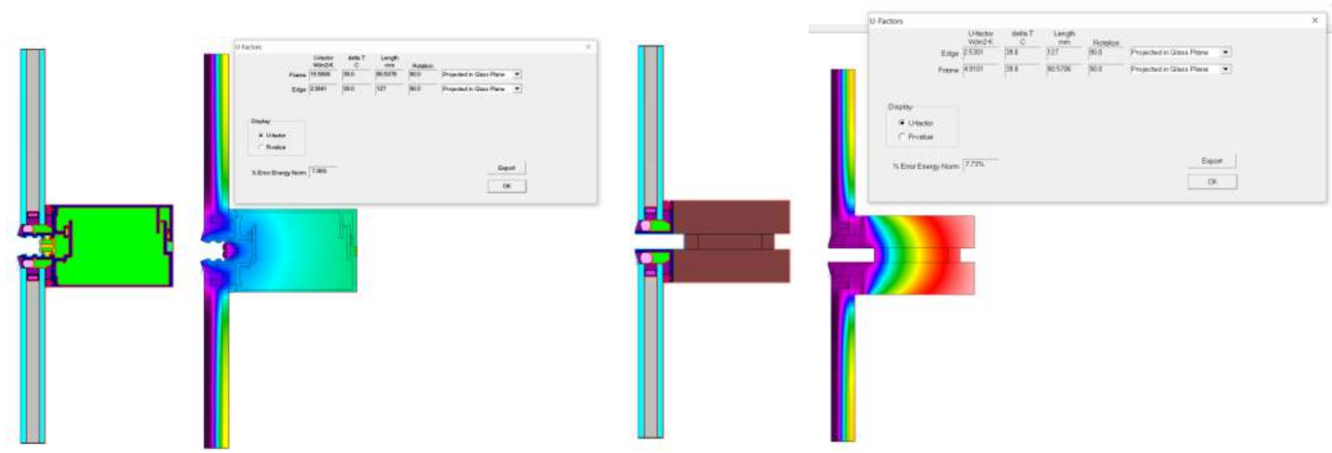

Figure 3: THERM models (using NFRC boundary conditions) indicating an aluminum frame section (mullion) on the left, U value of frame = 15.5W/m^{2}K. The frame element on the right is based on hardwood frame element (oak, maple), U value of frame = 4.9W/m^{2}K. The lower U value of the timber frame section indicates that the timber frame provides significant benefits in reducing thermal bridging in façade frames.

DURABILITY

Certain timber products have demonstrated durability issues such as uncontrolled dimensional stability (warping), surface deterioration (cracking, blistering), staining and color fading or changing. Various timber treatment process can reduce these effects, as can management through design strategies and maintenance regimes which can include maintenance (such as regular sanding and re-coating).

Before launching into the discussion of the durability of timber products it is important to discuss and consider the design intent and expectations of a natural material. As timber ages it changes, whether that be color or surface finish. However, this is not unlike many materials adopted in facades for these exact qualities. Metal finishes such as copper and zinc patina over time and this is often thought of as adding value to the appearance of a building. As a designer if you want timber there must be some expectation and understanding of how it will perform over time and how it may change appearance. The designer must consider the following questions:

- Does changing over time matter, does it degrade the look of a material, or does it add value?
- What does it mean to the design integrity as materials age?

Figure 4: Indicates sampling for color variation range for blind slats on 200 George Street Sydney project

The aging and eventual deterioration of timber products can be caused by all environmental factors including the key drivers of moisture, light including UV and heat effects. Some of these are aesthetic, whilst others can cause performance issues such as localized structural failures, joint sealing deterioration and general perception concerns. In the design process these factors can be established and potentially stabilized, controlled and managed through selection of product including selection of adequate species and treatments (composites, laminates, heat treatments and chemical treatment and surface coatings) or through system design such as incorporating timber blinds within glass cavities protected from UV light and direct contact to occupants.

In order to quantify the longevity of a timber product various tests are to be considered. These include Accelerated weathering tests. These could be similar to those prescribed by test standards ASTM D4459 for plastics, which can simulate combined effects of heat, UV light and moisture (through relative humidity conditions). For any given environment or design these can be modified to suit the actual conditions. Any accelerated weathering test is limited by time and comparative assessments are often used to benchmark results. Other tests such as dynamic cyclic testing can be used for moving elements (such as blinds or dynamic sunshades) to test for durability of the elements and systems. The specimens can be tested before and after the cyclic weathering testing for any material property changes such as strength and ductility, dimensional changes, surface finishes and color changes. Suitable numbers of samples and specimen sizes (preferably full scale) should be tested to accommodate natural variations in the wood and properties. From the results estimates on life expectancy and performance can be determined. This is an iterative and time consuming process and may require testing and re-testing of various make ups or products to determine suitable design. The project program and planning should allow for such design and testing processes.

UV light will impact the timbers structure and can change color. Based on results seen from various sources the color change of timber will depend mostly on species and treatments to timber and moisture content. Some timbers demonstrate stability after certain exposure time and these results seem repeatable through testing. Figure 2 of the 'Riba Lab Report number 12661' demonstrates the color change experienced by various samples adopting the accelerated weathering testing per DIN EN ISO 11341 A and prEN927-6). The majority of the color change occurred within the first 250 to 750 hours of testing, the color seemed to stabilize at this point nominally delta E of 12 to 28, depending on the sample. This was also demonstrated on the testing by CSIRO for 200 George Street, see Figure 5.

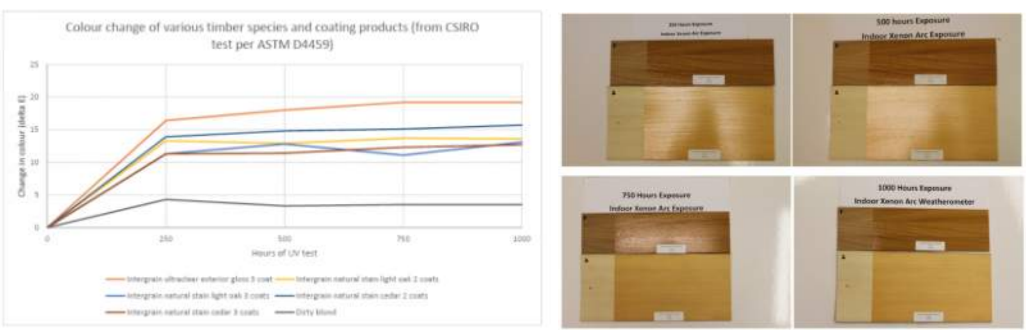

Figure 5: Left side indicates test data for various products and finishes for color change based on accelerated weathering testing, the right side images indicate photographic record of some of the samples after different exposure times (photos courtesy of CSIRO)

FIRE

To briefly touch on this subject, suffice to say that as a combustible material relevant decisions about the use of timber is required early in project. The use and location of the timber elements may impact on fire engineering strategies and alternative fire engineering controls. Certain timber products and composites contain fire retardants and certain dense hardwood species provide significant fire resistant properties where they char but do not spread flames when exposed to significant fire loads.

MANAGEMENT THROUGH DESIGN

Consideration for protection to timber from the environmental conditions and also from human interaction is a consideration that has been adopted on several projects including 200 George Street Sydney where the timber reveals and timber cladding are encased within glass cavities, Peter Doherty Institute in Melbourne where the timber fixed shading slats are within a double glazed unit, and also Sydney University Law School where the operable timber shade devices are within the double skin façade. In these facades the timber is expected to perform for longer design than if they had been exposed to the environment or if the blinds had been exposed internally to human interaction. The encasement within glass facades also provides protection from fire and enhances the fire engineering solution for these buildings. However, it should be noted that encasing elements within cavities provides a risk of off gassing causing staining (if not identified and managed within the fabrication process) and maintenance of these elements is inhibited by their entrapment within glazed cavities.

WORKABILITY AND PRODUCTION CONTROL

In brief, timber is simple to manufacture and fabricate however strict compliance with manufacturers recommendations are required particularly when it comes to cutting, drilling and fixing details. Strict quality control and management strategies should be adopted to ensure suitable production techniques within any project.

MAINTENANCE

As with all building materials maintenance regimes and strategies should be determined through the design stages. Timber elements should be treated specifically and subject to durability verifications inspected and maintained accordingly. This may require re-coating, re-finishing (sanding) and where significant deterioration replacement. If replacement required re-use and recycling should be considered and form part of the sustainability strategy for the project. The requirement should be allowed for within building owners life cycle cost assessments and planning. The understanding and development of these strategies for timbers exposed to environmental conditions could form future research topics and studies.

SELECTION PROCESS IN PRACTICE

The following section summarizes the selection process and results for the timber blind slats to be adopted for the 200 George Street project in Sydney. The project included timber blinds that are encased within the glazed closed cavity façade. Whilst the environment within the cavity is protected from occupant interaction potentially causing damage the blind, the cavity is exposed to higher than normal temperatures. Figure 6 indicates the initial selection process between several different species and products. Within this table several performance properties were considered. This process included review of available literature and test data available, as well as review of available procurement possibilities. This selection process would have been aided by a standardized test regime, however much documentation was collated from various sources, costing time and money. From this initial selection process Accoya was identified as preferred.

Species	Visual Appearance (New)	Visual Appearance (UV And Heat Exposure)	Impact on Facade Performance	Dimensional Stability	Supply	Fire Resistance Properties	Sustainability
European Ash	Extremely Dark	[illegible]	[illegible]	Not pursued further	Not pursued further	Not pursued further	Not pursued further
Western Red Cedar	High variation in natural colour	Not pursued further	Not pursued further	Not pursued further	[illegible]	[illegible]	Not pursued further
Bamboo	Raw timber is light in colour	[illegible]	Not pursued further	[illegible]	Not pursued further	Not pursued further	Not pursued further
Cottonwood (Heat Treated)	Raw product is light in colour	Testing complete to 1000 hours	Heat treatment darkens the timber and causes a reduction in reflectivity properties	Hotbox testing confirm stability	Supply possible within project program constraints	Class III under ASTM E-84	FSC approved
Radiata Pine (Accoya Treated)	Raw product is light in colour	Testing complete to 250 hours. Timber will lighten in colour following UV and Heat exposure	Reflectivity confirmed as acceptable	Literature provides high dimensional stability and durability to class 1 according to EN 350-2, EN 113 and ENV 807 in has class 1 to 4 according to EN 335-1	Supply possible within project program constraints	Class III under ASTM E-84	From FSC®, PEFC™ and other regionally certified woods. Naturally renewable

Key	Acceptable	Subject to further testing	Not acceptable	Not pursued further

Figure 6: Summary of initial selection process for the blind slats of 200 George Street Sydney. Several species were considered, this table summarized the short list.

Figure 7 indicates the developed analysis and summary of the available data for the product, this assessment assisted the design team in developing specific test regimes to confirm durability of the blind system within the glass cavity. This testing procedures included exposure to UV, heat and moisture, cyclic operation of the blinds within a hot box simulating the cyclical and raised temperatures of the cavity (this test not only tested the timbers durability but the durability of the entire system including the ladder braids, lifting tapes, mechanisms and motors).

Performance requirement	Test	Description	Test result			Reference document	Notes/comment
			Target	Uncoated	Coated		
Durability							
Colour, colour variation and colour fastness	Accelerated weathering test under light (UV)	Testing in accordance with ASTM D4459	Visually acceptable per architect	Pass (per architect)	Pending final colour selection	CSIRO report "CMSE Report XC3222"	
Twist	"Dimensional stability of timber slats" test by Pisa and accelerated weathering cyclic testing by Pisa	Testing of slat under cyclic temperatures, effects of cyclic humidity (conservative as CCF) and cyclic loading due to lifting.	As per BS EN 13659 and BS EN 13120 2mm/m	0.6mm (maximum measured)	0.6mm (maximum measured)	"Dimensional stability of timber slats" test by Pisa and accelerated weathering cyclic testing by Pisa	
Camber	"Dimensional stability of timber slats" test by Pisa and accelerated weathering cyclic testing by Pisa	Testing of slat under cyclic temperatures, effects of cyclic humidity (conservative as CCF) and cyclic loading due to lifting.	As per BS EN 13659 and BS EN 13120, 3mm over 1500mm	0.6mm (maximum measured)	0.6mm (maximum measured)	"Dimensional stability of timber slats" test by Pisa and accelerated weathering cyclic testing by Pisa	
Bow	"Dimensional stability of timber slats" test by Pisa and accelerated weathering cyclic testing by Pisa	Testing of slat under cyclic temperatures, effects of cyclic humidity (conservative as CCF) and cyclic loading due to lifting.	As per BS EN 13659 and BS EN 13120, 5mm	2.2mm (maximum measured)	2.2mm (maximum measured)	"Dimensional stability of timber slats" test by Pisa and accelerated weathering cyclic testing by Pisa	
Cupping	"Dimensional stability of timber slats" test by Pisa and accelerated weathering cyclic testing by Pisa	Testing of slat under cyclic temperatures, effects of cyclic humidity (conservative as CCF) and cyclic loading due to lifting.	As per BS EN 13659 and BS EN 13120 3mm	0.2mm (maximum measured)	0.2mm (maximum measured)	"Dimensional stability of timber slats" test by Pisa and accelerated weathering cyclic testing by Pisa	
Material compatibility							
Offgassing	Various standards (refer to Fraunhofer report)	As per DIN ISO 16000-9 and -3	No staining	No staining witnessed	No staining witnessed	VFF Guidance Sheet. Further full scale prototypes (visual mock-ups) being constructed to demonstrate no staining risk.	Relevant process to be employed by Pisa to maximise off gassing prior to blind installation. Not different to other materials including other timbers and metal blinds. Maximum workplace VOC concentrations were not exceeded per VFF report.
Compatability with sealant and gaskets	Various standards (refer to VFF report)	as per VFF Guidance Sheet	No impairments	Compatible	Compatible	VFF Guidance Sheet	
Compatability with fittings and fasteners	Various standards (refer to VFF report)	Corrosion resistance EN 1670	No impairments	Compatible	Compatible	VFF Guidance Sheet	All metal materials to be stainless steel to resist corrosion
Coating compatability	Various standards (refer to VFF report)	as per VFF Guidance Sheet EN 927-3	No impairments	Compatible	Compatible	VFF Guidance Sheet	Specific coating supplier endorsment also received (AkzoNobel - Sikkens Cetol WF771)
Fire properties							
Fire properties	As per BCA	Fire resistance properties to comply with BCA and as per fire engineers requirements. Includes spread of flame index, smoke developed index.	Material Group 3 (per BCA)	Compliant	Compliant	CSIRO Fire Science and Technology Laboratory report CMIT Doc. 02/276	Testing data also available per ASTM E84 and European Standards (per VFF)
ESD requirements							
Thermal property (reflectivity)	Reflectivity tests/studies by UNSW	Testing in accordance with ISO 9050	Minimum 44% (As set by ESD engineer)	>44%	>44% (subject to final colour selection by architect)	Test reports by UNSW	

Figure 7: Indicates collation and summary of test data available for the Accoya product for the key performance criteria of durability, compatibility, fire and sustainability.

CLOSING NOTES

As an engineering material, timber has been developed and engineered by industry for use as a structural element. The design requirements for structural elements are standardized around the world in relation to materials properties and capacities. Further development and standardization for the requirements of timber for use in facades is required particularly in relation to detailing connections, longevity and durability performance, fire engineering requirements and further development of sustainability. In the current market engineers and designers are required to develop project specific verification procedures which can involve accelerated weathering testing and specific fire engineering solutions. This paper has discussed some aspects of this process and recommended that these assessments are standardized to assist building owners and designers.

The key benefits of timber in buildings, and in particular in facades, has been discussed including using Timber to provide sustainable facades and assist in the eventual goal of zero carbon buildings. As a surface finish timber provides benefits in productivity and health through its ability to provide affiliation with nature and the environment.

REFERENCES

Gerry Eccleston "Weathering of Accoya Window Timber Slat 200 George Street, Sydney" CSIRO test report XC3222R3
Raphael Meyer "Performance evaluation of acetylated wood from Titan Wood Ltd. Riba Lab Report number 12661"
Robertson, A. B., Lam, F. C. F. & Cole, R. J. A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office Building Construction Alternatives: Laminated Timber or Reinforced Concrete.).
Planet Ark. "Wood Housing Health Humanity."
Anme, T. Behaviour Changes in Older Persons Caused by Using Wood Products in Assisted Living.
Augustine, S.; Fell, D. Wood as a restorative material in healthcare environments.
http://www.designcurial.com/news/biophilic-design-and-architecture---10-of-the-best-biophilic-buildings-4527750/
Standards Australia, AS1720 Timber Structures
SAI Global, SA 108 HB 2013 Timber Design Handbook
Eurocode 5 Design of Timber Structures

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BREAKING THE BARRIER

Developing formal partnerships between architects and extruders

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ABSTRACT

CAN WE TALK? Historically, architects and aluminum extruders have had limited direct relationships. Architects have worked primarily with curtainwall manufacturers directly. Or, a project's general contractor contracts directly with the extruding company, which has no contact with the architect even though it supplies the materials and service the architect specifies.

But the time appears ripe for more direct communication between architects and aluminum extruders, such as Sapa Extrusions North America, Bonnell Aluminum Extrusion Company and American Aluminum Extrusion Company. For one thing, architects are employing more complicated aluminum curtainwall systems for their projects as they specify larger areas of glass and other aesthetics that deliver more daylight and visual design. For another reason, too much time -- and cost – is often spent with communications late in the project between architect and the manufacturer.

Let's develop a formal partnership between architects and extruders. The benefits are significant for both parties. Such direct collaboration would vastly improve cost efficiencies, timeliness and design for manufacturing. Architects would gain insights and counsel from extruders as they think about and plan new projects. They would determine more quickly if their plans meet specifications and maintain their design and the critical budget. They also would glean expert insights from extruders on fresh innovations, including finishing options and design for manufacturability, or DFM, which is the general engineering art of designing products so they are easy to make.

Extruders would acquire valuable information and insights about a structure's design as well as the architect's vision so that they could provide the best counsel for the use of aluminum. For the curtainwall manufacturer, these conversations between architect and extruder would ensure a manufacturable design and help keep the project and its details on track.

KEYWORDS

Design processes, collaborative project delivery strategies, Design for Manufacturability, Metal Curtainwall Systems

INTRODUCTION

It's the nature of the construction business that architects generally have little if any direct contact with the subcontractors, sub-subcontractors and suppliers that supply nearly 100 percent of the materials and equipment the architects specify and nearly all of the labor. The general contractor acts as the go-between, even though the suppliers are critical to a project's success to be ignored entirely by the architect. Consequently, misconnections between architects and extruders occur. They mirror many missed opportunities that happen regularly in the global business world to link key participants more directly – and enabling them to benefit from the fast-changing advances in the manufacturing, construction and services sectors. The competitive environment is shifting rapidly throughout the economy as technology breakthroughs, in particular, evaporate the need for middlemen.

Examples abound. Produce and livestock farmers are serving more restaurants directly, benefitting restaurant-goers. Airbnb, Uber, Snapchat, Lending Club and other sharing-economy businesses that embrace sophisticated technology are bonding directly with their customers and consumers.

So why haven't the nation's 100,000-plus licensed architects and 25,000 student architects forged an established, enduring and direct alliance with the aluminum extrusion sector? Why have they traditionally been separated by a general contractor and subcontractors? And, why is their dialogue and collaboration so critical now?

A direct path between the two offers multiple benefits to each and serves to spotlight other similar connections in business and industry that can benefit from closer ties.

BACKGROUND

ARCHITECTURE SCHOOL CURRICULUM

A close relationship between architects and aluminum extruders doesn't exist today as general contractors and other intermediaries keep such collaboration practically nonexistent. This is true also as it applies to departments and schools of architecture. Few professors, programs or curricula spend much time on the use and flexibility that aluminum extrusions deliver (or even aluminum, for that matter). Meanwhile, under the material science umbrella, students gain multiple lessons about concrete, steel, wood, glass and plastics.

For example, the endless architecture curriculum at Harvard's Graduate School of Design – often ranked No. 1 among the nation's architecture programs -- has little mention of aluminum in its curriculum. It seems difficult to find a class that specifically deals with aluminum or aluminum extrusions, even though the school in its description of architecture asserts that "the field grows increasingly complex and requires new techniques of inquiry and design." Its portrayal continues, "Today's graduates in architecture continue this tradition by pioneering new design approaches to the challenges posed by contemporary society."

Some 2015-2016 school year courses appear to touch on aluminum extrusion. One is Course STU-01304-00, Material Performance: Fibrous Tectonics & Architectural Morphology. This course offered in the fall 2015 semester, might have cited extrusions. But its description doesn't suggest it, even though it begins with the assertion, "A new understanding of the material in architecture is beginning to arise." The studio class description cited "advanced fiber composite materials" and "glass- or carbon-fiber-reinforced plastics." Students experimented hands-on with "robotic fiber lay-up and filament winding processes" and pursued the development of fibrous systems in architecture that help uncover "novel fibrous tectonics and formerly unexplored architectural morphologies, and hints at an emerging material culture."

At another Top 30 U.S. architecture school, Rhode Island School of Design, one course – on Steel Structures – offered in the fall of 2015 tangentially touched on aluminum. For students, the course, according to the course description, "exposes them to alternatives to steel such as aluminum and fiberglass." Other RISD courses focus specifically on concrete and wood. One, "Structural Analysis," served as a pre-requisite for the courses on steel, wood and concrete structures. And while it' format was mostly lecture, students take field trips.

An examination of several other academic architecture programs and an online search indicates very few courses in the United States or abroad deal primarily with aluminum or aluminum extrusions. However, the University of Michigan's Taubman School College of Architecture and Urban Planning noted in its 2012-2013 brochure that its 120 credit-hour undergraduate architecture curriculum includes a course that includes aluminum "based on a digital model." In the most direct connection to aluminum, although not specifically mentioning extrusions, the Eindhoven University of Technology in the Netherlands lists an architecture course entitled "Advanced steel and aluminum structures."

MODERNIZING ARCHITECTURE CURRICULUM

The architectural profession has devoted a large amount of time over the years to what many consider a crisis in architecture education. In the United Kingdom, for instance, research by the Royal Institute of British Architects, found in a so-called "skills survey" that 80 percent of employers and 75 percent of students think architectural education puts theory above practical ability. The majority of both groups agreed graduates lack the knowledge to build what they design on paper. This includes grasping advances in building materials that, by nature, includes aluminum extrusions.

In the U.S., in an article entitled "A framework for architectural education," Yale-educated architecture professor (now emeritus) Alexander Tzonis relates the recent and past history of architectural education. In it, he states that despite "the dynamic and aggressive construction developments of our times," little real change has occurred in architecture school programs to address these developments.

Among other factors, Tzonis suggests that "one can blame the numerous, top down university initiatives or committee interferences that based their thinking on abstract theories of learning and standard pedagogical formulas of university education ignoring the reality of architectural professional practice as well as the reality of the built environment and of the desires and aspirations of its users for a good sustainable equitable environment."

He continued, "The presence in several such high-level academic committees of prominent architectural practitioners has not facilitated change because most of these illustrious members of the profession were looking into the short term practical conveniences of their firms rather than long term goals of sustainable natural and social quality. In most cases they did not encourage any fundamental rethinking of the structure and operations of schools of architecture in overcoming the gap between the obsolescing institutions and the dynamic real world."

Another factor: "The explosion of differentiation and specialization of architectural knowledge and division of labor in architectural practice as a result of technological, epistemological, economic, and social forces demanding a place in the curriculum (as well as equivalent quantities of people and spaces)."

INDUSTRY TRADE GROUPS, EXTRUDERS AND ARCHITECTURE SCHOOLS

It's not as if the aluminum industry has been absent in spreading the word about aluminum extrusion and architectural use cases. Both the Aluminum Extruders Council and the Aluminum Association, as well as aluminum manufacturers, have worked with architecture schools and professors, attempting to interest them in working collaboratively. But they largely have been dismissed out of hand. The professors and architect school deans frequently cite lack of funds, overloaded schedules and/or lack of interest for their reluctance.

At least one Purdue University architecture professor, however, has been supportive of using aluminum extrusion materials and participation by at least one company's officials. In addition, an aluminum extrusions manufacturer, partnering with The American Institute of Architects, designed a special AIA Continuing Education course curriculum for design/build architecture students at Virginia Polytechnic Institute and State University. The company also provided extensive resources, expertise and products.

The aluminum industry trade groups also hold daylong seminars, events and even student design competitions to help jumpstart a dialogue. One idea floated would enlist a manufacturer or trade group to offer an accredited course on aluminum extrusions, but that idea hasn't gained much traction.

EXPLANATION

ARCHITECTS AND ALUMINUM EXTRUSION

The clear absence of direct collaboration between architect and the aluminum extrusion industry still is surprising when the benefits seem so obvious. For an aluminum extruder, a relationship with an architect from the very beginning of a project produces numerous rewards. It allows an extruder to validate the feasibility of an architect's planned design at the concept stage, therefore enhancing the project's timeline and costs. Now, the extruder usually must wait until the architect has finished the design, it has been approved by the project owner, passed along to the general contractor and sent to subcontractors who then inform the aluminum extrusion company.

A more direct collaborative approach also would erase most of the frustration and dissatisfaction that materializes between architect and subcontractors such as extruding companies. An architect, for instance, voices a criticism to the general contractor about an extruder's suggestion or question. The contractor passes it along to the extruder, which must actually bear the disappointment, inconvenience and, at times, economic loss. And the architect is usually insulated from hearing the practical difficulties of using an extrusion product that an architect specifies. With the contractor as middleman, the extruder's complete viewpoint isn't always expressed effectively.

And while architects can communicate with suppliers and manufacturers about their new products and innovations before a construction contract is signed, architects can't have interactions with second- and third-tier contractors under the contract.

This process simply doesn't acknowledge the issue: An architect can draw a design concept but that doesn't mean it can be achieved. It's the food chain and its middlemen that explains why architect and extruder don't directly collaborate. The absence comes as a revolution is underway in both the architectural design and building materials and construction arenas.

This revolution also comes as the entire building construction industry seeks to reduce costs. This plays to aluminum extrusions' strengths. For example, a typical die casting or injection molding can cost $25,000 and up, while the typical tooling part costs $500 to $5,000.

Here are the significant trends that play to aluminum extrusions' strengths:

TECHNOLOGICAL AND DESIGN BREAKTHROUGHS

Aluminum extrusions often are a predetermined element in a building product, but custom shapes available today stir the imagination of designers and architects. Quite simply, advances in material science have enabled extrusions to help deliver a design aesthetic and visual effect – whether external or internal – that few other building materials can achieve. Joining the traditional lexicon applied to extrusions such as the "stick" systems of curtain wall applications and systems are terms such as lightweighting, anodizing and pixilation that play to extrusions' strengths in architectural design.

Designing aluminum extrusions offers limitless flexibility. The material permits innovative design, such as texturizing the surface to deliver aesthetic appeal or incorporate graphics in extrusions. Consider the Empire State Building. A few years ago, when its windows were replaced, the aluminum extrusions used to house the glass replicated the original design to a tee. Its design elements prove to be a huge appeal to building owners and designers.

Several notable buildings have incorporated inventive extrusion techniques in recent years, including buildings that appear impossible to stay erect. A prime example, especially of the pixilation effect, is Herzon & de Meuron's 56 Leonard residential tower in New York's Tribeca. It is a vertical glass expression of sculpted surfaces, cantilevers and sparkling glass that appears to begin to disintegrate as it rises to an ethereal crown. It uses extruded aluminum in several ways, including novel lighting fixtures and extruded floor plates that provide outdoor terrace space to the projecting glass boxes that hold the living rooms.

As for other design innovations that combine with technology, it now is possible to begin work in a shop environment to assemble an entire network of framing materials into finished panels. Each model then is fit together like an enormous jigsaw puzzle on site. For builders and general contractors, this translates into substantial cost savings. A contractor doesn't have to hire an $80-to-90-an hour specialist in the field to install the framework laboriously, saving an estimated 15-35 percent in labor, by some estimates of aluminum extruders.

STATE-OF-THE-ART MATERIALS AND ENGINEERING PROCEDURES

Lightweighting serves as a perfect illustration of the advances in materials and processes. Lightweighting employs structural aluminum including extrusions rather than steel to deliver lightweight, floating design visions that also maximize material strength. This practice by architects and engineers uses extruded aluminum components bolted together, which makes it easy to disassemble and recycle a building. In addition, aluminum extrusions can be upcycled forever into fresh uses while keeping its strength and integrity. And from an economical standpoint, lightweight aluminum components generally weigh 35-80 percent less than steel yet while producing equal strength.

As a result, aluminum extrusions are being used to construct residential and shopping centers, bridges and stadiums; to restore historical buildings; to manufacture large solar panels; and to deliver a safety feature to storm shutter systems in hurricane-prone regions. And the demand grows.

SUSTAINABILITY AND "GREENBUILD"

Saving the planet has become a growing mission of architects and the construction and construction-related industry, in general. It is a rapidly growing movement and involves showcasing how aluminum extrusions and other structural materials can produce and maintain a sustainable and enduring environment.

Aluminum is one of the most energy-efficient and sustainable construction materials. It possesses recyclable content of 50-85 percent and, in recent years, LEED-certified buildings have earned many international sustainability rewards with their inventive ways of using aluminum extrusions. For example, building owners are using photovoltaic panels in their buildings to increase their energy efficiency. The panels are housed in aluminum extrusions to accommodate the additional hardware needed for them.

The emerging and rapidly expanding movement to use aluminum extrusions demonstrates how architecture and pioneering applications of aluminum extrusions and other building materials can deliver an enduring and sustainable environment. In addition, advances in extrusion capabilities gives extruders the ability to provide better finishes, different geometry for aesthetics and better machinery for more efficient production.

Architects and architectural students are getting more involved in the sustainability effort – and they need to stay in touch with advances in aluminum extrusions, among other materials, that help make that possible. Because they often contain recycled content and are recyclable themselves, aluminum extrusions are especially beneficial when thinking green.

This recyclability factor cannot be downplayed. Aluminum extrusions lessen the impact of growth and industrial development on the environment in various ways, including:

- Through extensive, resource-friendly recycling from production through end-of-life.
- By delivering in-use benefits via reduced environmental impact of products in which extrusion is used.
- By reducing emissions and other undesirable byproducts of the production process.

Aluminum extrusions play a major role in sustainability because they offer a distinct combination of attributes, including lightweight strength, design flexibility, longevity, low maintenance and their recyclability. For architects, working with this highly workable material enables them to create shapes that yield flexibility and aesthetics, while providing superior cost effectiveness and sustainability.

Increasingly, aluminum extrusions are be employed in their natural appearance or finished with energy-saving and reflective coatings. They can be bent and formed in countless ways to deliver the architectural features a project seeks.

Extrusions also make buildings more efficient, which is critical as commercial buildings account for 18 percent of U.S. energy consumption. Thus, the use by architects of improved window and façade systems, sunshades – often with integrated photovoltaic panels, light shelves and other extrusion-based building components – can reduce operating costs and energy usage significantly over a building's life.

The reduction in energy use by aluminum producers and extruders over the past two decades has led to a steady decline in the industry's carbon footprint. A Life Cycle Analysis study in late 2013 by The Aluminum Association concluded that aluminum production in North America is more sustainable today than ever. It examined the environmental impact of modern aluminum production and reviewed the 2010 production year. The study incorporated data from aluminum extruders representing an estimated 60 percent of North American capacity. It was peer reviewed by a third-party expert to ensure conformance with International Organization for Standardization (ISO) standards.

In 2014, The Aluminum Association released an Environmental Product Declaration specifically for extruded and other aluminum products produced in North America. It was developed according to ISO 14025. The Aluminum Extruders Council is finishing an Environmental Product Declaration that covers the U.S. and Canadian aluminum extrusion industry. Expected to be completed in 2016, it constitutes the most comprehensive assessment of extrusion’s environmental footprint. In addition to the input required to produce two EPDs – one for thermally improved extrusion and one for unimproved product – the data will provide important information on recycled content as well as finishing mix and characteristics.

CONCLUSION

HOW TO BRING THE TWO TOGETHER

It's clear that architects and the aluminum extrusion industry should consistently work more closely and directly together since practically every building project today requires custom applications that involve extrusions. Extrusions are not a commodity, although they generally are viewed as such. Architects should express their desire to a project's general contractor to be actively involved in selecting extruding companies for subcontracting jobs so they can match their visions with the companies' ability to deliver on them. Extruding companies and their trade association should keep architects – and architectural schools – current with the latest advances in extrusion capabilities. The trade groups might consider publishing information, perhaps quarterly, on the latest extrusion innovations with case studies of how they were used in projects. Architect associations can also schedule workshops or forums with aluminum extruders on the cutting edge of building design advances.

In addition, architecture schools' curricula must be modernized to capture the advances in the usefulness of building materials, notably aluminum extrusions – and the technology that can be used to help architects and students grasp these breakthroughs. The emergence of 3D printing itself is an avenue to demonstrate how extrusions can help them today and in the future. Schools would benefit by adding a course on aluminum and extrusions, especially if the industry and extrusion producers themselves contribute to the effort with resources and talent.

Architecture professors also need to embrace progress more quickly as it applies to non-steel materials, particularly focusing on pioneering applications for aluminum and aluminum extrusions and showcasing and embracing them in design studios for architecture students and young architects.

Further, the Aluminum Extrusion Council and the Aluminum Association must step up the initiatives they have undertaken to involve architects and student architects in their programs. This is an essential element in creating a strong, lasting partnership. An easy implementation is to invite student architects and architects to aluminum industry events for education and networking opportunities. Indeed, both architects and aluminum extruders and their trade groups should step up opportunities for networking since one-on-one conversations often lead to much more direct communication between disparate parties. In short, architects and aluminum industry leaders must awaken to today's renaissance sparked by pioneering breakthroughs in building materials that help to design and construct tomorrow's buildings, both inside and out.

REFERENCES

"NCARB - National Council of Architectural Registration Boards." *NCARB - National Council of Architectural Registration Boards*. Accessed September 7, 2016. http://www.ncarb.org/.

2013 Annual Report, National Architectural Accrediting Board, Accessed September 7, 2016. http:// http://www.naab.org/wp-content/uploads/2013-Report-on-Accreditation-in-Architecture.pdf.

"Harvard University Graduate School of Design." *Harvard Graduate School of Design*. Accessed September 7, 2016. http://www.gsd.harvard.edu/#/academic-programs/architecture/index.html.

"Harvard University Graduate School of Design." *Harvard Graduate School of Design*. Accessed September 7, 2016. http://www.gsd.harvard.edu/#/academics/courses/stu-01304-00-fall-2015.html.

"Architecture." *Courses*. Accessed September 7, 2016. http://www.risd.edu/academics/architecture/courses.

"Architecture." *Courses*. Accessed September 7, 2016. http://www.risd.edu/academics/architecture/courses.

"Architecture." *Courses*. Accessed September 7, 2016. http://www.risd.edu/academics/architecture/courses.

Taubman College of Architecture and Urban Planning. "Taubman College Brochure 2012-13." *Issue*, July 2012. https://issuu.com/taubmancollege/docs/taubmancollegebrochure_2012-13.

"The Department of the Built Environment." *The Department of the Built Environment*. Accessed September 7, 2016. https://www.tue.nl/en/university/departments/built-environment/the-department-of-the-built-environment.

"RIBA Survey Finds Skills Gap among UK Architecture Students." *Dezeen UK Architecture Schools Fail to Equip Students with Skills Needed for Practice Comments*, October 2015. http://www.dezeen.com/2015/02/02/uk-architecture-schools-fail-equip-students-skills-riba-appointments/.

"A Framework for Architectural Education." *A Framework for Architectural Education*. Accessed September 7, 2016. http://www.sciencedirect.com/science/article/pii/s2095263514000612.

"**CRL-U.S. Aluminum Contributes Hardware and Expertise to Education Development at Virginia Tech's design/buildLAB," C.R. Laurence Co., Accessed September 9, 2016. http://www.crlaurence.com/adv/press_releases/releases/USAlum_VirginiaTech.html.**

"Using Aluminum Extrusions to Meet the Challenge of Sustainable Buildings." Aluminum Extruders Council, 2015.

http://c.ymcdn.com/sites/www.aec.org/resource/resmgr/applications_pages/aec-usingalexttomeetprodchal.pdf.
"Home - 56 Leonard." *56 Leonard Home Comments*. Accessed September 7, 2016. http://56leonardtribeca.com/home/.
"Sustainability: In-Use Benefits - Aluminum Extruders Council." *Sustainability: In-Use Benefits - Aluminum Extruders Council*. Accessed September 7, 2016. http://www.aec.org/?page=stn_benefits.
"Semi-Fabricated Aluminum Products LCA." The Aluminum Association, 2013. http://www.drivealuminum.org/research-resources/pdf/research/2013/ornl-lca-report.
"Environmental Product Declarations." *The Aluminum Association*. Accessed September 7, 2016. http://www.aluminum.org/epd.

WORK DIFFERENT FOR DIFFERENT WORK

Changing the way we collaborate to achieve artfulness in the façade

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ABSTRACT

As the façade has become its own specialization, consultants have gravitated towards refining its role within building systems and improving overall building performance in a linear process. This has led to better waterproofing, reduced glare and heat gain, and a range of other positive functional results. But what happened to the art of the façade? How can we re-balance the approach to façade specialization to better incorporate performance goals with the development of new and emerging architectural languages?

Our team's process and tools change with every project, but the principles remain consistent. First and foremost, we break down the silos between designer, fabricator, engineer and builder, collaborating through non-linear, iterative processes. This fluid working method is far less prescriptive (because the best ideas can come from anywhere!), and enables us to test concepts faster. Secondly, developing intimate knowledge of digital design tools and digital fabrication techniques (including how they can enhance one another) is critical to our process. It allows us to transcend conventions and it fosters clear communication between team members.

We have used this approach in commercial, institutional and residential projects, and in doing so, have discovered that it

liberated our process from antiquated constraints. The results have varied from the development of an award-winning, customizable slumped-glass panel to establishing new digital design processes to exploit the flexibility of robotic fabrication. This methodology has helped our clients achieve their goals and paved the way for new architectural languages to take shape in the façades designed by our team.

KEYWORDS

Design, digital fabrication, design processes, project delivery, means and methods, building information modeling (BIM), project management, construction management

INTRODUCTION

Working methods in the construction industry are changing, but at various speeds across services and firms. Some consultants and contractors are reacting and adapting to new technologies and techniques as quickly as they become available, while others are stuck in their ways, reluctant to acknowledge the change around them, or simply unsure how to move forward given the significant financial and resource commitment. This disparity, which continues to grow, is becoming more and more problematic: expectations vary drastically, communication and process become inefficient, and project outcomes are negatively affected. Nowhere is this more visible than in façades where the status quo and the avant garde are particularly polarized; made to order systems versus designs that develop new architectural languages are the result of these divergent attitudes. However, progress cannot be stopped. The industry must respond by collectively becoming more flexible to bridge this gap, adopting more collaborative approaches and sharing risk in order to proliferate the art of the façade.

Façades are a breeding ground for this growing chasm: design discussions within this specialization often play second fiddle to those about the engineering, where, one could argue, innovation is easier to find, and the systemization of the façade has in many ways separated design process from fabrication, construction and installation. Although BIM has been able to slowly change the construction industry through clash detecting multi-disciplinary models before a shovel hits the ground, façades in particular provide a good opportunity to observe the difference digital tools and techniques and their adoption have on project delivery and outcomes regardless of scale or typology. Perhaps because they are especially influential on the performance, construction and 'art' of the design, façades demonstrate the positive effects of collaboration and coordination with multi-disciplinary teams, and how a flexible approach to their design and execution can support new and emerging architectural languages.

BACKGROUND

There are several voices that have been especially outspoken about the need for change in the construction industry in light of new technology and the lagging quality in project results. The promotion of Integrated Project Delivery (IPD) by the American Institute of Architects is one of the more visible attempts to encourage adaptation and changes to process to promote design excellence. IPD realigns the goals of the client and that of each project team member by re-distributing the risk and rewards in a shared model. By shifting everyone's focus and resources to "increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction", the hope is that it will create a robust and efficient process and product. However, contractual issues (with respect to negotiation and liability) and fear of the lesser or yet known still impede broader adoption by clients and consultants alike years after its introduction.

Frank Gehry, a spokesperson for the proliferation of technology in construction, went so far as to found Gehry Technologies to develop and leverage software and processes to aid communication and collaboration among consultants and contractors. His success as a practicing architect and in the progress of Gehry Technologies is evident in many of the most ambitious architectural projects from the past 15+ years. However, design does not always require such a large investment from architects, clients, or consultants. Scale and complexity of both the project and the team are large factors in this respect, and there are countless projects that can gain traction in using collaborative design working methods by having a willing and able project team.

The biggest obstacle to adapting project process to prioritize 'art' and design innovation in construction is the ever-increasing industry-wide aversion to risk. Certainly professional liability insurance has helped fuel this attitude, encouraging the existence of silos among consultants, and limiting their roles and responsibilities. However, this slows, or even removes, the tight feedback loop necessary for testing and quality control. It also negatively affects the façade design, engineering, fabrication, and installation, which has seen a significant isolation from one another and from the overall design team since the systemization of façades.

But there are significant efficiencies to be gained if each team member can contribute freely, and if those contributions are part of an early, multi-disciplinary discussion. In removing silos, and particularly when using digital tools and techniques that may or may not be familiar to the team, everyone is taking on a more dynamic role; clients, architects, engineers, contractors, sub-consultants, and fabricators. Risk is a necessary by-product of the construction industry, but mitigating it should be done by opening lines of communication.

CASE STUDIES

There are numerous ways working methods have been adapted and improved in the name of progress across the industry. The following case studies use the façade specifically to test different processes and products while adapting and exploring technology and techniques.

CASE STUDY #1

Figure 1: The glass in the façade of The Gores Group Headquarters in Beverly Hills, USA was the result of a close collaboration between the architect and several fabricators. The innovated material and production process was developed specifically for this project. (Photo by Bruce Damonte.)

The challenge in Case Study #1, the Gores Group Headquarters in Beverly Hills, was not altogether uncommon: transform the experience of an existing office building (Fig. 1). This renovation became a materials investigation led by the architectural team that questioned the design potential of a standard glass façade. Although it was only one of several lines of inquiry for this project, the exploration necessitated an unconventional team approach. Fundamental to the process was the involvement of fabricators and the use of various software platforms to translate ideas to building.

In the search for a solution for the project, the architects first envisioned a standard curtain wall system with a simple screen in front to add visual interest and assist with acoustic isolation (Fig. 2). With early input from fabricators, it became clear that achieving a unique aesthetic would be more complex.

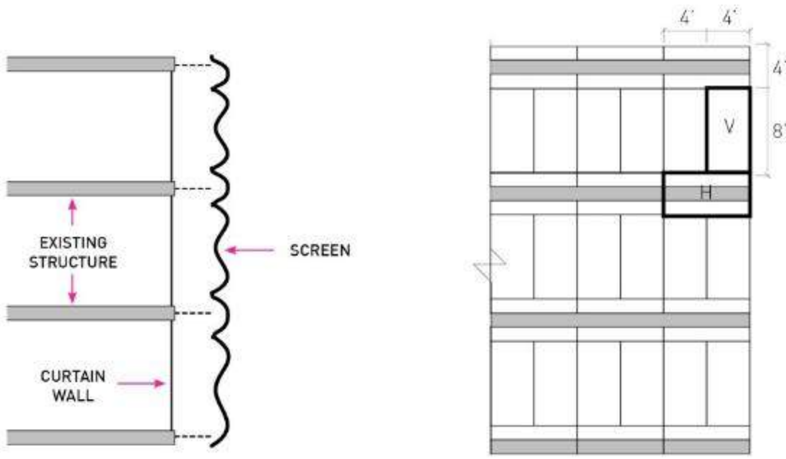


Figure 2: These diagrams illustrate how the existing structure informed the early thinking behind the design of the façade of The Gores Group Headquarters – on the left is a curtain wall and attached screen; on the right is the rationalization of the 4' x 8' panels of the glass. (Photo credit withheld to maintain anonymity during review)

Having rationalized the façade into standard 4' x 8' panels to maximize visibility and disguise the floor plates (Fig. 2), they began collaborating with Rayotek, a research and development firm that specializes in engineering-design and manufacturing precision glass and other materials. Rayotek helped test designs, fabrication processes (Fig. 3), and installation techniques with borosilicate at first and, as confidence in the design grew alongside a better understanding or the possibilities, California Glass Bending (CGB), a custom glass fabricator, and Pulp Studios, a fabricator that specializes in laminated glass, were brought onboard to continue the development process. Together, CGB and Pulp Studios helped the design team combine curved glass with a laminated interlayer (Fig. 4 and 5). The collaboration between the three studios involved several visits to the workshops of the fabricators in order to understand how each team member works: how the equipment is used, what it can do, what types of digital files can be used. The close working process, which included small scale and full size, on-site mock-ups, ensured a feedback loop that was time efficient.

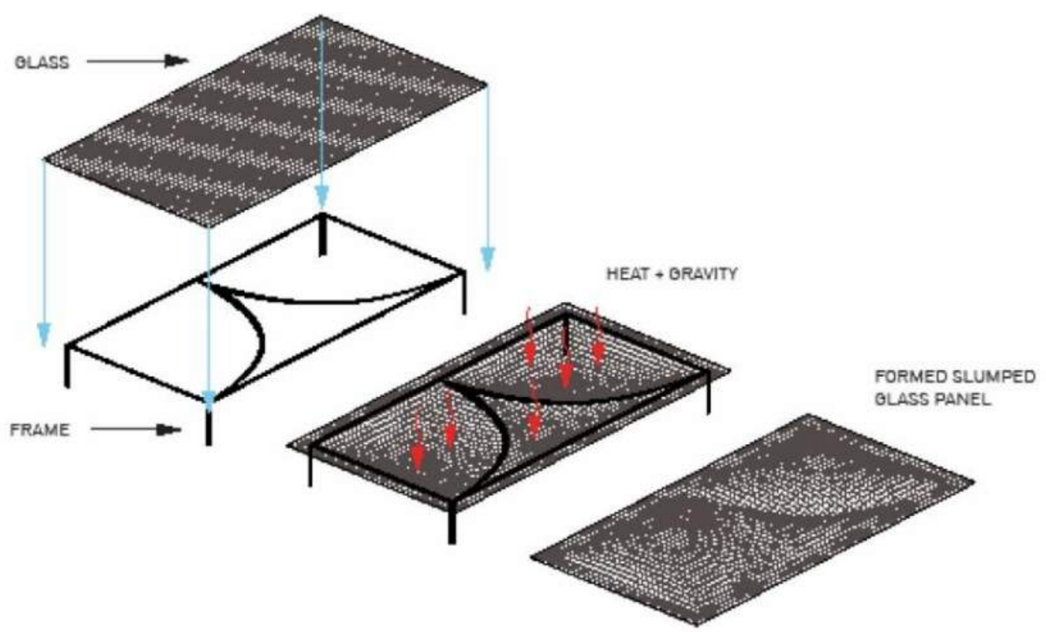
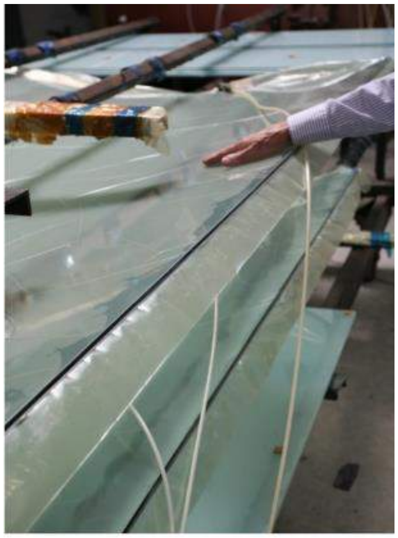


Figure 3: Rayotek's slumping process used a frame rather than a mould to shape the glass panels. Various tests were done to establish the timing and temperature necessary to achieve the curvature of each of the 12 panel designs. (Photo credit withheld to maintain anonymity during review)



Figures 4 and 5: These images show part of the process to insert the PVB interlayer between the slumped glass panes developed for The Gores Group Headquarters – left shows the slumped glass panels with PVB interlayer prior to being vacuum sealed (the pattern only appears after the sealing process); right, the design team is being shown the autoclave where the final vacuum-sealing of the panels is done. (Photo credit withheld to maintain anonymity during review)

The result of this effort was a new double layer of glass, slumped using a frame-heat-gravity process with a vacuum-sealed Sentryglass Expressions (SGX) interlayer. SGX, a printable PVB interlayer, simultaneously added a gradient and pattern that would enhance the perception of the curvature and vary the overall opacity, and safety rating to the glass. Understanding fabrication methods and input from fabricators greatly informed the design process as well as the approach to project delivery and installation.

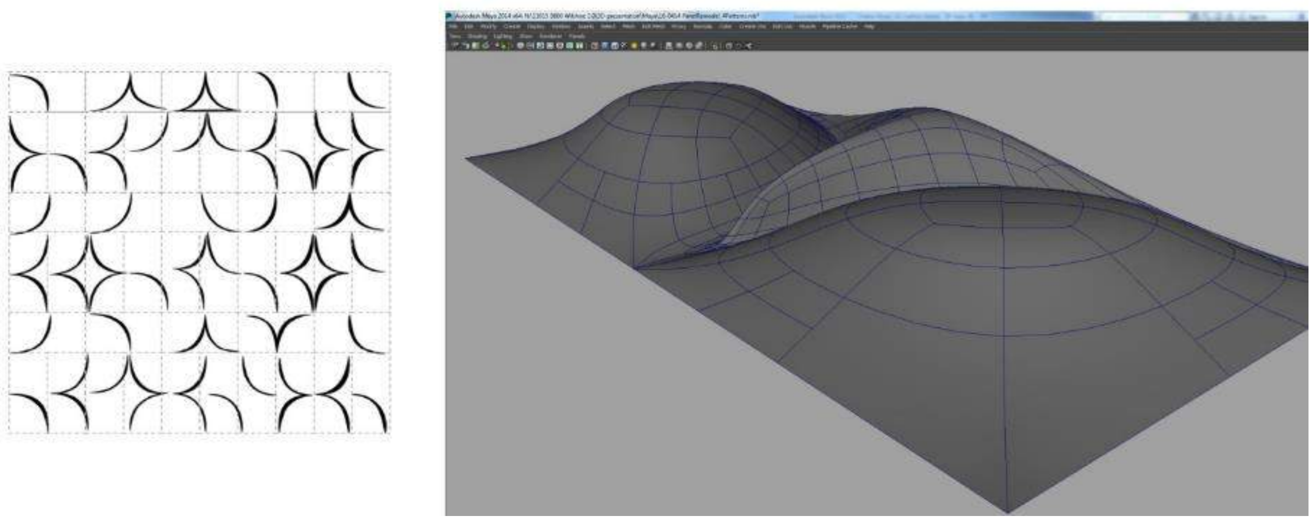


Figure 6: A non-repeating pattern based on the varied curvature of the 12 different slumped glass panels was developed to breakup the uniformity of the façade (left). Using Maya, the printed pattern in the interlayer was derived from the slump of the glass (this image accentuates its shape).
(Photo credit withheld to maintain anonymity during review)

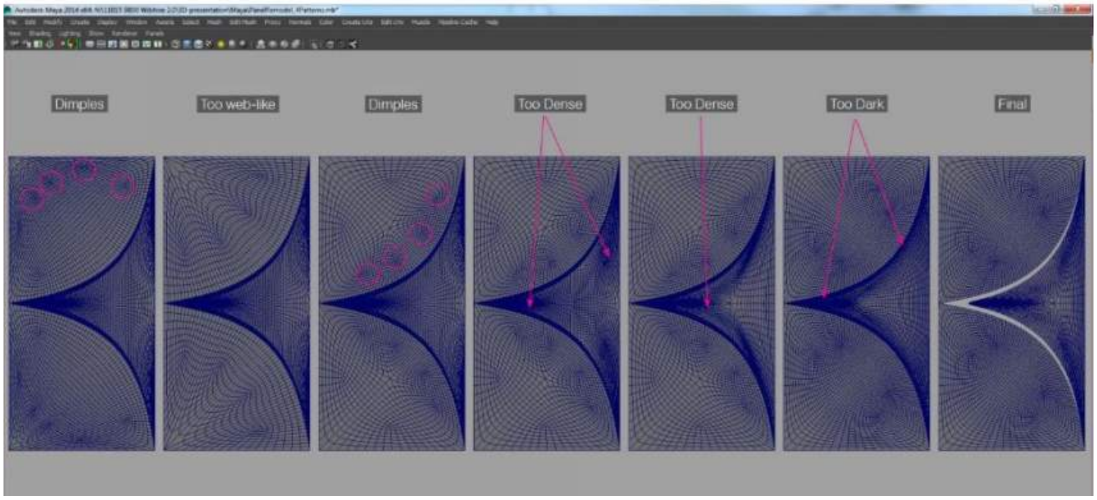


Figure 7: The image above illustrates the iterative process of developing and selecting the final pattern for the PVB interlayer for the glass panels. (Photo credit withheld to maintain anonymity during review)

In addition to the materials and installation investigation, the architects used various software to develop the panels. In Maya, a 2D pattern was derived from the 3D slump of the glass (Fig. 6 and 7); Rhino and Grasshopper were used to map out a subtle undulation in the horizontal bands along the façade; finally, Illustrator was used to translate the Maya/Rhino/Grasshopper-generated pattern into gradients for a print-ready file. This sequence of software was an improvisation informed by experience and knowledge of the tools at hand and could not have been executed without understanding the communications methods of the rest of the delivery team.

The research and development for the façade of this project combined existing mainstream technology to create a unique result and a new, customizable product. Efficiency in achieving these results was only possible because collaborators were involved early in the process to quickly test the parameters that drove the design intent and because the team was versatile enough to establish a new digital process for communication. This hands-on approach ensured clarity in communication and a better understanding of how the design would translate in production. The process used was one of many options available to the team, however its success is evident in the final project and product.

Figures 8 and 9: The appearance of the façade of The Gores Group Headquarters changes drastically depending on the time of day, weather conditions, and the angle and distance from the building as evidenced by the above photos. (Photos by Bruce Damonte.)

Figure 10: This rendering of Rio Tiber 29 illustrates the design intent of the façade – the curvature of 'fins', a combination of materials and the experience of the building as a result. The project, currently under construction, is due for completion in summer 2016. (Photo credit withheld to maintain anonymity during review)

Rio Tiber 29 is the first of a series of low-rise commercial office buildings that are transforming a central neighborhood in Mexico City. The project was a prompt to re-assess the role of the façade in speculative office design. Rio Tiber 29 incorporates curtain wall glazing and a layer of continuously curving aluminum "fins" that move from interior to exterior to demarcate occupiable space on both sides of the wall. The experience of these spaces, as well as the appearance of the fins moving in and out of the curtain wall, dissolves the solidity of the glass itself (Fig. 10). To develop the design, engineering, fabrication, and installation across teams in both Mexico and the United States, this façade required intensive and continuous coordination between the architects, engineers, fabricators, and contractor throughout the design phases.

Beginning at Concept Design, the client, architects, SMEP and acoustic engineers, and contractor collaborated to develop options. At that early stage, a design with curved fins was proposed and pursued with each team member contributing research and existing knowledge to create a holistic vision of the final building and carefully forecasting variables and issues in the project's design, performance, the project workflow, logistics, and operations.

Digital tools, as well as paper models, were used in design team meetings as proof of concept, but ultimately the fabricator's participation, which began at the beginning of Schematic Design, helped the team understand how to develop the fins. For instance, their input with respect to the geometry helped refine the curvature of the fins into three-dimensions – with a triangular cross-section as opposed to a square (Fig. 11). Their full-scale mock-up also guided the decision to use a powder-coated aluminum that was more malleable and cost effective, but also had similar weather resistant properties to stainless steel.

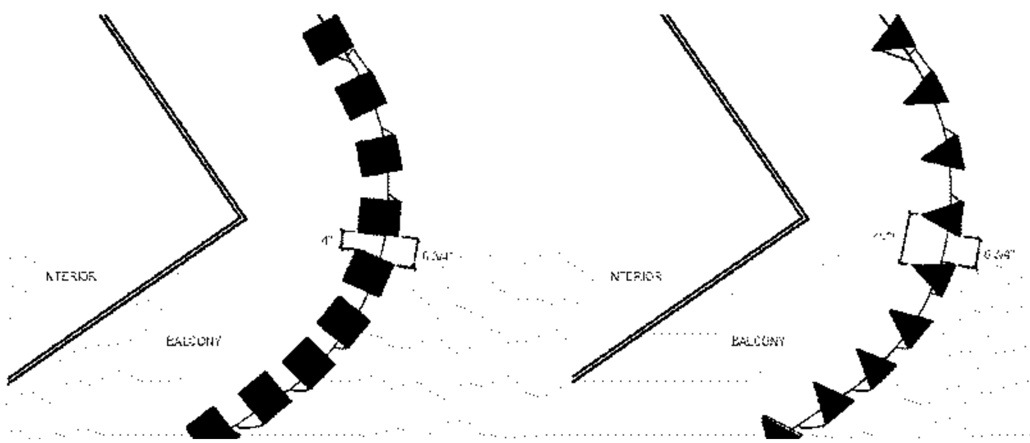
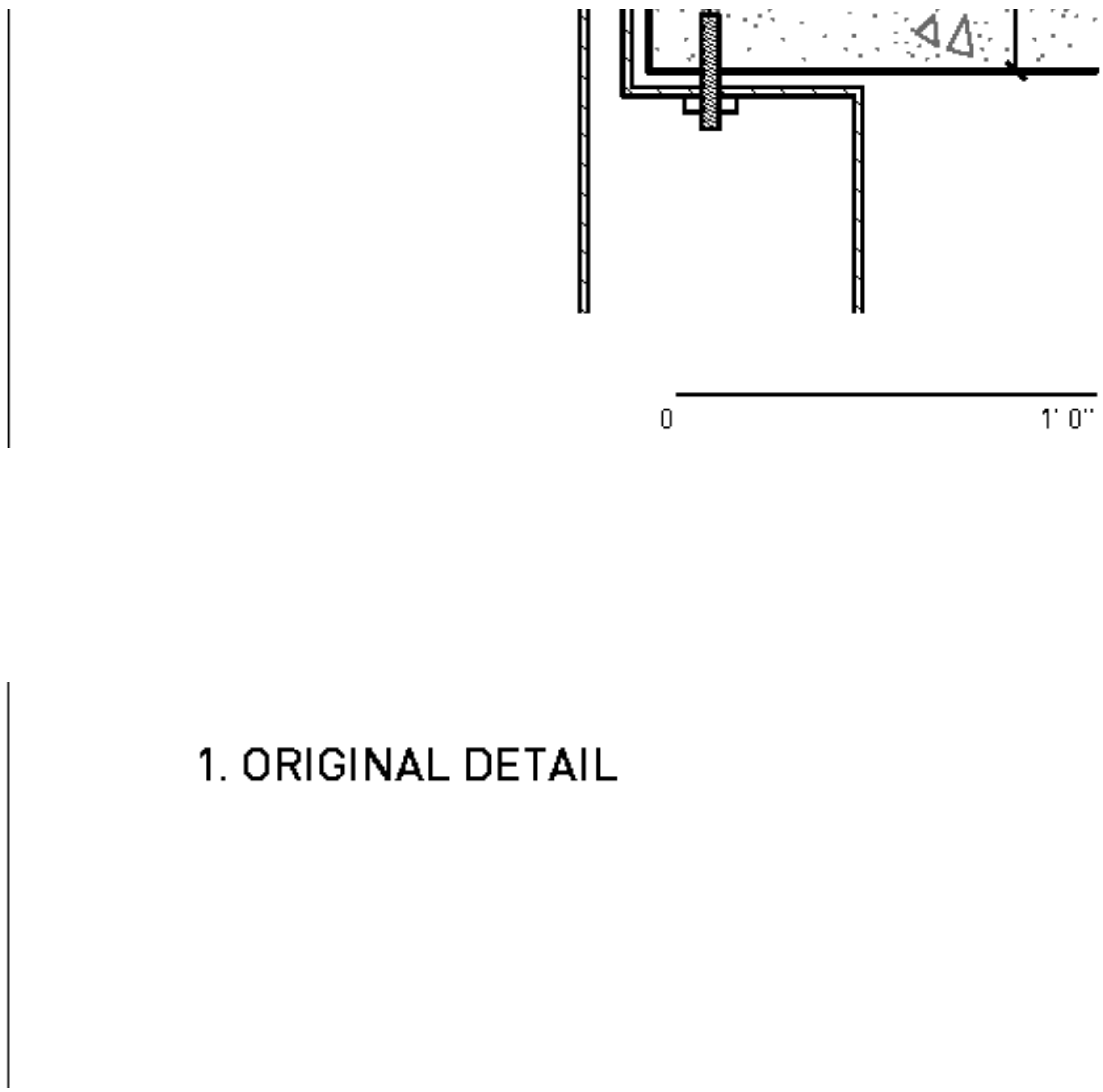


Figure 11: Figure 11: The challenge to design, engineer, fabricate and install the aluminum 'fins' was resolved by an inter-disciplinary team. These cross-sections of the fins illustrate early design options. (Photo credit withheld to maintain anonymity during review)

One of the other design challenges that were resolved through an inter-disciplinary, iterative process early on was how the fins would connect to the building. Prior to the material selection, the team considered making the members structural, however the building code would not allow for this. Instead, the fins have two key connections: a. to the concrete slab on the interior and on the balconies, and b. when they appear to penetrate the curtain wall. Between the architects, engineers, fabricators, and contractor, the design of the connection and the various components were designed and produced in several mock-ups, the tolerances and performance were tested, and the logistics of fabrication and installation analyzed.



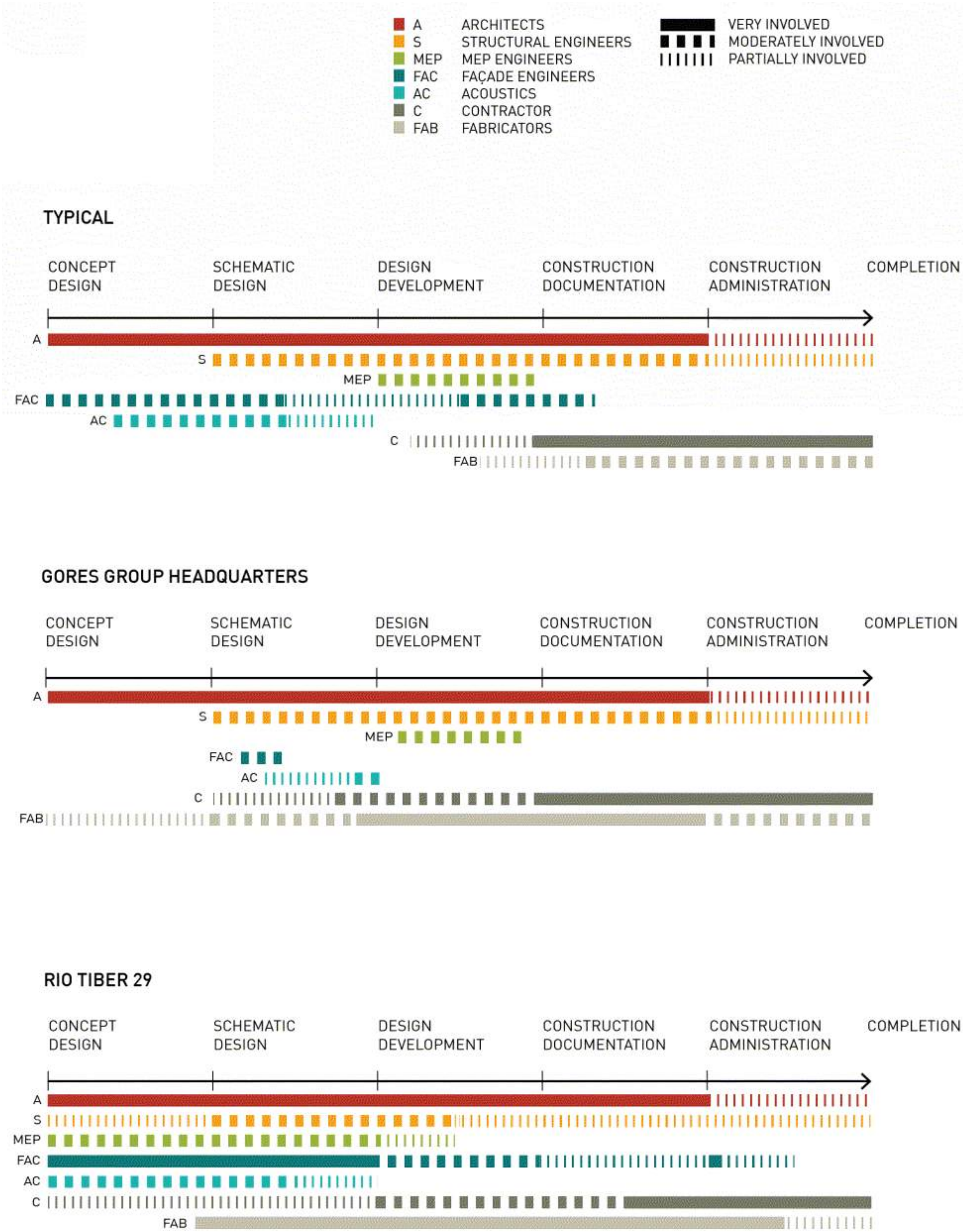
Figures 12: Figure 12: These diagrams illustrate the changes made during testing and development of the connection between the fin and the floor slab along the façade. Architects, fabricators and the contractor worked collectively with guidance from the team of engineers who were checking tolerance and overall performance. (Photo credit withheld to maintain anonymity during review)

The realization of Rio Tiber 29's distinctive architectural language was a direct result of a fully coordinated and continuous collaboration from the beginning. Only in collaborating with the multi-disciplinary team could critical design, engineering, fabrication, installation and logistical challenges be resolved in a timely manner. The team's deep knowledge of the project and its history, gained from their continued engagement throughout project delivery, is a reflection of the project leaders' commitment to a collaborative approach. By maintaining a shared goal (the realization of the design intent) for the duration, risk was shared and the result is a thoughtfully executed design: an 'artful' response to the design challenge.

EXPLANATION

There are various methods of project delivery that prioritize the design intent (some examples are shown in Fig. 13). In both instances, in lieu of clients and project teams committed to the IPD process, these projects had more traditional contracts: the architects and each consultant held individual contracts directly with the client. There was no bidding phase since the general contractors (GC) were already on board during the design phase; in the first case, the client had a preferred GC from the beginning, and in the second, a division of the client's organization provided GC services. This proved to be an advantage in both instances, for example, to refine the design at an early stage to take into account production and installation issues.

These case studies both succeed in allowing the delivering a façade with a new architectural language. Although the results are difficult to quantify, the timelines remained similar to a typical project plan; time and energy saved in several areas compensated for instances where more time was needed to test and iterate. Overall, project costs were competitive relative to the level of quality for custom solutions we provide. Value must also be given to gaining a tremendous amount of knowledge, developing good working relationships and adaptable methodologies, and education and experience gained from exploring or working with new tools and technology. In order to continue such progress, all consultants need to adopt a healthier attitude towards change and risk in order for innovation and the 'art' of design to increase across the construction industry.



Figures 13: These infographics show when key consultants participated in the run of projects: typical, The Gores Group Headquarters and Rio Tiber 29. They also provide an indication of the level of involvement those consultants had as well. (Photo credit withheld to maintain anonymity during review)

CONCLUSION

With new technology and new techniques for design, fabrication, and construction comes a learning curve that requires versatility as new processes emerge. Despite a rampant aversion to risk, traditional project roles and responsibilities need to adapt to allow a more collaborative approach; removing silos will allow project teams to problem solve earlier in the hopes of maintaining efficiency while realizing the overall design intent. The multiplicity of options in project delivery means that there is no one 'best practice', however a cultural shift amongst consultants (architects included) would encourage the kind of collaborative workflow that would foster innovation in design.

Certainly the value of design innovation is difficult to quantify and cost-benefit analysis even harder to define. However, achievements in the 'art' of the façade can and should be prioritized in discussion and analysis. Regaining a holistic view of project delivery and establishing a collaborative spirit from the beginning of a project will help design, engineering, fabrication, and construction progress in tandem; the results of this will improve the quality of 'art' and design within façades and across the built environment.

REFERENCE

Cook, Richard, Forrest Lott, Brad Milton, Patrick O'Connor, Christopher Smith, Jim Suchiro, Barbar Price, "Integrated Project Delivery: A Guide." *The American Institute of Architects*, V. 1 (2007): 2.

Gehry Technologies. "About Gehry Technologies." http://www.gehrytech.com/en/main/about/ (accessed May 24, 2016).

CELLULAR SHELLS AS STRUCTURAL NETWORKS

Mesh-based engineering optimization in freeform aggregated structures

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ABSTRACT

This paper describes the development of a novel structural shell system consisting of modular cells that comprise a freeform, free-standing surface. The shell is a single-layer aggregation of 3-dimensional polygonal cells that are fabricated from flat and folded stainless steel sheet. The panelization of the cells is generated through a set of custom non-deterministic meshing algorithm that directly incorporates structural analysis results in order to optimize the distribution of material. The resulting structure behaves in the domain between true compression vaults and stressed skin structures, and therefore requires a unique analytical approach that incorporates structural considerations from both of these typologies.

The architecture and structural system were developed in parallel, such that each process informed the other. Therefore, the analytical methods needed to be parametric and flexible to allow for rapid iteration between architects and consultants. A custom, tightly integrated Building Information Model workflow enabled a single process to proceed from initial definition of the continuous 3-dimensional design surface, through structural analysis, to the automated generation of fabrication documents.

This paper will illustrate the workflow described above, including the methods used for structural analysis and the custom parametric tools that enabled the transfer of information through multiple stages.

KEYWORDS

Parametric workflows, design optimization, computational design, innovative or unique, finite element analysis (FEA), case study, digital fabrication

INTRODUCTION

The unbuilt project is a cellular, freeform structural shell in a residential area of Pennsylvania, approximately 12 miles from Philadelphia. The design team was charged with developing a design for a linear art gallery that served as a literal and programmatic bridge between an existing residence and a private art gallery. The system was designed to be a free-standing, ground supported, weather-proofed enclosure that maintained optimal temperature, humidity and ultra-violet exposure as required to preserve artwork and provide occupant comfort.

Discretization of the shell into cellular units was motivated by several design constraints, but also allows for individual programming of unit types to accommodate local conditions such as glazing interfaces or HVAC ductwork. The discretization pattern is generated by a customized Dynamic Remeshing Algorithm (DRA) in conjunction with circle packing routines for aesthetic smoothing. Structural analysis results provide the inputs for the DRA so that size and density of the structural cells is optimized for material distribution.

While many novel constructions systems have been developed for temporary uses or as pavilions, the project proposed was to be a permanent construction, thereby requiring detailing and structural analysis of a level consistent with building code and industry practices. A series of studies is performed to enable the novel system to be evaluated in the terms of existing engineering practice.

Figure 1: Rendering of project. (Image courtesy of the Point B Design)

The design process serves as an example of how technology can be leveraged to integrate many contemporary agendas in the AEC industry, including BIM modeling, advanced meshing algorithms, complex free-form geometry, structural optimization, computational simulation, CNC fabrication, integrated project delivery, and others.

BACKGROUND

Structural shells have a long history in architecture and, especially in contemporary times, provide a robust and active field of research (Adriaenssens, et. al. 2015). Much of this research is oriented on global form-finding, as a structural shell's performance is derived primarily from its shape, as well as the material system used. Because the project's geometry is prescriptive, the structure must respond in other ways, such as variation in shell depth and the concentration of cells. The concentration of cells is directly correlated to the connectivity of the edges, thereby becoming a topology optimization problem, which is an active field of research covered thoroughly by others (Bendsoe, et. al. 2004).

The panelization of freeform surfaces into planar polygons is also a widely studied topic (Eigensatz et. al. 2010). For this project, many strategies were evaluated independently and in combinations:

- UV-subdivision
- Laplacian mesh-smoothing
- Particle-Spring System mesh relaxation
- Planar-quad optimization
- Conformal mapping
- Grid projection

Existing research has used structural analysis to drive the panelization of planar-quad meshes (Schiftner et. al. 2010). Due to the inherent structural behavior of quadrilateral panels, these methods focus on aligning panelization with principal stress directions. The proposed structural solution has more in common with methods that focus on the topology of the mesh as a means toward structural optimization (Pietroni et. al. 2014). That research employs voronoi methods for topology generation and a method called Regularization for aesthetic smoothing. The solution proposed herein employs dynamic remeshing for topology generation and circle packing for aesthetic smoothing (Piker 2016). In addition, the methods below extend the research into another structural typology beyond moment connected steel frames to an approximate stressed skin typology, where the depth of the surface being optimized is not uniform. Buckling is also evaluated at the scale of the structural unit, and the loads driving the form-finding algorithm are not self-weight but the envelope of all load cases and combinations described by the relevant engineering code (ASCE, 2005).

CONSTRAINTS AS DESIGN DRIVER

Multiple design criteria motivated the evolution of the unique structural solution. A brief note about each constraint is provided below in order to illustrate the sequence of decisions that produced the proposed system.

SHORT TIMELINE

The project's rapid delivery time necessitated a design-build approach and emphasized solutions that could be realized quickly with short lead times. The structural system therefore needed to be one that could be engineered in parallel with changes to the architectural design surface as it evolved.

SINGLE CONTINUOUS SYSTEM

The architectural intent was that the shell performs as primary structure and primary roof enclosure with the appearance of a single continuous system.

FIXED DESIGN SURFACE

Given the continuity of surface and aiming to optimize the amount of material being used, several form-finding approaches were evaluated, including catenary vaults and membrane structures; these ultimately were not suitable because the control of the architectural design surface was paramount, as it was specifically sculpted to provide certain views and precise architectural moments.

LIGHTWEIGHT, PIECEMEAL CONSTRUCTION

The site and surrounding area features protected landscape and ecology, including a set of mature trees whose root structures occupied the same space as the proposed construction. In addition, the client required as little disruption to the site as possible during construction, due to active occupancy of the existing structures. This precluded any significant excavation or site work or, more importantly, the use of large machinery. The structure would therefore need to be lightweight and delivered to site in small sections that would not require large construction machines.

FABRICATION CONSTRAINTS

Because of the desired geometry, CNC fabrication methods were already anticipated. However, in order to reduce cost and schedule, time consuming methods such as 3D milling were unacceptable.

DESCRIPTION OF SYSTEM

ASSEMBLY

The system is constituted by an aggregation of structural cells that have the approximate shape of a taper-extruded convex polygon of irregular edge length. The outer surfaces are flat CNC cut plates of stainless steel, which will also be called "diaphragms". The walls of the tapered shape, which serve as the structural webs, are made from a single CNC cut shape that is then folded into 3-dimensions, including tabs that fold to provide an interface with the diaphragms (Fig. 2). Cells are fastened to each other through adjacent webs, and the seams between the outer faces of adjacent cells are welded to provide membrane-stress continuity. While the welding is a labor-intensive process, the welds are simple and do not have to meet strong aesthetic criteria due to a layer of exterior cladding. The labor costs were deemed acceptable, and the other advantages provided by the system allowed the project to proceed. While the envelope will be waterproofed, stainless steel is used throughout to ensure that no corrosion occurs during the fabrication, assembly, and erection processes.

Aggregate systems in particular are at risk of construction problems due to the accumulation of tolerance issues across many elements. The proposed system has some self-corrective attributes. Because the diaphragms are flat, laser-cut shapes, they are highly precise and act as their own assembly jig: inaccuracies in the manual folding process are corrected because of the geometric interface with the diaphragm. The diaphragm also forces cells to only nest together in a specific orientation. The flexibility of the sheet metal also allows for alignment issues to be accommodated by local deformation of the plate. Medium scale mock-ups (Fig. 2) confirmed that these characteristics would largely reduce and accommodate assembly tolerances. It also established that large swaths of cells should be assembled before welding, because the flexibility in the un-welded state allows for any misalignments to be accommodated by a distribution of minor adjustments. Further mockups would need to be built to confirm this performance over the span of the structure.

STRUCTURAL PERFORMANCE

The structure is best categorized as a stressed skin in the form of a flexural shell: a continuous system resisting both bending and compression forces. Bending forces are resisted by the moment couple produced by the offset of the thin sheet metal skins, with shear transfer occurring through a network of webs that connect the outer and inner surface. Compression forces are also resisted by the stiffness of the sheets, but with the webs acting as bracing for the skins against out-of-plane buckling.

THERMAL DESIGN AND WATERPROOFING

Thermal performance is achieved with rigid insulation blocks that have been 3-axis CNC milled to conform to diaphragm geometry at each cell. Self-adhering non-permeable air-and-water barrier with mastic tape at penetrations provide primary air and water barrier. Silicone weather seal at each cell joint acts as secondary water barrier.

NON-STRUCTURAL CLADDING

Using variable and adaptable upstands with thermally broken connection to cells, a number of skin cladding options could be deployed. This layer would perform similar to an open jointed, pressure equalized rainscreen wall cladding. There are a number of valid options that were tested which are not covered in the scope of this paper.

DESIGN CONSTRAINT SATISFACTION

The system proposed requires only 2D CNC laser cutting, which requires little to no jigging or tooling, is simple to program, and produces pieces that can be easily transported and readily assembled by an individual person. Large portions can also be pre-assembled and transported to the site with limited machinery required. Using thin gauge sheet metal dramatically reduces the weight-to-volume ratio of the structure, and stainless steel sheet is a readily available stock material with little to no lead time.

The cellular system proposed allows for units to be separated into types that perform different functions, such that the entire system is designed using a rule-based, algorithmic, parametric approach. Design developments within a specific category of cell, such as those housing HVAC ductwork or those supporting the glass walls, can be modified without impeding the development of the rest of the project. Finally, the panelization could maintain a close approximation of the design surface, which is discussed in more detail below.

Figure 2 – Assembly of cells (Image courtesy of Point B Design)

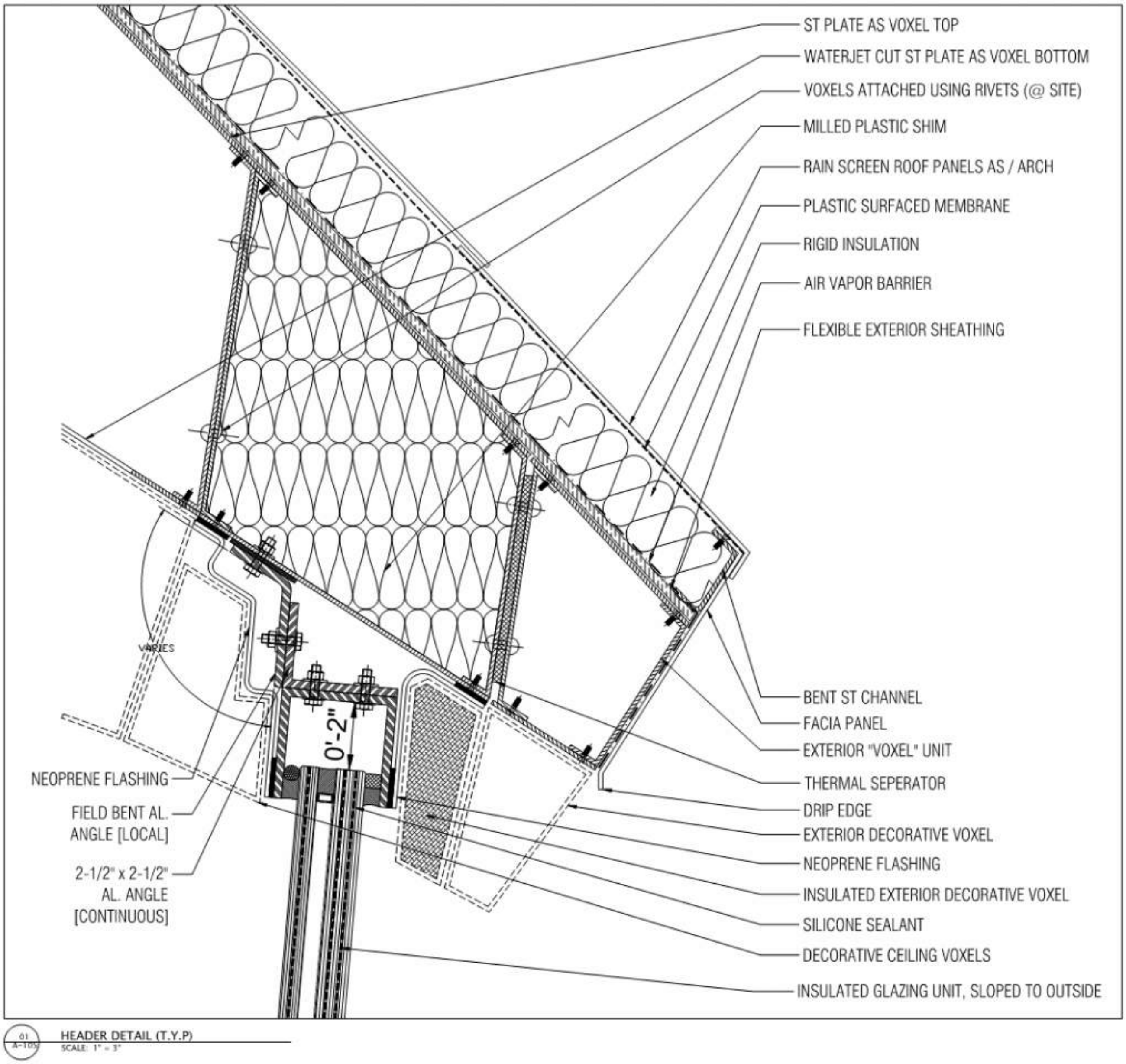
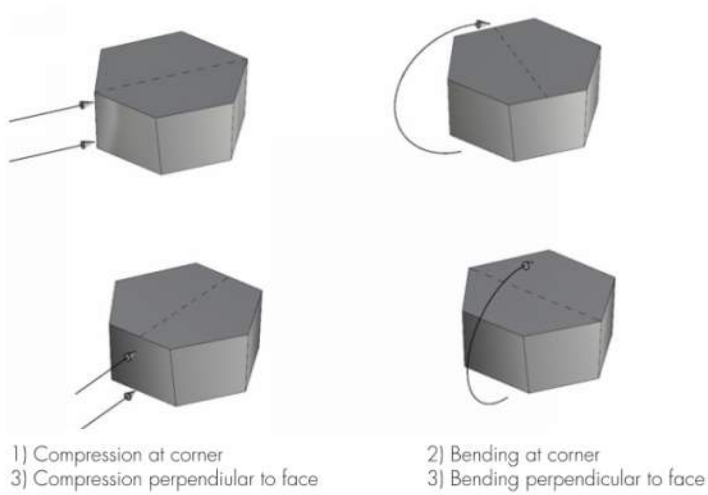
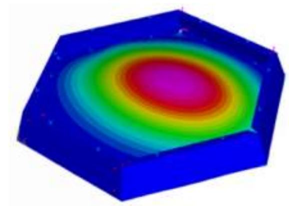


Fig. 3: Typical detail illustrating layers of structural system and engagement with glazing

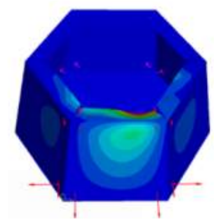
STRUCTURAL VALIDATION

In order to confirm that bending and compression resistance could be achieved through the geometric variation of the cells, a series of Finite Element Analysis models were generated that varied in radius and depth. Because the shell is non-directional, cells may be subject to bending and compression forces in any direction. In reality they are subject to forces in multiple directions, but the vector sum of these forces are equivalent to a single line of action. Therefore, cells are analyzed with unit forces/moment applied on the broad face ("perpendicular") as well as across opposite corners (Fig. 4a) Cells are evaluated at four different sheet gauges: 12, 14, 16, and 18 (2.78mm, 1.98mm, 1.59mm, and 1.27mm). Below are results for two cells of varying gauge thickness with two different Aspect Ratios (AR). Cell A has a radius of 36" and a depth of 8" (AR > 4). Cell B has a radius of 12" and a depth of 12" (AR = 1) (Fig. 4b).

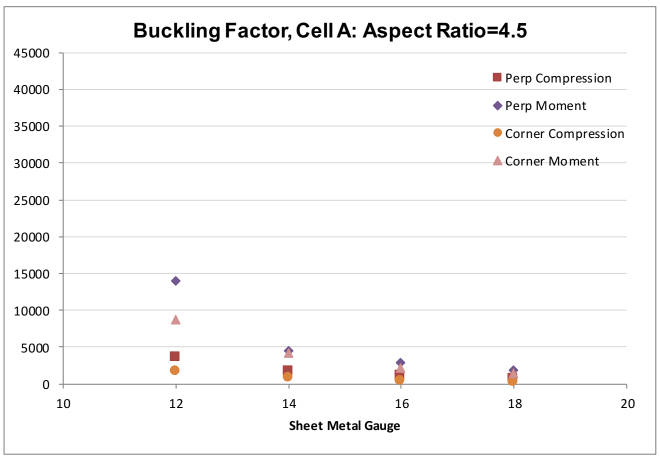




Cell A Buckling Shape: Buckling occurs in the large outer cap, due to the overall slenderness of the cell



Cell B Buckling Shape: Buckling occurs at the point of application



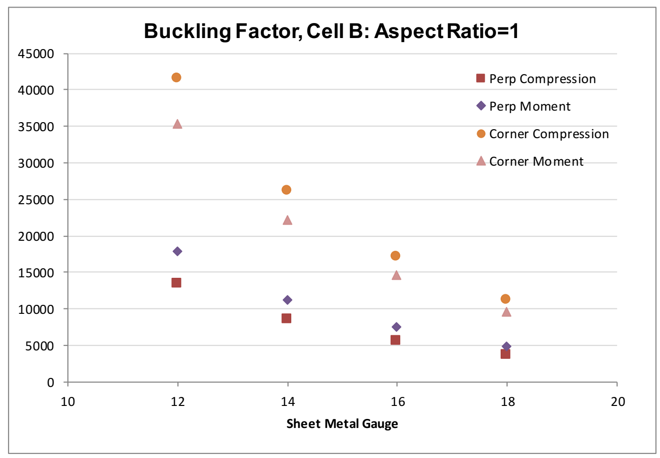


Figure 4a (Top Left) – Application methods for isolated cell studies. Figure 4b (Top Right) – Samples of FEA buckling analysis. Figure 4c (Bottom Left) – Buckling Factors of flatter cell. Figure 4d (Bottom Right) – Buckling Factors of more stout cell.

The results illustrate a number of points (Fig. 4c and 4d):

- The deeper Cell B has a much higher resistance to buckling under the applied moment
- Cell A, with the larger radius, has a lower buckling capacity than the deeper Cell B
- The flatter Cell A is controlled by compression, regardless of the load direction. By comparison, Cell B is controlled more by load direction than compression vs. bending
- Plate thickness has a substantial effect, though less substantial than cell dimensions

These results directly inform the panelization of the shell.

STRUCTURAL OPTIMIZATION

INTEROPERABILITY

The project was heavily enabled by the use of a custom API library that allowed for the scripting platform, Grasshopper, to execute operations in the FEA package, Strand7. This allowed for a 1-to-1 correlation between each model. Mesh vertices have an equivalent FEA node, meshes faces an equivalent FEA plate, and so on. This enables the automated construction of models in the event of a change to the design surface; the parametric application of loads meant avoiding the laborious process of rebuilding complex FEA models. Structural analysis results could then be directly imported into the modeling platform and attributed to geometry either through color maps or through the application of metadata.

PANELIZATION

The panelization of the shell is driven by the structural behaviors illustrated above. A preliminary analysis is performed on the design geometry provided by the architects: the surface is meshed automatically and taken into FEA structural analysis. The resulting moment and compression results for these meshes are reconstituted in the modeling environment, creating stress “maps” that can be used as inputs for the subsequent optimization algorithms.

Compression forces are resisted by the cross section of the cells. Compressive capacity is limited not by material yielding, but rather by buckling resistance, which is a product of sheet thickness and the unbraced span of the cell. This is confirmed by the isolated cell studies in the previous section. In the proposed system, the bracing is provided by the tapered webs, and the span is the diameter of the polygonal diaphragm cap. Therefore, the diameter of the individual cells is adjusted in direct response to the compressive force demands.

Altering the diameter of a single cell has a direct effect on the size and shape of adjacent cells. It is therefore necessary to be able to change the connectivity of the underlying mesh in a non-deterministic way; that is, it is impossible to predict the density and location of cells in advance. To accomplish this, the project employed a Dynamic Remeshing Algorithm.

DYNAMIC REMESHING ALGORITHM

Dynamic Remeshing Algorithms allow direct alterations of the connectivity of a polygon mesh. The algorithm deployed in the project stores the information about vertices and their connections in a half-edge mesh data structure. This enables operation on the mesh connectivity, the primary operations consisting of edge flips, edges splits, and edge collapsing.

These operations inherently change the edge lengths of the polygons of the mesh. For example, if the long edge of two obtuse triangles is “flipped”, the new edge is shorter. The edge operations are therefore driven by target edge lengths: if a mesh edge is longer than its target value, that edge will either be split or flipped. In this case, the edge length is directly informed by the compressive stress at the location of that edges’ midpoint, as predetermined by the FEA analysis and read from the stress map (Fig.5). Specifically, areas of the surface that have higher stresses have smaller target lengths, leading to smaller cells, therefore smaller unbraced lengths and increased buckling capacity (Fig. 6).

The DRA used in this project (Piker 2016) operates exclusively on triangular meshes. The cells are then determined as the dual of the triangular mesh.

CELL DEPTH

The depth of each cell is then generated from this mesh, based on the bending requirements at that location, similar to the process described above. At each vertex of the mesh, the algorithm reads the results from the bending moment maps of the preliminary FEA analysis, and translates that vertex in a direction normal to the mesh; the translation distance is proportional to the bending moment demand at that location. Because the mesh in continuous, the offset face will also be continuous, though the lower diaphragm is unlikely to be a parallel offset of the outer diaphragm.

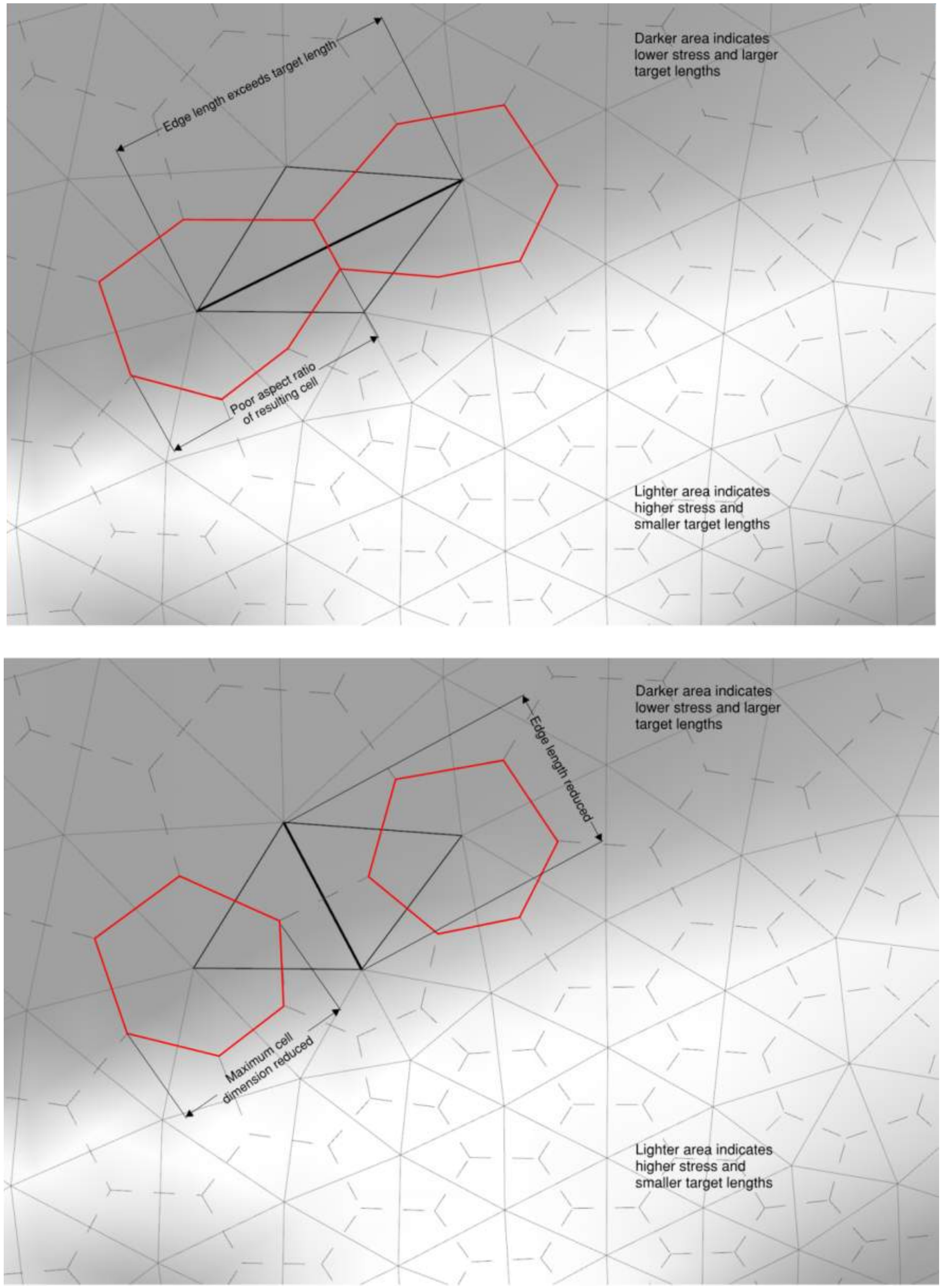


Fig. 5 – Dynamic Remeshing and its effect on cell dimensions

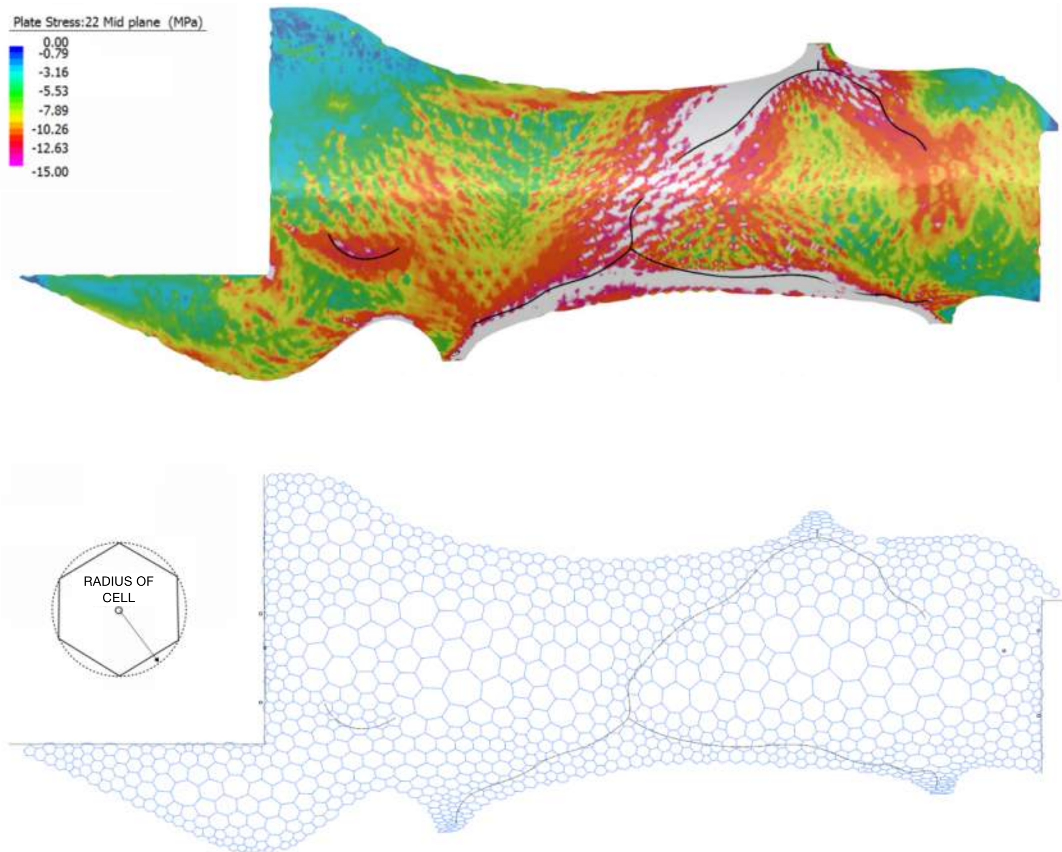


Fig. 6 – Dynamic Remeshing according to compressive stress. White areas indicate zones of peak compression, with medial line added for emphasis.

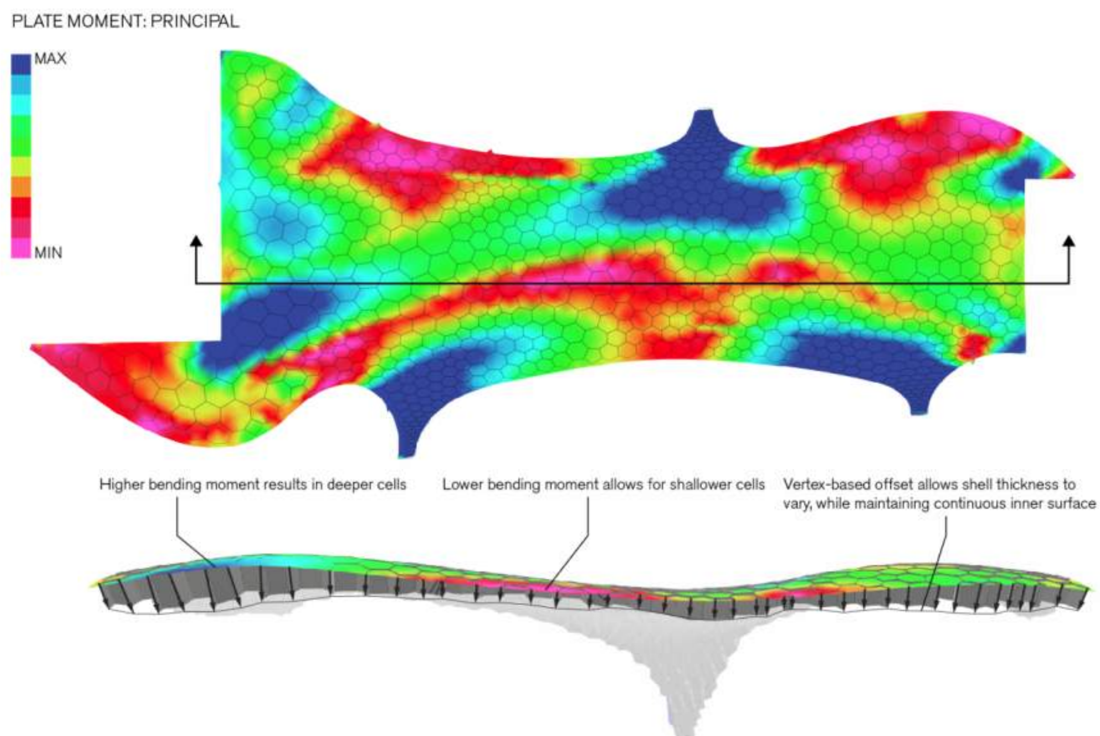


Figure 7 – Envelope bending moments, the corresponding offset, and resulting cell geometry

FINAL ENGINEERING

PLATE BUCKLING

Final engineering requires a calculation based in engineering theory and a comprehensive model of the cells as they will be constructed. The proportional dimensioning of cell diameters achieves a broad level of optimization, but does not guarantee absolutely that every cell is sufficiently sized. The welds along the seams of the cells transfers membrane forces directly from one cap to the next, such that each cap can be conservatively approximated as a simply supported plate and can be analyzed according to the plate buckling equations per Timoshenko (Timoshenko 1959) and standard engineering reference manuals (ASCE 2002).

Euler buckling capacity of thin plates is the result of geometric dimensions, material constants, and a buckling coefficient "K". The material constants are predetermined, while cell dimension are variable. If the buckling coefficient K can be determined, then the plate thicknesses can be adjusted to meet required buckling capacity.

The buckling coefficient "K" depends on the support conditions and load application of the plate. For rectangular plates, the K-factor for various edge support conditions is already known (Fig. 8a). Because the caps are not rectangular as depicted, and do not have truly "simply-supported" edges, linear buckling analysis was performed on a series of FEA models to back-solve for a K value that would represent the buckling behavior of actual conditions (Fig. 8b). From these studies, a minimum K factor of 6 is assumed to be a conservative envelope for all structural cells. This value can be seen to be between Case 1 and Case 2 (Fig. 8a).

$$F_{ol} = \frac{K\pi^2 E}{12(1 - \nu^2)}\left(\frac{t}{b}\right)^2$$

constants

cell dimensions (variable)

Case	Boundary Conditions	Loading	Buckling Coefficient (K)	Half - Wavelength
1	S.S / S.S / S.S / S.S	Uniform Compression	4.0	b
2	S.S / Built-in / S.S / Built-in	Uniform Compression	6.97	0.66b
3	S.S / S.S / S.S / Free	Uniform Compression	0.425 0.675	L = ∞ L = 2b
4	S.S / Built-in / S.S / Free	Uniform Compression	1.247	1.636b

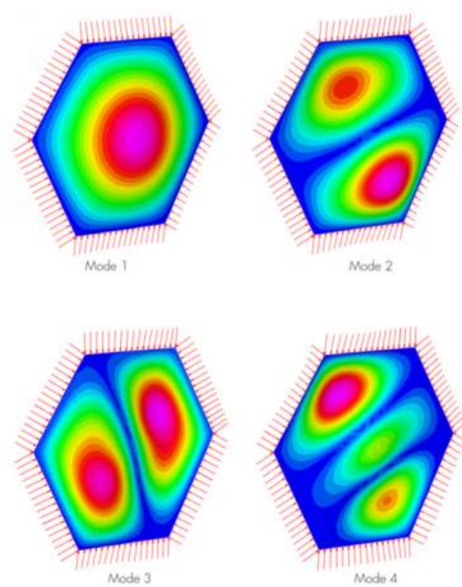
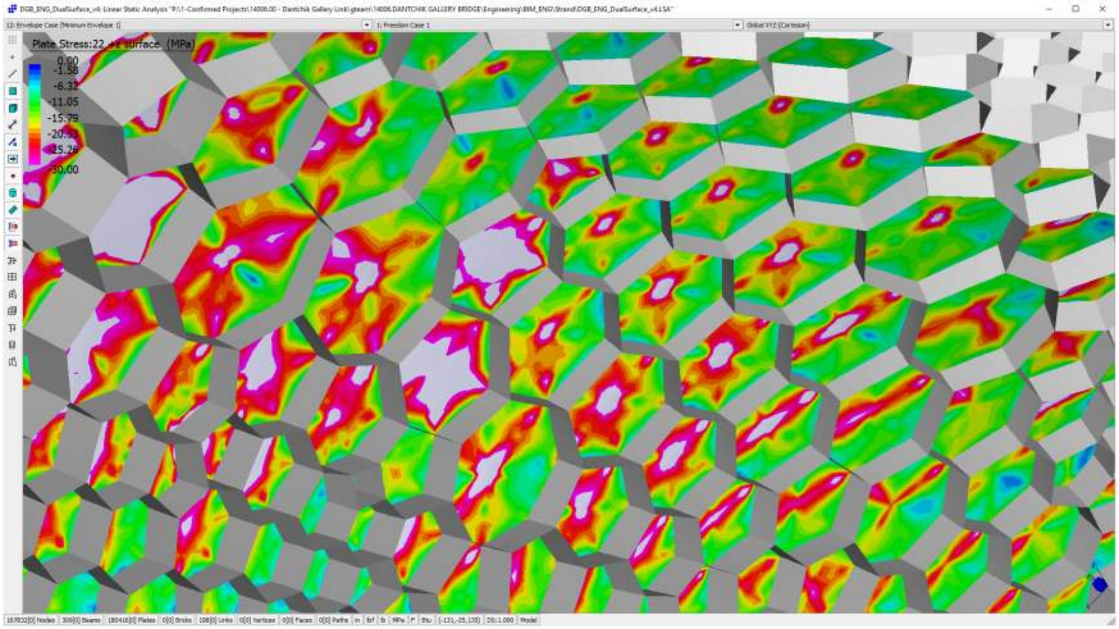
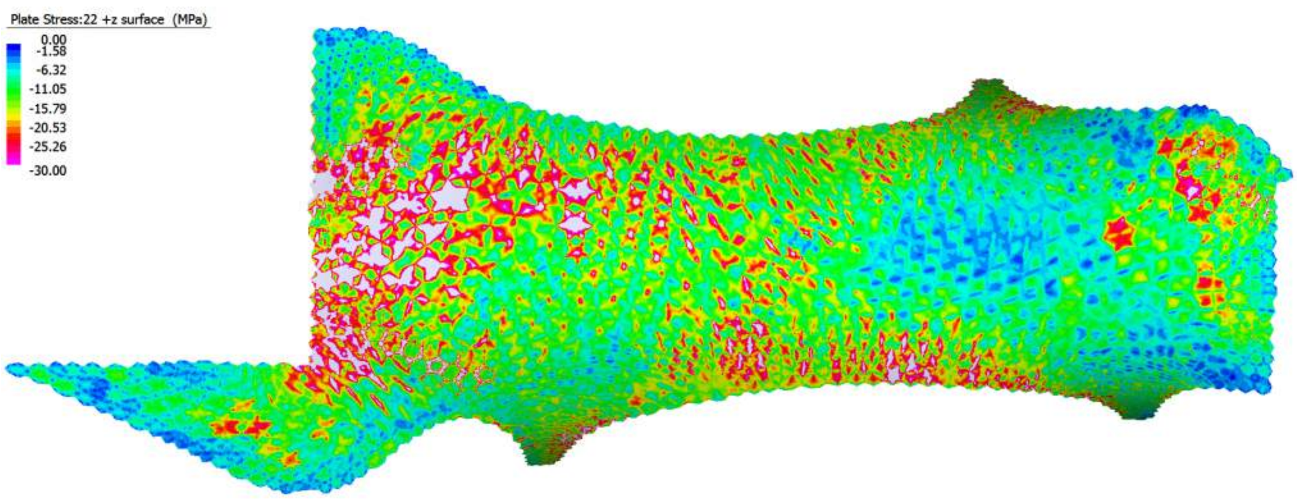


Fig. 8a (Left) Plate buckling equation and buckling coefficients for rectangular plates. Figure 8b (Right): Buckling modes of cell diaphragms with uniform loading.

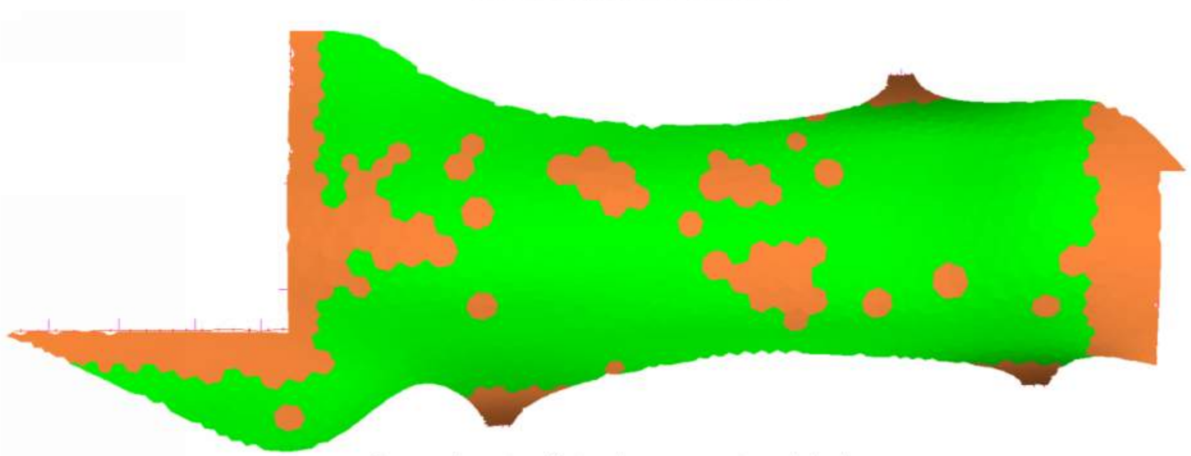
After the preliminary analysis is performed to determine areas of peak compression and the Dynamic Remeshing Algorithm is executed, the final geometry can be run through FEA to find the true resulting compression in the extreme surfaces. Using custom scripting libraries to connect the 3D modeling environment with the FEA software, the Finite Elements can be "tagged" with information corresponding to the design model. The radius of the cells can be extracted from the 3D design model, and using the information attributed to the BIM model of the cells, these radii can be collated with the stress results of the FEA model. The radii are used to determine the allowable buckling stress and the FEA results are compared against these allowable limits. Any cells that experience forces beyond the allowable limit must be stiffened. Because the FEA plates correspond to the BIM geometry, the distribution of stiffened cells can be directly mapped back into the structure (Figure 9).

This method provides a rules-based engineering solution that is not tied immediately to the global geometry. In other words, as the design team refines or modifies the global geometry, the entire panelization and finalization process can be re-executed automatically.





Structural analysis results of outer surface



Orange cells require stiffening due to compression and slenderness

Figure 9 Distribution of cells that require increased plate thickness due to buckling

FABRICATION DOCUMENTATION

The selection of sheet metal as a material, in conjunction with the information-rich geometric model allows for the generation of fabrication-ready documents. Through the process of prototyping, feedback from sheet metal fabricators could be incorporated into the unrolling routines, even accounting for the distortion of the metal in the bending process. 2D line drawings were generated that could be imported directly into most CNC programming software (Fig. 10). There are also existing solutions for conversion of this geometry directly into machine G-code without having to import into programming software. This would be a logical extension of the current workflow.

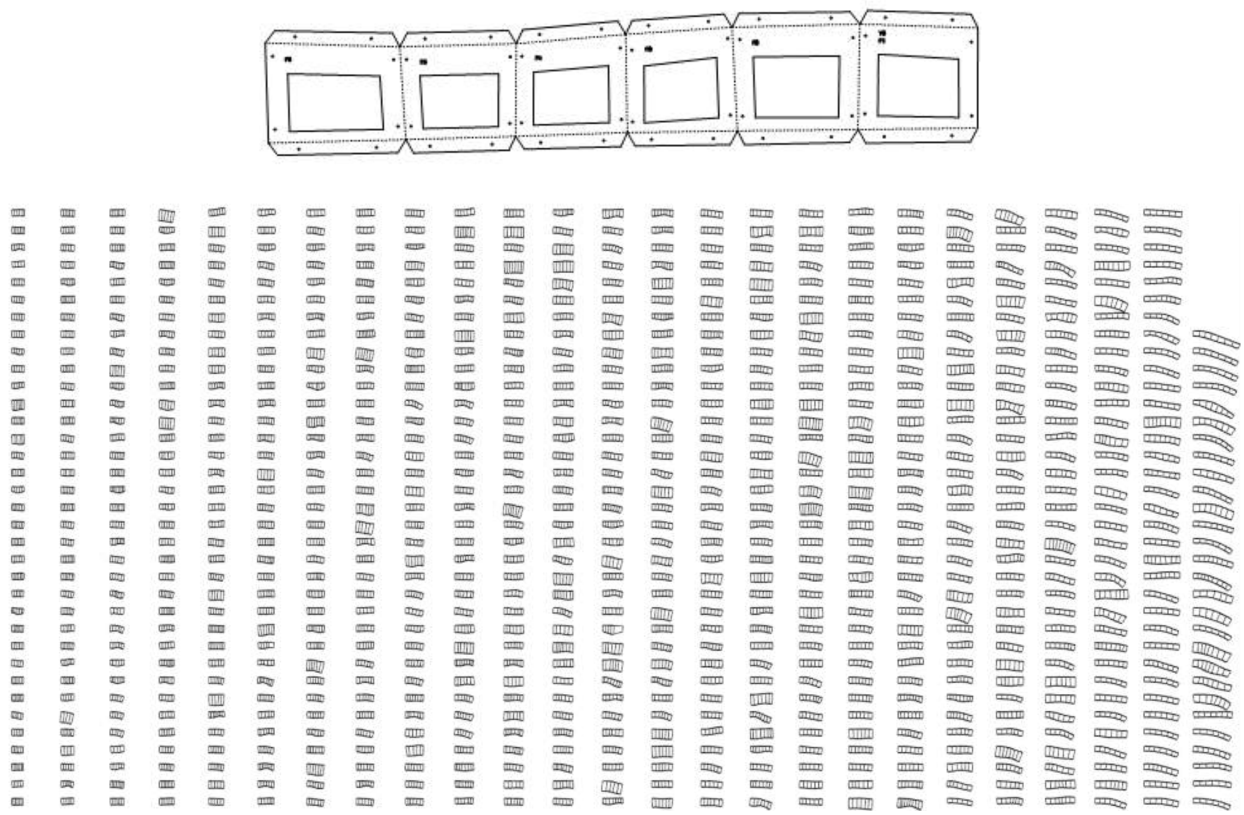


Figure 10: Unrolled cell drawings for all cells.

CONCLUSION AND FUTURE WORK

The proposal presents an implementation of digital design and parametric workflows that satisfies a number of architectural and structural requirements. Structural topological optimization is achieved through iterative revisions to the panelization of the surface. Discretization of the structure into units allows for local adaptation to design requirements such that structural analysis can be performed globally without hindering the evolution of design for various local conditions. This allows for parallel design development among the many disciplines involved, with a digital model serving as the shared reference point. The entire design process, from initial geometric outset, to structural optimization, to final engineering calculation, and ultimately fabrication document generation is controlled by a central model (Fig 11). The resulting aesthetic is achievable through other means, though the workflow and tools presented above allow for a dynamic and flexible design process.

Future study should include cycles of prototype development and testing. In particular, these studies should validate structural performance and behavior, as well as the implications of construction tolerances across a larger assemblage. Evolutions of the design to further define interior and exterior cladding will require a re-evaluation of the workflow described heretofore. In addition, physical tests should be performed on prototypes to validate FEA simulations.

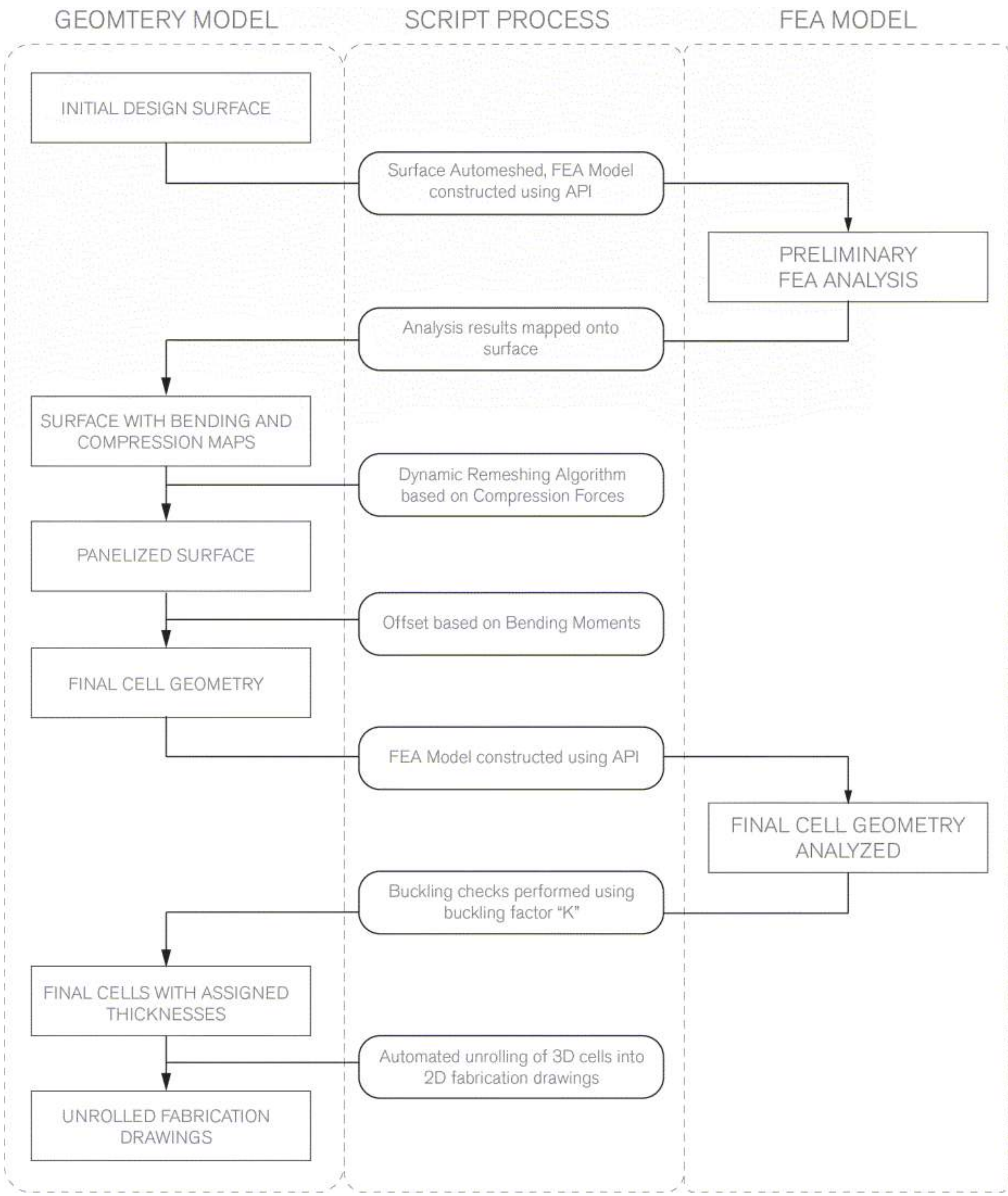


Figure 11: Flowchart of parametric process

ACKNOWLEDGMENTS

The design of the project was led by Point B Design, with consulting services provided by Front, Inc. The ambition to pursue the development of a unique structural system was motivated and nurtured by the architectural team and funded by the project owner. The processes described above relied on many tools developed in house by Front, Inc. as well as those produced by others and made available in industry forums and online, especially the generous and supportive Grasshopper community and in particular the meshing tools developed by Piker, et al. Any images not specifically credited are courtesy of the authors.

REFERENCES

American Society of Civil Engineers (ASCE). 2002. *Specification for the Design of Cold-Formed Stainless Steel Structural* Members. Virginia: American Society of Civil Engineers.

American Society of Civil Engineers (ASCE). 2005. Minimum Design Loads for Buildings and Other Structures. Virginia: American Society of Civil Engineers.

Bendsoe, M. and O. Sigmund. Topology Optimization: Theory, Methods, and Applications. Springer, 2004.

Eigensatz, M. and M. Kilian, A. Schiftner, N. Mitra, H. Pottman, M. Pauly. Paneling Architectural Freeform Surfaces. ACM. Trans. Graphics, 29/4, #45, 2010.

Pietroni, N. and D. Tonelli, E. Puppo, M. Froli, R. Scopigno, P. Cignoni, Voronoi Grid-Shell Structures, arXiv 1408.6591

Piker, Daniel. 2016. "Dynamic Remeshing – now with feature preservation, curvature adaptivity, and minimal surfaces." Accessed April 8, 2016. http://www.grasshopper3d.com/profiles/blogs/dynamic-remeshing-now-with-feature-preservation-curvature.

Piker, Daniel. 2016."meshmash – GitHub." accessed April 8, 2016. https://github.com/meshmash

McGuire, Max. 2016 "The Half-Edge Data Structure." Accessed April 8, 2016. http://www.flipcode.com/archives/The_Half-Edge_Data_Structure.shtml

Schiftner, A. and J. Balzer. Statics-Sensitive Layout of Planar Quadrilateral Meshes. Advances in Architectural Geometry Proceedings, 2010.

Schiftner, A. and M. Höbinger, J. Wallner, and H. Pottmann. Packing circles and spheres on surfaces. ACM Trans. Graphics, 28(5):#139, 1-8, 2009.

Timoshenko, S. and S. Woinowsky-Krieger. 1959. Theory of Plates and Shells. McGraw-Hill College.

Williams, C. J. K., 2001. The analytic and numerical definition of the geometry of the British Museum Great Court Roof. Adriaenssens, S. and P. Block, D. Veenendaal, C. Williams. Shell Structures For Architecture. Routledge, 2014.

CANADIAN WINDOW WALL

Design challenges and opportunities

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ABSTRACT

One of the defining characteristics of new high-rise residential apartment building design in Canada today is the thermally broken, open-back aluminum frame ‘window wall’ building envelope system. Until recently, Canadian building codes and Canadian and North American fenestration standards have not recognized window wall as a distinct cladding system. Canadian window wall systems have evolved on a largely trial and error basis. This changed earlier this year with the release of the most recent edition of the model National Building Code of Canada that includes, for the first time, a category of ‘other fenestration assemblies’ to address window wall and other glazing systems, setting out required and recommended performance and testing requirements. Work is also in progress on an installation standard under the aegis of the Canadian Standards Association. While performance requirements are being sorted out at home, Canadian window wall manufacturers are promoting their systems in the United States (USA) to compete with similar systems in that market. However, there are significant technical and aesthetic differences between Canadian and USA window wall systems that should be taken into consideration by architects, builders and developers. This paper gives a brief overview of the development of Canadian window wall, design in the context of incoming NBC 2015 requirements, assembly and installation details that could affect the design, construction and performance of the building envelope when used for residential high-rise construction in the USA.

KEYWORDS

window wall, design, installation, performance, air leakage, water leakage, rainscreen

INTRODUCTION

Canadian window wall systems have evolved over time from simple face-sealed ‘punch’ windows as an isolated element surrounded by other cladding to sophisticated building envelope systems that enclose most, if not all of the exterior of high-rise residential buildings. Canadian building codes and window performance standards have evolved more slowly, only recently recognizing window wall as a distinct form of glazing system. The recently released 2015 edition of the model National Building Code of Canada (NBC 2015) includes a category of ‘other fenestration assemblies’ including window wall and setting out specific performance and testing requirements. Work is also in progress on an installation standard under the aegis of the Canadian Standards Association. It will be some time yet until the new NBC 2015 requirements and recommendations and the as-yet to be completed CSA standard requirements are adopted by each Canadian province and are enforced by authorities having jurisdiction. In the meantime, generic building envelope performance requirements in the NBC 2015 must be relied upon, tempered by experience and sound judgment. There are significant differences compared to window wall systems that are manufactured in the USA that should be considered by architects, builders and developers. In this paper, we will discuss the development of Canadian window wall and incoming NBC 2015 requirements to set the stage for a discussion of differences in frame design, installation, structural anchorage and air leakage and water penetration control which could affect the design, construction and performance of the building envelope when used for high rise residential buildings in the USA.

THE EVOLUTION OF CANADIAN WINDOW WALL

Apartment building construction in Canada into the early 1960s was characterized by small, mid-rise buildings with modest amounts of glazing. Most windows were a single product type, such as a horizontal sliding window, or a composite window with two or more openings infilled with fixed single or double glazing and horizontal sliding sashes, set into openings in load-bearing masonry mass walls ('punch' style windows). The advent of reinforced concrete structural frame construction employing 'flying form' technology enabled a rapid increase in building height so that by the 1970s, buildings were reaching upwards. However, exterior walls were still mass masonry but as non load-bearing infill between exposed floor slabs, shear walls and columns. In the late 1970s and through the 1980s window openings were often extended to the floor slab to create vertical bands of windows from top to bottom of the building or extended horizontally to create horizontal bands of windows extending around the width of the building. Beginning in about the mid 1990s and accelerating in the 2000s, vertical and horizontal extension of punch windows merged into what is now known as window wall, with windows spanning from floor to floor, joined together at the jambs to enclose the full perimeter of the building. There is still need for opaque portions of cladding to conceal building structure, services or provide privacy to occupants so floor to ceiling window wall may include fixed and operable sash vision glazing and opaque infill of various types (Fig. 1).

Figure 1: The evolution of Canadian window wall, from punch window (left) to the entire building envelope (right). All Photographs © Morrison Hershfield, 2106.

Interesting features in the evolution of Canadian window technology were the early adoption of open-back, extruded aluminum frames with integral brick mould, thermal breaks and factory installed glazing. Masonry mass walls for apartment buildings, both load-bearing and non load-bearing, were typically two-wythe construction of face brick and concrete masonry units (CMUs) behind with a joint (collar joint) between. The brick mould was used to conceal the collar joint around the perimeter of the window opening. Thermal breaks were at first extruded poly vinyl chloride (PVC) at about mid-depth of the frame interlocked tongue-and-groove style with the aluminum extrusions to the interior and exterior. In the 1980s roll-crimp clamping of aluminum extrusions to the thermal break was introduced which created a rigid composite construction for greater structural strength. This coincided with the increasing use of floor-to-ceiling windows and a general change in masonry wall construction in which the outer wythe of masonry was moved off the floor slab to be supported by shelf angles with the inner wythe moved forward to align with the slab edge. Windows were similarly displaced outwards so that only the inner half of the frame rested directly on the floor slab. Slabs were concealed with masonry cladding at first and later with insulated, prefinished sheet metal covers. In the 1990s, the sheet metal slab cover was replaced by extending the aluminum extrusions outboard of the thermal breaks on the jambs and sill to the bottom of the floor slab, above the head rail of the floor-to-ceiling window below. This 'slab by-pass' has become a defining feature of modern Canadian window wall systems (Fig. 2).

Figure 2: Canadian window wall system during installation. Left, story high panels have been installed with the other half of the frame extended to cover the floor slab. Centre, view from above showing projection of window frame beyond the slab edge with self-adhesive membrane and metal flashings to shed water. Right, slab by-pass at a balcony curb showing how 'split frame' approach with aluminum extrusions at jambs outboard of the thermal break are extended downward to allow the spandrel panel to cover the curb face, concealing it from view. All Photographs © Morrison Hershfield, 2106.

NATIONAL BUILDING CODE OF CANADA 2015 REQUIREMENTS

Canadian window performance standards have evolved over the years, merging with US standards in 2008 as AAMA/WDMA/CSA 101/I.S.2/A440-08, *NAFS – North American Fenestration Standard/Specification for Windows, Doors, and Skylights* (NAFS-08). Canadian windows standards prior to NAFS addressed only 'punch' style windows, ignoring floor-to-ceiling windows and later window walls. NAFS-08 and the updated version NAFS-11 also do not include a window wall product type. As a result, the evolution from 'punch' windows to window wall has fallen into a grey zone between window standards that do not acknowledge the type and generic principles for all types of building envelope systems included in building codes. This changed earlier this year with the release of the model NBC 2015 which for the first time defines 'other fenestration assemblies' including window wall and sets out specific performance and testing requirements and recommendations.

In Appendix A of the NBC 2015, window wall is defined as follows:

> *A window wall is considered to be a wall cladding fenestration assembly that spans from the top of a primary floor structure to the underside of the next higher primary floor structure. Window wall assemblies do not support vertical load other than their own weight. Primary provision for anchorage occurs at head and sill conditions to the adjoining floor structure. Window wall assemblies may include separate or integral floor edge covers.*

The last sentence of the definition allows for older floor-to-ceiling window systems with insulated sheet metal slab edge covers as well as modern window walls with slab by-pass style.

NBC 2015 performance and testing requirements for 'other fenestration systems' are set out in Division B, Part 5 *Environmental Separation*, Subsection 5.9.3. These requirements are described following with commentary, to provide to potential users of such systems in the USA some insight regarding current design capabilities of Canadian window wall systems and how designs may change in the next few years as the NBC 2015 is adopted or adapted across Canada.

- Structural and Environmental Loads, Article 5.9.3.2.: no specific requirements are included for structural design. Instead, reference is made to Article 5.1.4.1 which sets out generic requirements for all building envelope materials, components and assemblies. However, in the non-mandatory Appendix A for Article 5.9.3.2, ASTM E330 is identified as the 'applicable' test method. That is the same test method required by previous Canadian window standards and currently by NAFS for 'punch' windows, doors and skylights. Canadian window wall manufacturers should be able to furnish test reports to this standard. Appendix A also identifies AAMA 501 *Methods of Tests for Exterior Walls,* AAMA 501.4 *Recommended Static Testing Method for Evaluating Curtain Wall and Storefront Systems Subjected to Wind Induced Interstory Drift* and AAMA 501.6 *Recommended Dynamic Test Method for Determining the Seismic Drift Causing Glass Fallout from a Wall System* as other test methods that can be used to assess structural performance. Currently, many Canadian window wall systems are not tested to these AAMA standards.

- Heat Transfer, Article 5.9.3.3: reference is made to Section 5.3. which sets out generic requirements for heat transfer for all building envelope materials, components and assemblies (Sentence 5.9.3.3.(1)) Metal-framed fenestration assemblies are also required to incorporate a thermal break to minimize condensation (Sentence 5.9.3.3.(2)). The accompanying discussion in Appendix A recommends compliance to National Standard of Canada CSA-A440.2, *Fenestration Energy Performance* which in turn references procedures developed by the National Fenestration Rating Council (NFRC) for simulation or physical testing to determine U-factor (NFRC 100 *Procedure for Determining Fenestration U-Factors* and NFRC 200 *Procedure for Determining Fenestration Product Solar Heat Gain Coefficient and Visible Transmittance at Normal Incidence*, respectively). Two physical test methods are identified for assessing condensation resistance: the 'Temperature Index' method in CSA-A440.2 or measuring room-side surface temperatures during one of the cold cycles of AAMA 501.5 *Test Method for Thermal Cycling of Exterior Walls*. The 'Temperature Index' method is unique to the Canadian window industry with fixed indoor ambient air temperature of +20 +/- 1°C (68 +/- 2°F, approximately) and an outdoor ambient air temperature of -30 +/- 1°C (-22 +/- 2°F, approximately). Results are not directly comparable to methods for measuring condensation resistance in the USA, such as NFRC 500 *Procedure for Determining Fenestration Product Condensation Resistance Values*. Therefore, results for condensation tests for Canadian window wall systems should be reviewed carefully to ensure they are applicable for projects in the USA.

- Air Leakage, Article 5.9.3.4: reference is made to Section 5.4. for generic requirements that apply to all building envelope materials, components and assemblies (Sentence 5.9.3.4.(1). A specific requirement is made for testing to ASTM E 283 *Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen* with specified maximum allowable air leakage rates (Sentence 5.9.3.4.(2)). For fixed glazed and opaque portions the maximum allowable air leakage rate is 0.2 l/s/m^2 (0.039 cfm/ft^2) at a pressure difference of 75 Pa (1.57 psf) which is consistent with requirements in the Canadian Supplement to NAFS (CSA-A440S1 *Canadian Supplement to AAMA/WDMA/CSA 101/I.S.2/A440, NAFS — North American Fenestration Standard/Specification for windows, doors, and skylights*) for fixed windows but more restrictive than the performance levels used in the USA (1.5 l/s/m^2 (0.30 cfm/ft^2)), for R, LC and CW performance classes). The NBC 2015 performance level is also less than the maximum recommended in AAMA 501 (0.30 l/s.m^2 at 75 Pa (0.06 cfm/ft^2) at 1.57 psf)). For operable portions the maximum allowable air leakage rate is 1.5 l/s/m^2 (0.30 cfm/ft^2) at 75 Pa (1.57 psf) which is the same as required in Canada and the USA under NAFS for R, LC and CW performance classes. There is no requirement in the NBC 2015 for testing at a 300 Pa (6.27 psf) air pressure differential as required by NAFS for the AW performance class or under AAMA 501 in buildings in which greater control of indoor air quality and/or humidity is required. However, the authors are aware of Canadian window wall manufacturers who test their products to such levels. Care should be taken by USA designers, builders and developers to ensure that a Canadian window wall under consideration has been tested to suitable performance levels for air leakage control.

- Water Penetration, Article 5.9.3.5: reference is made to Section 5.6. for generic requirements applicable to all envelope systems of buildings. Lab testing is also required to ASTM E 331 *Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference* as in the USA for fenestration systems, or to ASTM E 547 *Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Difference* which is required in Canada for 'punch' window systems. Regardless of the test method, the test pressure is determined in accordance with CSA-A440S1, the Canadian Supplement to NAFS, using the Driving Rain Wind Pressure (DRWP). Water penetration resistance of windows in Canada is not based on a fraction of the wind load (Design Pressure) as in the USA but instead on wind pressures measured during rainfall at specific locations across Canada (typically airports), for a 1/10 return period probability, modified for terrain condition (open or rough) and building height. This can result in the test pressure for water penetration resistance being lower or higher than required by NAFS for locations in the USA. Consequently, water penetration test performance levels need to be checked carefully for systems imported to the USA. The authors have worked with Canadian window wall manufacturers who have tested systems similar to curtain wall systems, to AAMA 501 at 300 Pa and 600 Pa (6.24 psf and 720 psf) pressure differentials so such systems are available.

- Appendix A also identifies AAMA 501.1 *Standard Test Method for Water Penetration of Windows, Curtain Walls and Doors Using Dynamic Pressure* as a test method that can be used to evaluate the performance of 'other fenestration assemblies'. The reference to AAMA 501.1 is significant because it recognizes that Canadian window walls systems are similar in some respects to unitized curtain wall systems, often installed at similar building heights (50 stories or more) and therefore, subjected to dynamic wind forces. Typically, in the past Canadian window walls were tested to static cyclic pressure differentials only (ASTM E 331 and E 547) which may not adequately duplicate service conditions when installed on very tall buildings. The authors have worked with several manufacturers of Canadian window wall systems who have tested to AAMA 501.1.

These new requirements and recommendations in the NBC 2015 will be used as a basis to highlight some critical differences between current Canadian and USA window wall assembly and installation details. The differences described following should be taken into account when considering importing a Canadian window wall system for a residential high-rise apartment building construction in the USA.

STRUCTURE AND ANCHORAGE

Attachment methods for Canadian window wall systems evolved from methods originally used for ‘punch’ windows set into two-wythe face brick on concrete block mass walls. In mass walls, windows were often secured with mounting flanges around the perimeter of the frame let into the collar joint between the face brick and back up concrete block. Where windows were set against concrete structural floor slabs, strap anchors were used to secure the window head to the underside of the slabs. Mounting flanges have long since disappeared (as have the surrounding brick on block mass walls) but strap anchors continue to be used by some manufacturers to secure floor-to-ceiling window wall panels to the concrete structure, precast concrete panel cladding or wind load bearing steel stud frame. Strap anchors generally consist of aluminum flat stock cut into narrow strips and screw fastened to the window head or extruded aluminum strips formed with a T-head to interlock into a formed race in the frame. Strap anchors were originally anchored to the concrete structure and the inner wythe of concrete block masonry with powder actuated fasteners and later, with pre-drilled concrete screws. In more recent buildings with wind-bearing steel stud framed walls behind the cladding, self-drilling, self-tapping screws or pre-drilled tapping screws would be used to fasten strap anchors to the stud frame or to wood buck liners on the steel frame.

Strap anchors are still favoured by many Canadian window wall manufacturers because of their flexibility, allowing installers to adjust to site conditions rapidly by bending the strap to suit variations in head to floor slab gap or easily repositioning the strap (if secured via interlock into the head rail) if fastener installation be frustrated by hard aggregate or embedded reinforcing steel or some other conflict. The length of strap anchors is usually kept short to minimize interference with interior finishes. These benefits can also be a liability. Strap anchors may not be long enough to extend across larger than expected window head to slab gaps. Installers sometimes stitch together two or more straps to reach the slab, providing dubious structural attachment and interfering with interior finishes. Repositioning straps to where frame to structure gaps are narrower or to avoid some type of interference may compromise needed anchorage for the window wall frame to resist lateral loads (wind, soft body impact/guard loads, etc.). Forethought is required to avoid conflict and adapt to construction tolerance errors (Fig. 3).

Figure 3: Examples of strap anchors at the head rail of a window wall. Left, straps secured with concrete screws to the underside of the floor slab with one component polyurethane foam air sealant foam in the rough opening gap as an air seal. Right, rough opening gap exceeds the length of the strap so straps are extended by stitching end-to-end. A gunned sealant was applied over the foam to ensure continuity of the air barrier. Encapsulating the perimeter of the straps may needed if access behind the strap for sealant application is restricted.

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Strap anchors at the head have flexibility for vertical movement but little for lateral movement, such as might be caused by seismic activity. In seismically active regions, some manufacturers have adopted USA style head receivers and in some cases, jamb receivers also. Receivers may also have benefits in allowing easier relocation of fasteners from design locations to avoid hard aggregate, embedded reinforcing steel, damaged concrete, etc. The use of head and jamb receivers is not universal and should not be assumed to be provided.

At the floor slab, it has become common to secure window wall systems with a continuous extruded aluminum angle (back angle) along the room-side face of the window panels, fastened to the sill rails and bottoms of mullions with self-drilling, self-tapping screws and to the floor slab with concrete screws. Such connections are rigid. Movement capability for interstory drift and seismic activity can occur only at the head and jambs. Extruded aluminum sub frames/sill pans for structural anchorage and air and water leakage control, typical in USA window wall systems, are not common in Canadian window wall systems. The continuous back angle provides similar functions but is not as robust, and typically is not shimmed to adjust for slab irregularities and variations in floor to floor height. Variations in floor-to-floor height thus is typically accommodated at the head only which may lead to the problems with strap anchors being too sort, as discussed. Floor to floor variations can also affect the overlap of head expanders on the window wall panel head so just as with strap anchors but it is easier to correct by shimming down the head receiver.

Window wall panels are often manufactured in widths similar to unitized curtain wall panels, 1220 to 1524 mm (48 – 60 in.) wide, typically the width of one fixed-glazed insulating glass unit or operable window. Panel width is limited by rail strength to support the dead load of insulating glass units within allowable deflection amounts, overall panel weight that can moved manually and by hoist, overall panel size that can be accommodated by shipping services, etc. Adjacent panels are joined together by some form of mechanical interlock between the jamb mullions. Methods vary by manufacturer. Common approaches are to nest the open-back mullions with one mullion being slightly deeper than the mating mullion on the adjacent panel, and using connector plates H-shaped in cross-section (H-bar connectors) that slip over the exterior and interior faces of the open back mullions, tongue and groove style. These joining methods typically increase the depth of the mullions beyond the exterior and interior faces of the rails which can cause some difficulties when installing air and water seals and head and sill, as will be described later.

Where window walls pass in front of columns and shear walls there may be conflicts with the installation of strap anchors, head receivers and back angles. It may be possible to offset strap anchors laterally but head receivers and back angles must be continuous not only for structural anchorage but also to maintain air and water tightness of the wall/window interface. Columns and shear walls should be recessed behind the slab edge sufficiently for the anticipated width of the anchor system plus working room to install fasteners and also for air and water leakage control membranes, sealants, etc. This requires careful forethought during architectural and structural design. Unfortunately, the window wall manufacturer may not be selected early enough in the construction process to provide necessary design input so modifications may need to be made on site. Any modifications affecting the structure of wall panels should be reviewed and approved by a licensed design professional (Fig. 4).

Figure 4: Examples of interference/lack of coordination between structure, mechanical services and window wall systems.

Left and centre: column not recessed to allow the window wall frame to pass in front. The installer's solution was to cut away horizontal components including rails, and head receiver.

Right: kitchen and bathroom exhaust duct bulkhead installed before head rail/underside of floor slab joint air seal was complete (compare to Fig. 3, right).

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As noted, a defining feature of Canadian window wall is the slab by-pass. Typically, the sill extrusion inboard of the thermal break is anchored to the upper surface of the slab with a continuous back angle and mullion extrusions and sill extrusion outboard of the thermal break are extended down to the head rail of the window panel below, concealing the slab edge. In early window wall systems the by-pass was face sealed with composite panels consisting of metal skins sandwiching a rigid extruded or expanded polystyrene core glazed into the frame from the exterior. Such systems often had poor water leakage resistance. Today, most Canadian window wall systems employ rainscreen design principles, including at the by-pass. The spandrel infill is a cladding that needs to resist gust wind loads. Air leakage and water penetration control are provided by waterproofing membranes and sealants behind. These functions will be discussed in more detail later (Fig. 5).

Figure 5: Examples of continuous sill angle with self-adhesive membrane waterproofing at exterior.
Left, continuous angle installed at the edge of the floor slab. Right: membrane installed at a curb at a balcony with the self-adhesive membrane overlapping the thermofusible waterproofing membrane for the balcony. All Photographs © Morrison Hershfield, 2106.

AIR LEAKAGE AND WATER PENETRATION CONTROL

As surrounding wall systems have changed from mass masonry construction to rain screen systems, window design and assembly and installation detailing has also changed. Today, most Canadian window wall systems are designed and installed according to the rainscreen principle. This consists of designing the systems so that exterior surfaces and sealants present a deterrent to precipitation ingress with barrier air and water seals located inboard, protected from direct wetting, gust wind pressure, solar radiation, etc. which should ensure long service life. The interstitial space between the exterior surfaces and sealants and internal seals is typically vented to moderate wind pressures on the internal air seals and drained to remove moisture that may penetrate back to the exterior.

Generally, window wall panels are factory prefabricated including infill glazing, vents and spandrel panels. On-site fabrication is limited to connection details such as inside and outside corners and junctions to adjacent enclosure systems. Frame openings are individually sealed, drained and vented to the exterior. Cascading, internal drainage to a sub frame/sill pan that is wept to the exterior, as is common in the USA, is unusual in Canadian window wall systems. However, allowance for leakage through frame joinery and through interface joints between window wall systems and adjacent wall systems is provided at the sill. The interface joints are typically waterproofed with gunned, liquid-applied sealants (caulking, bead-applied polyurethane foam) and membranes (self-adhesive, field-applied adhesive and/or thermofusible). Window wall systems used on the Canadian west coast and bound for the USA are likely to incorporate head receivers and sometimes jamb receivers instead of gunned sealants and membranes.

Insulating glass units are typically laid-in glazed from the building interior side of the frame. Rain screen design at the perimeter of insulating glass units is accomplished with gunned, liquid applied sealants and/or preformed elastomeric rubber gaskets around the full perimeter of each unit to the surrounding frame mullions and rails. Each frame opening in a window wall assembly (both vision and opaque areas) is usually wept directly to the outside through openings in the horizontal rails below, similar to a rainscreen designed curtain wall. Opaque areas (spandrel panels) are constructed similar to Canadian style rainscreen curtain walls with a sheet metal back pan sealed to the surrounding mullions and rails, with insulation mechanically secured to the outside face of the back pan, and with a cladding at the exterior glazed into the surrounding frame. The interstitial space is drained and vented to the exterior.

Strap anchors projecting beyond the interior, building interior face of window wall systems breach the interior seal at head and often, at jambs also. To maintain air leakage and water penetration control, each strap must be carefully encapsulated which is tedious, time consuming and expensive work. It is difficult to apply sealants to the edge of open back frames because the frame edge is narrow, providing little bond area for the sealant to the frame. A more robust fillet bead application to the room-side face of the frame provides more certainty of adhesion and long-term performance. However, such sealant application may interfere with interior finishes (refer to Fig. 3). An alternative is to use a head receiver with preformed elastomeric rubber seals to the frame head to permit interstory drift and seismic movements and gunned, liquid-applied sealants for the static connection between the head receiver and the structure. Head receivers are available from most manufacturers serving the Canadian west coast markets. Some manufacturers can also supply jamb receivers.

At the sill, air and water leakage control is typically provided by application of a membrane over the edge of the floor slab behind the slab by-pass, extending from a head flashing or head receiver above the panel on the floor below to the vertical upturn leg of the continuous back angle used to anchor the sill. The membrane upturn is sealed to the window wall sill rail with gunned, liquid-applied sealant. The quality of the back angle membrane/window wall sill rail seal can be affected by the joining method between adjacent window wall panels. As described previously, nested mullions or H-bar connected mullions are deeper than the rails. When the mullions are set against the back angle, gaps are created between the upturned membrane on the back angle and the rails. The gaps must be filled with sealant. A common installation technique is to apply sealant to the membrane upturn prior to moving the panels in place, relying on squeezing of the sealant to fill the joint. This ‘smash glazing’ approach may not completely fill the gaps. A similar problem occurs at the head when head receivers are used. Preformed elastomeric rubber gaskets typically provided between the receiver and the window wall panels must be sufficient flexibility to seal the narrow gaps at mullions and the wider gaps at rails. Installation techniques should be reviewed carefully during construction and the method adjusted if inadequate sealing is detected (Fig. 6).

Figure 6: Careful thought in 3D is required to ensure continuing of air and water leakage control.
Left, a head receiver butts against a self-adhesive air barrier and WRB returned into the rough opening from an adjacent envelope enclosure system. A gunned sealant was applied to ensure continuity. Right: at another junction condition, the continuous sill angle and self-adhesive waterproofing membrane are extended past the jamb mullion into the adjacent wall assembly. Continuity between envelope systems was not adequately considered during design and construction. All Photographs © Morrison Hershfield, 2106.

A weakness of using different methods to seal the interface joints between window wall perimeter and adjacent wall systems at sill, jamb and head is ensuring continuity at junctions. Architectural and window wall manufacturer shop drawing details are almost exclusively two dimensional so junctions between different sealant systems must be discerned through careful study. If not addressed in the drawing review stage the installer is left to figure out a solution on site. The knowledge, experience and skill of the installer greatly affect the quality of the solution which can range from simply applying more gunned sealant to bridge or fill gaps to well thought out and installed flexible membranes, brake-shaped aluminum closures, etc. In this regard the common approach in the USA of using head and jamb receivers and a sub frame or sill pan at the sill, designed as a system with similar components, is superior to the Canadian approach.(Fig. 7).

Figure 7: Careful thought in 3D is required to ensure continuing of air and water leakage control.

Left, a head receiver butts against a self-adhesive air barrier and WRB returned into the rough opening from an adjacent envelope enclosure system. A gunned sealant was applied to ensure continuity. Right: at another junction condition, the continuous sill angle and self-adhesive waterproofing membrane are extended past the jamb mullion into the adjacent wall assembly. Continuity between envelope systems was not adequately considered during design and construction. All Photographs © Morrison Hershfield, 2106.

To be fair, it should be noted that the success of window wall systems in the USA also rely to a great extent on gunned, liquid applied sealants to prevent air and water leakage. Both families of window wall systems need good design and diligent shop and site personnel to correctly assemble and install frames and infill. A good QA/QC program should identify issues of concern in the shop and on site to ensure successful performance of the window wall and the building envelope as a whole.

CONCLUSION

This paper attempts to outline the distinctive characteristics of Canadian window wall systems to an audience outside of Canada, and primarily from the USA, some of whom may be considering the use of imported Canadian window wall systems. Within the limited space available in this paper we have provided a historical overview of the development of Canadian window wall and incoming model National Building Code of Canada requirements to set the stage for a discussion of key aspects of design, construction and installation detailing. There are significant differences from USA window wall systems which need to be considered. Despite the identified issues, with careful architectural, structural and manufacturer design and drawing review, careful factory prefabrication and site installation, Canadian window wall systems can provide cost effective and durable enclosures for high-rise residential apartment buildings in Canada and in the USA.

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REFERENCES

Kesik, Ted and Saleff, Ivan, *Tower Renewal Guidelines for the Comprehensive Retrofit of Multi-Unit Residential Buildings in Cold Climates*, University of Toronto, 2009.

Hoffman, Stéphane P., *Adaptation of Rain-Screen Principles to Window-Wall Design,* Thermal Performance of the Exterior Envelopes of Whole Buildings VIII, 2001.

PRECISION ON THE JOBSITE

Tight tolerance features in a low tolerance world

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ABSTRACT

Over the last 2 decades huge advances have been made in digital design tools and processes. Architects, engineers and façade designers are now able to incorporate an unprecedented amount of data in the digital drawing database. There are many well documented and high profile examples of the design and fabrication of geometrically complex building skins and the transmission of that complex 3D geometry from the envelope CAD model to the shop floor. The focus of this paper is the technical and commercial challenge of adding high precision and close tolerance features into buildings that are more conventional in nature. This paper identifies the successful use of technologies not normally associated with building construction and the impediments to integrating high precision features into the built environment in 2016.

The use of high precision tools, machinery, and measuring technologies is the norm in most manufacturing environments (automotive, aerospace, consumer products etc). The fabricators of unitized curtain wall systems have been proactive in utilizing the highest levels of automation and precision technology in their manufacturing plants. However, the implementation of these technologies has been much slower in the broader construction marketplace. We have identified several highly successful uses of innovative technology to create unique features for buildings in stone, metal, wood, composites, and glass. The processes used include robotic 3D cutting and polishing, 5-axis machine tool cutting, and automated composite layup systems. Features such as 100' wood and steel roof trusses, 52' tall-fabricated stainless steel box mullions, and 3D machined stone features can be manufactured to tolerance of less than +/- 1mm.

The discussion addresses what can be done to integrate high precision features into low precision site conditions and what can be done in the future to bring a higher degree of precision onto the jobsite.

KEYWORDS

Curtainwall, digital fabrication, fabrication assembly, fabrication installation, BIM, future trends, erection standards

INTRODUCTION

The interface between the building envelope and the building's core structure is an unheralded key to the commercial and technical success of many curtain wall and façade installations. In 2016 the vast majority of glazing systems and specialty architectural features are designed using state of the art design software. They are highly engineered and precisely detailed. Many are manufactured to tolerances in the +/- 1 to 2mm range. Likewise, structural steel and concrete forming systems are increasingly designed and manufactured with machinery that is capable of very close tolerances. And yet, all building professionals are agonizingly familiar with situations like that shown in Figure 1. While this image depicts what is clearly an error in the field, it is an oversimplification to write this off as simply "a field mistake". This is a symptom of a larger issue. The march towards higher precision design and shop manufacturing tools has not been matched with a concurrent increase in either the expectation for close tolerance work on the jobsite nor the development of tools and systems to facilitate the aforementioned. Until there is movement towards a systematic improvement in erection, concrete casting, and the associated site work, the construction community will not realize the full benefit of the digital era. In this paper the author will give an historical prospective, a synopsis of the currently relevant guidelines, examples of high precision specialty work, and a look towards how and why this gap in technology might be remediated.

Figure 27: This 4x4TS was meant to be cast in the location that was later core drilled. (photo courtesy of W&W Glass, LLC.)

PROBLEM STATEMENT

In general, the precision of the building core is not given any more attention today than it was 50 years ago. Many building owners view this as a means and methods issue until delays set in and the finger pointing starts. From the design team's perspective, in an environment of reduced fees, shorter duration design cycles, and increased emphasis on design-build, this area does not receive heavy emphasis. And yet, there are an unfortunate number of jobs that suffer from the following issues:

A) the core structure is built outside of the agreed upon tolerances (this is often not discovered until well after any effective mitigation is out of the question)

B) the core structure is ultimately found to be within specifications that the owner agreed to, but that spec was not well enough understood by the skin detailers. In some cases, the detailing of the skin system does not provide enough clearance for the core structure. In non-standard buildings, there are conditions that require very large clearances to accommodate the allowed tolerance build up. Even in very ordinary buildings, there are things like composite beams, fireproofing and other interface items that do not have clearly defined erected tolerance limits.

C) the skin detailer designs the skin system from incomplete and/or inconsistent geometric data.

The last item on this list has had the attention of software developers, designers, builders, and owners for quite some time. Owners are increasingly demanding comprehensive BIM modeling. The advent of collaborative design platforms has the promise of helping to alleviate the dissemination of incorrect design data to subcontractors. All parties recognize that avoiding the expense of subcontractors designing with incomplete or inconsistent data is worth a large investment.

The ultimate costs involved in any combination of the 3 problem modes listed above can be very large.   These costs are not solely born by the “guilty” party. No matter the contractual terms and obligations, there are no winners with back charges, liquidated damages, and notices of delay. In many cases, there are enough mitigating factors that finding root causes is impossible. These problem jobs may go to arbitration and/or litigation. Surely, this is good for the lawyers- but few others. Even when these issues are settled amicably, a late building turn over costs the owner in operational proceeds and extended time on the jobsite costs contractors and subcontractors.

Items A & B on the list above have not received anything like the attention that building modeling has.   The reduction of these issues requires solutions that go well beyond static building models. Three steps that would improve this situation are:

- In the design/modeling phase it should be possible and would be hugely beneficial if tolerance mapping were integrated into some form of the BIM. This is a very complex task as it involves a number of variables and a good deal of judgment. In addition, there are legal and contractual issues involved in who is ultimately responsible for both setting these bands and insuring that the work complies with the agreed upon standards.
- A realistic look at “standard” construction tolerances. Given the use of digital design and manufacturing tools for building steel and concrete formwork, how is it that the erection tolerances set in the 1950’s are still “best practices”?
- Real time confirmation that the ongoing work is in geometric compliance. As will be discussed below, there are a myriad of highly accurate measuring technologies available. However, a methodical and comprehensive implementation of them is elusive on most jobsites. This is not simply a matter of measuring what has been done. Indeed, more beneficial than after the fact measuring would be real time availability of digital grid lines, a rich array of comprehensive datum on every floor and a digital database that understands where every datum is w/r/t the theoretical gridlines.

The inclusion of high precision and/or geometrically complex objects is no longer seen exclusively in landmark buildings. Figures 2,3, 4, 5 & 6 illustrate specialty elements being integrated into buildings with core structure built to standard tolerances. In each case, special accommodations had to be made to deal with the large tolerances of the core.

Figure 28 The Renzo Piano Building Workshop addition to the Kimbell Art Museum on Fort Worth, TX. The roof beams are 32M wood and metal composite Glulam beams. (photo by author)

Figure 29. Factory production of the roof beams for the Kimbell Museum. The white painted pedestals were set on high precision bridge bearings. These bearings are in turn set on mounting pads that accommodated the location tolerances of the reinforced concrete walls. The beams were profiled and pocketed on a CNC router. (Photo by author)

Figure 30. 31M long steel trusses provide the wind load support for the lobby at 601 Massachusetts Avenue in Washington DC. The steel trusses were machined after fabrication to insure the dimensional accuracy of the glass attachment points and the pin to pin length of the truss itself. (photo courtesy of W&W Glass)

Figure 31. The precision of the steel trusses at 601 Mass Ave in Washington provided both the dimensional accuracy needed to properly capture the glass lites and a level of fit and finish that is not otherwise achievable. In 4 of the 18 building connection locations custom mounting brackets had to be fashioned to accommodate steel outside of the agreed upon tolerance band. (photo by the author)

Figure 32.: This composite steel and carbon fiber roof is being fitted on all glass walls at the new Apple Headquarters in Cupertino, CA. The composite roof is fitted to the glass with very little room for error. The entire construction is fitted onto the roof of a reinforced concrete building. (photo courtesy of Apple/Digital Trends)

CONSTRUCTION TOLERANCES AND ERECTION STANDARDS

For steel framed buildings the fabrication and erection tolerances acceptable for beams and columns is established in the AISC "Code of Standard Practice for Steel Buildings and Bridges". (AISC 303-05). For cast in place reinforced concrete construction the governing standards are found in Section 2.4.1 of the American Concrete Institute "Specifications for Tolerance In concrete Construction and Materials" (ACI 117-10). At present, there are no governing standards for buildings of composite construction (AAMA Curtain Wall Manual).

Quoting from the current steel standards (AISC 303-15-7.13 (commentary)- 2010), "The erection tolerances defined in this Section have been developed through long-standing usage as practical criteria for the erection of Structural Steel. …. AISC adopted new standards for erection tolerances in Section 7(h) of the March 15,1959 edition of this code. Experience has proven that those tolerances can be economically obtained." The currently applicable steel erection standards were adopted 57 years ago. As a point of reference, the original World Trade center was designed when the 1959 edition of the code was current. (see Figure 7). This code of practice is still the starting point for all discussions about the acceptable tolerance of erected steel.   In 2000 the AISC added the AESS standards for the specification of tighter tolerances for exposed structural steel. To date the steel industry has been reluctant to allow these reduced tolerances to be implemented on a broader basis and without a significant price premium. The steel erection standards were developed by combining the allowable geometric tolerances of the mill steel sections, cost effective fabrication tolerances for the component pieces, and allowance for temperature changes during the erection process.

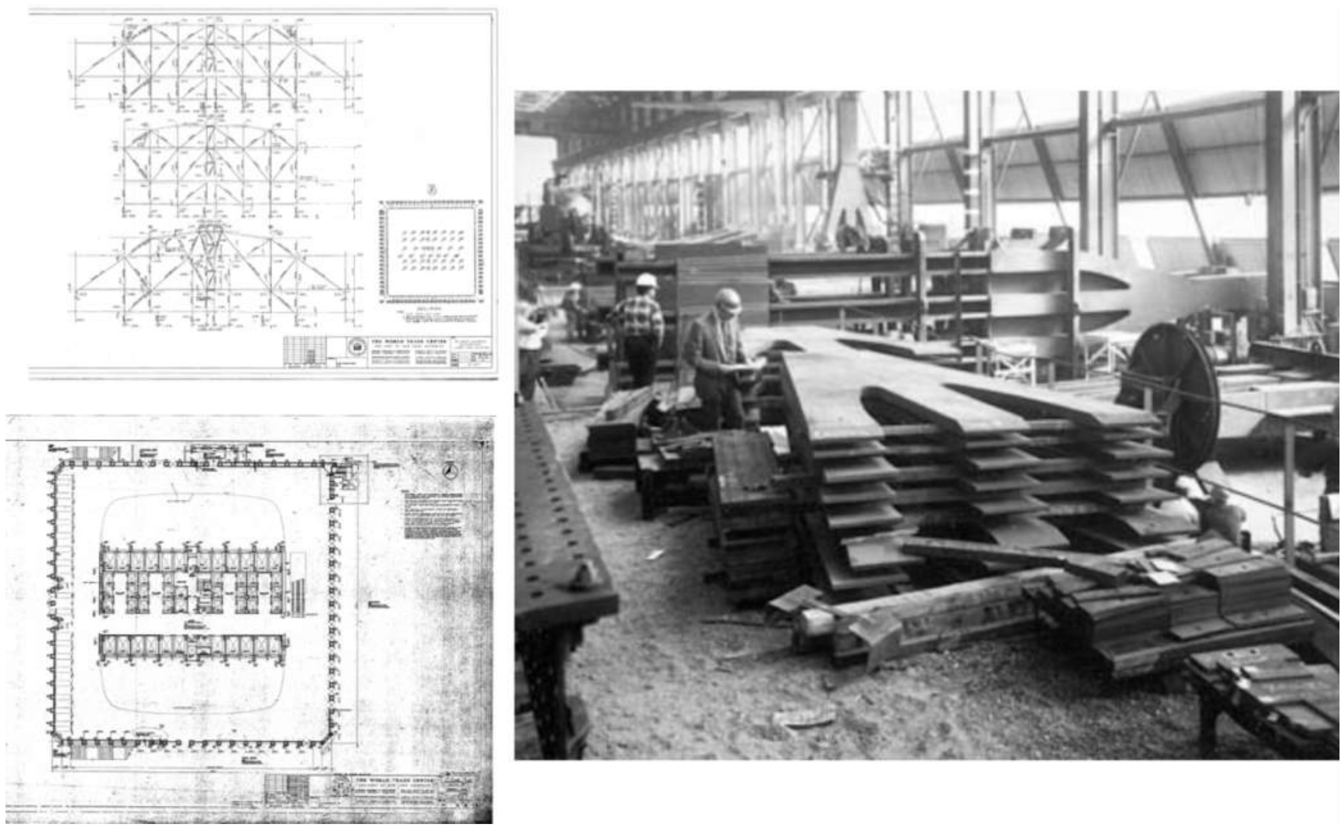

Figure 33: The current AISC erection standards were adopted in 1959. These images of the World Trade center drawings and fabrication facilities are circa 1967.   (drawing scans courtesy of 911research.wtc7.net , fabrication at the Pittsburgh-Des Moines Steel Company, image courtesy of lukenshistoricdistrict.org)

Much like the steel standards, the concrete standards define acceptable tolerances for slab edge locations, column locations, and elevations. They too have failed to take into account the major advances in the design and fabrication of formwork. As an example, all of the forms for the kinked column shown in Figure 8 were detailed in the context of the 3D model.   The cross sectional shape of the column was geometrically better than promised by the subcontractor. There were issues with the placement and rotation of the columns in the space that seem to have been a function of the setout of the column bases with respect to the building gridlines. In concrete construction there is less clarity as to what standards govern the location of imbeds, boxouts etc. Fig 9 illustrates this situation for the cable anchorages on that same conoid wall shown with the kinked columns in figure 8. You will note in figure 9 that none of the embeds are placed within the agreed upon tolerances.

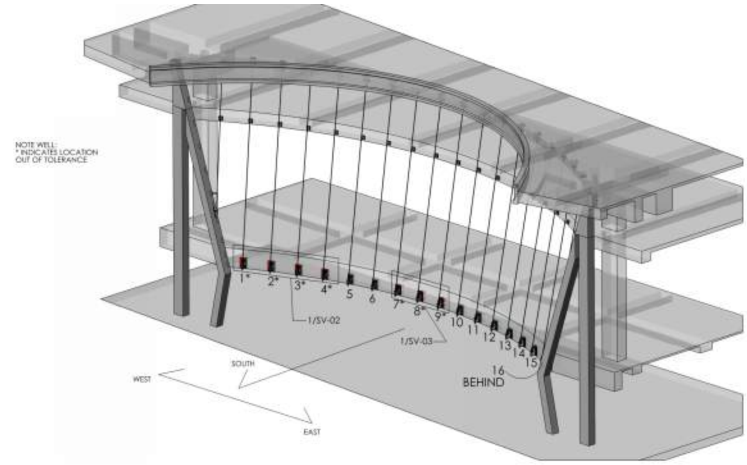

Figure 8: The kinked columns on this conoid wall are cast-in-place reinforced concrete. The cross section was extremely close to the design dimensions.

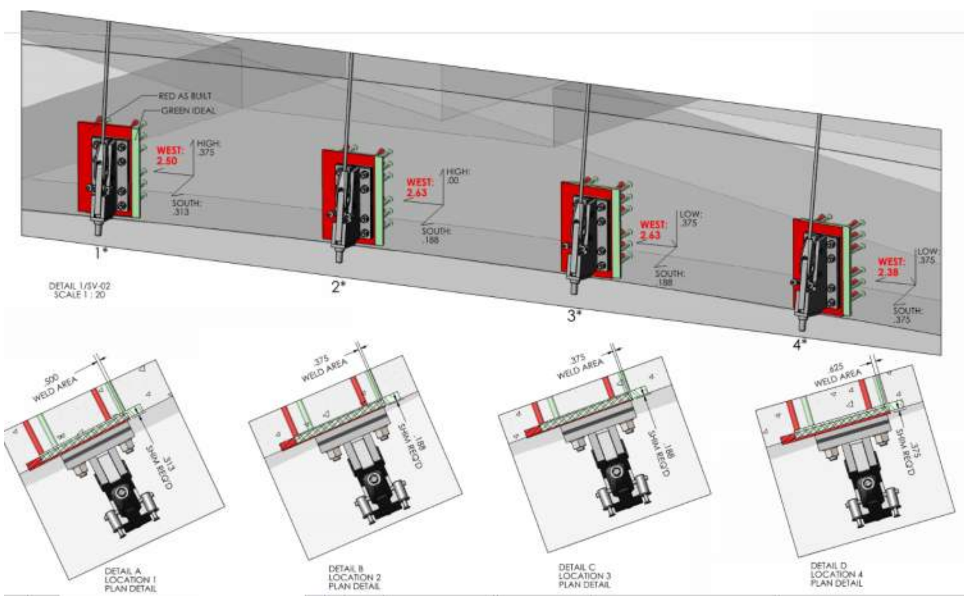

Figure9: These are the cable base anchorages on the same conoid wall. This illustration depicts the location of the embed plates w/r/t their ideal locations. All of the embeds long this face were well out of spec. In these locations the cable brackets could be used as designed since the wall design team assumed that the embeds would be substantially further out of place than the agreed 25mm.

TECHNOLOGY IN 2016

At the design and modeling end of the building construction cycle, there is no technical limit to the accuracy with which a building can be modeled. Historically there were inherent inaccuracies in construction documents as fractions of an inch were added and subtracted and manual drafters transferred plans and elevations onto detail sheets. In theory, CAD can eliminate all of these inaccuracies. As a matter of practice in 2016, building geometric information continues to be transmitted in 2D PDF drawings and dimensioned in fractions of an inch. Additionally, it is true in 2016 that building drawings are issued wherein the plans, elevations, and details are not geometrically consistent. This is not a technology issue, but it does point to issues of craftsmanship, CAD model ownership, and responsibility.

The use of CNC production machinery, robotic assembly lines, and highly accurate QA measuring devices has made in house fabrication of curtain wall panels, individual steel elements, and dimensionally critical steel welded assemblages extremely precise. Walls panels made to +/-1mm are the norm, high precision beam lines (See Figure 10) can get the hole locations in 13M long beams correct to +/- 0.5mm (Amada). The staircase illustrated in Figures 11 & 12 was assembled to a final dimensional tolerance of +/-2mm in all three dimensions. It was subsequently installed in a space where the mating steel was contractually obligated to be +/- 25mm in location and was installed to +/- 50mm.

Figure 10: A CNC beam line for the automated cutting and drilling of structural steel. (photo courtesy of TMG Machine)

Figure11: The stringer assemblies for a glass and SS stair for an office space in Beverly Hills. Note the dial indicator to monitor deflections as the unit is welded together. (photo by the author)

Figure 12: A typical subassembly of the Beverly Hills stair being machined in a 5 axis milling machine with 6M of travel. This machine is capable of tolerances better than 0.012mm anywhere in its work envelope. (photo by the author)

Measuring technology too varies in complexity and accuracy. The device shown in Figure 13 is an automated laser tracker with an accuracy of 0.12mm over 60 meters(Faro). Simple hand held laser distance measuring devices are accurate to 1.0mm over a range of 50 meters(Leica).   The same laser technology used in the tracker shown in Fig 13 is the basis of LiDAR scanners. With this technology, the laser head scans an area and records a point cloud of data. Resolution of +/-2mm over a range 30M are common- while collecting 976,000 points/second (Trimble).

Figure 13: The head of this laser tracker follows the target (held by the operator) as the target is moved through 3D space. The operator can read the location of the target's center directly off the laptop's screen. (photo by the author)

DISCUSSION

With the increased use of technology across most aspects of the construction supplier marketplace, there have come higher expectations from all stake holders as to what can and should be achievable in new construction. Owners continue to demand faster, better, and cheaper. Designers would like more freedom to incorporate non-orthogonal geometries, precision built features, and/or other unique items. These heightened expectations are achievable, but the solution will involve the inclusion of all members of the construction team. Given that the technology exists to make the core building geometrically more precise, will that precision solve problems for the owner, will it get them better and unique buildings, and will it be cost effective?

Empirical evidence is hard to come by. Owners and contractors are generally silent when asked about the mitigation costs for work that is out of spec. For the most part, the participants are forbidden from disclosing the problems and the costs of their resolution. There are many well-documented cases where the mitigation has run into millions of dollars. This does not count the soft costs. In the case where a fast track job is slowed down by a mitigation effort, every trade and stakeholder on the job is adversely affected. Work forces are not totally elastic and resources that are tied up on a delayed job are no longer available for the next job. Rarely, if ever, can these costs be recaptured. In addition, the owner will suffer- even with hold harmless and liquidated damage clauses it is rare that anyone is made whole in these events.

Other direct costs of a low precision building core involve the cost of adding adjustment brackets, shim packs, spacer panels, and all manner of other devices to allow for the construction tolerances of the core. In a steel building, if an owner and their designers want a curtain wall to be truly plumb for its full height, the façade provider needs to take into account that the columns (and thus the beam connection work points) may be out location by 75mm below 20TH floor and 125mm above. (ref AISWC 303-05 figure C-7.5). In addition, the beams spanning from work point to work point are allowed an additional 25mm if they span 12 meters. That is, with a steel core, to achieve a truly plumb and flat skin the designer must count on 150mm (6”) of adjustment between the skin and the steel core. Clearly there is a cost here in terms of dollars for brackets, aesthetics (if the flatness and plumbness requirements are relaxed), and potentially water tightness if the core is outside of the designed for tolerances and the installation is allowed to continue.

The less direct costs of the imprecision in the core is the reluctance by owner and contractor to attempt something unique. When the design team pitches a unique feature, many owners look at it as a construction liability. Of necessity, contractors put a price premium on work that appears to carry extra risk. The reduction of that premium involves convincing all stakeholders that the risk is controllable.

Implementing the types of changes suggested herein will require a change in attitude at the top of the construction pyramid. In evaluating 3 projects that utilized comprehensive digital surveying and monitoring programs (The Burj Khalifa, The Overstock.com Circle headquarters (Winke), The Bow (Speed)), these systems are driven by the owner and GC.   The subcontractors did not do their own primary set out. Instead, an owner supplied measuring system provided all of the data needed to the subs in an agreed upon data format. This is in sharp contrast to seeing each trade completely set out their own work off of datum that can be contradictory, imprecise, and is often quite distant from the work zone.

The hard costs for integrating universally available digital survey data on a jobsite are directly related to the project’s requirements. The system used at The Bow was quite complex. The data system tied to fixed stations in the neighborhood, the city’s topographical survey data, and many points within the structure. This allowed the building team to precisely monitor the lean of the building. Clearly, this is more than is needed in a low rise building where the objective is simply to insure that all parties are working off of the same data set in order to insure that the concrete embeds are correctly located.

Effecting changes in erection standards will require a large effort. Certainly, much can be done to improve the core to shell interface without changing these standards. However, updating the standards when show that the status-quo is no longer good enough. Would this be expensive in steel? The current AESS guidelines indicate that adjustable connections must be provided in order to allow erection to AESS tolerances. However, if the individual components are properly detailed from a digital model, produced on CNC drilling/cutting lines, and made with tight tolerance holes there should be no need for adjustability at the connections. Once the need for adjustable connections is removed then there is little or no additional work over what is done today. Automated beam lines already turn out 100’s of tons per day to extremely tight tolerances. If the erectors had real time digital surveying tools in hand that corrected for temperature fluctuations then tighter erection tolerances seem achievable at a very modest premium.

NEXT STEPS

To understand the real costs of out of tolerance work on the shell, real data is required. As builders and design professionals, the first step may be to seek permission to share information about what is seen on the jobsite. Collectively, all in the trade celebrate the landmark buildings and publicize the innovative solutions and new technologies that were used to build them. Rarely do building professionals talk publically about the jobs that went poorly or ended in lawsuits. In general, we only read about what was settled in lawsuits. In other domains this is not the case. In the manufacturing environment there are case studies done continuously to evaluate the efficacy of certain manufacturing methodologies. In the safety domain, every airplane accident is studied- from the smallest experimental aircraft to commercial airliners. The result of this comprehensive look at the way planes are designed, manufactured, and operated has led to an extraordinary safety record in commercial aviation.

In many landmark buildings it is a given that extraordinary measures are needed to get the project built. Part of the job of the design team is to wrap their minds around the means and methods required to build something so unique. Often the lead S.E. or lead Architect approach the role of master builder to spearhead the discussions with the building team as to how to implement surveying systems, or how to redesign the core to accommodate innovative ideas from a subcontractor to save time and money.

As owners encourage designers to individualize their projects and invite the incorporation of special features into them, perhaps a little bit of that master builder philosophy would be helpful. How often do building professionals look at something like the oops in Figure 1 and lament the sloppy work of the "field guys". Most builders and owners can produce photos like figure 1 and many have nightmare stories to go along with those images. An alternative view of these photos is that they are a call to action for the owner, GC, and the entire building team to collaborate to put systems in place to make geometric misses a rare event. This involves an investment of capital, a shifting of perceived risk, vision, and leadership.

CONCLUSION

Whether in the factory or at the jobsite, historically, the men and women in the building trades take great pride in what they build. When armed with the correct tools and shown how to use them, they can produce amazing results.

So how do we arm the crews who work on the jobsite with better tools? Will the benefits outweigh the costs? These same questions were asked when practitioners saw the first, very expensive, Catia CAD systems. The price of that Catia seat has not come down very much since 1986. Catia continues to have a place in the market but it now has countless competitors that fill other niches. There is a CAD system for most any use that can be bought for a reasonable price and are perceived to be a good value. There are very few design offices with typewriters and drafting boards left. Why do builders go to job sites every day with the core built to 60 year old standards and antiquated methods for sharing grid lines, setouts, and elevations? A concerted effort to bring digital measuring and data processing onto the jobsite should reduce errors and increase the ease with which precision elements can be incorporated. This will result in better buildings.

REFERENCES

Amada Corp, "Specifications 6bh-1000", http://www.amt.amada.co.jp/english/products/steel/drilling/6bh-1000_3.html#pn_s (visited 18 May 2016)

American Aluminum Manufacturers Association, "Curtain Wall Manual – Section 4 Building Tolerances", Draft 6/9/2015

American Concrete Institute, "Specification for the tolerance of Concrete Construction and Materials." 117-110 , reapproved 2015

American Institute of Steel Construction. "Code of Standard Practice for Steel Buildings and Bridges.", 303-05, April 14, 2010.

Faro, "Technical Specifications for Laser Tracker Vantage." http://www.faro.com/en-us/products/metrology/faro-laser-tracker/features#main (visited 12 May 2016)

Leica, "EZ500i Specifications.", http://lasers.leica-geosystems.com/disto/e7500i (visited 12 May 2016)

Speed, Vicki, "Controlling the Bow." Point of Beginning / BNP Media. July 2011

Trimble, "Technical Specifications Trimble TX8." http://www.trimble.com/3d-laser-scanning/tx8.aspx?tab=Technical_Specs (visited 10 Mat 2016)

Winke, Jeff, "3D Technology Helps Build A Circle." Point of Beginning / BNP Media. March 2016.

FAÇADE OPTION ENGINEERING

Optimization of transparency in a mega glass lite project

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ABSTRACT

A successfully engineered structural glass structure requires a rigorous process to ensure the client receives an optimized, safe and cost efficient solution while maintaining and improving on the original design intent. The process to arrive at a logical and efficient solution is termed an Option Engineering process. This is a collaborative emergent design method Walter P Moore (WPM) promotes to ensure integration of teams to provide the communication and technology necessary to deliver rapid innovative solutions. The goal is to produce the best possible solution from the project parameters and constraints that maintain and enhance the design intent. To illustrate this philosophy, this paper presents the engineering and design process of a mega glass lite for a lobby renovation project in Dallas, Texas.

Through an iterative design and engineering process, a family of structural options is established by considering constraints of operational strength, deflection, fabrication, constructability, cost, and aesthetics. The iterative process allows for consideration and evaluation of a variety of structural options that eventually lead to a final solution that best meets the project goals.

The new exterior wall design comprises twenty 10 ft. wide by 30 ft. tall monolithic glass lites at the lobby. This paper details the evolution of the design parameters to arrive at a working design for the glass panels. Given the height of the glass lites, the goal was to provide adequate support for the high lateral wind loads while satisfying the client's request for maximum transparency and a slim transparent structural back up system.

The process of refining the design involved various considerations including: (1) different analysis procedures and comparisons of their respective modeling accuracy, (2) studies of current glass code and the prescriptions compared with analysis program results, (3) structural sealant modeling limitations and challenges, and (4) the effects of the glass support or detail conditions on the deflection and glass stresses.

From the initial design proposal of a composite steel fin and cable truss between each panel, the progression of design and engineering evolved towards the optimization of transparency and the final solution.

KEYWORDS

Mega Glass Lites, Cable Wall, Metal Fin, Structural Sealants, Glass Engineering, Structural Glass, Laminated Glass, Design Processes, Option Engineering

INTRODUCTION

Decisions taken during the early stages of design have long lasting implications on performance of the façade system. This paper is important for designers and clients to understand how iterations, from early design through development, help in steering the design intent toward a cost effective and a performance based optimized final solution. With improving sophistication of façade technology, comparative assessment of multiple options has become fundamental to the design process in order to find the best possible solution. This iterative process, known as option engineering, requires collaboration between the client, architect, façade designers, structural engineers and the project contractors.

The paper lays out the steps of the design and engineering processes of a high transparency glass façade for a tower lobby re-clad project in Dallas, Texas. Option engineering is the method used to assess the performance of multiple facade solutions based on project specific parameters such as design intent, façade system design, material properties and strength, deflection criteria, impact to existing building structure and cost implications. The process is reliant on embedding these project logics into the design process. The process also considers constructability and fabrication parameters.

PROJECT BACKGROUND

The client's main intent was to maximize transparency of the lobby with a proposed long span hybrid cable/fin truss system to provide structural support to mega lites of low iron laminated glass. Minimal structure and minimal glass capture was the architectural vision. Through the option engineering process, multiple structural backup systems were developed and compared in order to generate a performance matrix and finally arrive at the final solution of an efficient glass façade, thus adding value to the project.

Option engineering has recently gained popularity with advancement of digital tools that allow parametric modeling, simulation-based analysis and interoperability between multiple disciplines. Walter P Moore and other AEC firms have started promoting this emergent process to ensure integration between teams and rapid delivery of best available solutions.

For renovation of the tower lobby, the façade and structural engineering teams at Walter P Moore, in Los Angeles and Austin respectively, worked as an integrated team to assist the team from Gensler and James Carpenter Associates, the designers of the glass façade system. The design intent was to maximize transparency of the façade; hence, the designers proposed a system composed of full height laminated glass lites, 28 ft high x 10 ft wide, supported by pre-tensioned cable and steel fin vertical truss system providing lateral resistance for deflection. The thought behind the cable was to reduce the structure to a bare minimum and provide maximum transparency.

The SD facade design criteria was developed to analyze the structural performance of the proposed system. The preliminary approach was to minimize the pretension loads in the secondary systems to reduce the impact on primary structure and save retrofitting costs.

METHOD

Through design iterations, multiple structural system types were established using Finite Element Analysis by considering constraints of operational strength, deflection, fabrication, construction, codes, and aesthetics.

Design Criteria: Applicable engineering codes, design loads, material stress limits, and deflection limits were identified in the design criteria for the project.

Analytical Model: The general analysis model was comprised of three typical glass panels (3x30'x10') of the proposed atrium lobby wall. These panels were modeled using 1.5" thick (triple laminated) glass, 1.5"x 3" to 5" 50 ksi stainless steel vertical fins, 0.75" to 1" structural strand cables, and structural sealant that bonded the glass edge to the steel fin. Throughout the analysis process, various components were adjusted accordingly as the design evolved.

The geometry was generated in Rhino, parametrically using a digital workflow utilizing a live Grasshopper link to the structural analysis program. The parametric digital workflow allowed multiple iterative geometries to be quickly generated, processed and analyzed. The model was analyzed in Oasys GSA and CSI SAP2000 to assess glass stresses, membrane action of the glass, and deflection behavior of the structural system.

The glass was checked for maximum tensile stress under strength load combinations and deflection under service load combinations. Moment and axial forces for the fin and reactions for top fin support and bottom glass supports were simulated. Using the maximum forces from this analysis, dimensions of the structural sealant were calculated.

ITERATION 1: CABLE TRUSS SYSTEM WITH VERTICAL FINS; PINNED SUPPORT; STRUCTURAL SEALANT

The preliminary structural analysis checked the strength and deflection performance determined an appropriate cable pretension to meet a deflection criteria limit of L/50 in the wall system (where L is the height 28 ft of the glass panel and backer structure span).

Model Attributes: Per the architects' requests for a transparent and minimal structural support system, the initial model was composed of large laminated glass mega panels of height 28 ft x width 10 ft. Each glass panel was base loaded and captured along the short edges for lateral loading through a sill. Along the long edge of each mega panel a vertical fin cable truss of an 8 in depth was used to provide lateral restraint. The 3" front steel fin ran continuously along the vertical edge and a non-mechanical silicone joint was used to capture the glass. Horizontal struts run from the fin back to a vertical pre-tensioned stainless steel cable. The structural sealant was not modeled at this time. Figure 1 below shows the various structural components in the GSA model.

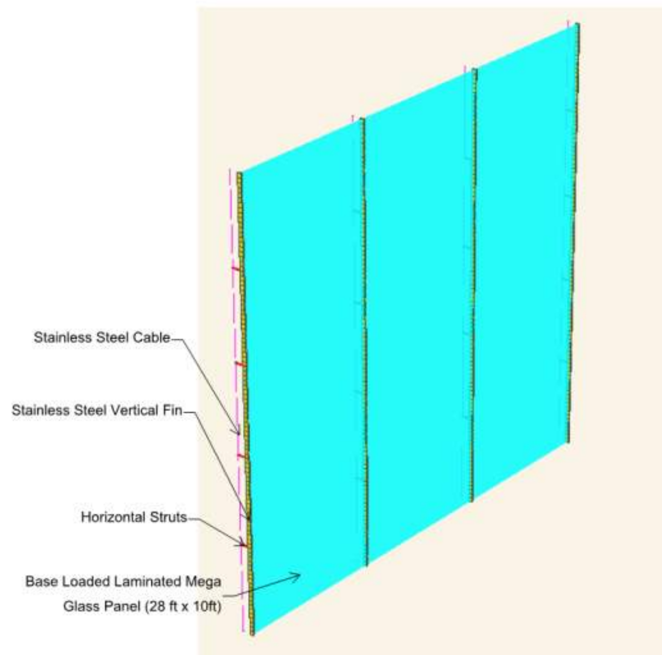

Figure 1: Façade System Baseline Model – Glass Lites Supported by Vertical fins and Pre-tensioned Cable Truss System

The cable was pretensioned to a suitable value to provide lateral resistance for deflection and minimize the working stresses in the glass. For each option, the cable pretension was varied from 10 kips to 20 kips, returning a suite of viable designs. The models were analyzed with ASD level components and cladding wind loads for glass strength checks and a 10 year mean return interval for deflections checks. Figure 2 is a summary of the preliminary design criteria used.

Summary of Facade Design Criteria

The design and deflection criteria are based upon those specified in IBC 2012, ASCE 7-10, and ASTM E1300

Self-Weight (SW)	As Computed by Structural Analysis Software
Dead Load (D)	13 psf for 1in. thick glass panels
Wind Load (WL1 WL2)	Risk Category II Building Site Wind Speed of 115 mph (ASCE 7-10) Exposure C C&C (ASD Design Wind Loads) WL1 - Windward: 26.5 psf WL2 - Leeward: 41.6 psf Deflection Limits TBD Deflection (Serviceability) based on 10 yr. MRI wind WL1 - Windward - Service: 18.5 psf WL2 - Leeward - Service: 30.1 psf
Seismic Lateral Load and Drift	________
Temperature Load	Not Applicable
Roof Live Load (LLr)	Not Applicable

Figure 2: Façade System Preliminary Design Criteria Summary

Inference: Based on the analysis models, a pretension of 10 kips ensured acceptable glass stress levels (ignoring edge stresses) and met the deflection limits. While the higher pretension options also returned working designs, the lower the pretension meant less load acting on the primary structure. Note that the glass strength was reviewed for probability of breakage of 8 per 1000 lites for a 3-second load per GANA Glazing Manual recommendations. Therefore, these are the maximum allowed principal tension or design stress for different finishes: Annealed – 3.4ksi; Heat Strengthened – 6.7ksi; Tempered – 13.5ksi. Preliminary analysis showed that a 1.125” laminated annealed glass was appropriate. Images (Figure 3) below show an example stress plot, axial load in the fins, and deflection contours.

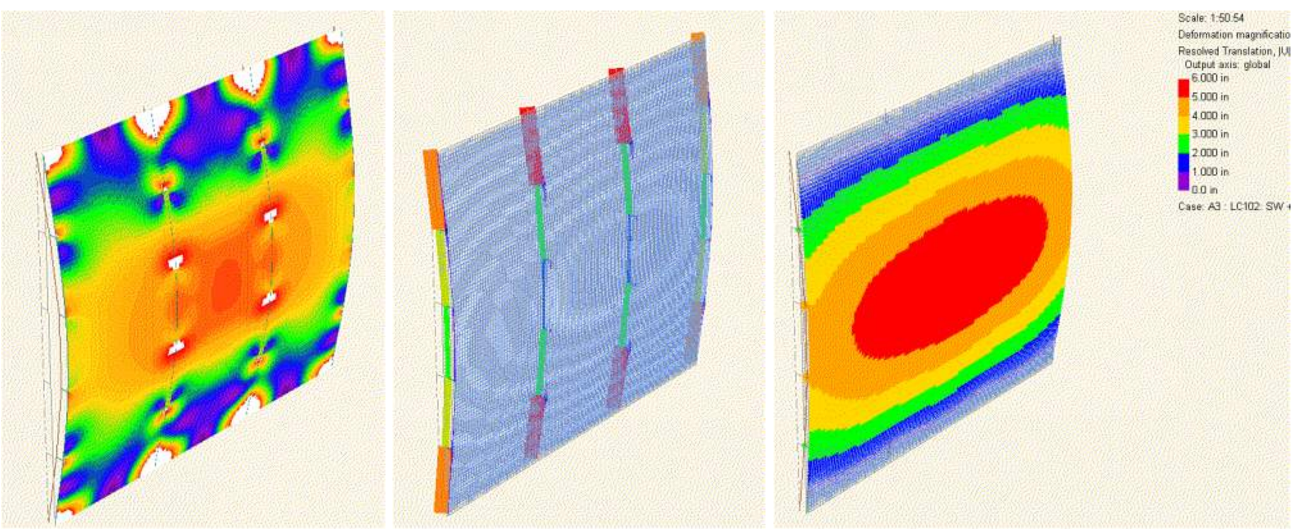

Figure 3: Preliminary Analysis: Example Stress Plot, Axial Load, Deflection Contour

In sum, preliminary pretensions and reactions for the cables, appropriate to control deflections to L/50, were developed from the analysis. The reactions were coordinated with the primary structural engineering in order to gauge the impact of the support beams and connection at the floor and soffit interfaces. Figure 4 is an extract from an Excel table listing the reactions for the model with 10 kip cable prestress.

Reactions	V	H
Cable Top	21 kip	6 kip
Cable Bottom	21 kip	6 kip
Sill Bottom	0 kip	0.6 lbf/ft
Sill Top	0 kip	0.6 lbf/ft
Fin Top	6 kip	15 kip
Bottom	4 kip	15 kip
Setting Out		
Block Bottom	6 kip	1 kip
Note:		
All reactions ASD		
Reactions are for a 10 kip cable Pre-Tension		
All reactions are PRELIMINARY		
V: Vertical reaction		
H: Horiontal Reaction		

Figure 4: Cable Interface Reactions

ITERATION 2: CABLE PRETENSION COMPARATIVE ANALYSIS

From Iteration 1, preliminary reactions to be carried by the primary structure were obtained. Given the magnitude of the reactions, it became apparent that the strength and deflection demands were problematic for the primary design. If the cable forces were too great, it could cause the primary structure to deflect above a prescribed allowable. Then the cable could go slack, rendering the system ineffective. If the primary structure was strengthened to handle the demand, it could be expensive or visually obtrusive.

Although an acceptable working façade design was available, the effect of the cable forces on the primary structure was a concern. Therefore, the studies with a range of new options were carried out to see if the pretension in the cable could be lowered to reduce reactions. The study investigated the interaction between the cable pretension, the depth of the cable truss, the size of the steel fin, and the deflection of the glass and fin system. The effectiveness to transfer loads, from the glass to the backer structure, of the structural sealant that bonded the glass edge to the steel fin was also reviewed.

Model Attributes: The analysis model was comprised of three typical glass panels (3x28’x10’) of the proposed atrium lobby wall. These panels were modeled using 1.5” thick (triple laminated) glass, 50 ksi stainless steel vertical fins, and 3/4” structural strand cables. The depth of the cable truss ranged from 8 to 11 inches. The size of the vertical steel fin ranged from 1-1 ½ in wide by 3-5 in deep. See Figure 5 for an option where the cable and struts are to be removed.

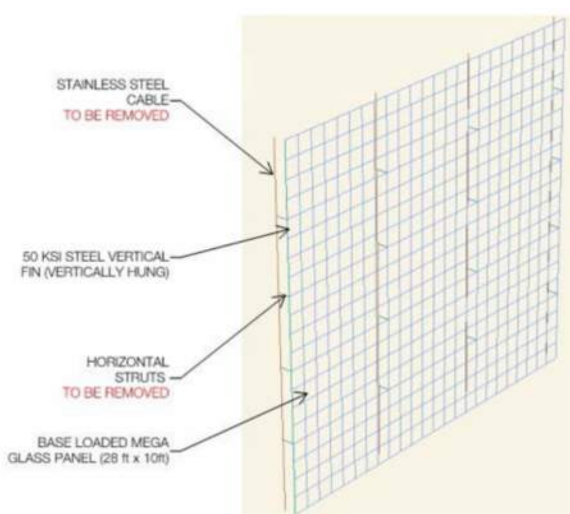

Figure 5: Façade System Modified Model with Glass Lites Supported by Vertical Fins – No Cables and Horizontal Struts

Inference: A matrix with different depths of the cable truss, sizes of the steel fin, and cable pretensions was created – See Figure 6 for an extract of the matrix.

Model Name	Option	Depth	Cable	Cable PT	Fin Size	Glass Thickness (Analysis)
SealantModel_06-1.5x5_003-2.5in	Option A	11.00 in	0.75 in	10.0 kip	1.5x5	2.500 in
SealantModel_06-1.5x5_007-2.5in-no-cables	Option A_1	11.00 in	0.75 in	NA	1.5x5	2.500 in
SealantModel_06-1.5x5_006-1.125in	Option B	11.00 in	0.75 in	10.0 kip	1.5x5	1.125 in
SealantModel_06-1.5x5_008-1.5in-no-cables	Option C	11.00 in	0.75 in	NA	1.5x5	1.500 in

Figure 6: Extract of Options Matrix

As the pretensions in the cables were reduced and eventually brought to zero, it was clear that the cable contribution in the performance of the structural backer system was minimal to none as Figures 7 through 8 tabulate. In other words, if the glass and fin configurations are held constant, the addition of the prestressed cable did not significantly decrease the glass and fin stresses. This introduced an opportunity to eliminate the cable and supporting elements completely. The impact of removing the cable was significant in the reduction of cost since the primary backer structure could be reduced as well.

Option	ASD Cable Force		ASD Strut Force		ASD Fin Forces			
	Windward	Leeward	Windward	Leeward	Windward		Leeward	
					Axial	Moment	Axial	Moment
Option A	10.5 kip	11.2 kip	0.1 kip	0.2 kip	1.01 kip	44.5 kip-in	2.73 kip	70.8 kip-in
Option A_1	NA	NA	NA	NA	0.99 kip	47.9 kip-in	2.85 kip	76.6 kip-in
Option B	14.6 kip	19.2 kip	0.4 kip	0.8 kip	1.52 kip	141.3 kip-in	8.11 kip	199.6 kip-in
Option C	NA	NA	NA	NA	2.11 kip	135.7 kip-in	7.80 kip	212.7 kip-in

Figure 7: Element Forces for the Pretension and No Pretension Options

Glass Stress:

Option	ASD Glass Stresses			
	Windward		Leeward	
	Max Tensile	T DCR	Max Tensile	T DCR
Option A	2.00 ksi	0.59	3.19 ksi	0.94
Option A_1	2.15 ksi	0.63	3.43 ksi	1.01
Option B	3.11 ksi	0.23	4.33 ksi	0.32
Option C	3.85 ksi	0.28	6.05 ksi	0.45

Glass Deflection:

Option	Service Deflection			
	Windward	Leeward	W DCR	L DCR
Option A	1.4 in	2.2 in	237	152
Option A_1	1.5 in	2.2 in	218	150
Option B	4.5 in	6.4 in	76	53
Option C	3.9 in	6.3 in	86	53

Figures 8: Glass Performance Data

The individual elements (glass, fin, and cable) were reviewed with the glass and fin interaction being reviewed in more detail. The lack of any mechanical capture element from the glass to the fin resulted in the sealant having to transfer the load from the glass surface to fin. This was not the most effective way to transfer the loads and resulted in higher glass stresses at the glass lite mid-span and the silicone joint being larger than just a simple weather sealant joint.

ITERATION 3: GLASS PANELS WITH VERTICAL STEEL FINS. PRE-TENSIONED CABLES ELIMINATED

Analysis Model: The natural progression of optimizing the system resulted in the removal of the cable completely. This action removed the pretension forces from the system. The link between the glass and the steel fin remained as the structural silicone element with no other mechanical fastening between the two elements. The steel vertical steel fins were hung and were designed to be 1.5” thick x 5” deep. The glass was a triple laminated unit, 1.5” thick, with tempered glass and SGP interlayer for stiffness.

As the analysis was being refined, the project loads were reviewed and refined as well as shown below:

Design Codes and Specifications:

ASCE 7-10; Steel Construction Manual; 14th Edition; GANA Glazing Manual; ASTM C1401-14

Design Loads:

Wind Loading:

Components and Cladding Wind Load Parameters: Risk Category II Building; Site Wind Speed of 115 mph; Exposure C
Calculated Wind Load Values:

LRFD (MRI = 700 years):	Windward (WL1_LRFD) = 44.2 psf	Leeward (WL2_LRFD) = 69.3 psf
ASD for strength design:	Windward (WL1_ASD) = 26.5 psf	Leeward (WL2_ASD) = 41.6 psf
Serviceability (MRI =10 years):	Windward (WL1_Service) = 18.5 psf	Leeward (WL2_Service) = 30.1 psf

Self-Weight (SW): The self-weight of the elements are calculated by the analysis software. There is no superimposed dead load (DL).
Seismic Loading: Negligible

ASD Design Load Cases

ASD Strength	LC1: SW + WL1_ASD	LC2: SW + WL2_ASD
ASD Serviceability/Deflection	LC3: SW + WL1_Service	LC4: SW + WL2_Service

Design Limits

<u>Stress Limits:</u>
Per GANA Glazing Manual, the maximum allowed principal tension or design stress is for a probability of breakage of 8 breaks per 1000 lites for a 3-second load. For fully tempered glass, this design stress is 13.55 ksi.
The steel is checked per AISC Steel Construction Manual.
Silicone stress is checked using ASTM C1401, a factor of safety of 6, and material specifications.

<u>Deflection Limits:</u>
Proposed glass deflection for all service load combinations is limited to L/50.
Proposed façade fin steel deflection is limited to L/50.
Proposed façade header steel deflection is limited to L/175.

Materials
Stainless Steel: Fins and header plate, Fy, min = 50 ksi- 1.5”x5” vertical fins
Glass: Fully tempered 1 ½ in. laminated with SGP interlayer -28’x 10’ panels
Fasteners: Stainless Steel, Fu, min = 75 ksi

Structural Sealant: High-strength silicone, minimum tensile strength of 493 psi, allowable stress is 82 psi based on a factor of safety of 6 per ASTM C1401. (Note: this is a bespoke high capacity sealant provided by the sealant manufacturer, C1401 recommends a minimum factor of safety of 2.5 and the typical industry standard for the allowable stress is 20 psi. A performance mock up test would be used to justify this higher allowable stress).

Analysis Results: The elements of the system were analyzed for performance, and the results of the analysis are presented below. See Figures 9-14 for the glass performance, Figure 15 for the steel fin forces, and Figure 16 for the silicone calculations.

Glass Performance

Glass Stress:

ASD Glass Stresses			
Windward		Leeward	
Max Tensile	T DCR	Max Tensile	T DCR
3.08 ksi	0.23	4.40 ksi	0.32

Figures 9: Glass Stress

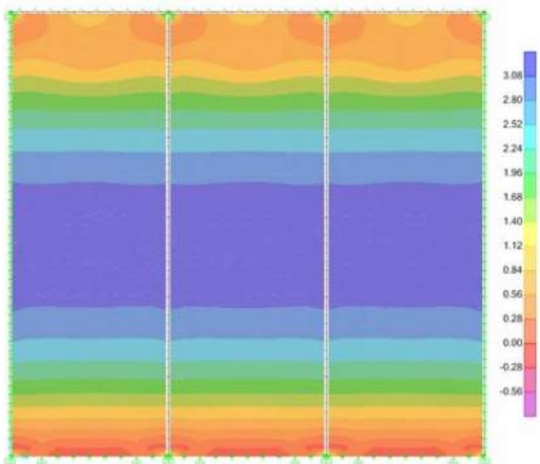

Figure 10: Maximum Tensile Glass Stress – Windward Load

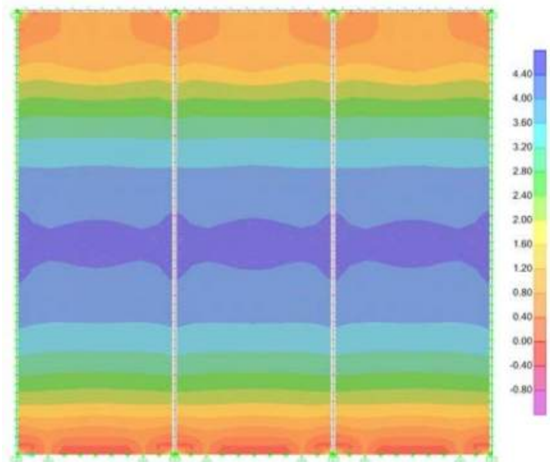

Figure 11: Maximum Tensile Glass Stress – Leeward Load

Glass Deflection:

Service Deflection			
Windward	Leeward	W DCR	L DCR
3.4 in	4.9 in	100	69

Figures 12: Glass Performance Data

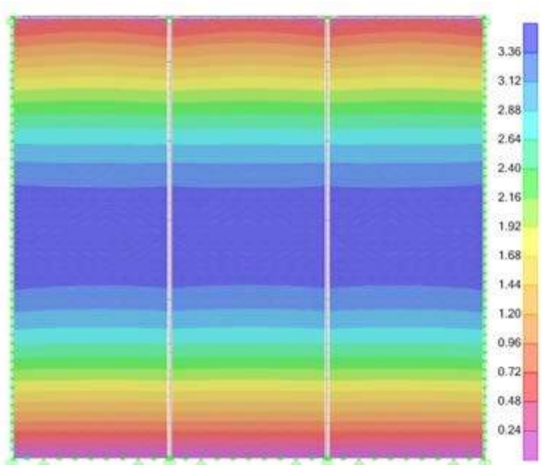

Figure 13: Glass Deflection – Windward Load

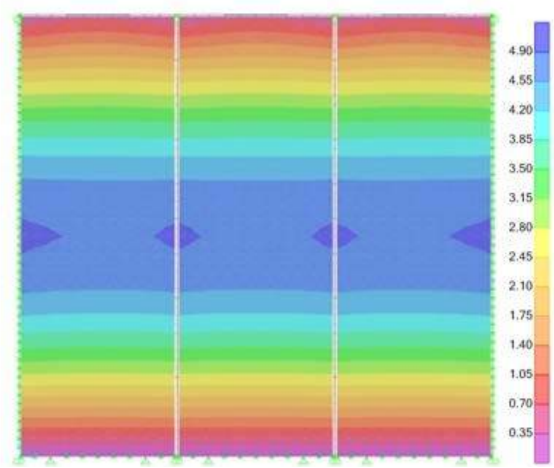

Figure 14: Glass Deflection – Leeward Load

Secondary Element Performance

Maximum Steel Fin Forces

ASD Fin Forces			
Windward		Leeward	
Axial	Moment	Axial	Moment
12.68 kip	110.2 kip-in	23.82 kip	147.9 kip-in

Figures 15: Steel Fin Data

Sealant Design

The structural sealant between the glass edge and the steel fin was designed to be the load transfer element. The bite was 1.5" thick, and the glue-line thickness is 0.5" thick. These were calculated using the maximum forces from the analysis model.

Figure 16 show the required bite sizes for different structural silicone allowable stresses. Based on architectural conditions, a high-strength silicone with an allowable stress of 82 psi was required (See Design Criteria for further detail).

Sealant Type	Direction	Nonlinear Results P Force	Nonlinear Results V2+V3 Force	Nonlinear Results Combined Force	Req. Bite
Dow Corning 895	Vertical	0.284 kip	0.329 kip	0.613 kip	6.0 in
	Horizontal	0.007 kip	0.402 kip	0.409 kip	2.3 in
SikaSil SG550	Vertical	0.284 kip	0.329 kip	0.613 kip	1.2 in
	Horizontal	0.007 kip	0.402 kip	0.409 kip	0.5 in
SikaSil SG-20	Vertical	0.284 kip	0.329 kip	0.613 kip	1.9 in
	Horizontal	0.007 kip	0.402 kip	0.409 kip	0.7 in

Figure 16: Required Sealant Bite

Inference: The structural elements of glass, steel fin and sealant work together to resist and transfer loads. In using the structural sealant as the transfer element from glass to steel, allows for a clear aesthetic. This allows for clean visual lines in the high transparency wall. The removal of the cable and hanging of the steel fin makes the system very efficient with a low reactions and thereby allows for minimal modifications and additions to the existing building.

ITERATION 4: STRUCTURAL GLASS LITES WITH FIXED TOP AND BOTTOM EDGES; NO STEEL FINS, NO CABLES

The final aesthetic required one more iteration as the client expected a cable wall, but now has steel fin backed wall. The innovation of engineering a minimal fin and using structural silicone was not enough of a positive to overcome the objections to a simple fin wall. The team looked as one additional development to address this issue.

Analysis Model: The analysis model comprised of three typical glass panels (3x30'x10') of the proposed atrium lobby wall. These panels were modeled with the top and bottom edges fully clamped and no additional vertical structural members. The glass panel was analyzed for deflection and stresses and the designed to perform as the primary structural element for the façade.

Inference: The glazing subcontractor suggested a challenging and simpler solution to the development of the design that removed all secondary structure. This logical development came out of the reaction of the client to the steel fin. He expected a cable wall but when the cable became redundant in the engineering, the steel fin backer was not an aesthetic the client was comfortable with, even though the wall system was structurally innovative with no mechanical capture of the glass and the silicone load transfer from glass to steel. This led to the continued optimization of the system and the exploration of the glass as the primary and only structural element in the façade. The 'glass only' solution was embraced by the design team and the client due its visual simplicity and the resultant maximum transparency. This solution needs further engineering study to ensure the issues of cost, constructability, building retrofit requirements and reactions all work within the project parameters. The loads, stresses, and deflections for the initial design calculations, from Sentech, are shown in Figures 17-18.

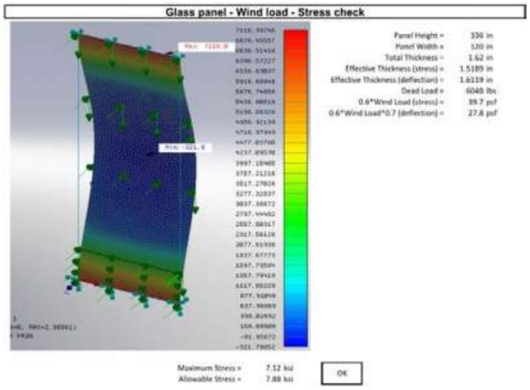

Figure 17: Sentech Glass Stress

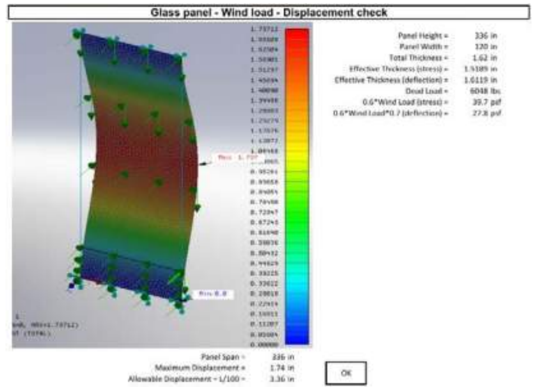

Figure 18: Sentech Glass Deflection

DATA COMPARISON

A comparison of the analysis of the various options was catalogued in Figure 19 to get an overall view of the main features of each system.

Subject	Issue	Sentech	WPM Cable 10/12/2015	WPM 11/5/2015
Wind Criteria	Exposure Category	B	C	C
	Building Height	720 ft.	730 ft.	730 ft.
Design Criteria	Allowable Breakage	1:1000	8:1000	8:1000
	Allowable Stress (field)	10.04 ksi	13.55 ksi	13.55 ksi
	Considered Edge Stress	Yes	No	No
	Deflection Limit	L/100	L/50	L/50
Loads	Critical Buckling/Eigenvalues	Yes	None	None
	Live Load	200 lbf / 50 lbf/ft.	None	None
	EQ Load	Yes	None (deemed insignificant)	None (deemed insignificant)
	Temperature Loads	Yes	No	No
Modeling/Analysis	Software	NEiNastran	SAP, GSA	SAP, GSA
	Total Glass Thickness	1.5"	1.125"	1.5"
	Glass Type	Fully-Tempered	Fully Tempered	Fully Tempered
	Laminate Type	Trosifol	SGP	SGP
	Bottom/Top Edge Support Condition	Fixed	Pinned	Pinned
	Structural Sealant Modeled	Unclear	Yes	No
	Aluminum Fins Modeled	No	Yes	Yes
	Solver	Unclear	Nonlinear Large Displacement	Nonlinear Large Displacement
Results	Max Stress	7.12 ksi	4.33 ksi	4.40 ksi
	Max Deflection	1.74 in	4.5 in	4.9 in

Figure 19: Design Comparison Table

CONCLUSION AND FUTURE WORK

A successful option engineering process was presented that through a process of iterations and feedback loops with the client, a highly transparent engineered glass façade was arrived at.

Future advances in high transparency facades depend on the capacity of the glass manufacturers to produce larger and larger glass lites, use of higher stiffness structural glass interlayers, and development of stronger structural sealants that can be shown to satisfy existing highly restrictive prescribed design codes. The balance of engineering, design and materials performance is the true goal of any structural façade. A collaborative digital work flow facilitates the option engineering process.

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DATA AND ORDER

The making of complex architecture

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ABSTRACT

The City of Dreams Hotel in Macau designed by Zaha Hadid Architects features an array of façade systems including a bespoke, double curved, aluminum rain screen cladding system that covers more than 18,000 m2 (193,000 ft2) of façade area, consisting of more than 22,000 unique panels and millions of framing components. The complex geometry, scale, and variability of this project are emblematic of a modern Architecture enabled by the proliferation of computational resources that allow design teams unfettered ability to describe an Architecture that simultaneously responds to aesthetic, political, and performative constraints. Even outside the formally complex contemporary Architectures, modern building design and construction processes rely on an ever-increasing ability to generate and synthesize information to inform decision-making at all stages of a project. This paper describes a design, modeling, and documentation process used to realize the City of Dreams project, and others, from the early stages of design through the stages of making: prototyping, documentation, fabrication, assembly, construction, and building lifecycle management. The process discussed in this paper generates a modern construction information model based on aggregating and synthesizing streams of information to produce an intelligent set of linked information models. These intelligent information models allow for small teams to manage complex geometries and large systems, to produce and iterate, at scale, with quality at the required paper and digital documentation output to describe the fabrication, assembly, and erection of building façade systems with entirely non-repetitive constituent parts at all phases of a project. The process discussed and examples presented here, represent a current snapshot of 15 years of project-based research and implementation, providing a means of integrated delivery of Architecture as a more product oriented approach and empowering design teams and stakeholders with alternative means of project delivery.

KEYWORDS

Façade, design processes, project delivery, building information modeling, parametric workflows, generative design, computational design

INTRODUCTION

The successful design, coordination and communication of fabrication and construction information is paramount to a project's success. In a design world increasingly defined by formally and technically complex building forms and programs, ambitious schedules, market-driven constraints, and a truly global procurement and production network, the ability to design, adapt, and communicate across all of the contributors to the project production lifecycle is more important than ever. (Eastman et al, 2008). The process and examples presented here are a product of project based research and implementation rooted in this emergent design and production ecosystem. The ideas presented aim to allow the complexity inherent to this modern environment to be realized with confidence by eliminating the barriers to how construction information is aggregated, coordinated, and distributed. The paper primarily uses examples from a recent project completed by the authors' firm in Macau by Zaha Hadid Architects as an example of how a modern design and construction process can be realized. The realization of innovative design is enabled in part by the increased effectiveness in managing the risk inherent to the fabrication and delivery through the enhanced engagement of the underlying project information.

BACKGROUND

The authors' firm is an integrated design and engineering consultancy practice specializing in façades and deeply rooted in a global practice. With offices in North America, Europe and Asia, their firm has completed more than 130 built projects at a variety of scales and types on five continents. Since its founding, the firm has worked directly with a wide range of international and local contractors, subcontractors, and fabricators and different construction approaches, and is well positioned within the industry to address practical concerns such as cost efficiency and constructability, with an understanding of global issues as well as the ability to resolve the fine details. These relationships with owners, architects, and contractors alike have resulted in a body of work that has engaged the design, documentation, and delivery of building enclosures of all scales, materials, and complexity. Over the past decade and a half, the firm has been involved in the production and delivery of construction and fabrication information for a variety of buildings (Fig 1) which has evolved into the process defined here as "Building Information Generation". Some previous works utilizing this process are HL23 (2011) by Neil M. Denari Architects, Kukje Gallery (2012) by SO-IL, Barclays Center (2012) by Ellerbe Becket/SHoP Architects, L'Assemblée Radieuse (in progress) by WORKac, BAM South (2016) by Ten Arquitectos, and the Jan Shrem and Maria Manetti Shrem Museum of Art (2016) by SO-IL.

Figure 1: (From left to right) HL23 by Neil M Denari Architects, Kukje Gallery by SO-IL, BAM South by Ten Arquitectos (Image from Ten Arquitectos).

BUILDING INFORMATION GENERATION

Historically, BIM models can be described as the product of a set of processes that serve to create a representative superset of building components used for design, fabrication, and construction (Kieran et al., 2004). Traditional BIM models, whilst representing vast improvements over conventional representative geometry, only describe a specific state of the model, preserving little to none of the logic or intelligence that was incorporated from previous states of the model. This static nature of traditional approaches means the opportunities for extending the generative foundation of the model building logic are limited, reducing the utility of the data described by the model for other processes dependent on information represented by the model (van der Heijden et al., 2015). Modern software and computational power has led to an explosion of ways to create, describe, and share information, creating opportunities for designers to re-evaluate the role of information in the design process and evolve the prevailing design and documentation methods to take advantages of these resources. Building Information Generation (BIG) attempts to extend the scope of traditional BIM by providing a structure to the information represented by the model through an emphasis on the generative logics used to create the models. BIG seeks to enhance and liberate that information by creating an adaptable framework that preserves and generates design and construction data throughout the design and implementation process. With each version of the model both the data and the logic used to synthesize the data are preserved and available throughout the design and documentation process. BIG itself is not a model, but a framework of logics used to collect, coordinate, aggregate, and give meaning to information generated in the design process and thereby give rise to a BIM model as one of the many products of the processes inherent to BIG.

Collaboration and scaling in contemporary parametric design environments can be a problem in a multi-user environment and has long been questioned in the design community (Aish, 2000 and Holzer, 2010). This being said, large-scale parametric, single-model BIM approaches have been successfully executed, allowing multiple parties to collaborate on large and complex projects (Hudson, et al., 2011). However, these configurations typically rely on centralized models on a single platform and a strict hierarchical control structure, limiting the scope and scale of collaboration. Traditional BIM processes employ a form of linear development, where the scale and complexity of the model grows uniformly as the design progresses, resulting in environments in which this very nature of the model is an impediment to progress and future utility of the information represented. BIG represents an evolution in thinking about the deployment of design and construction models by structuring the production environment around the non-linear schemata familiar to contemporary parametric design models (Fig 2), and the information created and the generative logic are treated with equal importance and are preserved for use in other parts of the ecosystem.

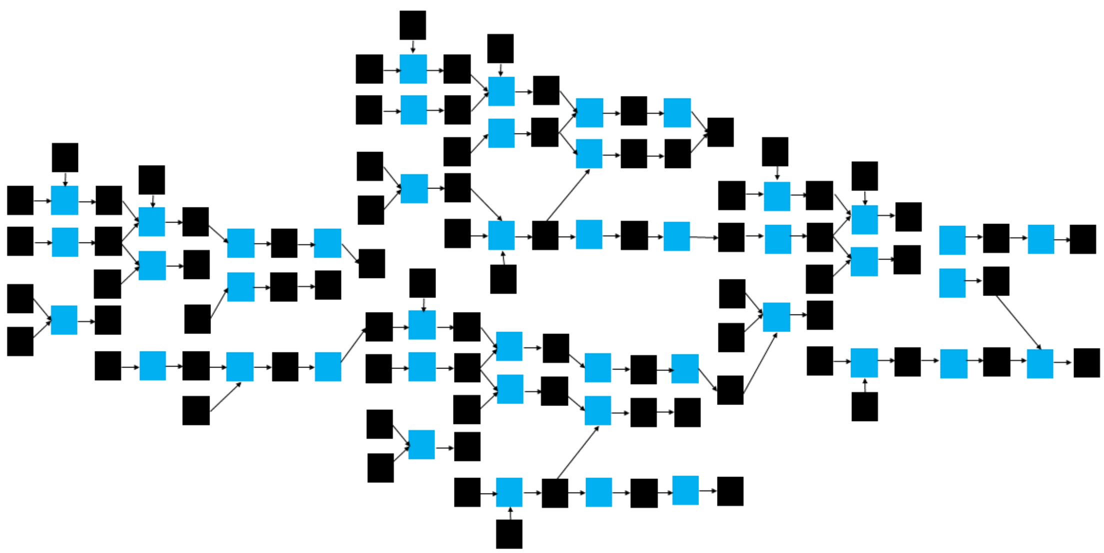

Figure 2: A BIG project workflow is organized in a non-linear network of logics, a scaled up version of an individual parametric model schemata. Data (Inputs/Outputs in black) are processed by functions (blue)

Validating design options through performance-based feedback at all stages of the project has long been a prime objective of generative modeling and to an extent BIM as a whole (Shea, et al. 2003). BIG attempts to address the limitations of traditional parametric workflows through the modular, non-linear, and collaborative nature inherent in the structure of the process. The discretization of tasks, ability for collaboration, and convenient integration of information from multiple outside sources into the workflow are encouraged; complex and novel Architectures that rely on this early and late stage performance feedback can be readily enabled. At the Kukje Art Center in Seoul, the methodologies of BIG were employed to develop and explore explicitly performance based feedback solutions for a totally bespoke, double-curved, tensioned mesh made of interlocking metal rings (Kock, et al., 2012).

The availability of both the previously generated data and generative logics at any stage of the processes used to create a BIM model can be used in novel ways to, amongst other things, enrich the design process through unimpeded access to information, foster a team-based collaborative production environment, enable massively scalable automation of both modeling and documentation production, and provide real-time iterative deterministic detailed component and system analyses.

METHODOLOGY OF BIG

BIG can be compactly described as a project ecosystem that is comprised of a collection of linked logics to develop a design to a useful end with the key constituent parts being inputs, functions, and outputs (Fig 3). The input/function/output paradigm is a tight assembly of data to be processed (input), code to process the data (function), and data that is the result of the function (output). A BIG model is generated through a directed acyclic graph of these input/function/output assemblies.

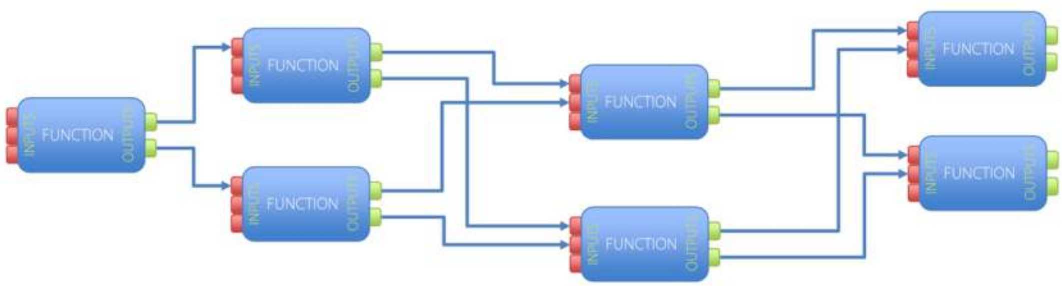

Figure 3: This is a depiction of the functional modeling paradigm.

Inputs are simply sets of structured data that are processed by functions to generate output. Inputs can take the form of a full 3d model, wireframe model, a drawing, spreadsheet, a diagram, database, analysis results, etc. As inputs are regarded as pure data, the BIG process does not depend on conventions such as file formats, software or versioning.

Functions are automated processes that perform a set of explicit tasks on structured data. The term “function” is used abstractly here and can take many forms such as conventional scripting, an application specific tool, or commonly available graph-based programming tools such as Grasshopper for Rhinoceros 3D (Fig 4) or Dynamo Studio by Autodesk. Functions can be created at various scales in the BIG process. A function could draw a line between two points, create a surface between two lines, or populate an entire building façade with unitized curtain wall panels onto a previously created wireframe.

Figure 4: A Grasshopper definition creating connections between sheet and frame.

Outputs can be considered simply as the results of functions that process the inputs at a given stage in the ecosystem. In the BIG workflow, each output is structured to perpetuate throughout the ecosystem. For that reason, it inherits as much of the project intelligence as the format permits and can thus form the basis of a new input for any future functions.

In this context, the process of creating models that use information from combined results of previously generated models is called staging. At each stage the previous input and generating logic is preserved and available to other stages in the project ecosystem.

The core concept of BIG is the ability to store information in a way that is functionally and logically connected with related geometry. This information is organized as attributes. Each entry has a key (name of attribute) and a value (variable associated with the key) (Fig 5). In the BIG framework, attributes have dual roles for describing the geometry and providing meaningful relationships between models in the project ecosystem. As a result, the geometry becomes intelligent through relationships implicitly defined through information, and not necessarily the physical representation of the geometry.

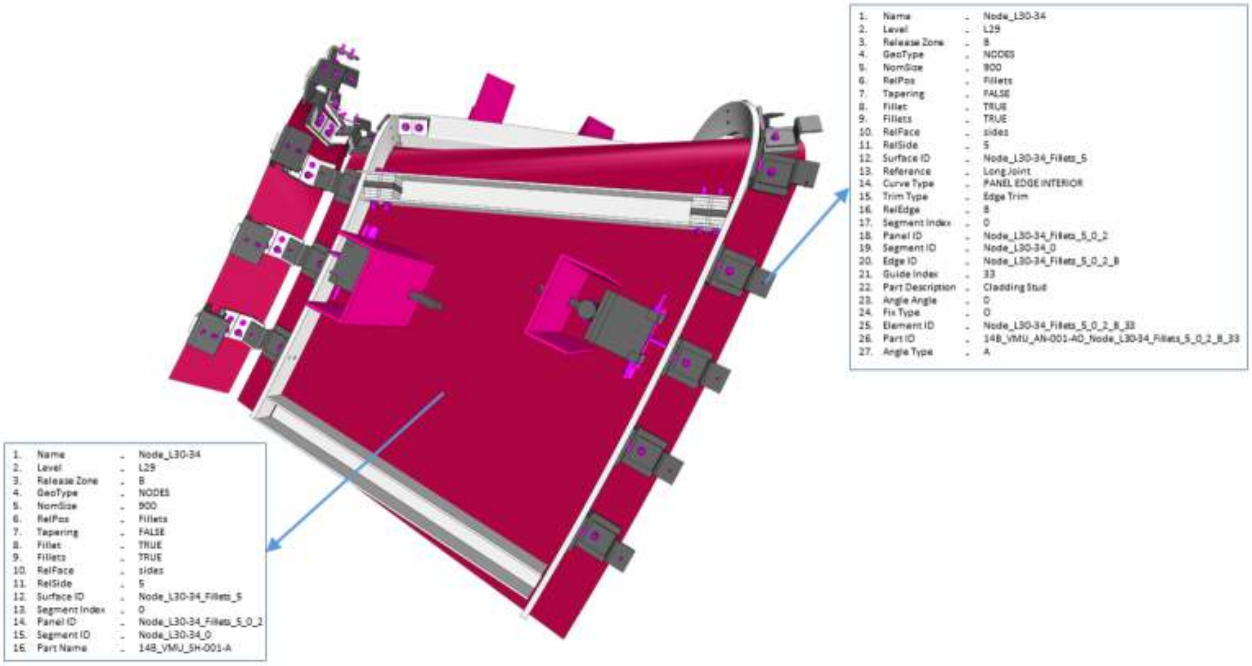

Figure 5: Attributes as key-value store embedded in the geometry.

The relationships between models of each stage are explicitly defined and will remain intact even if the previous models are updated through the defined functions and related attributes. This functionality is an enabler of collaborative design because it makes possible the straightforward and scalable distribution of tasks to more than one person through the explicit preservation of relationships. This environment fosters the discretization and genericization of logics and models, which serves to decrease the size and complexity of any particular model or logic, increasing the legibility of the parametric schemata (Davis, et al. 2011). Compared to traditional generative software, this allows for less complex stages, which are easily managed by a single person, and smaller files that can be processed much faster than a single large file. The discrete stages also allow for rapid error and bug tracking which in turn eliminates errors in modeling and subsequent documentation and fabrication production, yielding potential considerable savings down the project pipeline.

BIG IN PRACTICE

The ultimate product of a BIG project is the structured conveyance of information represented by the model. A project team needs to be able to describe a system to various levels of specificity regardless of complexity, and deconstruct and construct information as needed for any given party in an understandable context (Kokaturk et al., 2011). In a project like City of Dreams there is an inherent complexity given the sheer variability of the Architecture. A single author of a system design may understand this system as whole; however, production realities require that this information must be disseminated to hundreds of individual agents working in multiple capacities across many different physical locations and languages. The constructability of the system requires that the complexity be reduced to a single part drawing that is produced by a single person. This part is then tracked to another location and then assembled into a larger assembly by another person, then brought to another location and assembled into an even larger assembly by another person and so on. This process repeats itself millions of times until the final product is constructed, or rather reconstructed from the model's outputs. Expanded below are selected project specific examples of BIG in practice from City of Dreams - Macau.

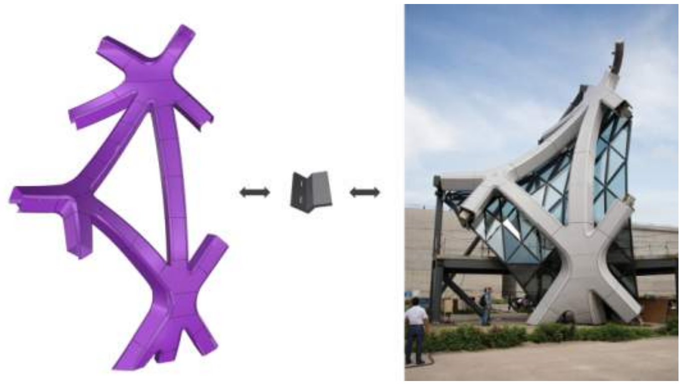

Figure 6: The authors' scope of works for the City of Dreams project is the cladding package shown in purple. The primary goal of a BIG project is to be able to convey complexity in rational and digestible forms across a project ecosystem comprised of hundreds of individual agents all with varying degrees of project knowledge. The documentation process needs to be able to start from a very high level of design description, then work down to a local and specific level (a specific bracket fabrication drawing, for example), and then be able to instruct an agent or agents on how to reconstruct to a very high level.

DETAIL DESIGN FOR A PARAMETRIC PROCESS

As the BIG process has developed, so has the authors' firm's approach to design, detailing, and engineering. Designing and detailing themselves are parametric, and act as diagrams that track fixed versus variable constraints and determine under what conditions certain strategies should be adopted (Fig 7). The drawings themselves become diagrams for functions, codifying an instruction set for how the design is organized and implemented at scale. The BIG workflow encourages this approach primarily for two reasons: 1) this method of designing and detailing reinforces the modeling and documentation process because it is a clear and understandable representation of how the design is implemented, and 2) the reduction of barriers downstream of the design process in analysis, organization, and documentation at scale allows for a highly parametric and optimal solution to be in place at the beginning of design.

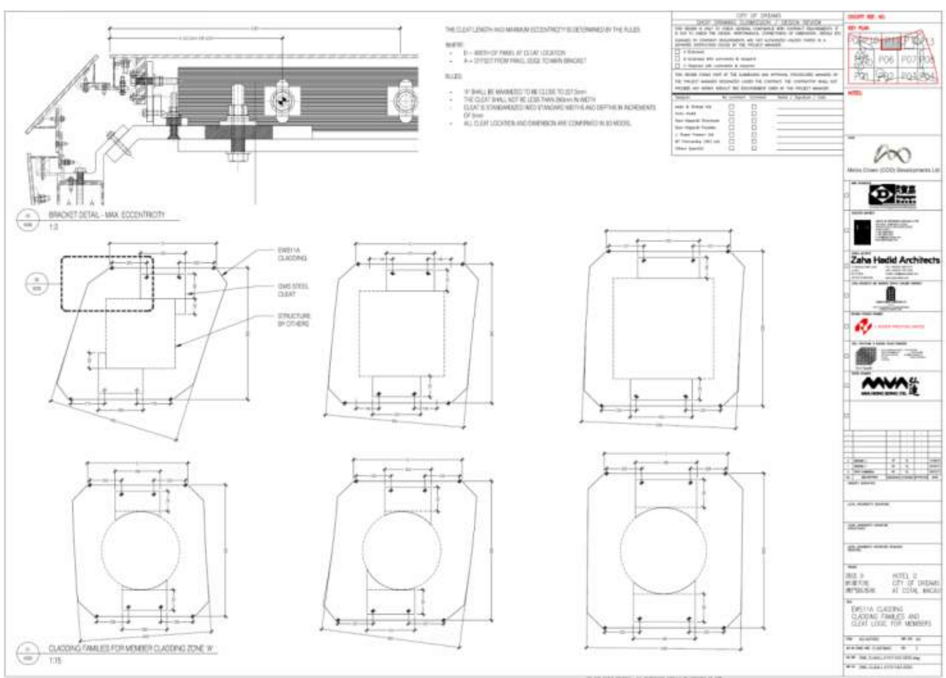

Figure 7: Detail design as a parametric functions. This diagram above is a shop-drawing document represents the logic for the deployment of the cladding primary structure tieback locations. In the project there were more than 17,000 of these attachment brackets and by allowing for a simple, but 100% non-repetitive design created conditions that allowed for easy adjustment for tolerances and installation, and allowed for a vastly reduced complexity in the framing design.

THE PROJECT ECOSYSTEM

For City of Dreams, for the exoskeleton cladding scope, the authors' firm was provided with the following eight inputs to seed the project ecosystem:

- A spreadsheet describing the names and coordinates of the structural steel nodes
- A wireframe model of the structural steel
- A surface model representing the orientation of the structural steel members
- A spreadsheet describing the steel sections of the structural steel members
- A surface model describing the cladding envelope
- A solid model containing geometry that represents the structural steel at the nodes
- Output specifications for the final product
- Fabrication limitations

At the completion of the project, there were 2,925 stages representing the creation, analysis, and documentation of 22,141 cladding panels comprised of more than 1,600,000 framing components (Fig 8). A staff of six people was responsible for the design, engineering, implementation, and full fabrication and assembly information and documentation of the cladding system. Using traditional methods one could easily expect this task to require up to 10 times as many people and the challenges that are present with large teams. This is an example of the kind of order of magnitude of improvement in efficiency that the BIG process can deliver.

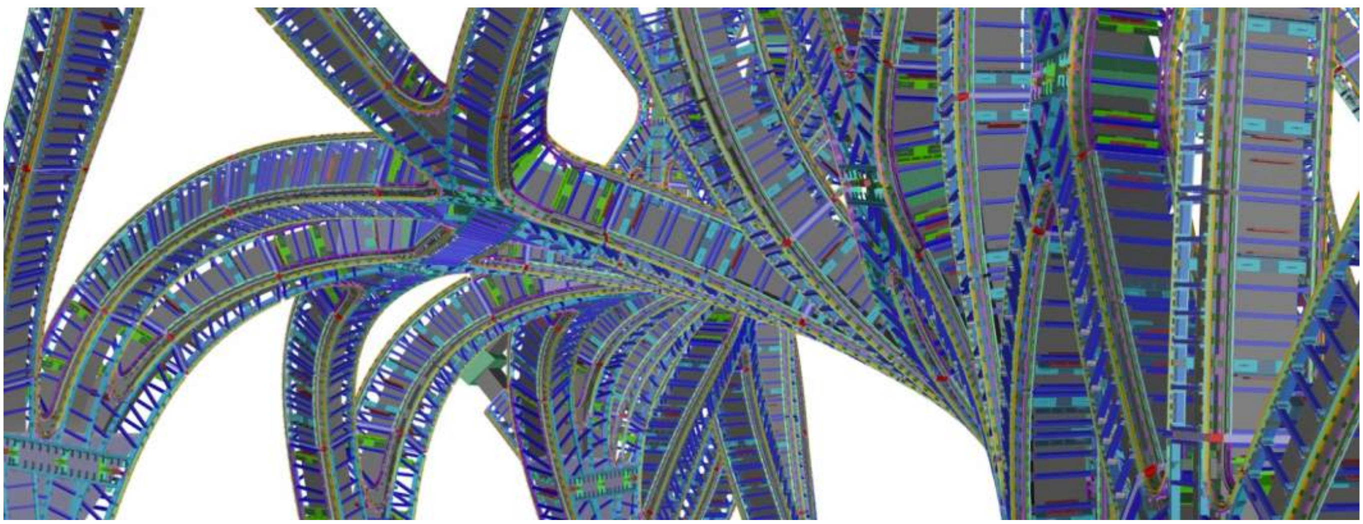

Figure 8: This image is s snapshot of the fabrication model with all framing components modeled.

Functions range in complexity from routines that name envelope surfaces as a concatenation of relative locations to project grid-line markers, to the more complex actions of locating panel stiffeners. For example, in the latter described function the model inputs, all also generated from other functions, would be the following:

- Primary structure support locations
- Primary structure reference planes
- Cladding system support locations
- Inside face of cladding panel
- Structural limitations of cladding panel and stiffener design

The panel stiffener location is a product of where the stiffeners are not permitted (clashes with primary structure, tiebacks, etc.) and the structural capacity of the sheet and stiffener design (Fig 9). The resultant model, or output, would be a fully attributed wire-frame of the stiffener locations inheriting all the location information (from the input cladding panel) and the profile designation from the structural design (Fig 9). Subsequent functions determine things such as the end cut planes, hole locations for welded stud penetrations, and formatted fabrication data for drawing production to name a few (Fig 9).

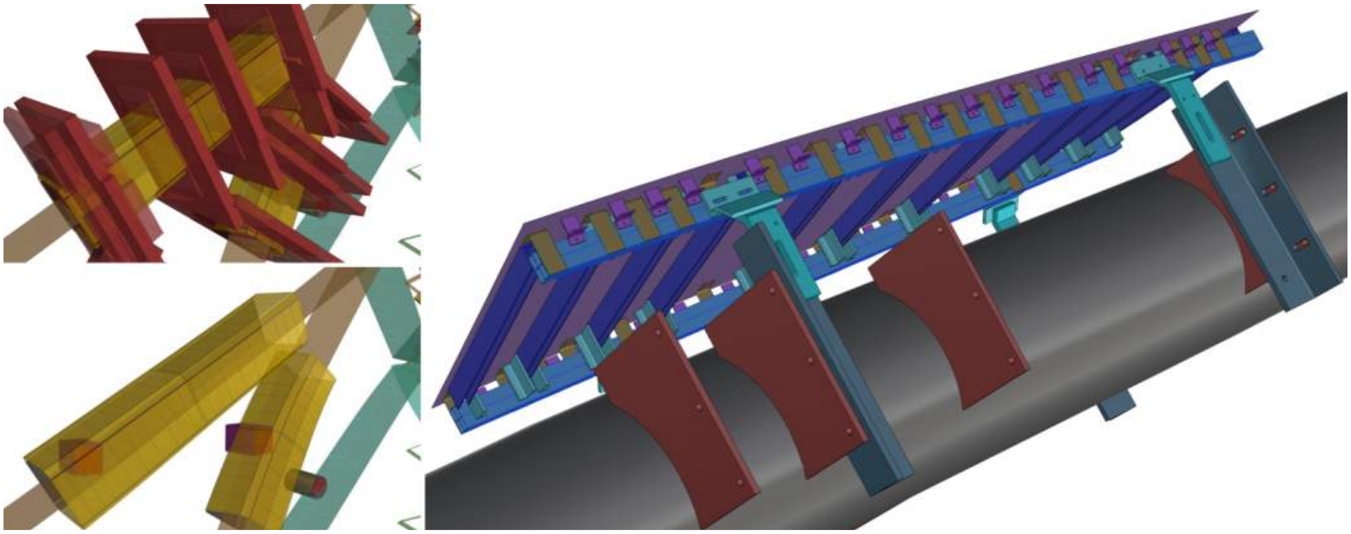

Figure 9: (Top-left) Visualization of the results of the function where cladding panel stiffeners are not permitted. (Bottom-light) Visualization of the resultant output of this function: a wireframe model of the cladding panel stiffeners. Each stiffener wire inherits all attributes of the cladding panel and adds stiffener specific attributes such as location on panel, profile type, etc. (Right) Completed panel with all constituent parts after all generative modeling functions are run and ready for fabrication documentation.

INTEGRATION OF INFORMATION ACROSS PLATFORMS

No software package is capable of performing all of the tasks required to complete any project. Furthermore, many software packages provide similar functionality in overlapping areas, but with varying degrees of resolution. Notwithstanding the traditional limitations of software interoperability, the highly structured information and modular design developed in BIG facilitates intelligence to move readily between software packages by being able to mold the data into natively understandable formats.

Engineering analysis of highly variable component systems is readily addressed using BIG. Project-wide engineering solutions for systems with extensive variability can often be overly conservative as they address worst-case scenarios, which can lead to an over-designed system for significant portions of the project. Thus, it is important to be able to empirically analyze and validate all parametrically derived components in an accessible format to ensure that the parametric rules being applied meet element-specific engineering requirements. Often this is as simple as a function producing tabular component data. The tabular data is then analyzed in Microsoft Excel, for example, and returned to the base model to apply the results of the external analysis. Since the data is structured, and the functions explicitly defined, this process can be iteratively run until some deterministic condition is met to satisfy engineering constraints without operator intervention.

Often, more detailed analysis is needed to either a) optimize the design in a specific way to meet an external constraint or b) provide feedback on the viability of a design as it is applied to tens of thousands of conditions. For City of Dreams, a function was created to translate the 3d model geometry to a Strand7 FEA model. A real-time link is established between the two software packages and the structured, attributed data is passed through. The resultant FEA model is a complete, fully and accurately restrained analysis model including panel specific shape, framing components, support locations, applied live loads (wind load, panel specific maintenance load, etc.) All elements are analyzed using the FEA solver and then the resulting data is returned (Fig 10). This allows the design team to test all conditions to identify and correct potential problems, optimize framing selection to reduce overall material usage, and achieve a high degree of confidence in the application of the engineering constraints being applied.

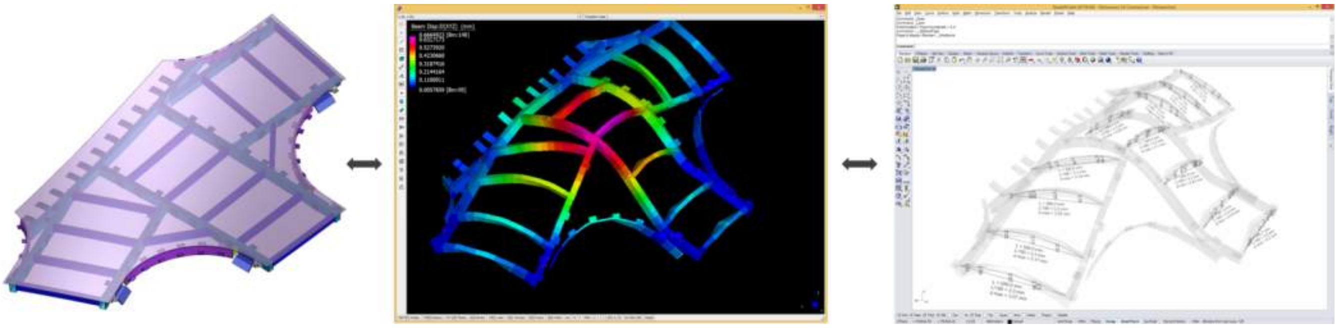

Figure 10: (Left) Fully modeled panel in Rhinoceros environment. (Middle) FEA model of showing deflection analysis in Strand7 for a single panel in the City of Dreams Project. (Right) The same data returned to the Rhinoceros environment and the deflection data analyzed on a per object basis to check compliance with the specification.

QUALITY CONTROL

Robust and well-designed QA/QC practices are critical to the success of any project, especially in projects where systems have functionally unlimited variability. Given the fabrication data output for a component can be treated as an input into another stage in the project ecosystem, automated tests can be readily created to verify fabrication data. In the case of City of Dreams, generated fabrication data is read and used to reconstruct model components, which are then verified against the as-modeled components. Since the reconstructed parts inherit all location and naming conventions from the generated fabrication data, running a part-by-part check is computationally trivial as model look-ups are kept strictly to a 1-to-1 comparison instead of a 1-to-many comparison. Any discrepancies are automatically reported, identified by the stage, and corrected by the modeler. The benefits of automated tests are numerous, with the chief benefit being functionally 100% crosschecked fabrication data reducing the scope of downstream fabrication errors and material waste.

AUTOMATED DRAWING PRODUCTION AT SCALE

Drawing production, conceptually, follows a specific series of instructions to create the drawing. Each line drawn has a specific meaning as well as a specific relationship to other lines. In this way, drawing can be thought of as a rule-based process. When all content is present and the relationships are known, it is clear what the drawing should contain. All that needs to happen then is to apply the rules to the content. This rule-based approach is compatible with generative modeling. The content is represented by 3d models, the relationships are determined by the design of the system and the rules can be converted into functions to produce a drawing (Fig 11).

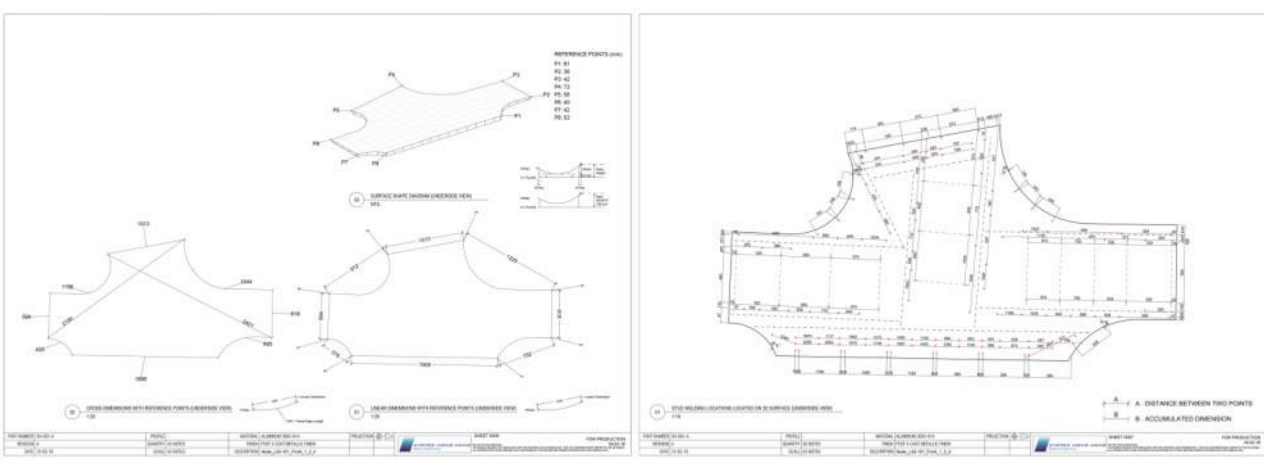

Figure 11: This is an example of an automated, rule based fabrication drawing that is a result of a function. This is one of the 66,423 drawings produced of this type for the City of Dreams project. Over the course of the 9-month production period for City of Dreams, this translates to 369 drawings produced per day for only this type of component, with each drawing being unique.

CONCLUSION AND FUTURE WORK

A design and the traditional BIM model that represents it are likely to be unfit for reuse, as no two buildings are identical. However, the inherent codified project intelligence and knowledge can be re-used. The BIG approach demonstrates the advantages of structuring the processing of information and dividing these processes into generic operations that are separate from project specific operations. This discretization fosters knowledge reuse and enables project teams to focus on improvements to the process and project-specific advancements in research and design. Knowledge itself can be incrementally added to the workflow thereby creating an intelligent process. Future research and development of this process will include creating a more user friendly and software-agnostic platform. The BIG process represents an opportunity to further shift the role that designers perform in the production of design and fabrication information. The role of manually producing singular instances of 3d models, as in the traditional BIM process, is shifting to being one of rule makers who establish logical relationships and build team consensus about project knowledge and execution. The influence this has on design and fabrication is significant, and it echoes the potentially enormous impact on the industry as a whole (De Landa, 1991). The centuries-old profession of architecture is in the process of being encoded and at least partially being entrusted to machines, with all of the workflow restructuring and culture changes that this entails.

The adoption of technology-enabled distributed generative intelligent knowledge capture and collaborative information management processes as described here, is likely to be scalable. Their influence will increasingly help to augment the course of innovation and productivity in the global industry of the built environment.

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All images are provided courtesy of the authors.

REFERENCES

Aish, Robert. Migration from an individual to an enterprise computing model and its implications for AEC Research. Berkeley-Standord CE&M Workshop, 2000.

Davis, Daniel, Burry, Jane, Burry Mark. Untangling Parametric Schemata: Enhancing Collaboration through Modular Programming. CAAD Futures 2011: Design Together, 2011. 55-68

De Landa, Manuel. *War in the Age of Intelligent Machines.* Zone Books, 1991.

Eastman, Chuck, Techholz, Paul, Sacks, R., Liston, K. BIM Handbook; A Guide To Building Information Modeling. John Wiley and Sons, Inc., 2008. Chapter 9

Holzer, Dominik. Optioneering in Collaborative Design Practice. International Journal of Architectural Computing, 8(2), 165-182.

Hudson, Roly, Shepard, Paul, Hines, David. Aviva Stadium: A case study in integrated parametric design. International Journal of Architectural Computing, 9(2), 187-203.

Kieran, Stephen, Timberlake, James. Refabricating Architecture: How Manufacturing Methodologies are Poised to Transform Building Construction. McGraw-Hill, 2004.

Kock, Jeffery, Bradley, Benjamin, Levelle, Evan. The Digital-Physical Feedback Loop: A Case Study. Proceedings of the 32nd Annual Conference for the Association of Computer Aided Design in Architecture. 2012. 305-314

Kokaturk, Tuba., Medjdoub, Benachir. *Distributed Intelligence in Design.* Blackwell Publishing Ltd., 2011.

Shea, Kristina, Aish, Robert, Gourtovaia, Marina. Towards Performance based generative design tools. Digital Design, 21st eCAADe Conference Proceedings. 2003. 103-110

van der Heijden, Ramon, Levelle, Evan, Riese, Martin Parametric Building Information Generation for Design and Construction. Proceedings of the 35th Annual Conference for the Association of Computer Aided Design in Architecture. 2015. 417-429

LIGHT AS FORM GENERATOR

Workflows for performance-based generative design


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ABSTRACT

This paper presents the use of Generative Design Systems to the design and optimization of facades with complex geometries. The design process was tested in the context of an advanced professional level Masters degree at UC Berkeley, Studio One. First, the geometries designed in studio are tested for their daylighting effectiveness, when applied to a virtual test cell. High accuracy daylighting simulations test the amount of light that permeates through the façade components, in terms of several daylighting metrics, both point-in-time and climate-based. Interior render images are created for specific days and times of the year, to provide a qualitative impression, as a fundamental complement to the quantitative approach. Physical prototypes, built using 3D printing and other rapid prototyping technologies, were taken to Lawrence Berkeley National Laboratory for physical measurements, to help validate simulation results. The complex geometry of the façade components is progressively fine-tuned, until more clear insights on what factors make the façade performance improve are achieved. The design is then fed to a Generative Design System, powered by a Genetic Algorithm, that uses the previously gained insights to generate more optimized geometries, in an inverse-design process, while following the design intentions of the architect. Finally, the new design produced by the Generative Design System is simulated in terms of daylighting, rendered in interior movies, and 3D printed in its final configuration. This relation between design and scientific approaches has proved highly fruitful at producing results that display both a high performance in terms of daylighting behavior, and compelling aesthetic conditions.

KEYWORDS

Generative design, daylighting - glare – shading, design optimization, physical testing - mockups, 3D printing, teaching - courses - degree programs, parametric workflows

INTRODUCTION

In recent years, advances in computation have made a large number of new tools available to architects, ranging from modeling and visualization to performance simulation to rapid prototyping. New workflows that seamlessly integrate these technological advances into the design process, from early design stages, have thus become a major area of interest, both in the research and professional domains. This paper presents an experimental approach developed in the context of the professional one-year MArch program at UC Berkeley, Studio One.

The workflow developed allows the progressive development and fine-tuning of façade characteristics, and its integration with whole-building design and performance, by generating a succession of feedback loops between design and performance simulation, each addressing specific scales and design stages. This workflow was successfully applied by the eleven students in the course, all of them holding professional degrees in architecture, to address different design questions and approaches, thus proving to be highly flexible and applicable in real life situations. Due to space limitations, only one example will be described in detail in this paper.

BACKGROUND

In the DIVA-for-Rhino project (Jakubek et al, 2011), the NURBS-based 3D modeling software Rhinoceros (McNeel, 2009) has been recently coupled with Radiance, a backwards raytracing lighting simulation engine, developed by Greg Ward at Lawrence Berkeley National Laboratory (Ward et al, 1988, 1998, 2005). This development allows an unprecedented access by architects to one of the best available light simulation software, which had traditionally suffered from a lack of an adequate Graphics User Interface, thus confining it to be used mostly by lighting professionals and other specialist users.

The subsequent inclusion in DIVA of EnergyPlus, a powerful whole-building energy simulation engine, has made possible the emergence of integrated studies between lighting and energy performance of facades with highly complex geometries (Omidfar, 2011). Furthermore, the combination of Grasshopper, the visual programming parametric modeler of Rhino, with Genetic Algorithms (GAs), implemented in Galapagos (Rutten, 2011), has made the use of GAs and generative design also accessible to an unprecedented number of non-specialist users. Genetic Algorithms were invented by John Holland in the 1970's (Holland, 1975) and later made known to a broader audience by David Goldberg, one of Holland's PhD students (Goldberg, 1989). Since then they have been widely used for stochastic optimization of problems in a high diversity of fields, and have recently become widely popular within the architecture domain. A GA starts by generating a number of possible solutions to a problem, calculates their fitness (objective function value), and applies the basic genetic operators of reproduction, crossover and mutation to the initial population, in a stochastic hill-climbing process. This generates a new population with higher average fitness than the previous one, which will in turn be evaluated. The cycle will be repeated for the number of generations set by the user. For more detailed information on GAs, see Goldberg, 1989.

Generative design in architecture has its roots in the late nineties, with the work of Monks in acoustics (Monks et al, 2000), Shea in structures (Shea et al, 1997, 1999) and Caldas in energy and daylighting (Caldas et al, 1999; Caldas, 2008). Since then, the field has dramatically expanded, and has become a major area of research in architecture and computation. In daylighting, some relevant recent work includes Andersen et al. (2008), Gagne et al. (2012) and Caldas et al (2016).

Daylighting simulations of complex façade systems have recently benefited from a major development, with the introduction of bidirectional scattering distribution functions (BSDF) simulations in Radiance (Ward et al, 2011). The high degree of reliability of these simulations (Saxena et al., 2010; Konstantoglou, 2011; McNeil et al., 2013), has provided new confidence for designers to use Radiance-based simulations in lieu of actual measurements of physical prototypes.

These new developments in available software and computational simulations of building performance, and their access to architects who are not specialists in sustainable design and energy simulations, requires the development of new approaches and workflows to ensure that the potential benefits to the added sustainability of the building stock are realized in practice. This paper describes and educational experiment in this domain.

METHOD

During the Fall semester, Studio One students developed a skin component solution, loosely inspired on biomimecry. Student Eleftheria Stavridi developed a large-scale mock-up loosely inspired by a pine cone, built out of concrete with white ceramic inserts that allow light through (figure 1). The trapezoidal ceramic elements vary in scale, orientation and size of aperture, to create diversity in the modes of capturing light.

Figure 1: The geometry of the pine cone surface (left) served as inspiration to the building skin concept developed by student Eleftheria Stavridi in the first semester of Studio One (right). The physical mockup was built out of concrete, with white ceramic inserts.

Further refinements of this concept lead to the adoption of a single material, and to the inclusion of both 'positive' (facing outside) and 'negative' (facing inside) prisms to better capture daylighting. The main design variable under study was the scale of the skin elements. A small scale creates a finely textured skin, while a larger scale generates a skin with high geometric variability, a strong tectonic texture, and marked light and shadow contrasts (figure 2).

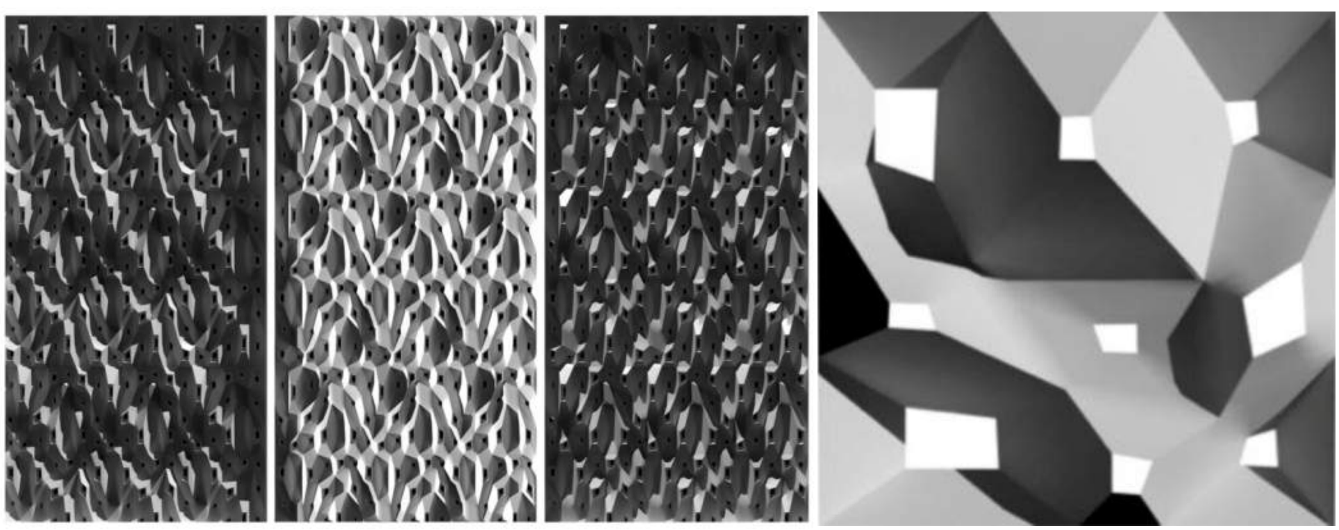

Figure 2: The initial concept depicted in figure 1 was further developed to consider the impact of scale. To the left, the visual effect of reducing the scale of the light capturing elements (three alternatives, under different light conditions). To the right, the visual effect of increasing the scale of the light capturing elements.

During the Spring semester, Studio One students were required to attend a graduate seminar, Light as Form Generator (http://162.144.122.118/~arch249/), in parallel with the Spring studio, to help them further develop their initial façade concepts to achieve the type of daylighting ambience desired for their buildings. The first step of this seminar adopted a 'reality check' approach, making students assess the daylighting performance of the façade system that they had previously designed in studio, without any daylighting domain-specific knowledge, not to computer simulations or physical measurements of prototypes.

In the design presented in this paper, the student had a specific research question in mind, regarding the effect on daylighting patterns of altering the scale of the skin elements. The goal was to create a building skin that would allow the existence of sun beams crossing the space at different days and times of the year, with different incident angles. The existence of a clear research question greatly improved the quality and effectiveness of the work produced, as it motivated a strong interaction with the work simultaneously developed in studio.

As an initial step, the geometries designed in studio were tested for their daylighting effectiveness using computer simulations. The 3D models for the two façade scale alternatives were applied to a virtual test cell, with dimensions 4x7x3m (figure 3). Daylighting simulations, performed with Radiance, were used to test the amount of light that permeated through the two versions of the façade components. Simulations were performed for several daylighting metrics, from traditional point-in-time (illuminance) to more recent climate-based metrics such as Daylight Autonomy (Reinhart et al, 2001) and Useful Daylight Illuminance (Nabil et al, 2005, 2006).

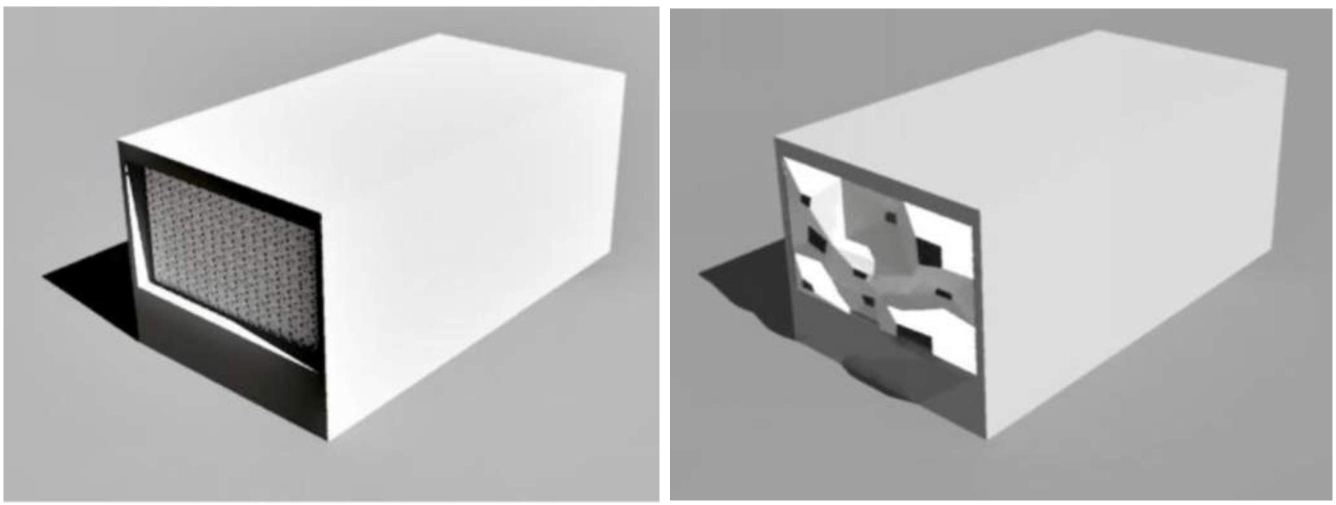

Figure 3: The 3D models for the two façade scale alternatives were applied to a virtual test cell, with dimensions 4x7x3m, to perform computer simulations of different daylighting metrics. Left: Small-scale alternative. Right: Large-scale alternative.

DATA

Radiance simulation results show that, in general, both versions of the building skin under study allow limited amounts of light into the building, thus creating a rather dark environment. Additionally, both systems perform in a similar way, in terms of the amount of light they admit. However, they do perform differently in relation to the light patterns that they create in the space. While the small-scale version (v1) created a 'dotted light' environment, the large-scale version (v2) is able to generate the type of direct sun beams that the architect was aiming for. These results are seen both in figures 4 and 5. The sectional results of v1 in figure 4, for a south orientation and noon, show the emergence of light dots in the space, while the results of v2 show light beams being generated, due to the effect of the larger scale of the openings. For a west orientation, in late afternoon (5pm), figure 5 shows that solution v2 allows light beams to cross the space and hit the back wall of the test cell, while the smaller openings on v1 once again are able to generate a smaller, dotted pattern in space. Based on this information, the student selected the large-scale solution (v2) to continue the work.

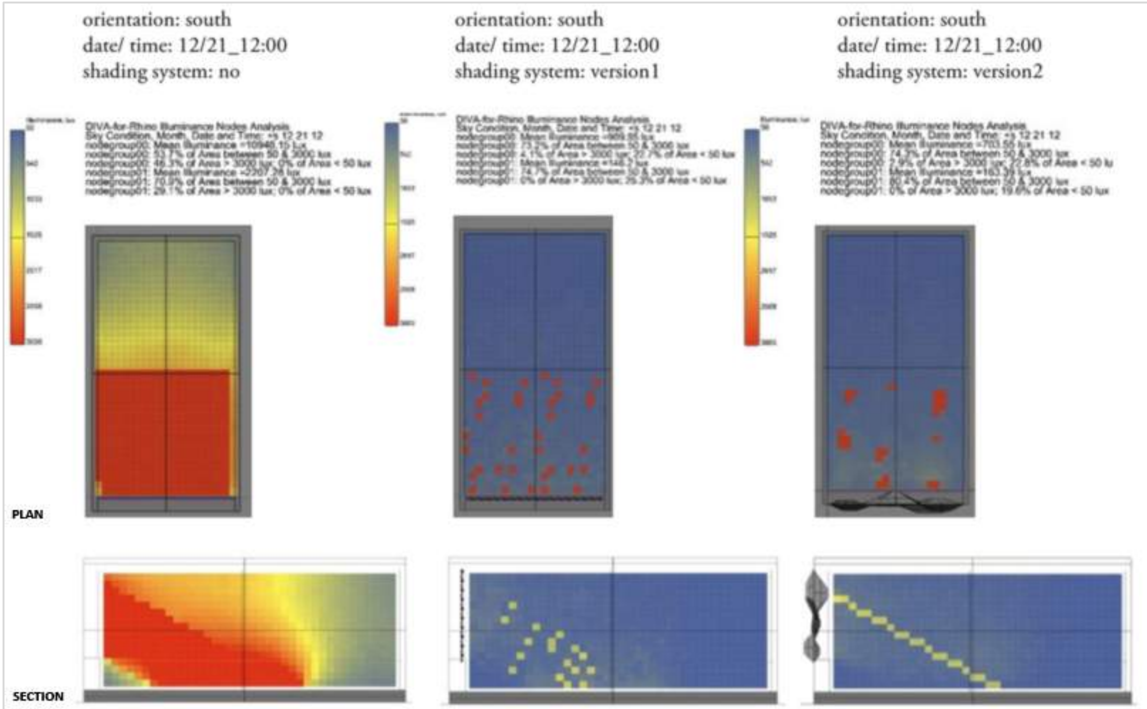

Figure 4: Illuminance simulations for a south-facing test cell, at noon. Left: Cell with glass only; Middle: Cell with small-scale shading system (v.1); Middle: Cell with large-scale shading system (v.2). The large-scale system provides the desired lighting effect (beams of light), while the small-scale system creates a more dotted light pattern.

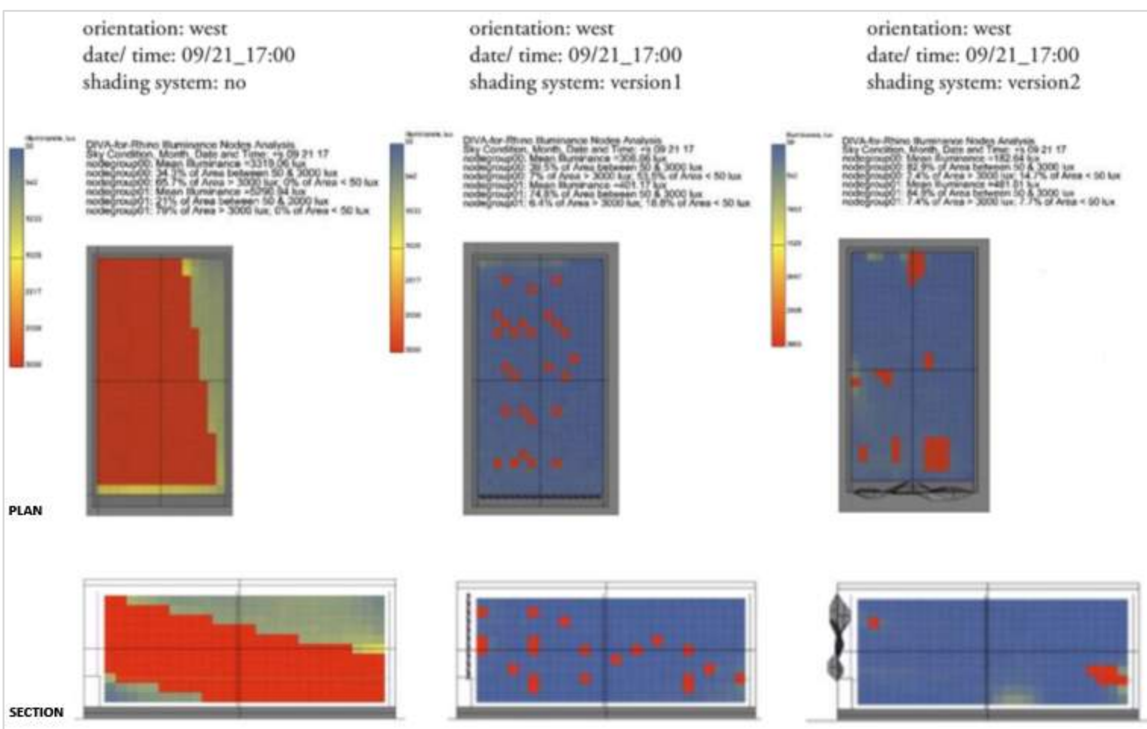

Figure 5: Illuminance simulations for a West-facing test cell, at 5pm. Left: Cell with glass only; Middle: Cell with small-scale shading system (v.1); Middle: Cell with large-scale shading system (v.2). The large-scale system provides the desired lighting effect (beams of light), while the small-scale system creates a more dotted light pattern.

The quantitative information provided by the illuminance simulations was then complemented by qualitative information (renders) that allows the architect to gain a better understanding of the aesthetical condition of the proposed design (v2), and the lighting environment that it generates. Interior renders (Figure 6) were created for specific days and times of the year, to provide a qualitative impression, as a fundamental complement to the quantitative approach. The presence of strong light beams in the space was confirmed by this visualization experiments. As the renders were not done using volumetric lighting, the beams themselves are not seen, but their effect on the surrounding surfaces can be easily identified.

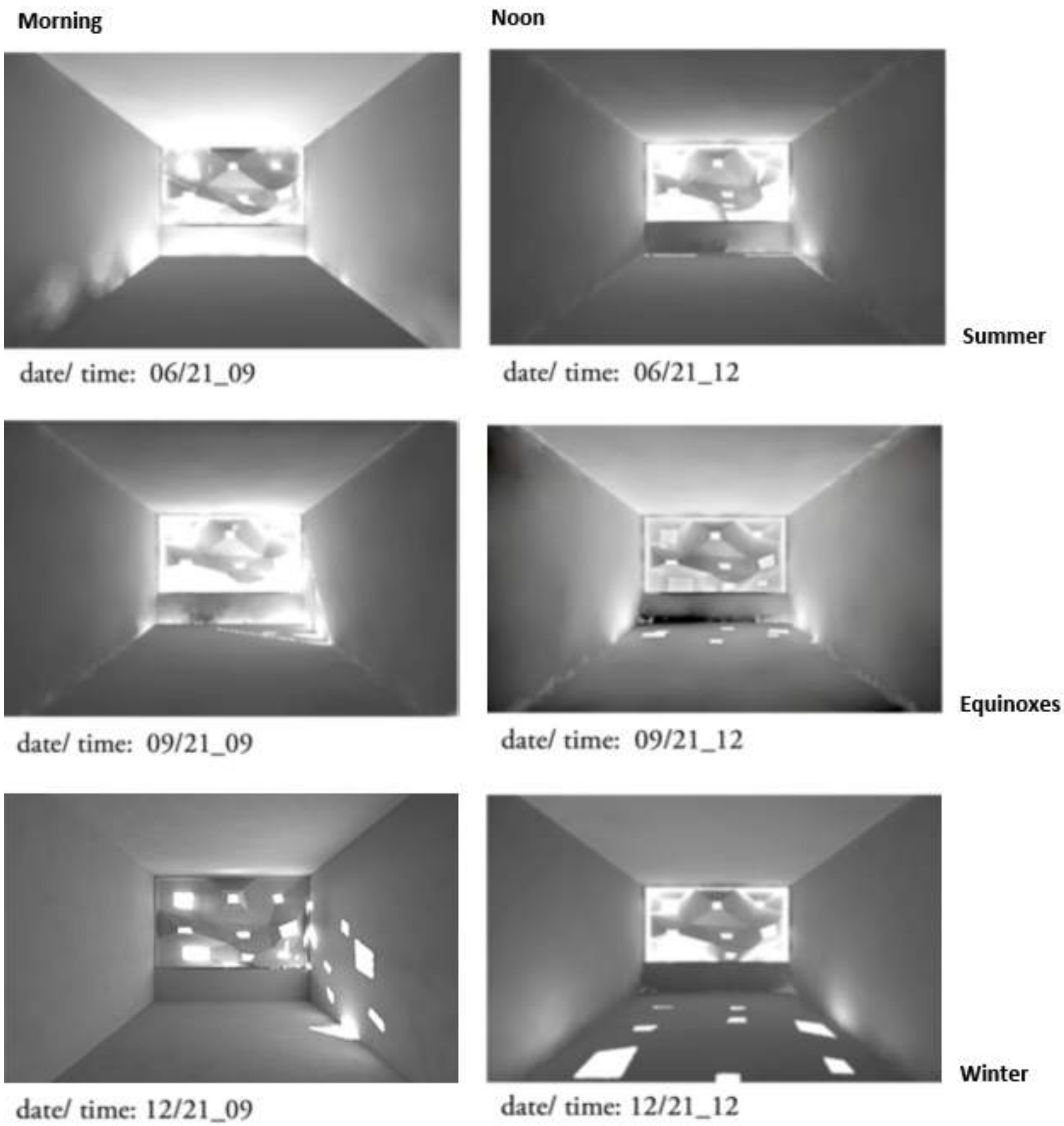

Figure 6: Interior renderings of south-facing cell with large-scale shading system (v.2), at different days and times. The patterns of chiaroscuro provide texture and resonance to the building façade. Direct sun beams permeate the skin at different times of the year, producing long beams crossing the space when the sun is low enough (as in the winter solstice, at 12pm).

In a parallel research path, physical prototypes of the small-scale skin system were taken to Lawrence Berkeley National Laboratory (LBNL) to perform daylighting measurements, to help to interpret and validate simulation results. Given the size constraints, it was not possible to prototype the larger scale version. Even in the case of the small-scale prototype, due to relative large dimensions of the prototype and its geometric irregularity, the only light measurement device that was possible to use at LBNL was the Integrating Sphere, as the goniospectrometer requires smaller samples, mostly with uniform geometry. The 20x20 cm prototype was placed in the Integrating Sphere, as illustrated in figure 4, and Visual Transmittance measurements were taken at 5-degree intervals, with 0 being the normal direction to the sun, and 80-degree being the maximum deviation from the normal that was measured. After an initial alignment with the sun position, at the day and time of the measurements, the sphere is rotated in relation to the normal, and sequential measurements are taken. Two series of measurements were performed, one for the sample placed with the trapezoidal openings pointing outwards, as shown in figure 7 (middle), and one with the trapezoidal elements pointing inwards (left).

Figure 7: Left: 20x20 cm physical prototype used for light transmission measurements. Middle: View of sample attached to the Integrating Sphere at Lawrence Berkeley National Laboratory, in the 'outside facing' position. Right: View of Integrating Sphere while rotating for measurement of light transmission at different incident angles.

Results from measurements at LBNL are shown in figure 8. In general, the Visual Transmittance of the sample is very low, oscillating between 2% and 4%. The 'outside facing' sample has a transmittance about 3% in angles of incidence closer to the normal to the sun position, dropping to about 2.5% when the angle of incidence is above 45 degrees. The 'inside facing' sample has a transmittance about 4% in angles of incidence closer to the normal to the sun position, taking advantage of the scooping effect of the larger white ceramic opening, but decays to about 2% at larger angles of incidence (Figure 8). These measurements helped to validate computer simulation results, confirming the low illuminance levels registered in the test cell interior.

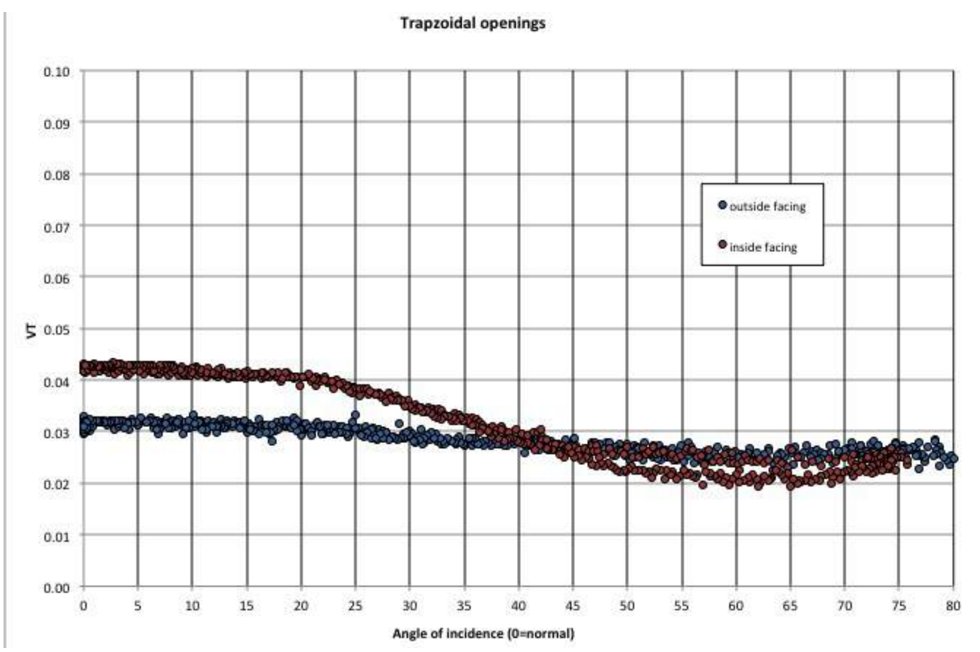

Figure 8: Visual Transmission (VT) measurement results for the sample, at different incident angles. 'Outside facing' results, in blue, correspond to the trapezoidal opening pointing outwards, as shown in figure 4, middle. 'Inside facing' results, in red, correspond to the trapezoidal opening pointing inwards.

After reaching the decision of adopting the large-scale façade components, due to their capacity to generate direct sun beams in the space, the student progressed to integrate those components in the building design that was simultaneously being developed in studio. The daylighting simulations and the physical measurements at LBNL had also helped to make clear that the selected façade system alone would not be able to provide the necessary amount of light for an adequate daylighting of the space. It was then decided to include a large skylight to provide the necessary daylighting levels, while the skin system would mostly be responsible for creating the atmosphere of floating sun beams within the space.

The interior renders produced (figure 9) and the schematic building section (figure 10) represented the next step of design development, and served as the basis for the application of parametric and generative design approaches to the fine-tuning of building proportions, façade characteristics, and skylight design.

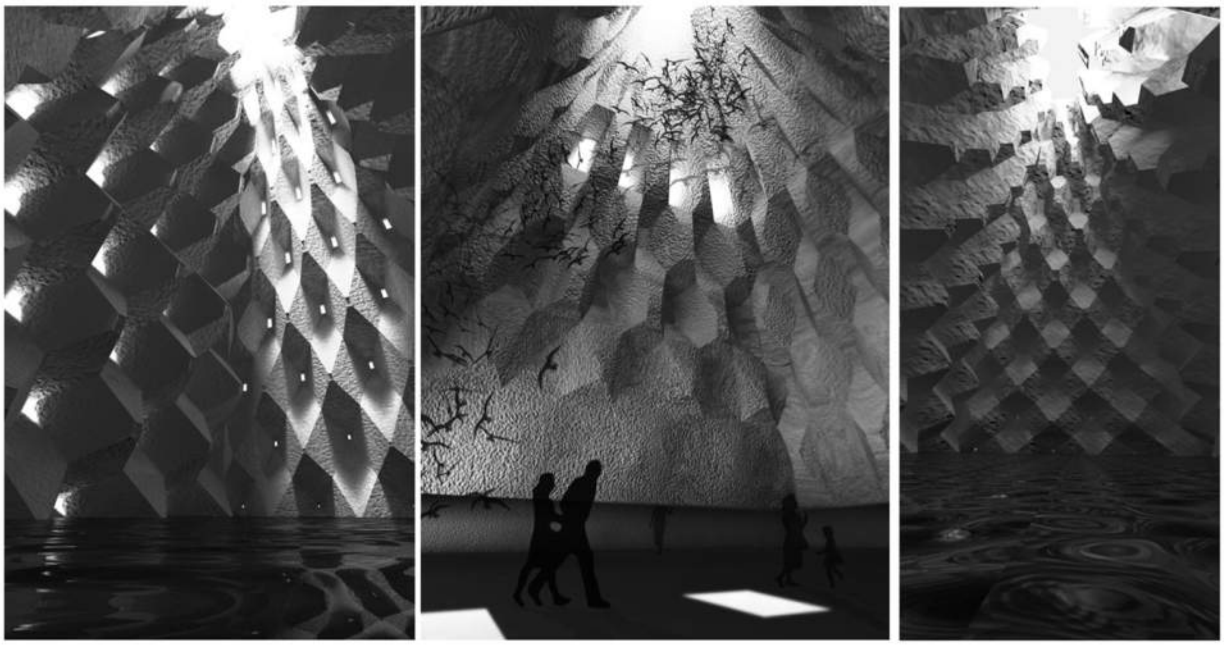

Figure 9: Visualization of intended interior of the spa building, with the desired granularity for the skin, and skylight added.

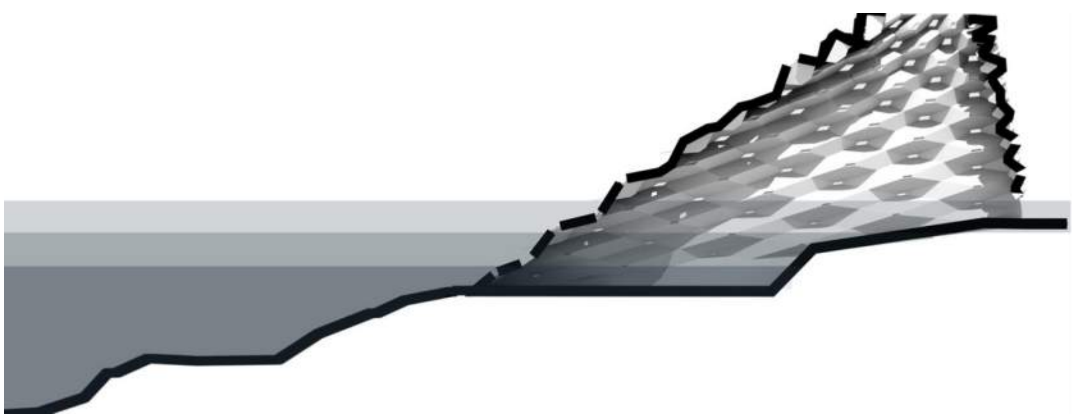

Figure 10: Schematic building section.

The student then produced a parametric model of the proposed building, implemented in Rhino and Grasshopper. The variables under study were the shape of the truncated pyramid building, the size and position of the skylight, and the size and granularity of the façade components, which were constrained to meet the approximate scale and dimensions that the previous simulation studies had suggested (figure 11).

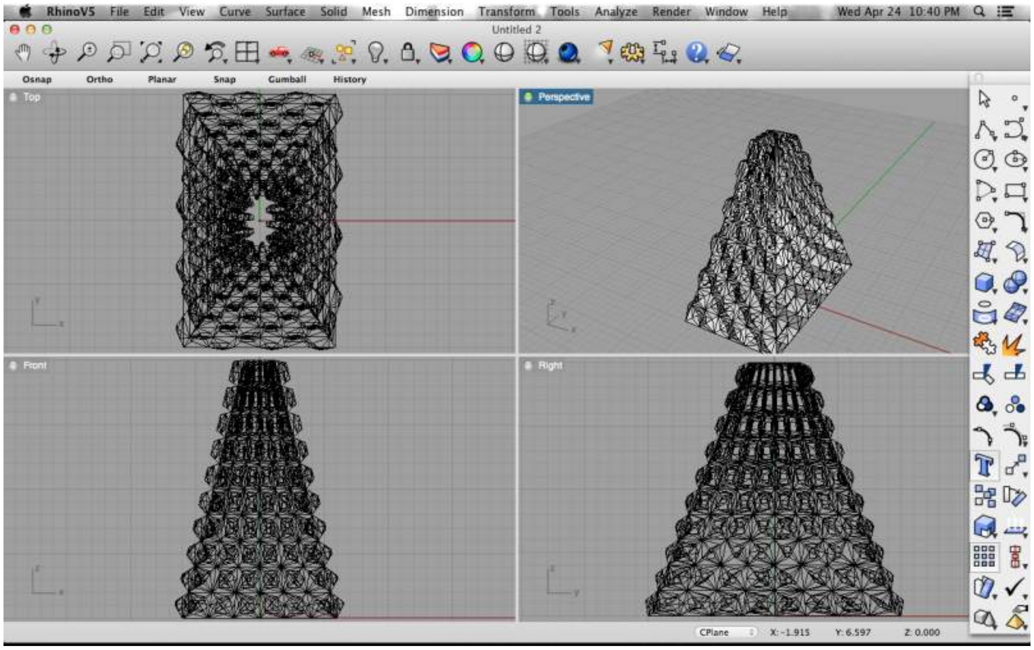

Figure 11: Parametric model of building shape and skin granularity, in Rhino and Grasshopper.

At this design stage, the overall daylighting goal set by the architect was to achieve a Daylight Factor (DF) of 5% throughout the space. DF is a simplified measure to assess the general illuminance levels of a space, but it was fast and simple enough to allow a large number of simulations to be quickly performed, to support almost real-time feedback to the designer as she was parametrically updating the building. By manually controlling the Grasshopper sliders, the student was able to iteratively generate a combination of variables that created the interior light conditions that she was looking for. Figure 12 illustrates the results produced. The yellow color in the results plan corresponds to a DF of 5%, the desired goal. The red stripe indicates the large horizontal glass area that marks the entrance of the building (see section in figure 10), and is not considered as part of the overall daylighting solution. The orange spot under the skylight indicates the effect of the large horizontal glass above. In general, the lighting conditions throughout the space were very close to the intentions of the architect. The building design was considered by the architect as highly satisfactory, thus proving a successful combination of both quantitative, performance-based requisites, and aesthetic design intentions.

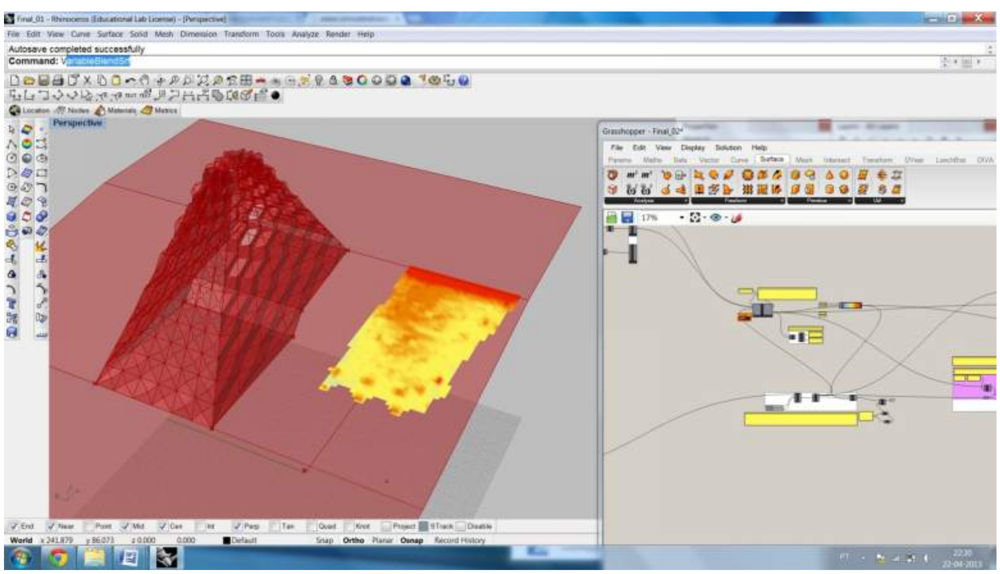

Figure 12: Parametric model of building shape and skin granularity, in Rhino and Grasshopper.

The last step of the design workflow was to progress from parametric design into generative design. The student used Galapagos, the genetic-algorithm (GA) based plug in for Rhino, to control the Grasshopper sliders, instead of controlling them manually. The daylighting design goal remained the same: achiving 5% DF throughou the space.

EXPLANATION

Genetic Algorithms are stochastic processes, which start by generating random combination of design variables and progress in a guided search based on the relative merit of the different design solutions generated. After a number of generations, a GA is typically able to find high-performance solutions to meet the problem specifications set by the user, within design constraints that are also user-specified. Thousands or millions of solutions are usually simulated in the course of a GA optimization, with many of them being random combinations of the proposed design variables, particularly in the early stages of the process. As an illustration of the GA operation process, figure 13 illustrates a poor quality solution generated by the GA, where the solution space is mostly colored in blue, indicating a very dark space (between 0-2%, according to the scale on the left). The only exception is once more the bright are near to the horizontal glass that marks the entance, shown in red in the simulation results.

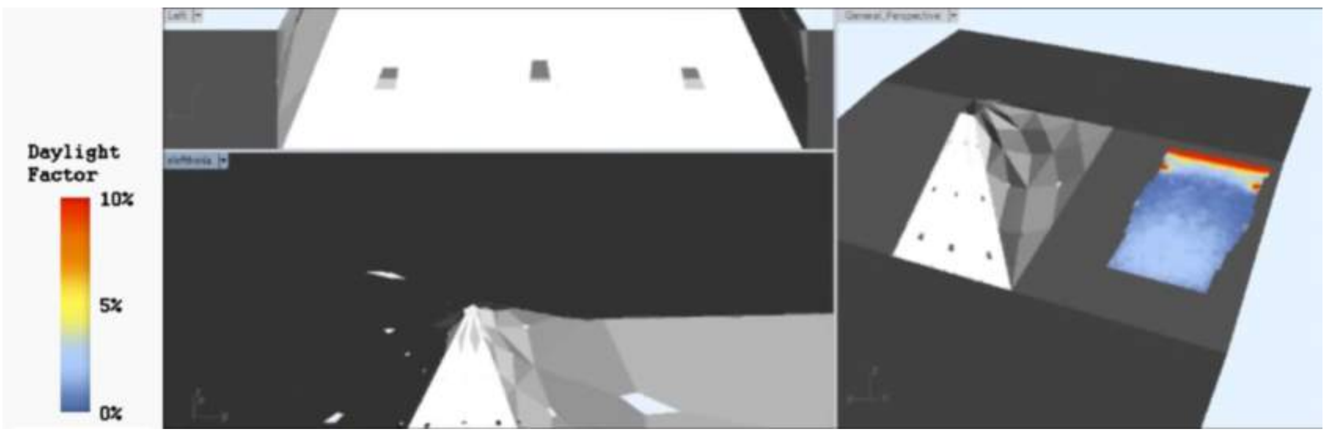

Figure 13: A combination of a small skylight and a high granularity for the façade, with a large number of punctures holes, created an over lit environment for the spa.

Figure 13 shows three different views of the building. The right image is the same as used in figure 12, including both a birds-eye view of the exterior building volume, and the plan showing daylighting simulation results. The top left image is a close-up view of the exterior building façade, showing the scale and size of the trapezoidal skin volumes, and the openings for light penetration. The bottom left image is a view of the building interior, looking up. It is possible to see the size of the skylight above, and the interior view of the building skin. In this solution, there is a combination of a small skylight with a building skin that is very closed, with few trapezoidal elements for capturing light, and small openings carved in them. It is thus not surprising that the interior lighting environment is so dark.

By contrast, figure 14 shows a GA-generated solution that is too bright. A large area of the solution plan is colored in red, what indicates a DF of 10% or above, thus creating the risk of glare and overheating. The skylight generated in too large, and the façade has a high density of trapezoidal pyramids, all contributing too an overlit interior environment.

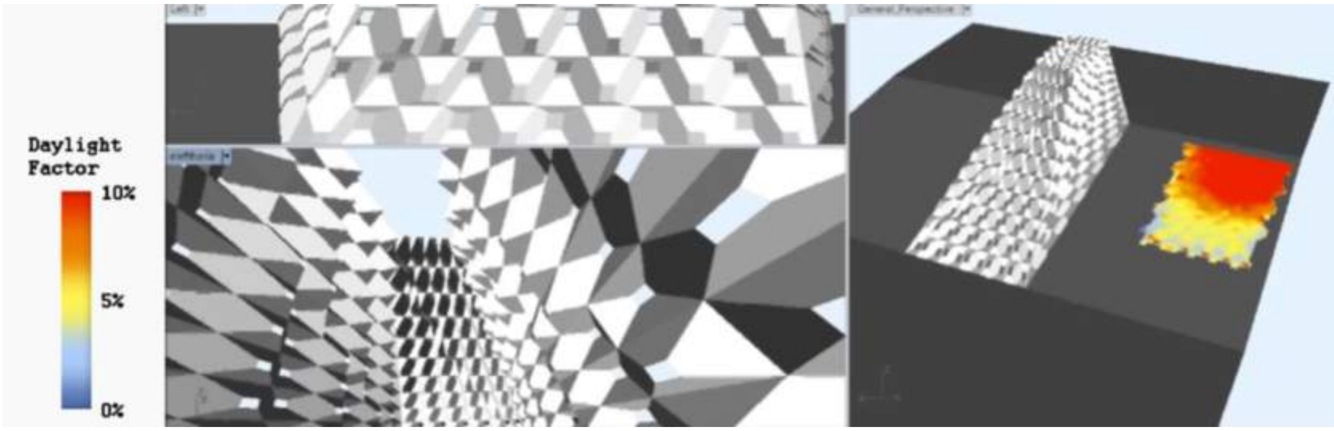

Figure 14: A combination of a large skylight and a high granularity for the façade, with a large number of punctures holes, created an over lit environment for the spa. The off-centered skylight promotes an uneven pattern of light.

Finally, figure 15 illustrates the final result of the GA run, displying the best possible solutuion that Galapagos could find for the problem. To see the video of the optimization process runningg in real time, please scan the QR code in figure 16, to access the web page with the respective movie (http://162.144.122.118/~arch249/eleftheriastavridi.html).

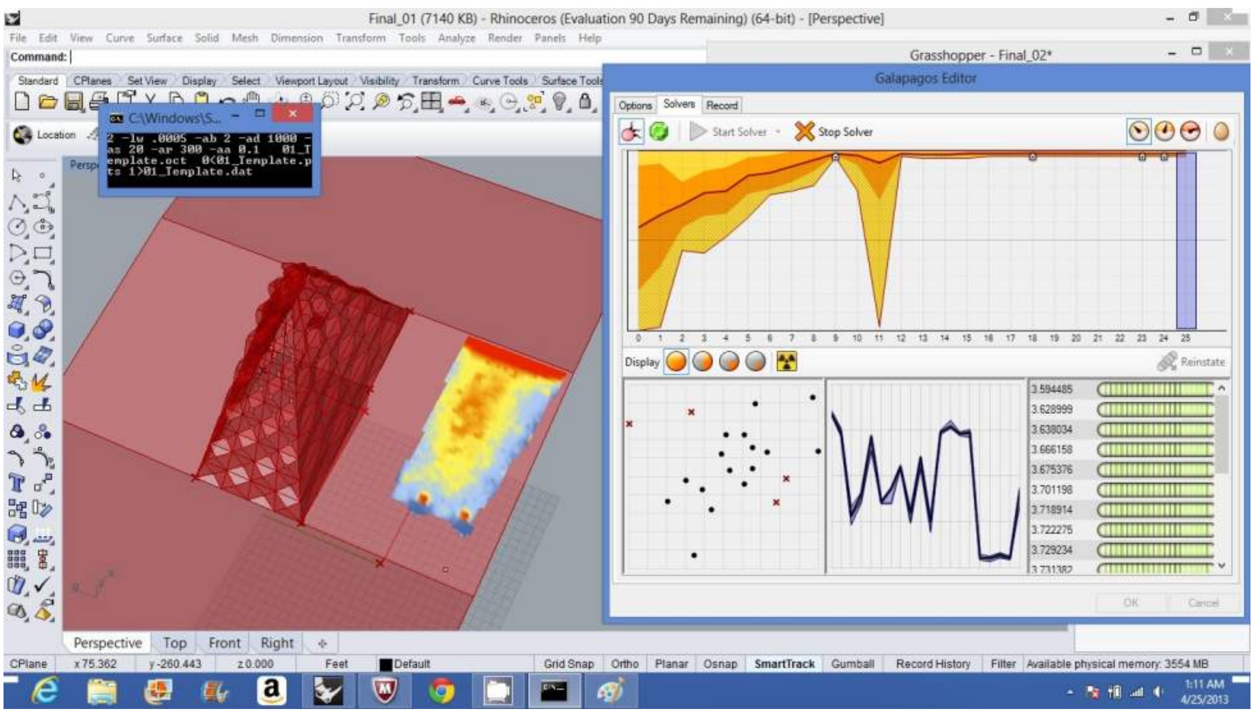

Figure 15: Results of Genetic Algorithm search, using Galapagos.

Figure 16: QR code for link to video with results of Genetic Algorithm search, using Galapagos. Scan with cell phone. http://162.144.122.118/~arch249/eleftheriastavridi.html

Interestingly, it is possible to see, by the amount of blue color in the results plan (that indicate areas that are too dark) that the GA was not able to find a solution as good as the architect (cf. figure 12). This is due to the specific way that the GA uses to calculate the quality of a solution (also known as the 'fitness function'). In this case, the GA is averaging the Daylight Factor throughout the space, as measured in a grid of nodes that covers the analysis plan, defined by the architect. Because the student included in this calculation the red stripe that corresponds to the entrance area, an overlit area as has been previously identified (DF>= 10%), the GA then looked for solutions that included blue nodes (underlit areas, DF 0-2%), so that the average would be close to 5%. If the student had not included those red nodes in the average calculation, it is hypothesized that the final solution found the by GA would not have included those blue areas, and would be mostly in the yellow zone (DF=5%), as expected. This fact emphasizes the important of the user understanding the design implications of the tool that they are using. The way the architect uses GA tool is not neutral, and has a strong impact in the quality of the design solutions.

The QR code in figure 16 also provides access to two final videos illustrating the lighting environment inside the final building proposed by the architect, as shown in figure 12.

Figure 17: Left: Video showing light patterns in the final building, in the summer solstice. Light beams generated by high solar angles float around the space from above, direct sun from skylight is also visible. Right: Video showing light patterns in the winter solstice. Light beams from low solar angles cross the space horizontally, direct sun from skylight is never visible. Scan QR code in figure 16 with cell phone. http://162.144.122.118/~arch249/eleftheriastavridi.html

CONCLUSION AND FUTURE WORK

The emergence of new simulation tools coupled with 3D modeling software, such as DIVA for Rhino, calls for the development of workflows to allow architects to integrate those capabilities into the design process. This integration is particularly significant when it happens at early design stages, when the most impactful design decisions are made, instead of detailed design stages.

The type of simulation to be performed, and the methods used, are most effective when they are target to the research question under study. For example, the choice between the two different scales for the façade elements could be solved by a simple, comparative study based on point-in-time illuminance simulations and interior renderings, which provided enough relevant information to support that decision. On the other hand, assessing the combined impact of building shape, façade design and skylight size and position required a full parametric model of the building, that could be easily modified each time a daylighting simulation was performed, according to the knowledge gained from that simulation. In this case, it would be too laborious to manually modify the design in the course of this iterative process.

Transitioning from parametric design required the adoption of adequate metrics to assess the relative merit of each design option. The most relevant area of research in this field is not on search algorithms, or the parametric models, but the development of clear assessment methods for the design alternatives under study. In the example presented in this paper, the quality of the search process by the GA was compromised by the user including in the assessment zone the nodes corresponding to an area of the space that was under other design objectives (the large horizontal strip of glass near the entrance). This inadequacy compromised the quality of the entire search process, and highlights the necessity that architects are fully aware of the design and performance questions involved in the tools they use. As those tools become increasingly more powerful, their use is not only representative but generative, and thus not neutral. To overcome some of these limitations, a new software has been recently developed, Painting with Light (Caldas et al, 2016), that allows architects to use color to finely detail different lighting levels desired for different zones in space, and use those 'painted' design objectives to guide the genetic algorithm search. Another potential field for future development concerns the evaluation of light quality in a space, complementing other, more quantitative daylighting metrics.

In what concerns the test of physical prototypes at LBNL, it was concluded that there is currently a lack of adequate equipment to measure the light performance of large-scale prototypes with complex geometries. Equipment that is able to perform complete and accurate measurements, such as generating BSDF data, like the goniophotometer, typically requires small sample sizes (up to one square inch), with a relatively uniform geometry. The only equipment that can be used for testing large scale samples is the Integrating Sphere, and that allows only more generic light transmittance measurements. While it was interesting for the students to perform the measurements, and the low light transmittance levels measured help to provide confidence on the simulation results, there was no direct way to feed the results from the measurements into the simulations, unlike the case when full BSDF measurements can be obtained. Given the fact that few people have access to physical measurements, and that computer simulations with Radiance have been thoroughly validated in the past with high accuracy levels, as long as adequately used, it is considered that relying on Radiance simulations alone is adequate for the type of research questions presented in this study.

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REFERENCES

Andersen, M., Kleindienst, S., Yi, L., Lee, J., Bodart, M., and Cutler, B. "An intuitive daylighting performance analysis and optimization approach." *Building Research & Information* 36.6 (2008): 593-607.

Caldas, L.G., Norford, L.K., 1999: A Genetic Algorithm Tool for Design Optimization, *Proceedings of ACADIA '99,* Salt Lake City, October 28-31, USA, pp. 260-271

Caldas, L. "Generation of Energy-Efficient Architecture Solutions Applying GENE_ARCH: An Evolution-Based Generative Design System", *Advanced Engineering Informatics*, 22.1 (2008): 59-70.

Caldas, L., Santos, L., "Painting with light: An interactive evolutionary system for daylighting design", Building and Environment (2016), DOI: 10.1016/j.buildenv.2016.07.023

Evins, R. "A review of computational optimization methods applied to sustainable building design." *Renewable and Sustainable Energy Reviews* 22 (2013): 230-245.

Gagne, J., and Andersen, M. "A generative facade design method based on daylighting performance goals." *Journal of Building Performance Simulation* 5.3 (2012): 141-154.

Goldberg, D., Genetic Algorithms in Search, Optimization and Machine Learning, Addison-Wesley Publishing Company (1989).

Holland, J., Adaptation in Natural and Artificial Systems: an Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence, University of Michigan Press (1975).

Jakubiec, A., and Reinhart, C. "DIVA-FOR-RHINO 2.0: environmental parametric modeling in Rhinoceros/Grasshopper using RADIANCE, Daysim and EnergyPlus." *Conference Proceedings of Building Simulation*. 2011.

Konstantoglou, Maria. "Simulating complex window systems using BSDF data." *Lawrence Berkeley National Laboratory* (2011).

Mardaljevic, John, Lisa Heschong, and Eleanor Lee. "Daylight metrics and energy savings." Lighting Research and Technology 41.3 (2009): 261-283.

McNeel, R. et al. "Rhinoceros 3D." *Retrieved Jan* 15 (2009).

McNeil, Andrew, and E. S. Lee. "A validation of the Radiance three-phase simulation method for modeling annual daylight performance of optically complex fenestration systems." *Journal of Building Performance Simulation* 6.1 (2013): 24-37.

Monks, M., Oh, B. M., and Dorsey, J. "Audioptimization: Goal-based acoustic design." *Computer Graphics and Applications, IEEE* 20.3 (2000): 76-90.

Nabil, Azza, and John Mardaljevic. "Useful Daylight Illuminance: a new paradigm for assessing daylight in buildings" *Lighting Research and Technology* 37.1 (2005): 41-57

Nabil, Azza, and John Mardaljevic. "Useful Daylight Illuminance: A replacement for daylight factors" *Energy and buildings* 38.7 (2006): 905-913.

Reinhart, C. F., and Walkenhorst, O. "Validation of dynamic RADIANCE-based daylight simulations for a test office with external blinds."*Energy and Buildings* 33.7 (2001): 683-697.

Reinhart, Christoph F., John Mardaljevic, and Zack Rogers. "Dynamic daylight performance metrics for sustainable building design" *Leukos* 3.1 (2006): 7-31

Rutten, D. "Evolutionary Principles Applied to Problem Solving." I Eat Bugs For Breakfast. 4 Mar. 2011. Web. 22 June 2015.

<https://ieatbugsforbreakfast.wordpress.com/2011/03/04/epatps01/>.
Omidfar, Azadeh. "Design Optimization of a Contemporary High Peformance Shading Screen – Integration of Form and Simulation Tools", 12th International Building Performance Simulation Association (IBPSA) Conference, Sydney, 14-16 November, 2011.
Saxena, Mudit, et al. "Dynamic Radiance–Predicting annual daylighting with variable fenestration optics using BSDFs." *Proceedings of SimBuild* (2010): 11-13.
Shea, K., Cagan, J., The design of novel roof trusses with shape annealing: assessing the ability of a computational method in aiding structural designers with varying design intent, Design Studies 20 (1), 3-23, 1999
Shea, K., Cagan, J., Fenves, SJ., A shape annealing approach to optimal truss design with dynamic grouping of members, Journal of Mechanical Design 119 (3), 388-394, 1997
Shea, K., Aish, R., and Gourtovaia, M. "Towards integrated performance-driven generative design tools." *Automation in Construction* 14.2 (2005): 253-264.
Ward, Gregory J., and Francis M. Rubinstein. "A new technique for computer simulation of illuminated spaces." Journal of the Illuminating Engineering Society 17.1 (1988): 80-91.
Ward, Greg, and Rob Shakespeare. "Rendering with Radiance: the art and science of lighting visualization." The Morgan Kaufmann Series in Computer Graphics, Morgan Kaufmann Publishers Inc., Los Altos, California, USA. (1998).
Ward, Greg. "Radiance Manual Pages." Radiance Documentation. 11 Sept. 2013. Web. 19 June 2015. <http://www.radiance-online.org/learning/documentation/manual-pages/pdfs/manpages.pdf>.
Ward, Gregory, et al. "Simulating the daylight performance of complex fenestration systems using bidirectional scattering distribution functions within Radiance." *Leukos* 7.4 (2011): 241-261.

PERFORMATIVE MORPHOGENESIS

A performance-oriented data-driven façade design process

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ABSTRACT

On a corporate campus project in Hangzhou City in China, the project team was challenged to develop an intelligent façade responsive to environmental needs such as energy efficiency and view quality. Building energy use, especially cooling load, can be reduced considerably through careful facade design. In addition, the view quality from the workstation has significant influence on people's work efficiency. In order to balance between view and shading requirements, the facade design became more complicated and demanded more simulated data to support.

The complexity of this kind of façade design has increased the need of large collection of digital tools, for simulation requirements, generative design and documentation needs. However, often times design teams' utilization of technology is segmented. An integrated, performance-oriented and data-driven design process is in need to ensure the quality and efficiency of the design work.

The process introduced in this paper focuses on generating and transferring data. Performance simulations such as solar radiance and view analysis done with Grasshopper for Rhino based on building massing provides initial data, which builds up the basic logic of generating façade components. Solar ray reflection simulation on the façade components then drives optimization process for several iterations to align with local code requirement. The results of the façade components, still in the form of data which is easily transferred into the BIM platform, in turn creates actual objects for visualization, documentation, energy simulation and cost estimate. This process allows rapid design iterations and generates façade elements with high complexity, high precision and complete building information.

摘要

在设计一个位于中国杭州的企业总部项目过程中，设计团队尝试使立面的设计智能地应对外部环境和视线品质的要求。通过精心的遮阳设计，建筑能耗尤其是制冷的能耗将会大为改善。而工作空间的视线质量能够显著影响员工的工作效率。在平衡遮阳与视线的要求下，立面的设计变得更为复杂，并且更需求模拟分析数据的支持。

这样的设计复杂性则需要大量的数字化工具来进行性能分析，生成演算以及建立信息模型。然而在很多时候设计团队对于设计工具的应用仍然是零碎孤立的。为了保证设计工作的高质与高效，迫切需要一种整合的，基于建筑性能的，并以数据驱动的设计流程。

在本文中将要介绍的设计流程着重于数据的生成和传递。使用犀牛(Rhinoceros)的蚱蜢(Grasshopper)插件运行的基于建筑体量模型的太阳辐射和视线分析的模拟提供了供生成立面构件逻辑的初始数据。继而基于这些立面构件运行日照反射模拟驱动优化构件分布，深度和朝向的运算以满足地方规范对于限制建筑幕墙反射至住宅的要求。运算的结果依然储存为数据的形式并且传递至建筑信息模型(BIM)平台，生成可供渲染，制图以及提取成本估算信息的模型。这个流程提供了快速且准确地更新立面设计；生成复杂的，信息完整的立面构件。

KEYWORDS

Parametric workflow, facade, performance, generative design, design processes, interoperability.

INTRODUCTION

The pursuit of high performance, beautiful architecture requires a tremendous amount of work with high complexity. High-performance buildings often feature the following: maximizing operational energy savings, providing healthy interiors, and limiting the detrimental environmental impacts of the buildings' construction and operation (City of New York Dept. of Design and Construction 1999). Simulation is an important method to evaluate if a design has a good performance before it is built. For the simulation purpose, a digital model prepared by design team is put into a computational environment with same or very similar conditions such as climate, sun angles and urban context.

The traditional method in evaluating building performance is linear and segmented, and most virtual simulations were "employed in the evaluation phase" (Oxman, Hammer and Ari 2007, 228). This type of utilization intends to prove specific expectations and offers little input back into the design. Sometimes, it fails to even prove the expectation. This kind of practice requires significant redundancy to revise the original scheme and pick up analysis feedback. "Many contemporary digital instruments have advanced to the point where their transformations of data into measurements of expected building performance can no longer be verified through an analog equation" (Davis and Miller 2014, under "Performance Art: Analytics And The New Theater Of Design Practice"). As stricter sustainability standards and requirements for better-performing buildings increase, such traditional methods can no longer satisfy the current market demands.

Parametric design brings changes from the conventional method and potential to transform design processes to meet, or even exceed, future standards. Unfortunately, it is a common misunderstanding that parametric design is a "one click magic". Many designers may also resist the idea of performative design, thinking that such actions forfeits a designer's diligence and intelligence. Nonetheless, performative design demands a clear logic for building up the algorithms and a high precision of both input and manipulation for getting the desired results. This requires designers to no longer simply add and erase, but also to relate and repair. Rather than creating the design solution by direct manipulation, the designer establishes the relationships by which parts connect, builds up a design using these relationships and edits the relationships based on the results produced (Woodbury 2010,). In a way, we no longer design the object itself, but the logic in which the object is derived.

For example, in the study of "Performative Design Prototype", Rivka Oxman and his team explored a method of employing animated simulations to generate designs. A two layered wall project using simulations of wind force and light penetration to generate a skin which responds to changing conditions of wind and light. (Oxman, Hammer and Ari 2007) The designer's control of the result is no longer a one-to-one relationship as in traditional design. Instead, performative-based considerations can be formulated as simulations and the results can be utilized "as a generative tool for the derivation of form and its transformation - *the digital morphogenesis*" (Kolarevic 2003, 13). The calculated result is generative rather than representative, therefore hardly achieved by any traditional method.

In other words, parametric design builds up a method to collect and manipulate data. It is advantageous not only because it can provide data for designers on how much to save in terms of energy use, but also because such data can be translated into parametric building components containing such information as how much the building will cost for clients and investors. "Beyond convincing clients of a design's apparent 'elegance' and 'beauty', data is used to gain insight into performance and is used to demonstrate value with the client and end user in mind" (Miller 2015a, under "Using Data In Your Design Process"). However, current available software tools can only cover part of these jobs, thus a project team has to use multiple different software tools to convert these data into architectural design. It is then inevitable to have data transferred between software platforms.

Nonetheless, data can often be lost when transferring information from one software to another. Therefore, interoperability, or "the ability to make different systems talk to one another" (Miller 2015b, under "Planning Your Project for Better Interoperability"), is a critical component in the design process. With the recent visual programming add-on Dynamo (Autodesk, Inc. 2016) and various packages (plugins) for Dynamo available, Revit begins to provide good interoperability with other 3D modeling, parametric design and simulation platforms.

It is then important to understand that parametric design is rather a process design. A workflow should be built up based on the design logic, with clear idea of when to use explicit modeling such as Rhinoceros (McNeel 2016), when to bring in its graphical algorithm editor plugin Grasshopper (Rutten 2016), and when to start using more specialized tools such as the Ladybug and Honeybee plugins for Grasshopper (Roudsari 2016) for performance simulation. More importantly, the project team should understand what kind of data (geometries, anchor points, or simulation results) to expect from each step, and use these data as efficiently as possible to solve outstanding problems.

The following section explores a case study of a Chinese corporate campus project's facade design development. It will provide insight to the logic that was established to generate a building performance based facade design. It will also disclose the methods designers took advantage of interoperability tools to keep design modifications up-to-date between design and documentation platforms. Lastly, it will also touch upon the advantages parametric design had on the project when reacting to client demands.

METHOD

The performance-oriented data-driven process was applied on a project that consists of a series of office and amenity buildings in the new campus of a famous Internet and technology company in China. The campus is located in suburban area of Hangzhou city in a hot-humid climate zone. The gross floor area of these buildings totals 175,306 square meters (1,886,980 square feet) on a site of 132,918 square meters (1,430,720 square feet), with the tallest building being seven stories. The project is located south of a river and adjacent to a natural wetland preserve. These natural elements, along with on-site landscaping, are highly important views to be considered. In addition, the climate data of the project site shows an extreme heat stress in summer, thus a shading design on the façade can help increase the comfort level of users and reduce energy use on cooling in summer.

In the Schematic Design stage, the project team consists of a core design (building floor plans) group of five architects and designs and a shell design (facade) group of three designers, each running parallel during the design process. The core design group provided updated building massing models and guide grids constantly to the shell design group. These massing models were the base geometries and alignment references to generate façade elements. Traditional design methods would not tolerate such working methods since the series of manual operations required from each massing change would be too labor intensive. However, because the logic and algorithms had been established in a parametric design process (Figure 1), the cooperative work mode between core and shell teams proved to be productive.

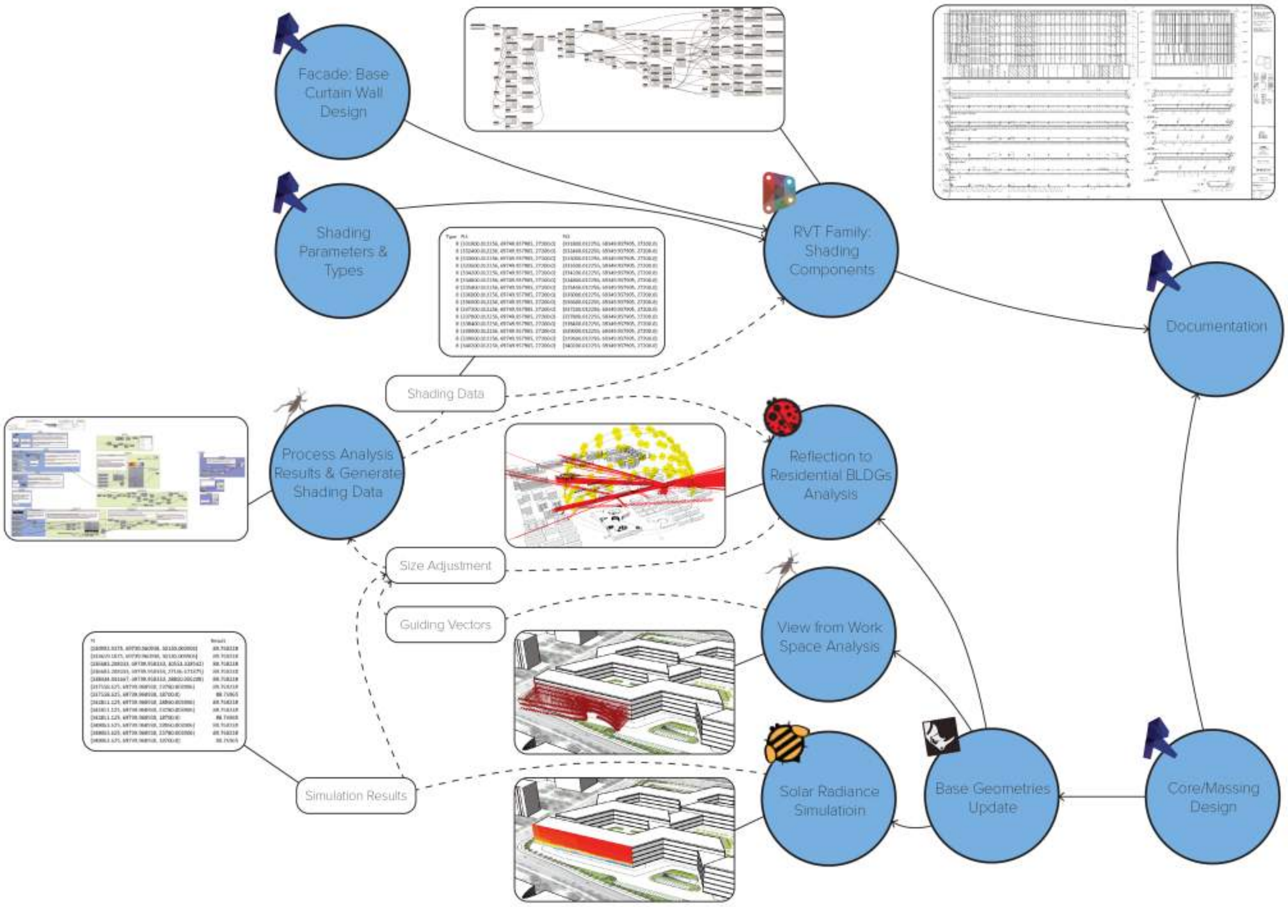

Figure 1: Diagram of overall workflow and software tools used.

SIMULATIONS AND DATA GENERATION

The façade design concept was a double skin system, which was developed during competition phase and appreciated by the client. The inner layer of the double skin system is a regular glazing-spandrel curtain wall, while the external layer is a series of vertical shading panels structurally supported by metal catwalk attached to main curtain wall structure. During the schematic phase, the project team intended to include energy reduction consideration and workspace view quality as developing the façade design.

The shell design group begin the design process through writing a series of algorithms that represent their design logic. The first algorithm (Grasshopper definition using Honeybee plugin) ran a solar radiance simulation using cumulative sky in the summer on the base surfaces to identify zones that need shading (see figure 2). This zoning increases efficiency in the calculation by omitting areas that does not require shading. Another parameter that affects the calculation's efficiency is the resolution (size of subdivision of testing surfaces) of the zones. Too high resolution would not only increase the calculation time of the simulation, but also likely to generate too fragmented façade pattern which is not aesthetically ideal; whereas too low resolution could now yield precise results to be the generative parameters for next steps. As the team's decision of balancing these considerations, these zones were established to be one level tall (4.2m or 10 ft) and one typical grid spacing wide (9m or 30ft).

Within the zones, the output of solar radiance simulation created a matrix of numeric results associated with their spatial coordinates. These results informs the vertical shading component spacing in each zone and depth parameter of each shading component. Data storage and passing was through Excel spreadsheets. In the Excel file, data of each base surface used one sheet, so that for updating specific surface, the algorithm would only run on that surface and overwrite the respective sheet data.

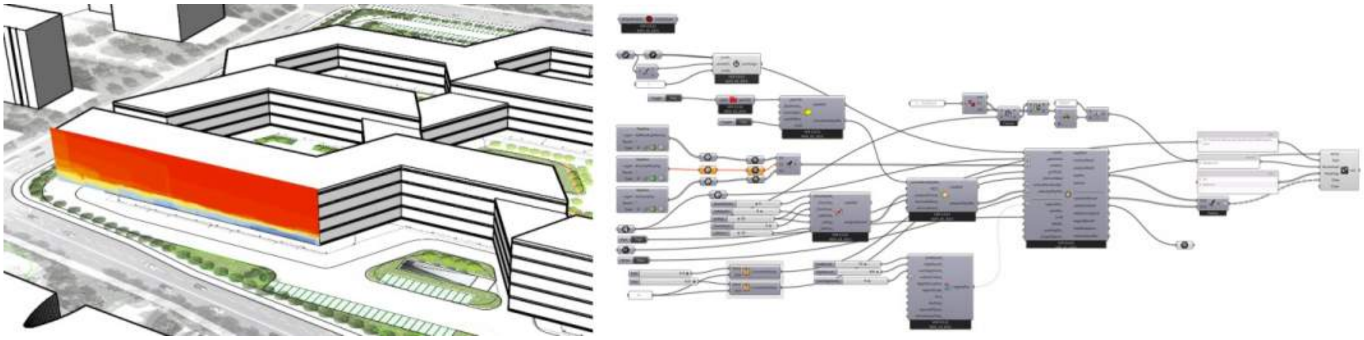

Figure 2: Solar radiance simulation on one surface. The Grasshopper definition uses Ladybug to produce heat map style visualization and generate data to combine with coordinates information and save as Excel spreadsheet.

The second algorithm took the data from the Excel file, and ran a view analysis from the analysis matrix to potentially good views in the campus that the landscape team were developing. The analysis calculated vectors from each point in the matrix generated by the solar radiance simulation to the designed and natural landscapes within a range of distance. If these vectors intersect with any of the building massing geometry, it means the views are blocked and should not be considered.

The algorithm also computed the angle between the vector and world XY (horizontal) plane, if the angle is too big, the view then is considered too difficult to be observed and thus excluded. The remaining vectors, which represent good views, ran a weighted average math by distance factors and generated two points. These points represent vectors from each point of the matrix, and the angles to the face normals of each hosting surface were calculated and modulated as rotation parameters of the shading elements. With these parameters, the algorithm generated a preview of the shading components for internal design reviews as well as a set of data for further simulations. Before 50% schematic design stage, data generated above determined the layout, sizes and rotations of the shading panels.

New requirement from local government came after 50% schematic review. The local building code had a zero tolerance on curtain wall glare on existing residential buildings from new constructions. Therefore, all curtain wall that could potential create reflections on the neighbors are dictated to be replaced by solid walls built with non-reflective materials. Needless to say, complying to this code in this manner would be detrimental to the design concept.

The shell design group then developed a third algorithm (Grasshopper definition using Ladybug plugin) to simulate the reflections and adjust the shading panels to eliminate all glare without changing material. The script back-traced the solar rays reflected from the base geometries to the surrounding residential buildings throughout the year. When these rays hit shading panels, they were considered resolved.

The algorithm then drove the shading components next to the remaining rays by extending them to reach and block the rays. If the algorithm detected a component reached its extreme of extension defined by maximum panel depth parameter but still could not block the target rays, it would try to rotate the panel further towards the rays at the same time. Similarly, if rotation still could not achieve the elimination, the entire zone of shading panels would increase the density and calculate the panels' rotation and depth again. After several iterations of the extension, rotation and increasing density, all the reflections to the residential buildings were eliminated (see figure 3).

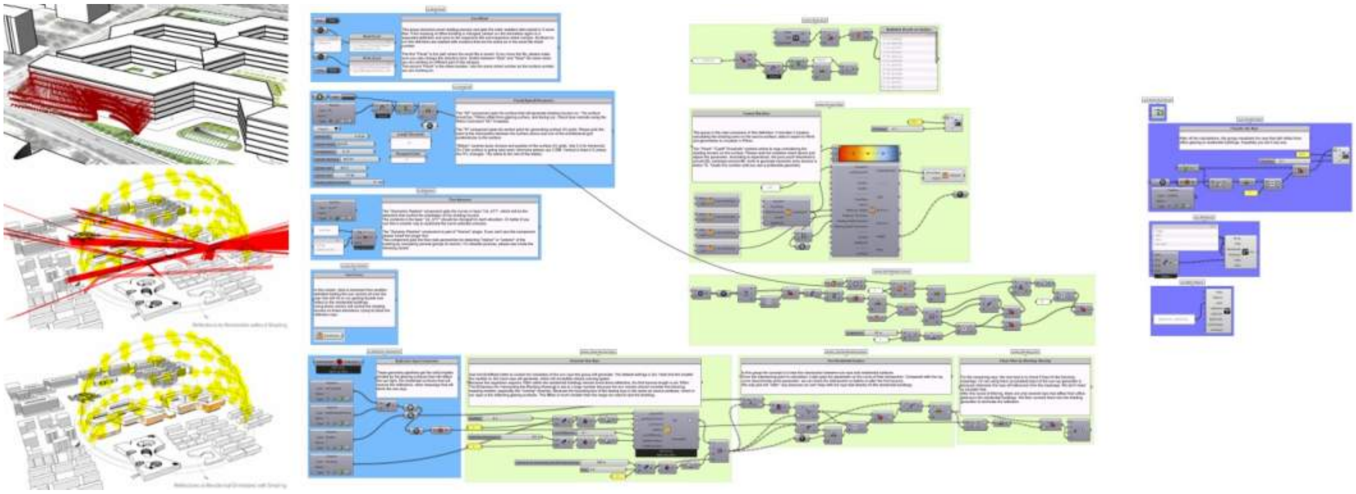

Figure 3: View analysis and solar ray simulation. The Grasshopper definition also takes solar radiance data from the previously generated Excel spreadsheet. The three groups of data altogether generates the type and position data of the shading panels.

There were several different versions of resulting shading components that all achieved the elimination under the given condition of maximum depth and rotation parameters. Through traditional methods, this problem may not even have been solvable, let alone the luxury of multiple solutions. At this point, previews of the multiple options allow the team to compare make decisions based on other design criteria. Simultaneously, the result of this simulation refreshed the two-point-vector and depth data, which are both ready to be synchronized with Revit for documentation.

INTERPRETING GRASSHOPPER DATA INTO REVIT OBJECTS

While in Rhinoceros, most of the processes are about determining positions, orientations, and sizes of the shading components in a format of abstract data. In Revit, detail designs such as panel profiles, assembly methods and materials are also developed at the same time. The shading component family in this project was defined as a vertical 2-point adaptive component, with the first point defining the anchor position and the vector from first point to second defining the orientation of each panel. The profile of the shading component was loaded as a family type.

While the positions and orientations are as instance parameters of adaptive component family, depth is configured as profile family type parameters which are also associated with adaptive component family types for synchronizing with Grasshopper generated results (see figure 4). The profile design can be updated by changing loaded profile family given that the replacing family is built up with the same logic. This method proved to be helpful. When the project went into design development phase, the project team received comments from curtain wall consultant and updated the profile without trouble.

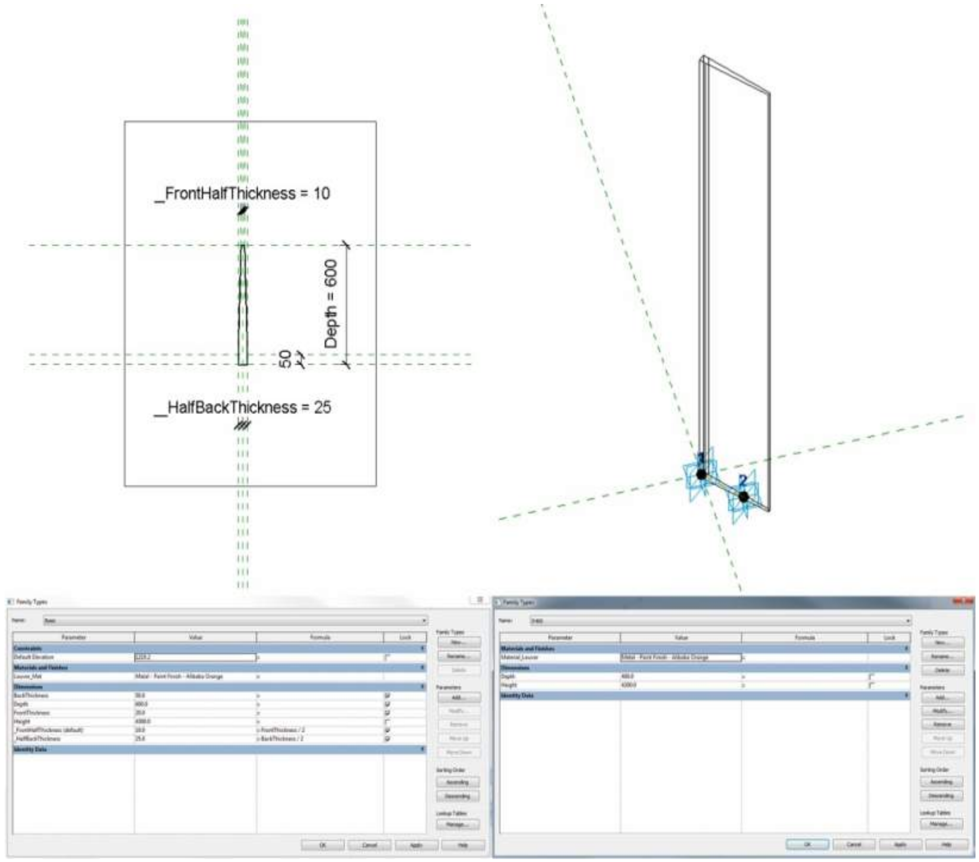

Figure 4: Shading component profile family and parameters setup and adaptive component family, parameters and types set up. Profile design showing here was for schematic design phase, the project team revised the design during design development phase.

After preparing above elements, the shell group was tasked to bring the Grasshopper data into Revit and convert it into native Revit objects. This process used Dynamo for Revit as an interoperability tool to receive and interpret data from Grasshopper. In the Dynamo algorithm, data were read and grouped by depth parameters, loading them with respective family types of the adaptive component family, and then placed them using the 2-point-coordinates data (see figure 5). After running the algorithm and loading into project, native information intact shading objects were placed in Revit project file. Compared with conventional export-import method, the project team was able to not only show the geometries as technical drawing background, but also generate schedule to report the count, overall surface area and volume of each type of panels that helps generate more accurate cost estimate.

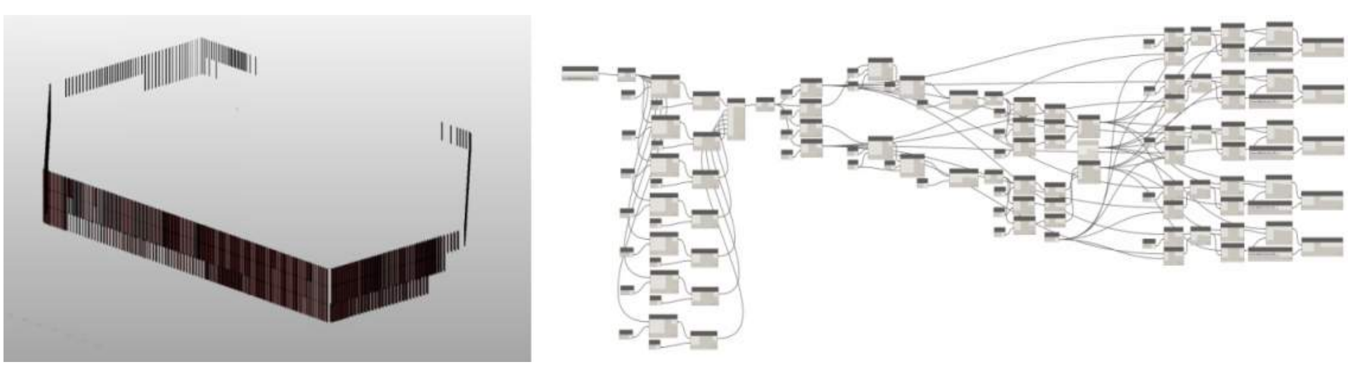

Figure 5: The Dynamo definition reads data generated by Grasshopper and creates shading components using adaptive component family.

The above steps, from simulations in Rhino to documentation in Revit, composed a complete design iteration cycle. During the schematic design phase, there were several rounds of building massing changes. The project team used this process to deploy a quick and precise facade design revision and produced good quality BIM models for both visualization and documentation in a short period of time. Again, this would not have been possible through traditional methods of design.

CONCLUSION AND FUTURE WORK

Through energy use simulation based on the BIM model the project team provided, the buildings' energy consumption reduced 5% compared with control group without shading devices. This reduction is estimated $4.6 million per year on electricity for campus of this size.

The project went into construction document phase in December 2015, and will start the bidding process shortly after construction document is approved. By the time, the project team will coordinate with curtain wall manufacturer and contractor on fabrication and installation.

The performance-oriented data-driven facade design process potentially introduces a direction in architectural design. By integrating performance simulation from early stages, providing parametric way of problem solving, and using interoperability tools, a design team is able to deliver a convincing design result both visually and logically. Moreover, as software developers and technical solution providers become increasingly aware of the importance of seamless integration between performance analysis, parametric design and building information, there will be also be more integrated tools available to improve the process. Such tools as Ladybug for Dynamo and Flux (Flux Factory, Inc. 2016) are already drawing designers' attention, replacing low-efficiency components with these evolving tools will be a continuing task for future development.

On the other hand, with the vast amount of computational tools used, the process also brings up new questions about the adaptability of these tools. Highly customized algorithms are also highly individualized. It is literally a materialized map of the creator's abstract thoughts. Therefore, it may often be difficult for others to decipher and manipulate. Such dependency of the algorithm on its creator will become an obstacle for future use if the creator is no longer available. Similarly, highly project-specific tools also find a hard time contributing to other projects. Developing an algorithm into a tool kit may be one of the ways to solve both of these problems. Yet in anyway, scripting requirements for the creators need to rise to a new level: he/she should not only make it work, but also make it work efficiently, adaptively, and in a format easier for the others to understand. By doing this, parametric design will be truly integrative, offering even more potential to transform the way we design architecture.

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REFERENCES

City of New York Dept. of Design and Construction. 1999. High Performance Building Guidelines. New York: City of New York Dept. of Design and Construction.

Oxman, Rivka, Roey Hammer, and Shoham Ben Ari. 2007. "Performative Design In Architecture". *Predicting The Futures, ECAADE07, Frankfurt*, no. 2007: 227-234.

Davis, Daniel and Nathan Miller. 2014. "Performance Art: Analytics And The New Theater Of Design Practice". In *Building Information Modeling: BIM In Current And Future Practice*, 1st ed. Wiley.

Woodbury, Robert. 2010. Elements Of Parametric Design. London: Routledge.

Miller, Nathan. 2015a. "Using Data In Your Design Process". *PROVING GROUND*. https://provingground.io/2015/08/27/using-data-in-your-design-process/, last accessed 05/13/2016.

Miller, Nathan. 2015b. "Planning Your Project For Better Interoperability". *Case-Inc.Com*. http://www.case-inc.com/node/508.html, last accessed 05/13/2016.

Kolarevic, Branko. 2003. "Digital morphogenesis." *Architecture in the digital age: Design and manufacturing* (2003): 12-28.

McNeel, Robert. 2016. "Rhinoceros Feature Overview". *Rhino3d.Com*. https://www.rhino3d.com/en/features, last accessed 05/13/2016.

Rutten, David. 2016. "About Grasshopper". *Grasshopper3d.Com*. http://www.grasshopper3d.com/, last accessed 05/13/2016.
Roudsari, Mostapha. 2016. "Ladybug + Honeybee". *Grasshopper3d.Com*. http://www.grasshopper3d.com/group/ladybug, last accessed 05/13/2016.
GSA, 2007. “GSA Building Information Modeling Guide Series 01 - Overview DRAFT,” http://www.gsa.gov/graphics/pbs/GSA_BIM_Guide_v0_60_Series01_Overview_05_14_07.pdf, last accessed 05/13/2016.
Autodesk, Inc. 2016. "Dynamo BIM". *Dynamobim.Org*. http://dynamobim.org/, last accessed 05/13/2016.
Anton, Ionuţ, and Daniela Tănase. 2016. "Informed Geometries. Parametric Modelling and Energy Analysis in Early Stages of Design." Energy Procedia 85 (2016): 9-16.
Flux Factory, Inc. 2016. “About”. *Flux.Io*. https://flux.io/about/, last accessed 05/22/2016.

GLAZING HAZARD ASSESSMENT

Collaborative design for high fidelity façade analysis

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ABSTRACT

The Window Hazard Analysis Module (WhAM) fully integrates a statistical glass fracture modeling approach into a finite element formulation for glass, laminated glass and structural and nonstructural elements (mullions, muntins and connections). The unique finite element analysis framework (LS-DYNA) and custom material models offer the flexibility to evaluate non-rectangular and out-of-plane configurations for wind, blast, seismic and impact loads. The software makes full FEA implementation available to façade engineers and researchers without requiring the infrastructure, licensing requirements and modeling expertise typical of high fidelity analysis.

Key computational features include a coupled nonlinear dynamic analysis model that is computationally expedient while maintaining designer-level fidelity, structural and architectural elements (mullions, etc.) represented with efficient equivalent beam elements, glass lites, PVB, and IGU spacers represented with shell elements, and IGU air gaps and silicone beads represented with solid elements. Advanced user-defined constitutive models (UMATs) have all been vectorized and implemented in SMP and MPP parallel processing structures within a computational model programmatically incorporating the multi-physics finite element code LS-DYNA.

Key numerical formulations include a new Glass Failure Prediction Model (GFPM) based LS-DYNA UMAT with an elastic constitutive model with flaw-based probabilistic failure criterion, a new PVB interlayer LS-DYNA UMAT that includes a post-break, strain-based stiffness increase due to interaction between PVB and adhered glass shards and a new structural silicone LS-DYNA UMAT that includes a hyper-elastic constitutive model.

Shock tube tests have been conducted to for validation. Tests included a 4-lite storefront exposed to 5 levels of blast load. DIC (digital image correlation) was used for surface displacement measurement. Improved FEA model comparisons with tests showed excellent correlation of predicted and measured results.

KEYWORDS

Glass, architectural glass, structural glass, glass engineering, design processes, computational design, collaborative design

BACKGROUND AND INTRODUCTION

Current glass hazard mitigation design approaches, graphically illustrated in Figure 1, typically use single degree of freedom (SDOF) methods to analyze the performance of window glazing and mullions. The flexural resistance and mass of each component must be identified to define the SDOF representation. Then, the resistance curve is calculated based on span, support conditions, cross sectional stiffness, assumed deformed shape, and a failure criterion. SDOF methods have significant limitations when used for analysis of complex glazing systems such as storefronts and curtain walls. Coupling effects are ignored in SDOF methods, and only single assumed modes of response can be considered. The use of FEA can eliminate the assumptions made regarding mass distribution and deformed shape and facilitates spatial fracture prediction at appropriate points on the glass surface. FEA can also ultimately remove SDOF analysis restrictions including rectilinear and flat glass.

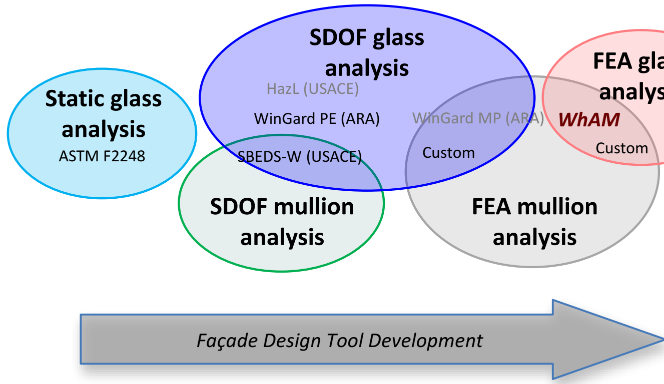


Figure 1: Glass Design Approaches for Hazards

METHOD

PEC performed five shock tube tests on eight identical full-scale curtain wall modules (two per test with one pair reused after Test 1) to evaluate the performance of a sample Enclos curtain wall system and to provide data for comparison with finite element analysis (FEA) response predictions. The blast load applied to the curtain walls was varied to achieve a range of responses from "no break" glass response up to glass fracture with significant polyvinyl butyral (PVB) and mullion response. The curtain wall modules included mullions, insulating glass units (IGUs), and top/bottom connections. The test matrix is shown in Table 1. Note that modules 1 and 2 were used in both tests 1 and 2.

Table 1. Test Matrix

Test No.	**Modules**	**Measured Blast Load**		**Test Results**
		Pressure (kPa, psi)	Impulse (kPa-ms, psi-ms)	
1	1 & 2	30.3, 4.4	151.7, 22	elastic response of system
2	1 & 2	53.1, 7.7	262.0, 38	begin to fail lower and upper glass
3	3 & 4	76.5, 11.1	406.8, 59	push upper glass to failure, begin to fail lower glass
4	5 & 6	93.8, 13.6	530.9, 77	exercise coupled glass and mullion response
5	6 & 7	104.1, 15.1	737.7, 107	push system to maximum response

METHOD – TEST MODULES

All curtain wall modules had a nominal dimension of 1.68 m wide x 3.15 m tall. A single test specimen consisted of two curtain wall modules and had a nominal width of 3.48 m. Each curtain wall module was composed of two insulating glazing unit (IGU) configurations. The upper IGU had a day light opening of 1.58 m x 0.63 m. The 33.3 mm heat strengthened (HS) IGU consisted of a 7.9 mm HS outer lite x 19.1 mm air gap x 6.4 mm HS inner lite. The lower IGU had a day light opening of 1.58 m x 2.15 m. The 34.9 mm HS IGU consisted of a 7.9 mm HS outer lite x 12.7 mm air gap x 12.8 mm HS laminated inner lite (6.4 mm HS x 1.5 mm PVB x 6.4 mm HS). In general, a 38.1 mm glass bite was provided on vertical window edges, while a 25.4 mm glass bite was provided on horizontal edges. Glass was purchased from PPG and all units were assembled and glazed by Enclos. Glass was secured to the aluminum frames with an 18.3 mm (minimum) bead of Dow Corning 983 Structural Glazing Sealant (structural silicone).

All glass provided had been manufactured in accordance with ASTM standards C1036, “Standard Specification for Flat Glass,” C1048, “Standard Specification for Heat-Strengthened and Fully Tempered Flat Glass,” and C1172, “Standard Specification for Laminated Architectural Flat Glass.” Insulated glass units were air filled with desiccant seals. Note that nominal glass and PVB thicknesses are cited here; actual thicknesses were used in subsequent analysis.

A 219 mm deep (178 mm behind the IGU), 6063-T6 aluminum unit frame was selected to support all units, as illustrated in Figure 2.

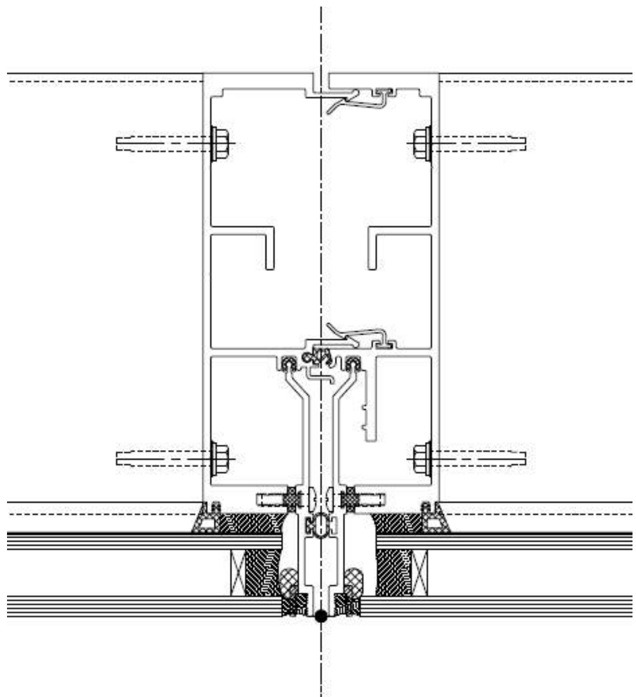


Figure 2: Glass and Mullion Configuration

D1500, D1501, and D1502 were used at all head, horizontal mullion, and sill locations (respectively), while D1000 was used at the intermediate vertical mullion and jambs. D1000 was snapped together in the front and back for on-site installation. In addition, the section was economized by optimizing metal placement (front and back walls were thicker), which increased the section modulus and flexural capacity. For analysis, the D1000 male and female mullion properties were combined assuming non-composite action. Jambs consisted of either the D1000 male or female mullion to more closely approximate the response of another vertical mullion with only half of the applied load. The top 305 mm of each jamb included a steel closure plate that was provided to prevent eccentricity into the top anchor connections.

METHOD – TEST SETUP AND INSTRUMENTATION

The shock tube opening is illustrated in Figure 3. Each vertical mullion and jamb was supported at top and bottom (spanning vertically) by the shock tube structural steel at the opening.

An HSS steel tube was provided behind the top connection to accommodate the Enclos standard anchoring system at three locations. The standard top anchors approximated typical construction details as closely as possible. The bottom connections were made with custom steel inserts to directly transfer bearing and shear similar to the typical stack joint. The connections were designed for the maximum reaction (based on ultimate capacity of the members) of 101 kN at the end of the vertical mullion and 50 kN at the end of each jamb (note, some connection failures were observed during Test 4 and 5).

Instrumentation during each shock tube test included pressure gauges, laser deflection gauges, digital image correlation (DIC) equipment, load cells, temperature gauges, string potentiometers, and high-speed video cameras (see Figure 4). Still photographs documented the modules before and after each test. The following sections outline the quantity, location, and type of instrumentation used during each test.

Figure 3. Shock Tube Opening with Window Assembly in Place

Four pressure transducers were installed on the shock tube walls (flush with interior wall) to determine the applied loads (peak reflected pressure, load duration, and peak reflected impulse), as shown in Figure 4. The pressure gauge measurements were averaged after each test to determine an applied load. The pressure gauges were located in the corner where the shock tube wall and front face meet to best approximate the load on the specimen.

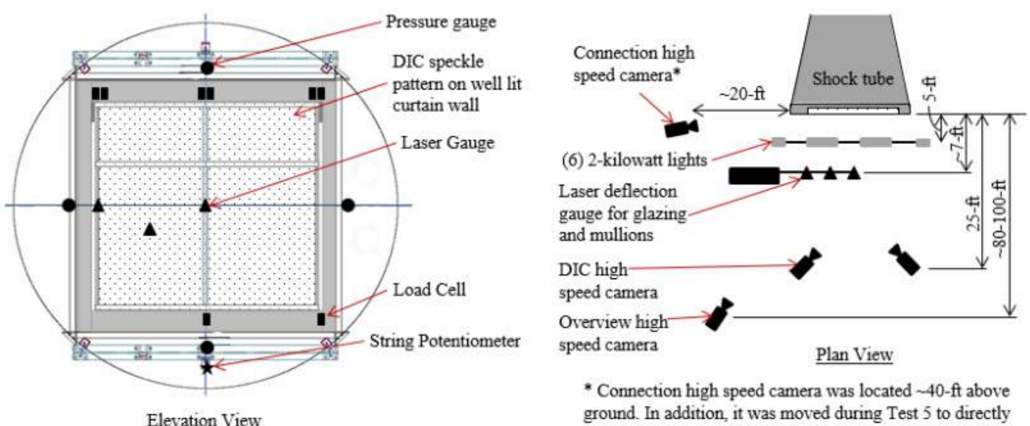


Figure 4. Typical Instrumentation Layout (laser gauges moved to 1/3rd points in Tests 4 and 5)

DIC was employed to record displacement measurements of the glazing and frame system. The DIC setup used paired Vision Research V711 high-speed cameras to record stereoscopically. Each camera was outfitted with a Zeiss ZE 35mm f/1.4 lens (f3.3 used during testing) and operated at 7,500 frames per second with a 1280x800 resolution. The cameras were mounted to a 203 mm HSS crossbeam on the camera tree; which was in turn mounted to the concrete floor with four epoxy set 12.7 mm Hilti Anchors.

A high contrast (black and white) speckle pattern was applied to the entire façade (all glazing and mullions) on the protected side (facing outside of shock tube), as shown in Figure 7. Glass and speckle paper temperature was measured with a non-contact temperature gage before and after each test. Temperature increases due to lighting were modest (no greater than 2-degrees C increase). Previous glass fracture research has shown that the speckle paper has little influence on fracture initiation or strength (Alberson, 2013). The raw DIC data was normalized to account for the shock tube movement. The shock tube movement was measured with a string potentiometer at the bottom of the shock tube. At each time step, all measured DIC data required a uniform shift in displacement with respect to a 1-D interpolation function that matched the string potentiometer data.

Figure 6. DIC Speckle Pattern

DATA

DATA – TEST RESULTS

Typical results from the shock tube tests on Enclos curtain wall assemblies are illustrated in Figure 7. Results were used to evaluate the overall system performance of the glazing and mullions. Coupled system response was observed where the maximum glazing response occurred at approximately the same time as maximum mullion displacement. For example, in Test 4, maximum window response occurred around 27.7-ms (color coded displacements determined from DIC data analysis are shown in Figure 8), while maximum mullion response occurred around 24.9-ms. Response of each IGU is summarized in Table 2. Typical IGU response covered the range of response conditions from no glass break to glass break with PVB response. Bite failure of the lower IGU with laminate was only observed in Test 5. Maximum window response (pre-bite failure) occurred close to maximum mullion response.

Figure 7. Typical Curtain Wall Response Observed in Tests

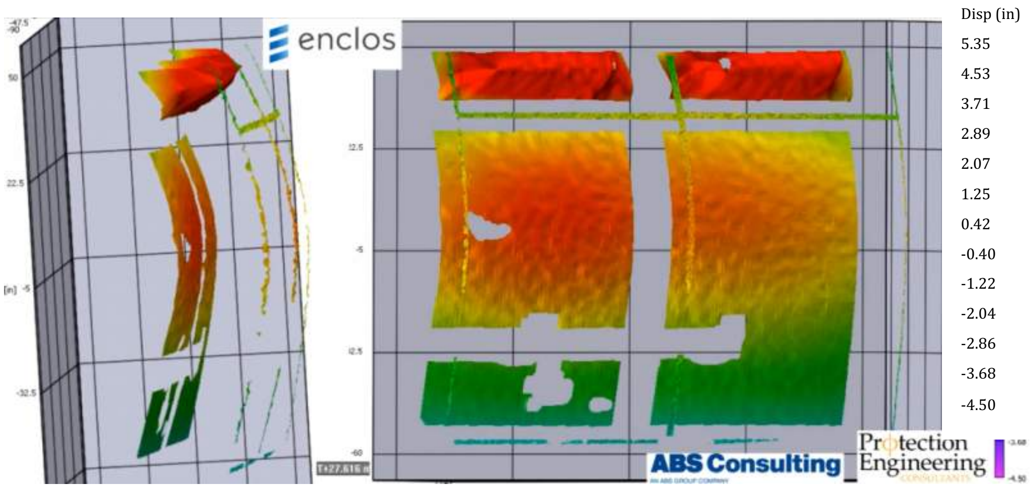


Figure 9. Shock Tube Test 4; Raw DIC Results (Color Coding Refers to Displacement (in)

Overall mullion response for all shock tube tests is summarized in Table 3. In Test 1 and 2, the vertical mullions and jambs responded elastically (with a parabolic deformed shape) and exhibited no yielding or residual displacement due to the relatively low magnitude of the applied blast loads. In Tests 3 through 5, the vertical mullions and jambs responded elastically (parabolic deformed shape), yielded to varying degrees with web buckling, and in Test 5 formed a plastic hinge at mid-span (as shown in Figure 10), and opened up along the interlock (or split reveal) on the back face of the vertical mullion.

No yielding or damage was noted in any of the connections in Tests 1 through 3. During Tests 4 and 5, some yielding of washers and hook anchors was noted during post-test inspection.

Table 2. Glazing Response Summary

Test	Side of IGU lite	Window Response				Measured Max. Response			Bite Failure	Debris hazard
		A	B	C	D	Disp. (mm, in)	Time (ms)	Location		
1	threat	NB	NB	NB	NB	28, 1.1[4]	86.4	center of C	none	no
	protected	NB	NB	NB	NB					
2	threat	NB	NB	NB	break[1]	43, 1.7[4]	85.0	center of C	none	yes
	protected	break	break	NB	NB					
3	threat	break	break	NB	NB	112, 4.4[5]	21.7	upper left corner D	none	yes
	protected	break	break	NB	break[2]					
4	threat	break	break	break	break	152, 6.0[5]	27.7	upper center C	none	yes
	protected	break	break	break[3]	break[3]					
5	threat	break	break	break	break	538, 21.2[5]	96.9	upper right corner C	C. pull out 2 sides	yes
	protected	break	break	break[3]	break[3]					

glazing location (viewed from protected side; see Figure 6):

A = upper left B = upper right

C = lower left D = lower right

NB - no break

[1] crack pattern consistent with failure on rebound

[2] outer lite break, protected (inner) lite not break

[3] PVB activated and stretch

[4] from laser gauge data at center of window C for protected (inner) lite, absolute displacement, first inbound response not captured, shock tube movement estimated

[5] from DIC data for protected (inner) lite, absolute displacement

Table 3. General Mullion Response Summary

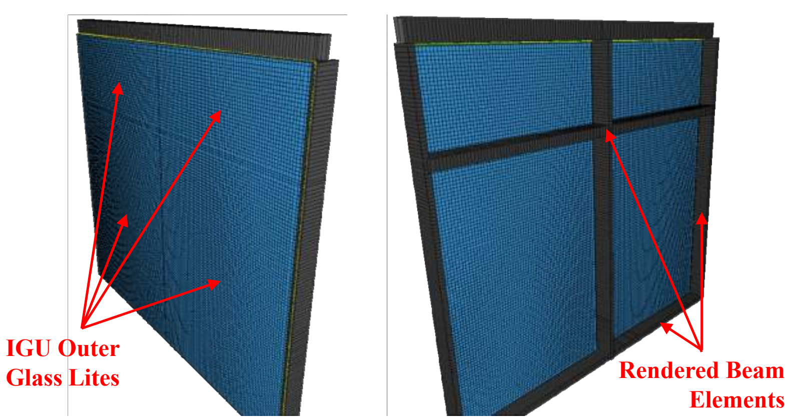
Member	Mullion Response	Test #
Vertical Mullion/Jamb	no yielding or residual displacement	1, 2
	yielding at mid-span, opened up along vertical joint	3
	yielding, opened up along interlock, local buckling of web, plastic hinge formation	4, 5
Head/Horizontal/Sill	no yielding or residual displacement	1, 2, 3, 4, 5

Figure 10. Vertical Mullion and Jamb Response – Test 5

DATA – MODELING AND VALIDATION

PEC performed a coupled analysis of the glazing and mullions to account for the influence of flexible glazing supports using a simplified design-level finite element modeling strategy within the LS-DYNA code (consistent with WhAM design methodology). The intent of this analysis effort was not to create the most rigorous 3-dimensional representation of every curtain wall specimen element, but rather to strike a balance between computational fidelity and expedience that aligns with the design-level objective of WhAM.

Isometric views of the curtain wall finite element model are presented in Figures 11 and 12, where both the blast-loaded face of the specimen (inside the shock tube) and the protected face of the specimen (outside the shock tube) are shown in Figure 11. It can be seen in Figure 12 that structural silicone and the IGU air gaps were both represented with constant stress (i.e., single integration point) solid elements, which is the default and most widely used (and most robust) hexahedron element in LS-DYNA. Constitutive behavior of the air gap elements was represented with a null material model and an ideal-gas equation of state. Combination of the null material model and ideal-gas equation of state was shown to adequately capture the dynamic behavior of an IGU air gap as it compresses and transfers load between glass lites during the blast response of a curtain wall system. Constitutive behavior of the structural silicone was represented with a hyper-elastic material model calibrated to test data for the Dow Corning 995 structural silicone product.



(a) (b)

Figure 11. Finite Element Representation of Curtain Wall Specimen, (a) Blast-Loaded Face, (b) Protected Face

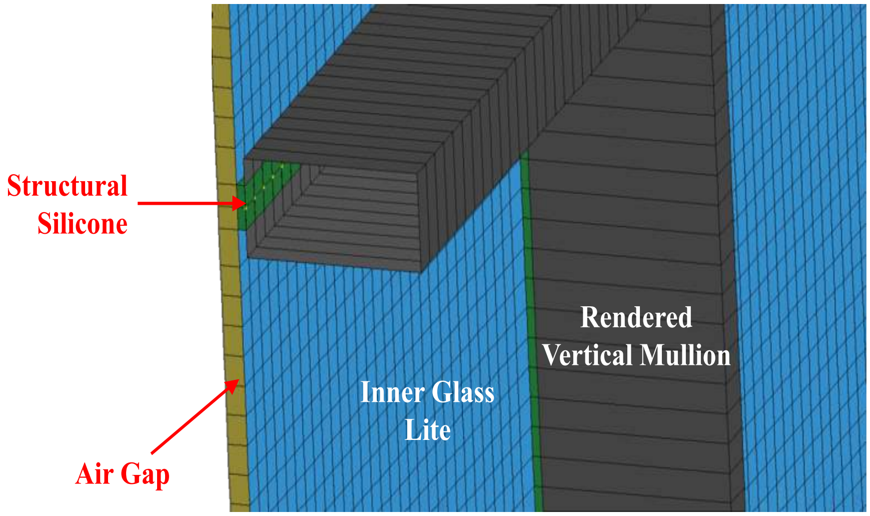


Figure 12. Illustration of Finite Element Details along Vertical Cross-Section through Centerline of Curtain Wall Specimen IGUs

The physical representation of glass-break during the computational simulations is shown in Figure 13. Once the maximum principal stress corresponding to glass break is reached (an initial stress-based glass fracture prediction approach), the entire computational part representing the failed glass lite is instantaneously removed from the computational domain. However, nodes of the failed finite elements are retained, and the mass of the failed finite elements is appropriately partitioned to the retained nodes based on tributary areas. As can be seen in Figure 1, retained nodes from a failed monolithic glass lite simply fly off into space as glass shards; whereas, retained nodes from a failed laminated glass lite transfer momentum of the glass shards to the PVB interlayer.

Figure 13. FEA Representation of Glass-Break Methodology in LS-DYNA

As a result of test data review and comparison with initial FEA model results, further development of computational software features was completed, including advanced LS-DYNA user-defined constitutive models (UMATs) for glass, PVB, and silicone (all have been vectorized and implemented in SMP and MPP parallel processing structures). The new glass UMAT incorporates an elastic constitutive model and a flaw-based probabilistic failure criterion derived from Beason and Morgan's (1984) Glass Failure Prediction Model (GFPM) that was extended to be compatible with finite element analysis techniques; consistent with ASTM E1300 Standard Practice for Determining Load Resistance of Glass in Buildings' current state-of-the-practice and future vision. The new PVB interlayer UMAT captures post-break, strain-based stiffness increase due to interaction between PVB and adhered glass shards and incorporates a dynamic increase factor that is dependent on both strain and strain rate. The new Silicone UMAT incorporates a hyper-elastic constitutive model that accounts for dynamic strength increase due to both strain and strain rate (supported by experimental data for DOW 983, 993, and 995 silicone products (DOW 983 is the only one currently implemented in WhAM v.1.0)).

Results of the improved finite element formulation and modeling approach were validated against several of the curtainwall tests described above. Results of the improved FEA model calculations as compared to Test 4 results are typical of the good correlation between the FEA and the tests. Figure 14 shows both the blast side and protected side of the curtainwall post-test. Monolithic spandrel panels were failed and lower IGU (both left and right) were fractured but remained in the frames.

Figure 14. Test 4 Blast Side (left) and Protected Side (right)

Figure 15 shows the comparison of predicted (labeled WhAM on the plot) displacement vs time results as compared to measured (red) jamb response. Initial predicted maximum excursions of about 89mm (3.5-in) compared well with measured results.

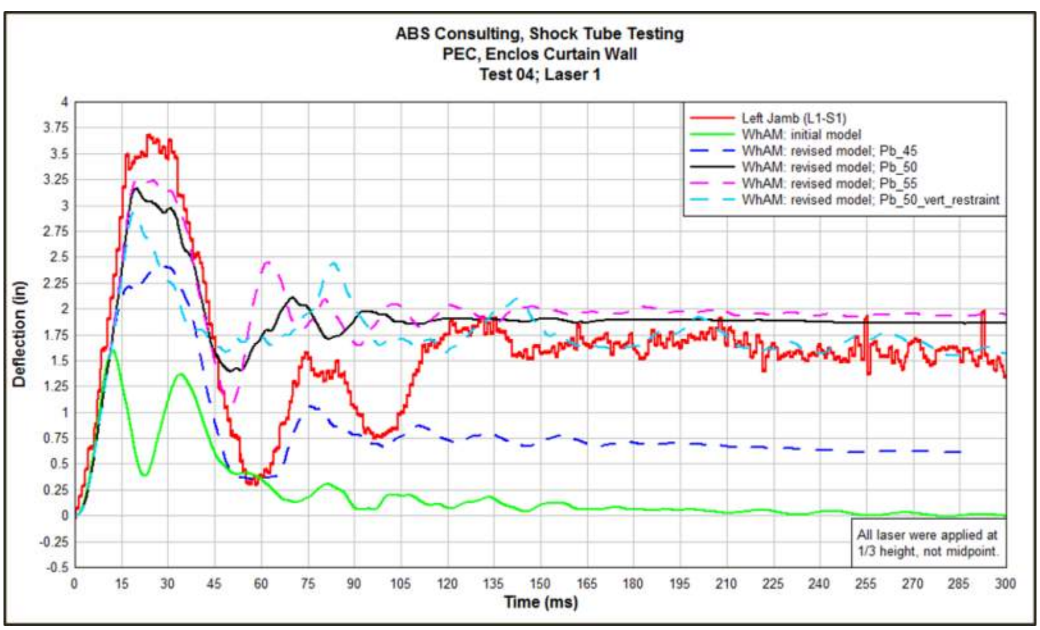


Figure 15. Test 4 Jamb Predicted vs Measured Results

Figure 16 shows the comparison of predicted (labeled WhAM on the plot) displacement vs time results as compared to measured (red) center mullion response. Initial predicted maximum excursions of about 83mm (3.25-in) compared reasonably well with measured results. It should be noted that nominal aluminum material properties were used for the mullions in all computational simulations.

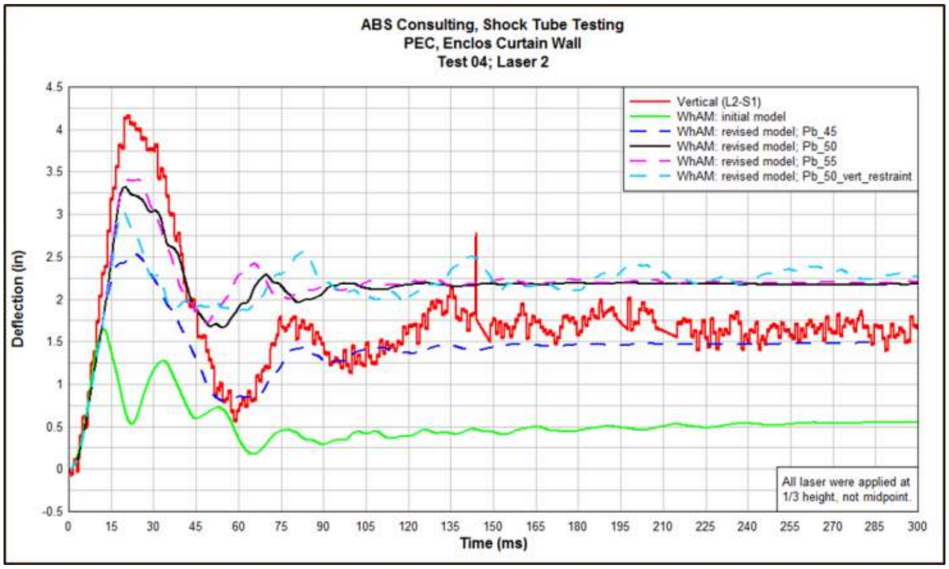


Figure 16. Test 4 Center Mullion Predicted vs Measured Results

Finally, Figure 17 shows the comparison of predicted (labeled WhAM on the plot) displacement vs time results as compared to measured (red) lower left IGU response. Initial predicted maximum excursions of about 75mm (3-in) compared very well with measured results.

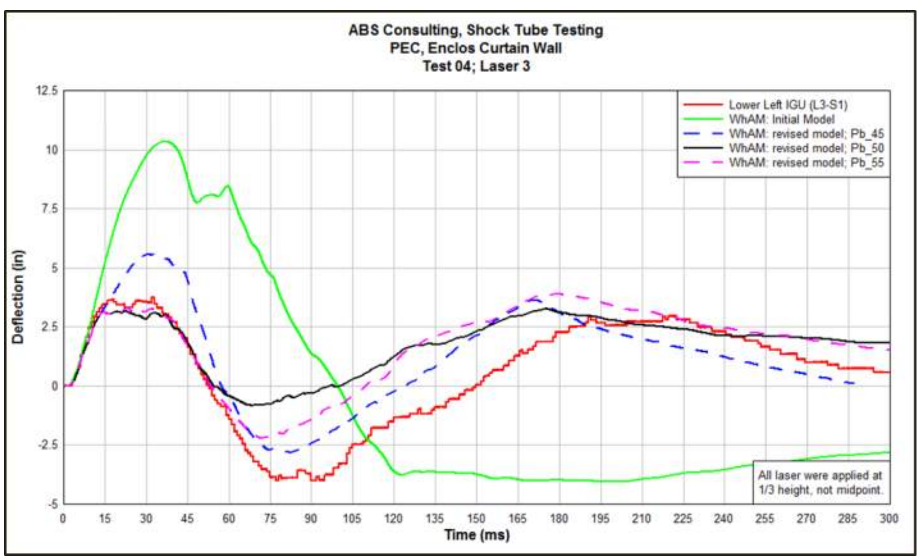


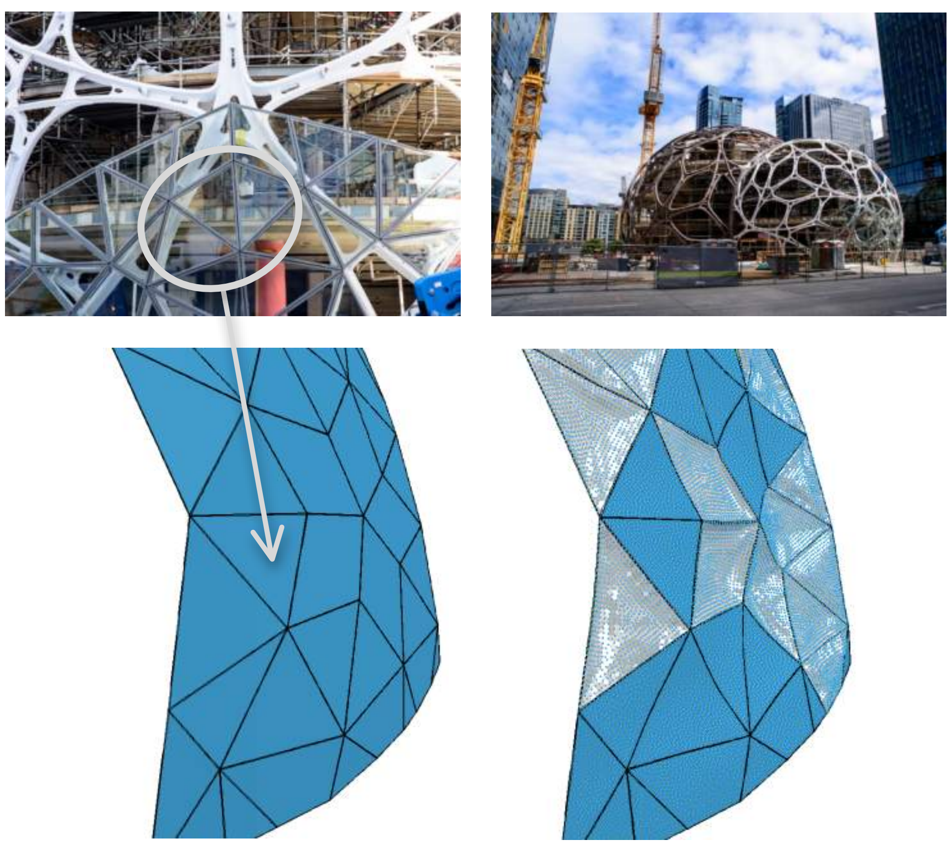
Figure 17. Test 4 Lower Left IGU Predicted vs Measured Results

Note that the green line in Figures 15 through 17 represents the results from previous FEA representation without GFPM, structural silicone or PVB material model enhancements. Those plots show that mullion response is underpredicted and glass response over-predicted (full coupling not captured) without the enhancements.

EXPLANATION

In order to keep up with the constantly advancing state-of-the-art in architecturally complex façade systems, the structural engineering community must continue to strive for parallel advances in structural analysis methodologies and innovative design approaches. The WhAM software and underlying computational modeling approach marks a significant step towards the goal of providing the industry with next-generation multi-hazard analysis and design capabilities for architecturally complex façade systems. From point-supported and curved glass to triple-pane IGUs and exotic types of glass, WhAM's versatile first-principles analysis approach permits a relatively quick and sufficiently accurate means to evaluate the performance of complex façade systems to a variety of extreme loading conditions.

The full capabilities of a coupled glass-mullion analysis using WhAM can best be described through example. Shown below in Figure 18 is a WhAM blast analysis demonstration for the Amazon Biodomes to be completed in Seattle in 2016, with its glazed façade system and curved geometry. Construction progress photos (used under license from SmugMug, license #5988034) are shown below in Figure 18 with the derived WhAM geometry. The bottom two images of Figure 18 illustrate the computational model representing a section of the ball-shaped façade; the bottom-left image being the initial state of the model and the bottom-right image a blast-loaded state captured during the nonlinear dynamic analysis. The façade system was taken to be comprised of planar, laminated glass lites supported by aluminum mullions and subjected to a variation (10% increase in overpressure values) of the average blast load recorded during Test 4 of the aforementioned shock tube tests. As can be seen from the bottom-right image of Figure 18, the coupled glass-mullion analysis was able to capture the effect of support flexibility on the dynamic response of the laminated glass lites. Unlike an SDOF dynamic analysis, a dominant mode of deformation for this complex façade system did not need to be assumed a priori. In fact, the ability to capture multi-modal response of dynamically loaded coupled systems is a key benefit of this analysis approach. Glass fracture of the non-rectangular lites was also captured, as well as post-break laminate response.



Initial State   Blast-Loaded State

Figure 18. WhAM Blast Analysis Demonstration for Amazon Biodome Glazed Façade System having Curved Geometry (photos used under license from SmugMug, license #5988034)

CONCLUSION, CURRENT LIMITATIONS AND FUTURE WORK

The tests and validation reported here has supported the development of the new tool called WhAM (Window hazard Analysis Module) that fully integrates a statistical glass fracture modeling approach into a finite element formulation for glass, laminated glass and structural and nonstructural elements (mullions, muntins and connections). Successful validation using dynamic test data demonstrates the tool's effectiveness for design and analysis of multi-lite storefront and curtainwall configurations. WhAM's unique finite element analysis framework (LS-DYNA) and custom material models offer the flexibility to evaluate non-rectangular and out-of-plane configurations for wind, blast, seismic and impact loads.

While the tool has been designed with capabilities for high fidelity modeling of high-performance facades that include non-rectangular and curved (non-planar) geometries, one-side adhered and point supports, and triple pane configurations, it has initially only been validated against physical tests and measurements of "standard" storefront and curtainwall configurations. Further validation should include full-scale tests with these geometries and configurations at various loads and rates of loading. For "near-failure" performance (as generated by natural and man-made hazards such as hurricane impact and explosions), where glass is cracked but interlayers provide significant residual resistance, the hyper-elastic constitutive behavior and enhanced strength of interlayers due to (a) strain-based stiffening due to the post-break presence of adhered pieces of glass and (b) stiffening due to strain-rate effects need to be quantified. Finally, while present codes and standards generally require tests of façade components subjected to extreme or abnormal loadings for application in building facades, this work and tool will be put forward as a pilot case for changes to industry standards such as ASTM Committee E06's Standard E1300 entitled "Standard Practice for Determining Load Resistance of Glass in Buildings," allowing high performance modeling as a part of performance based design alternate means of analysis procedures.

ACKNOWLEDGMENTS

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REFERENCES

Alberson, Ryan M., Davis, Carrie E., Marchand, Kirk A. 2013. High Strength Glass Testing and Model Validation for Static and Dynamic Loading. ASCE Structures Congress Proceedings, ASCE, 2013

ASTM Standard E1300. 2012. Standard Practice for Determining Load Resistance of Glass in Buildings. ASTM International, West Conshohocken, PA, 2012. DOI: 10.1520/F2248-09. www.astm.org

Beason, W. Lynn and Morgan, James R. February 1984. Glass Failure Prediction Model. Journal of Structural Engineering. Vol. 110, No. 2. ASCE, February 1984.

Cowper, G. R. and Symonds, P. S. 1958. Strain Hardening and Strain Rate Effects in the Impact Loading of Cantilever Beams, Applied Mathematics Report, Brown University; Providence, RI.

Thomson, T. William and Dahleh, D. Marie. 1998. Theory of Vibration with Applications, 5th Edition. Prentice-Hall, Inc.; Upper Saddle River, NJ.

US Army Corps of Engineers (USACE) Protective Design Center (PDC). 2014. Single Degree of Freedom Blast Effects Design Spreadsheet for Windows Version 1.0 (SBEDS-W). January 2014.

Vallabahn, C. V. G. and Wang, B. Y-T. June 1981. Nonlinear Analysis of Rectangular Glass Plates by Finite Difference Method. Institute for Disaster Research, Texas Tech University. Lubbock, Texas: June 1981.

Transparency <> Security

BLAST AND BALLISTIC PROTECTION

A new kind of protective curtain wall

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ABSTRACT

In a joint endeavor for the US Department of State (DoS) Bureau of Diplomatic Security, a unique and highly effective blast-resistant, steel stud curtain wall (SSCW) has been developed. This building façade was developed primarily as a re-cladding option for existing building envelopes, although it can also be used for new construction. The SSCW system meets DoS requirements for forced entry (FE), small arms/ballistic resistance (BR), and blast protection while leveraging the advantages of prefabrication to produce a rapidly installable modular design. The curtain wall's design also meets the typically high-performance requirements of an architectural building envelope. Utilizing a unitized 'cassette style' approach provides increased resilience and enables rapid repair and replacement of damaged sections. The cassette dimensions facilitate shipment in standard 20-foot ISO shipping containers and simplify and speed final installation. The analysis and design utilized state-of-the-art High Fidelity Physics Based (HFPB) calculations including both Computational Fluid Dynamics (CFD) and Computational Structural Dynamics (CSD) methods. Unlike many similar analysis and simulation efforts, this work was validated by a full-scale explosive test. This provided an opportunity to compare the calculation outputs with test data in order to determine the efficacy and accuracy of the calculation methods as well as providing indicators for further calibration of the analysis model for future designs. This paper will provide description and commentary of the design of the SSCW design including the data and lessons captured from the analyses and testing conducted. This discussion complements the DoS release of openly available engineering and fabrication drawings. These will provide a basis for adapting the SSCW design to specific buildings and environmental conditions, while ensuring that final system meets blast, small arms/ballistic and forced entry requirements.

KEYWORDS

unitized curtainwall, security, computational fluid dynamics (CFD), finite element analysis (FEA), physical testing - mockups, retrofit

INTRODUCTION

Under a multi-year program directed by Mr. Russell J. Norris of the U.S. Department of State (DoS) Bureau of Diplomatic Security—working in conjunction with research partners from Karagozian & Case, Inc. (K&C); the Energetic Materials Research & Testing Center (EMRTC) of New Mexico Tech University; Wiss, Janney, Elstner Associates, Inc. (WJE); and Physical Security LLC, a unique and highly effective blast-resistant, steel stud curtain wall (SSCW) was developed. This curtain wall system was designed in response to the DoS's need to reconcile security (physical, construction, and technical) while requiring operation and installation in potentially austere environments. This building façade was developed primarily as a re-cladding option for existing building envelopes, although it can also be used for new construction.

The SSCW system meets DoS requirements for Forced Entry (FE), small arms/ballistic resistance (BR), and blast protection while leveraging the advantages of prefabrication to produce a rapidly installable modular design. The system employs a modular approach in its construction, using a unitized 'cassette style' panel to fill in between its vertical mullions which allow for increased resilience and enables rapid repair and replacement of damaged sections. The cassette's nominal 60-inch width by 12 to 16-foot story-height facilitates shipment in standard 20-foot ISO containers and simplifies and speeds final installation.

An example of the steel stud curtain wall (SSCW) as it would appears in an actual building façade is given in Figure 1. A portion of a nearly identical configuration to this one was tested at EMRTC to prove its merit, where it was subjected to a blast load of over 2000 kPa-msec. This test article, which was limited in height to three stories, is shown in Figure 2. Measurement and analytic results for this structure including the manner of its construction are discussed in the paper.

Figure 1: Example of an installation of the steel stud curtain wall described in the paper.

Figure 2: Full-scale test article and setup employed for blast tests.

BACKGROUND

The SSCW test structure has a nominal 3.7m floor to floor span, although this system is readily adaptable for other story heights. The test structure was installed on a steel framed reaction structure; however, the concept is intended to be applicable to most kinds of building framing system. One of the goals of this design project was to provide guidance pertaining to best practices and determining a basis of design to allow subsequent projects a ready means to adapt and refine the techniques shown to suit structures and project execution strategies.

Erection of the SSCW (Figure 3) is initiated by installation of steel tube 'mullions' which span between and are anchored to the floor diaphragms of the structure. A vertical expansion/slip joint facilitates installation of the mullions and allows for vertical movement of the floor diaphragms. Gravity, seismic and wind loads are resisted by connections at each floor level. Blast loads are resisted by connections to the floor diaphragms, and rebound forces are resisted by unique 'rebound brackets' which engage the steel tube mullions. Once the mullion installation is complete, individual cassettes are then installed.

For the test structure, the individual cassettes were clad in granite at the first floor level. Individual FE/BR windows were included on the ground floor, and strip blast-resistant windows were included on the second and third floors, with spandrel glass over the curtain wall framing above and below the strip windows.

Test Reaction Structure

Installation of first floor mullions

Figure 3a: Installation of SSCW test structure: First floor cassette showing FE/BR window and ballistic steel plate prior to installation of granite cladding

Figure 3: Installation of SSCW test structure: Installation of second floor cassettes

BLAST LOADING

Advanced analysis techniques were used in developing the blast resistance component of the curtain wall's design. Numerous calculations were made as part of the design effort to study the benefits of various design options. In the final calculational efforts leading up to the test, CFD models were used to obtain the blast loadings striking the SSCW. These provided the load's characterization employed in the computational structural dynamics (CSD) model. The CFD model is discussed below, while the highly detailed CSD model used to make the predictions of the curtain walls performance is discussed in the next section.

PRETEST PREDICTION

A final pretest calculation was performed a few weeks before the blast tests to predict the response of the SSCW system as a means to validate the analytic models employed to develop the curtain wall's blast-resistant design. A computational fluid dynamics (CFD) code was used to predict the blast pressure time-histories on the exterior surface of the curtain wall, which were recorded at a grid of tracer points on the surface representing the curtain wall in the CFD model. Rigid non-responding surfaces were used to represent the SSCW. The equations of state (EOS) used to represent the behaviors for the air and Ammonium Nitrate Fuel Oil (ANFO) charges are described below.

The air was modelled using a polytropic gas equation of state of the form (in indicial notation):

$$p = (\gamma - 1)\rho[e - \frac{1}{2} v_j v_j]$$

where,

γ = Ratio of specific heats
ρ = Density of air
e = Specific total energy
vj = Fluid velocity in the x, y, and z-directions

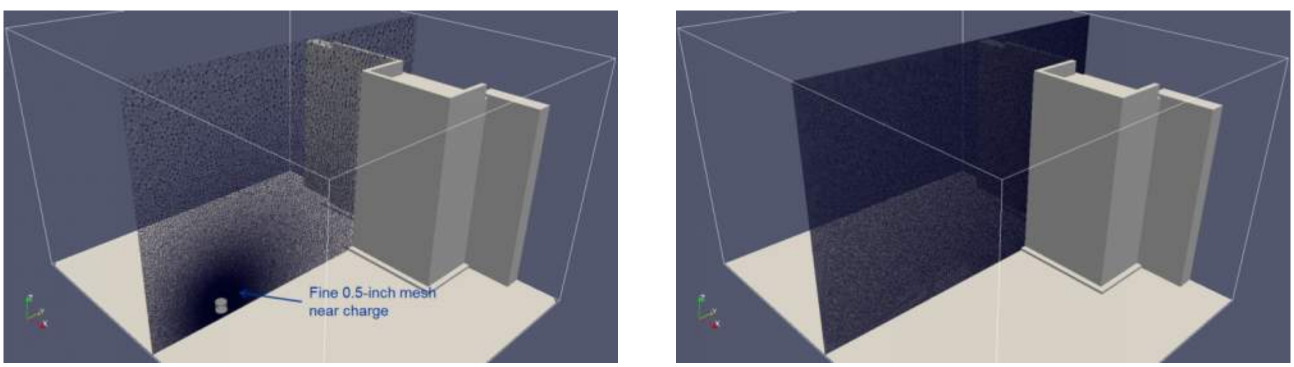
The parameters used for this polytropic gas equation were consistent with the anticipated atmospheric conditions present at the test site in Socorro, NM on the day of test. The energy, density and ratio of specific heats specified for the ambient conditions provide a pressure of 81kPa, which is consistent with the elevation of approximately 1890m at the test site.

The ANFO charge was modelled using a programmed burn and the Jones-Wilkins Lee (JWL) EOS. The parameters required to model ANFO in this manner are: (1) HE density, (2) Chapman-Jouguet (C-J) pressure, (3) C-J detonation velocity, and (4) JWL fit parameters. The parameters used to model ANFO were obtained from Davis et al. (2001), as follows:

R0 =	0.931 (density, gm/cm^3)	ω =	1/3	R1 =	3.907
A =	49.46e10 dynes/cm^2	DCJ =	4.16e5 cm/s	R2 =	1.118
B =	1.891e10 dynes/cm^2	PCJ =	5.15e10 dynes/cm^2	E0 =	2.484e10 dynes/cm^2

A large CFD domain was required to conduct the CFD analysis, which needed to be sufficiently large to encompass the SSCW structure and provide adequate space around the charge to allow for the expansion of the detonation products. Accuracy considerations demand a CFD mesh resolution that is sufficiently small to effectively the capture shock fronts and the shock propagation throughout the domain. To reduce the computational effort, the CFD problem was divided into an initial calculation covering the domain near the detonation, in which the mesh resolution is high. Once the programmed burn was completed, the CFD solution was remapped to a uniform mesh, which was used for the rest of the CFD calculation. A cut-plane in the CFD domain (Figure 4) is used to depict the element resolutions in the initial and remap meshes. The initial mesh is composed of 18 million tetrahedral elements and provides an element resolution of 0.5-inches near the charge. The remapped mesh is composed of 115 million tetrahedral elements and provides an element resolution of 3.5 inches across the whole of the CFD domain.

Outflow boundary conditions were used for all the surfaces in the CFD model except for the ground and the SSCW surfaces. The ground and SSCW surfaces were modelled using reflecting boundary conditions that are representative of a rigid non-responding surface. This allows the adjacent fluid to move tangentially to the surface but does not allow flow through the surface. Figure 4 shows the reflecting outflow surfaces from two different views; the clear surfaces are outflow planes while all the grey surfaces are reflecting surfaces.



Initial Mesh (18M elements) *Remap Mesh (115M elements)*

Figure 4: Mesh resolutions for CFD domain.

COMPARISON WITH TEST DATA

A pressure and impulse time-history plot for a single gage location is shown in Figure 5 along with the corresponding gage data from the test. The computational results showed good agreement with the test results for the ‘time of arrival' and, in general, for the pressure and impulse time-histories.

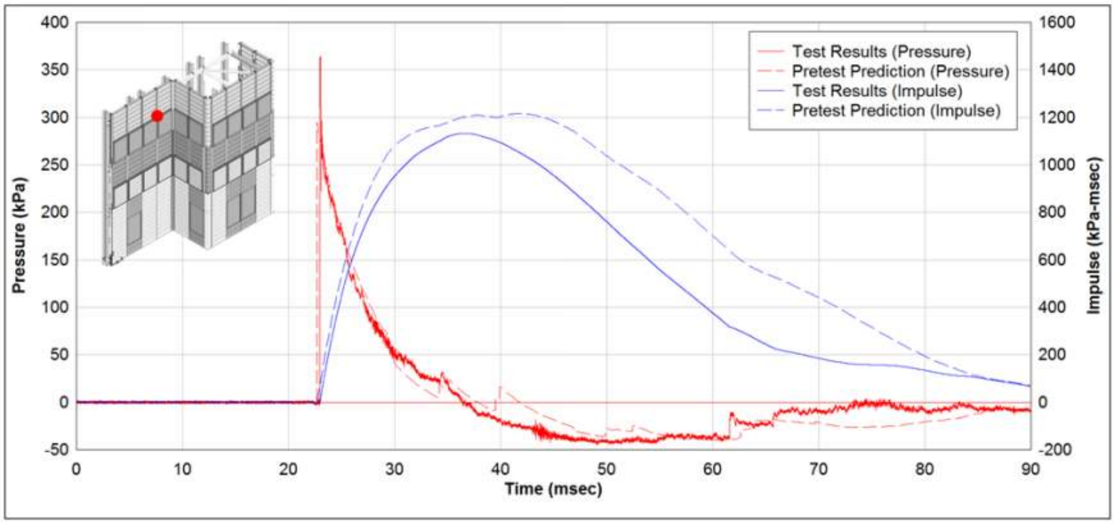
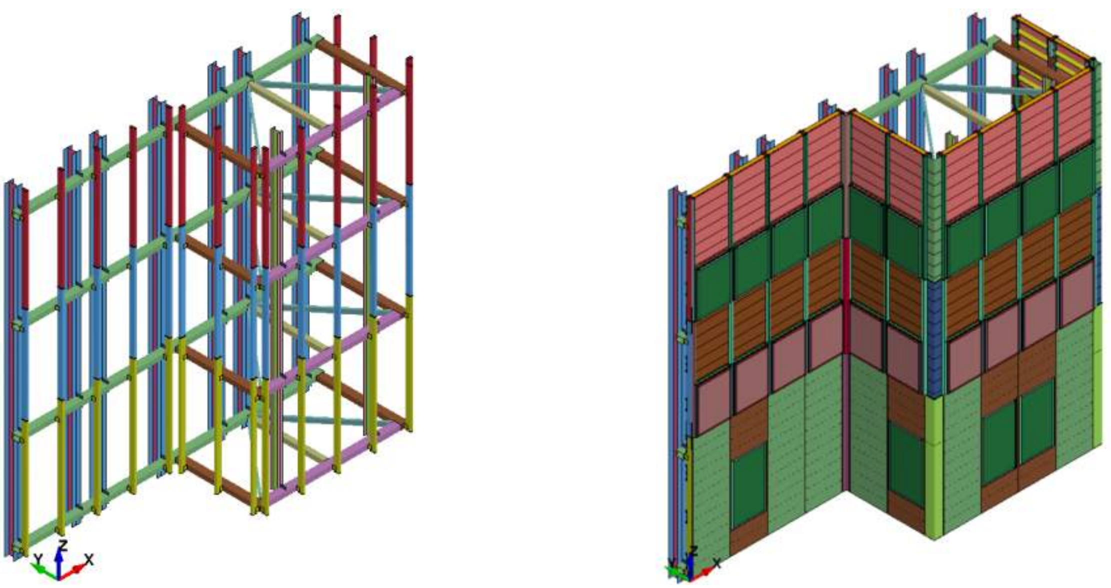


Figure 5: Pressure gage comparison with test data for gages on the SSCW.

STRUCTURAL RESPONSE

PRETEST PREDICTION

A computational structural dynamics (CSD) code was used to simulate the response of the SSCW to the blast load. The model was developed by combining the SSCW components into an assembled model of the test article (Figure 6).



Support Structure with SSCW Vertical Mullions Attached *SSCW Cassettes Installed*

Figure 6: CSD analysis model details

COMPARISON WITH TEST DATA

In general, observations during the test and responses gathered from the gages were consistent with those anticipated. Even though some gages were rendered inoperative during the test, the remaining time-histories of displacement, pressure, and strain garnered from the test were consistent with the analysis and the design itself.

Comparisons of calculation and test results for displacement gages X1, X3, and X5 are shown in Figure 7. In general, with the exception of Gage X1, on the first floor, the records compare favorably in magnitude and wave shape. However, the first floor Gage X1 peak is about twice the prediction, although both records show a rebound to a relatively small late time deflection. Part of this difference is due to the under prediction of the blast load in this region, which were approximately 15% lower than the actual test results. Another factor contributing to the larger than measured deflections is the extensive localized yielding in the support beam (i.e., the beam of the support fixture that supports the curtain wall but is not part of its design). These deformations were observed at the places where the plates attaching the curtain wall's mullions to the support structure were located. The support beam is intended to represent the floors of an actual building (i.e., their noncompliance), and it is not likely that in an actual building that could actually be dented in such a blast load. The upper floor displacements are much smaller and show a consistent behavior between the measured and predicted responses, and no localized response of the support structure occurred here.

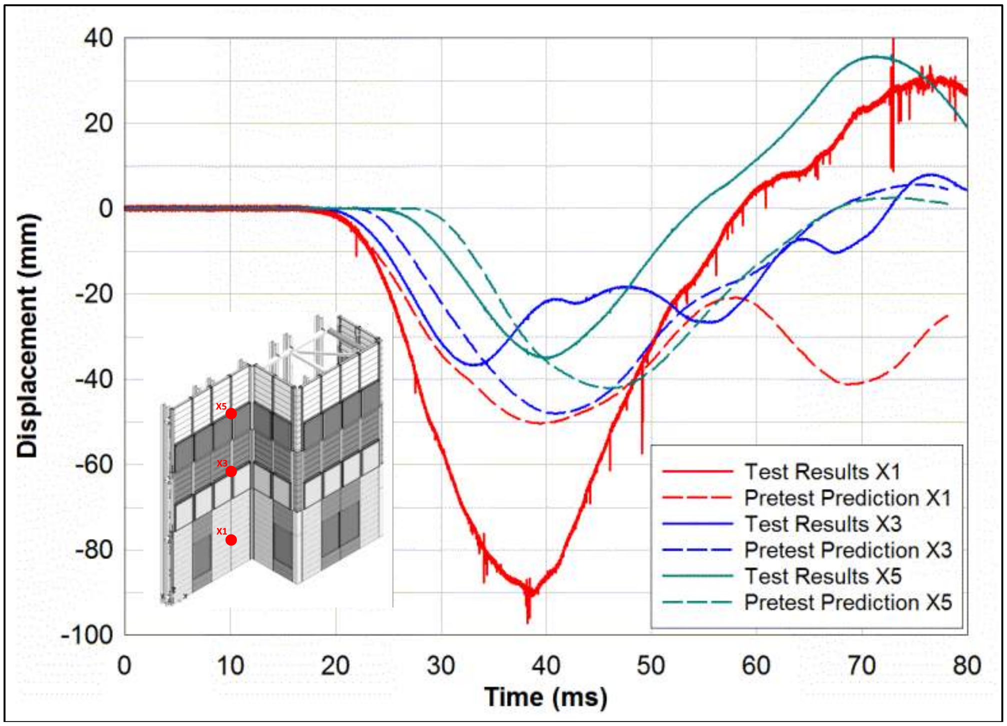


Figure 7: Displacement Gages X1, X3, X5

INTERNAL ENVIRONMENT

The interior environment created by the blast event, and the potential implications for the occupants and contents of a building with this reclad design, is a key metric in evaluating the efficacy of the blast protection afforded by this SSCW system. Considerable structural deformations (i.e., short of catastrophic failure) are permitted as long as the effects on the internal environment are sufficiently mitigated. Several measurement systems were employed to assess the acceptability of the SSCW. First, a series of high speed cameras were positioned inside the SSCW envelope at each floor level to record the response of the SSCW. Second, pressure gages were installed to measure the airblast effects inside the SSCW envelope. These active measurements were supplemented by posttest documentary photos of the interior.

The peak pressures measured within the structure during the blast were generally less than 7kPa, with the exception of a 9.5kPa peak at around 200ms (see Figure 8). This higher peak may have been due to the failure of one of the FE/BR window frames adjacent to the peak value gage, which happened because the frame was improperly installed.

The debris entering the interior space behind the structure primarily from window trim pieces and insulation from the SSCW, which broke free and were propelled into the interior space, albeit at a low velocity. These were deemed to be not much of a risk.

The only exception to this relatively benign debris environment being the debris from the failed FE/BR window frame (mentioned above), from which a heavy frame member was propelled into the interior space. In this regard, post-test inspection of this frame found that some of the bolts holding the frame to the cassette were not installed, which significantly weakened the window and allowed the one piece of injurious debris to enter the interior.

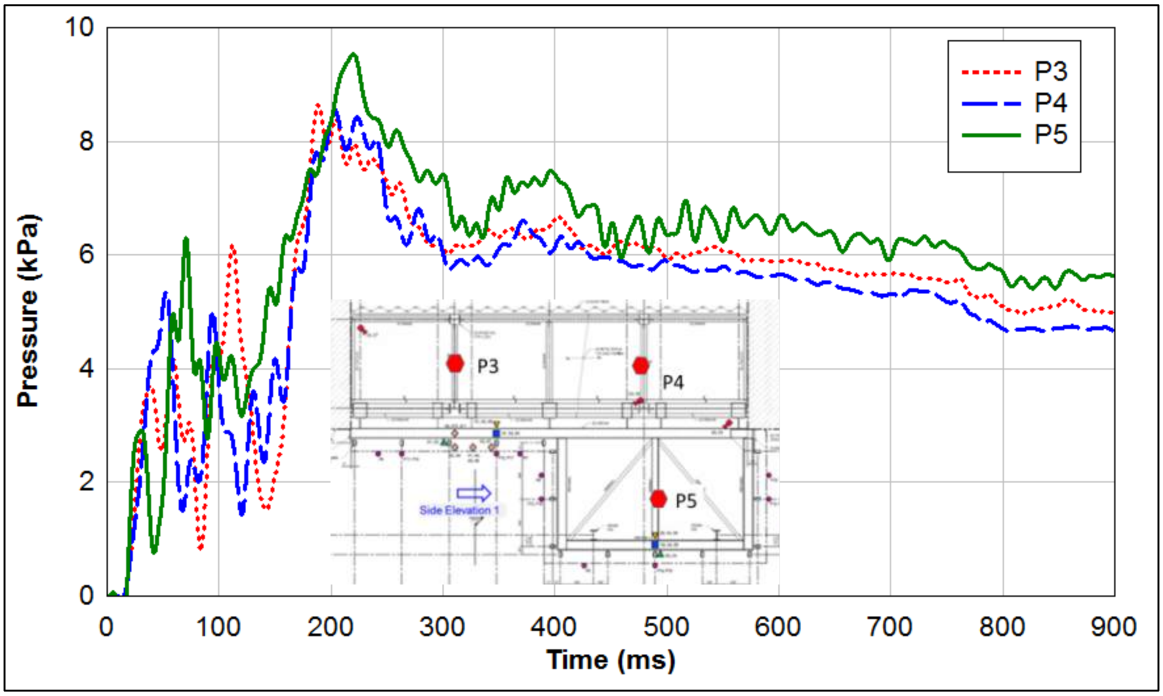


Figure 8: Internal pressures behind SSCW

The FE/BR frame and trim pieces separating from the SSCW are clearly visible in a frame from the high speed video taken during the positive phase of the response (Figure 9). The trim pieces entering the occupied space offers another reminder that due regard should be given to such items as plastic and wood trim to minimize its potential for causing injury if it becomes debris. Very little debris was seen at the 3rd floor as evidenced by a similar high speed camera frame of the 3rd floor (Figure 9).

COMPARISON OF THE CURTAIN WALL PRE AND POST BLAST

Damage to the exterior of the SSCW resulting from the test included fragmentation and removal of the granite cladding, blast window cracking (break safe), and failure of the spandrel glass with the supporting steel stud panels left intact. The design philosophy for the spandrel glass was to allow it to fail and just catch the debris with a thin steel plate attached to the mullions, which worked well. This allows the spandrel glass to be made conventionally, affording a considerable reduction in costs. Comparison of the pre and post-test condition of the SSCW is shown in Figure 10.

1st Floor

3rd Floor

Figure 9: Internal views during the positive phase of the blast.

Detonation

Pretest

Posttest

Figure 10: Pretest and posttest exterior views of SSCW.

CONCLUSION AND FUTURE WORK

This paper described the efforts expended in developing the SSCW curtain wall design, which also included its fabrication and blast effects testing. This SSCW design is both innovative and practical, and well posed to withstand the many blast threats considered in designing curtain walls for Department of State facilities.

Detailed pretest predictions of the structural response and airblast loading were performed using state of the art CSD and CFD codes and models. The structural response of the SSCW test structure was captured using an extensive suite of active instrumentation, which captured key details of structural response and airblast loading, as well as high speed video coverage of the exterior and interior of the structure. Comparisons of the computed and measured curtain wall response data indicated that the analysis model well captured the responses. This validates not only the capability of the designs, but also the capability of the analytical models to capture what are very complex response modes.

The initial benefit of this endeavor for the protective design community is the data and lessons captured from the analyses and testing conducted. This experience will be made available as a set of openly available engineering drawings. These will provide a basis for adapting the SSCW design to specific buildings and environmental conditions, while ensuring that final system meets the blast, small arms/ballistic and forced entry requirements of the DoS Design Basis Threat (DBT).

ACKNOWLEDGMENTS

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REFERENCES

Beckhard, H., "The Breuer-Beckhard Precast Facades," Exterior Wall Systems: Glass and Concrete Technology, Design and Construction, ASTM STP 1034, B. Donaldson, Ed., American Society for Test and Materials, Philadelphia, PA, 1991, pp. 154-169.

Boyd, J. M., "Over-Cladding of Aluminum Framed Curtainwalls and Skylights," Building Exterior Wall Systems, Journal of ASTM International, Vol. 4, No. 10, Chicago, IL, 2007, pp. 139-153.

Clift, C. D., "Curtain Wall Designs for Wind and Blast: Three Case Studies," Journal of Architectural Engineering, Vol. 12, No. 3, September 1, 2006., pp. 150-155.

Crawford, J. E., Lan, S., Ferritto, J. M., and Liu, C. "Blast Effects Analysis of Glazing Façade of Terminal 3 at Singapore Changi Airport," Karagozian & Case, Burbank, CA, TR-05-43.1, September 2005.

Crawford, J. E., Lan, S., Liu, C., and Ong, D. "Basis of Development for the Glazing Analysis Software BEA_CW, Volume I," Karagozian & Case, Burbank, CA, and K&C Protective Technologies Pte Ltd, Singapore, TR-07-6.2, October 2008.

Crawford, J. E. and Lan, S. "Design and Analysis of Blast-Resistant Curtain Walls," Karagozian & Case, Burbank, CA, and K&C Protective Technologies Pte Ltd, Singapore, TR-07-19.1, October 2007.

Crawford, J. E., Lan, S., and Dunn, B. W. "Cable Catcher Systems for Improving Blast Resistance of Glazing Façades," Proceedings of the 19th Military Aspects of Blast and Shock Symposium, Alberta, Canada, October 2006.

Crawford, J.E., Lan, S., Fu, S., Der Avanessian, H., and Palermo, D. "Advances in Blast-Resistant Glazing," for the MABS 20 International Symposium on Military Aspects of Blast and Shock, Oslo, Norway, September 1-5, 2008.

Davis, L.L.; Hill, L.G.; "ANFO Cylinder Tests," CP620 Shock Compression of Condensed Matter, 2001.

Freedman, S., "Architectural Precast Concrete: A Material for the 21st Century," Exterior Wall Systems: Glass and Concrete Technology, Design and Construction, ASTM STP 1034, B. Donaldson, Ed., American Society for Test and Materials, Philadelphia, PA, 1991, pp. 131-153.

Horowitz, J. M., "The Interrelation of Exterior Wall and Structural Systems in Buildings," Exterior Wall Systems: Glass and Concrete Technology, Design and Construction, ASTM STP 1034, B. Donaldson, Ed., American Society for Test and Materials, Philadelphia, PA, 1991, pp. 5-23.

Lawrence, J. B., "Evaluation, Recommendations, and Implementation for Overcladding the Tower Plaza Condominium" Proceedings, Symposium on Building Envelope Technology, Detroit, MI, October-November, 2008, pp. 87-96.

Lawrence, J. B., Johnson, P. G., "Envelop Remediation—A Case Study in Support of an Over-Cladding Approach," Building Exterior Wall Systems, Journal of ASTM International, Vol. 5, No. 10, Chicago, IL, 2008, pp. 121-138.

Li, S. S., McClelland, N., "Façade Renovation of the Wexner Center for the Arts," Building Exterior Wall Systems, Journal of ASTM International, Vol. 4, No. 9, Chicago, IL, 2007, pp. 154-160.

Lindow, E. S., Jasinski, L. F., "Panelized Wall Construction: Design, Testing, and Construction Procedures," Performance of Exterior Building Walls, ASTM STP 1422, P. G. Johnson, Ed., American Society for Test and Materials, West Conshohocken, PA, 2003, pp. 231-241.

Norville, H. S., Conrath, E., J., "Blast-Resistant Glazing Design," Journal of Architectural Engineering, Vol. 12, No. 3, September 1, 2006., pp. 129-136.

Sakhnosky, A. A., "Full-Scale Performance Testing of Curtain Walls," Exterior Wall Systems: Glass and Concrete Technology, Design, and Construction, ASTM STP 1034, B. Donaldson, Ed., American Society for Test and Materials, Philadelphia, PA, 1991, pp. 47-58.

Schwartz, Thomas. "Glass and Metal Curtain-Wall Fundamentals." JSTOR. Version Vol. 32, No. 1, Curtain Walls (2001). Association for Preservation Technology International (APT), Web. 6 Aug. 2010. http://www.jstor.org/stable/1504691.

Yeomans, David. "The Origins of the Modern Curtain Wall." JSTOR. Version Vol. 32, No. 1, Curtain Walls (2001),. Association for Preservation Technology International (APT), n.d. Web. 10 Aug. 2010. http://www.jstor.org/stable/1504688

TRANSPARENT SECURITY IN FEDERAL ARCHITECTURE

A case study in balancing transparency, security, and high performance

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ABSTRACT

The Benjamin P. Grogan and Jerry L. Dove Federal Building, located in Miramar, FL, is a new model in the GSA Design Excellence Program. Its integrated design approach breaks from preconceived notions of combining aesthetics and functional operation in governmental architecture. A unitized, high performance glass skin anchors the Miramar building's design. The skin allows the building to successfully:

- Project a transparent, contemporary aesthetic that captures the open values of the U.S. Federal Government
- Achieve the highest levels of sustainability
- Provide a work environment that sensitively responds to employee wellbeing and productivity

Meet stringent FBI security requirements and comply with the Miami-Dade County glass codes
This paper explores how these four primary project goals are achieved with a sophisticated glass skin. In particular, it gives an overview of the predictive modeling conducted in order to shape the design. It also gives a brief summary of post-construction analyses and their associated performance conclusions. It is the glass façade that drives the building's utility, both in terms of its short and long-term lifespan and its abstract and concrete ambitions. Thus, the Miramar federal building represents a new benchmark for high performance buildings, both within the context of the federal GSA Design Excellence program and for architecture at large.

KEYWORDS

Unitized Curtainwall, Security, Daylighting, Glare, Transparency, Shading, Laminated Glass

INTRODUCTION

The Benjamin P. Grogan and Jerry L. Dove Federal Building, located in Miramar, Florida, represents in built form the overarching principles of the federal General Services Administration (GSA): it reflects the dignity, enterprise, vigor, and stability of the United States government (GSA, 2016). While these characteristics are abstract in their nature, they are made concrete through the building's transparent design. This transparency is not figurative. It is a literal characteristic defined by the glass building skin that encloses the entire structure. Through this skin, the Miramar building balances architectural transparency, security, and high performance so that the facility can continuously embody the GSA's sensibility and operational norms. It is a new typology for federal architecture projects. The building's glass skin exemplifies how one building element can be designed and deployed in conjunction with basic building tectonics like orientation in order to accomplish complex, sometimes competing, architectural goals.

The 34,839 square-meter building, completed in 2014, is the South Florida headquarters to the Federal Bureau of Investigation (FBI). It is located only 40,234 meters northwest of downtown Miami and lies within the Miami-Dade metropolitan area. It consolidates 10 previous field offices into one campus and supports daily operations for over 1,000 FBI staff members. It is also the first building to be completed under the GSA's Design Excellence bridging contract program.

A set of unique, seemingly contradictory parameters defined the project from its outset. Per the GSA, the new building needed to:

- Reflect the dignity, enterprise, vigor, and stability of the United States government
- Thoughtfully respond to and engage the site's natural South Florida landscape
- Serve as an example of the finest contemporary architectural thought
- Serve as a model for modern office spaces
- Optimize performance and environmental impact via integrated, high performance features (façade, orientation, etc.)
- Meet and even exceed the stringent security requirements of the FBI

In order to fulfill these goals, the design team understood that the Miramar building would need to break from the engrained characteristics of many past federal government facilities. They proposed a new solution: the Miramar building would be defined by a glass façade that drove the holistic design approach, accomplishing all of the project goals by interpreting them in innovative ways. The finished building exhibits an aesthetic of lightness in mass and form that belies the robust security and high performance features that have been integrated into the innovative skin. It thereby satisfies the Design Excellence program requirements and sets a new, high standard for federal building projects (Fig.1) (Building Design and Construction, 2014).

Figure 1: The Benjamin P. Grogan and Jerry L. Dove Federal Building consolidates 10 FBI field offices into one campus building. The facility is located in Miramar, FL, 25 miles northwest of Miami. It was completed in 2014. Image © Hedrich Blessing.

BACKGROUND

The GSA established the Design Excellence program in 1962 and revised it in 1994 in order to reinvigorate the design quality of public architecture constructed for the federal government (GSA, 2016). By the GSA's own accounts, federal architecture built in the immediate decades before the 1990s had too often prioritized efficiency, functionality, and cost effectiveness. It did so at the expense of architectural beauty and long-term utility (GSA, "20 Years of Design Excellence" video, 2016). Today's Design Excellence projects therefore strive to overcome these pitfalls. Within this context, the Miramar building's glass façade is an ideal response to the Design Excellence program's contemporary tenets.

The design team began exploring the glass façade solution because it capitalizes on the inherent beauty of the project's site. The building sits on 80,937 square meters in suburban Miramar. Prior to construction, the area had been infilled with a 45.72 cm gravel layer, essentially killing off the natural Everglades landscape that had characterized the land before it was designated as a building plot. Because the GSA strives to treat the landscapes of its building sites as integral to their overall designs, the Miramar design team recognized an opportunity to restore the Everglades ecosystem and create a building that directly connects its occupants to the natural surroundings, characterized by thriving water, plants, and wildlife. In this way, the view from the building to the newly restored, lush landscape became a central feature to the design approach (Fig. 2).

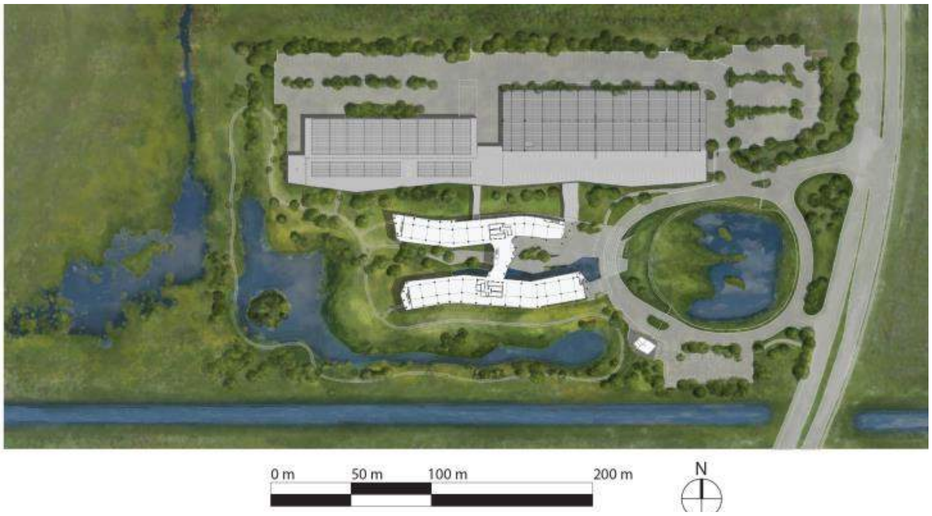


Figure 2: The Miramar campus sits on 20 acres and encompasses a restored Everglades ecosystem. The building design responds directly to the environment by utilizing transparency in order to connect to views.

Further environmental factors also made the glass skin a prudent design solution. South Florida receives high levels of daylight throughout the year thanks to its climate and geographic positioning. This is a distinct advantage, as current research across multiple professional fields (medicine, architecture, and others) has widely discussed and documented the health and performance benefits of daylight. The structures built in South Florida can therefore be designed so that they leverage daylight in order to improve occupant comfort, health, efficiency, and general wellbeing.

The benefits of daylighting in the office are so significant that many European countries require their workers be within 8 meters of a window (National Renewable Energy Laboratory, 2002). Wrapping the Miramar building in a glass skin and then tuning its form, floor plan, and program ensured that occupants of the building will experience ideal levels of daylight. In doing so, they will be able to work in a pleasant environment that positively impacts their health, mood, work attendance, and productivity, augmenting the positive effects established by connecting views from the interior to the natural surroundings.

Biologically, specific systems are dependent on exposure to specific wavelengths of light; the nervous system, circadian rhythms, pituitary gland, endocrine system, and the pineal gland are all affected differently by these wavelengths (National Renewable Energy Laboratory, 2002). Daylight can help these systems positively function, as it has the spectral distribution necessary for the body to carry out certain metabolic processes (National Renewable Energy Laboratory, 2002). Visual acuity is also best when the human eye receives a full-spectrum of light (National Renewable Energy Laboratory, 2002). However, many artificial sources of light are concentrated in specific areas of the spectrum and cannot stimulate the biological functions necessary for keeping our bodies in good health (National Renewable Energy Laboratory, 2002). When coupled with these compelling research outcomes and observations, designing the Miramar facility to maximize exposure to natural daylight became of great importance.

Furthermore, by strategically utilizing daylight as the primary interior light source, the design team knew that it would be able to reduce the building's daily energy loads and artificial lighting maintenance. This impact can be significant given that the building runs around-the-clock operations; relying on daylight during the daytime helps decrease the amount of energy required to power the building's core systems.

In terms of security, the Miramar building's glass skin represented both challenges and opportunities to devise a solution that fully integrates security measures into the glass itself. The project prospectus from the GSA required that the facility meet level 4 Interagency Security Committee (ISC) criteria (GSA, "Prospectus – Design/Build Federal Building-FBI District Office

Miami/Miramar, FL," 2009). Under the criteria, all new federal buildings are required to meet minimal security requirements that include a 30.48-meter secure perimeter setback, facades that can withstand mandated bomb blast thresholds, and structural designs that mitigate progressive collapse in the event of an explosion or collision. These requirements were mandated after the 1995 bombing of the Alfred P. Murrah Federal Building in Oklahoma City, OK (U.S. Department of Justice, 1995). The Miami-Dade code further requires that any glass used as part of a facade must meet the TAS 202 "large missile impact" requirements as well as withstand hurricane wind pressures and potential storm debris damage (Regulatory and Economic Resources, 2016.) In addition, at the Miramar building, the FBI required the incorporation of extensive anti-eavesdropping (radio frequency and infrared) security measures. Specific security details, including blast resistance and other specialized security requirements, cannot be further discussed here or in public, as they are highly confidential. Regardless, the design of the building's skin in response to these security demands goes beyond the typical design of other federal buildings—at Miramar, the security design details are not simply applied as features that enhance and protect the building skin, but are instead design components that cannot be separated from its assemblage.

METHOD

DESIGNING THE BUILDING FORM

The parameters of the glass curtain wall drove the Miramar building's major design moves, including its form and orientation. The H-shaped building is positioned near the site's center. It is laid out as a six-story North bar and a seven-story South bar connected by a six-story link. Both bars are 18-meters-wide by 111-meters-long and are sited in an East-West orientation in order to minimize solar heat gain (Daylighting, 2014). This form and orientation creates a narrow footprint that minimizes the building's impact on the restored landscape.

The design team shaped the bars in both plan and section in order to break up the monotony found in traditional linear bar buildings. Instead, the Miramar building form resembles a geode—its outer glass façade smoothly curves, while its inner facades fracture into crystalline planes. This contrast generates a geometrically complex structure that is visually intriguing and enables occupants to experience the space differently as they move across the building and from floor to floor. This form helps to set the Miramar building apart from its federal architecture predecessors; it elevates the standard federal building footprint, which has traditionally favored simple variations on the rectilinear volume. Inside, the narrow width, orientation, and overall shape of the bars also enable occupants to sit no more than 9.14 meters from the building perimeter with direct access to daylight. After taking the year-round, average climate and light levels into consideration, the design team determined that this distance optimizes the positive health and productivity benefits associated with daily exposure to daylight within the workspace environment (Daylighting, 2014).The distance also brings the landscape into the field of vision. Views are framed in such a way that they can be enjoyed easily from every seat on the office floors.

FINE TUNING THE UNITIZED CURTAIN WALL SYSTEM

The design team selected the unitized glass curtain wall as the single façade material due to a few key factors that push beyond the glass' literal transparency. While Miami experiences high heat, sun, and moisture levels, its tropical temperature only varies by approximately +/-30 degrees Fahrenheit over the course of the year (Florida, 2016). An insulated glass wall performs remarkably well in this kind of environment and does not require aggressive insulation for thermal reasons.

The units for the Miramar building's unitized curtain wall were manufactured in a highly controlled plant and shipped to the site for installation. The precise engineering and manufacturing process ensured that the unitized skin would achieve thinness while preventing air and moisture infiltration. Glass, the primary material in a unitized wall, is ideal because it is easy to clean and is impervious to moisture and air infiltration. A four-sided unitized wall is engineered with redundant caulk and moisture weep system should the exterior seal be compromised, meaning that the glass and sealants are unlikely to fail. The passive efficiency generated by this design, in turn, further enhances the comprehensive performance of the building and helps reduce projected overall maintenance costs.

Block model energy analysis was deployed in the bridging design process to determine the optimal solar heat gain coefficients (SHGCs) that would be achieved through the application of a low-e coating to the glass. The design team wanted to achieve the lowest SHGC as possible in order to minimize heat gain from solar radiation, which would directly affect the GSA's Energy Use Intensity (EUI) target for the building, which is less than 38 kBtu per square-foot (30% lower than ASHRAE 90.1-2004 baseline). Analysis indicated that a SHGC of .20 to .40 was required in order to meet the goal (Fig. 3). In order to effectively and comfortably illuminate the building's interior with daylight, the design team had to reduce the effects of the intensity of South Florida's sunlight (which measures approximately 100,000 lux) to less than 1,000 lux. They determined balanced inside light levels should measure a minimum of 300 lux across the office floors as recommended by the Illuminating Engineering Society of North America (IESNA) for office spaces. Levels varying too far from this measurement could potentially induce eye strain and difficulty when completing visual tasks (GSA "Facilities Standards: 6.15 Lighting," 2015). Additional models demonstrating visible light transmittance (VLT) were made so that the design team could select a glass that performs within the ideal SHGC range without too drastically reducing visible light within the building interior.

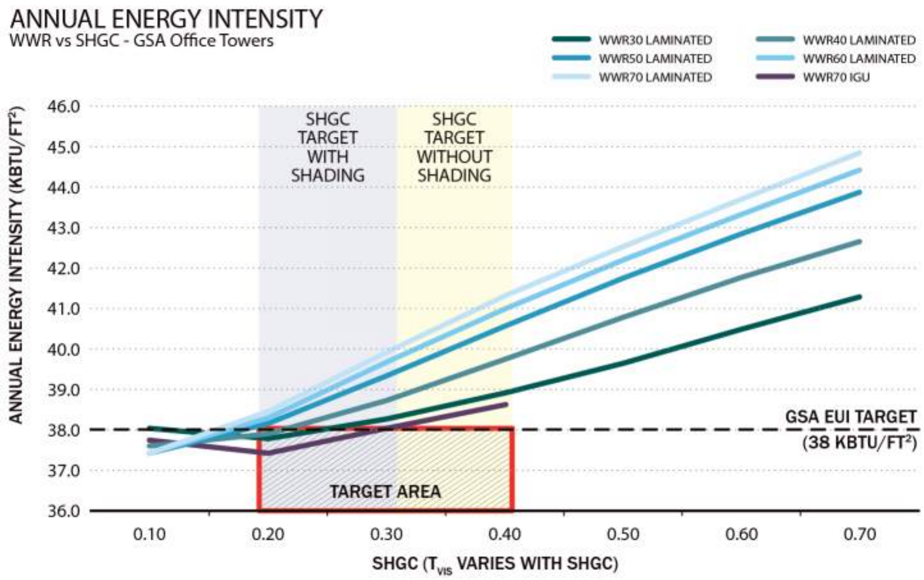


Figure 3: SHGC analysis indicated an ideal range of .20 to .40 in order to meet the GSA's EUI target of 38 kBtu/square foot. Image © Atelier Ten.

Each curtain wall unit is composed of an outer lite of 0.95-cm low-iron glass treated with a white ceramic frit and low-e coating on the #2 surface. The design team selected this glass thickness to reduce the roller-wave distortion (.003/ 1') and the low-iron to reduce the green tint of thicker glass. The white ceramic frit dot pattern along with the low-e coating was added to the #2 surface to block the solar energy from entering the cavity. The white frit was chosen primarily to reduce and soften the reflection of the high performance low-e coating. The sun reflects off the white dots, enabling the building to have a "whiteness" in its appearance. A 2.54-cm cavity of argon gas was selected to enhance the u-value and meet the FBI's 40 decibels (dB) acoustical transmittance specification. Two pieces of 0.64-cm laminated annealed glass with a 0.20-cm pvb interlayer were used to provide hurricane protection. They are treated with an anti-eavesdropping coating on the #4 and #6 sides in order to meet the stringent security demands. The low-e coating on the #2 surface provides the majority of the infrared protection while the radio frequency protection is provided by the #4 and #6 coated surfaces (Fig. 4).

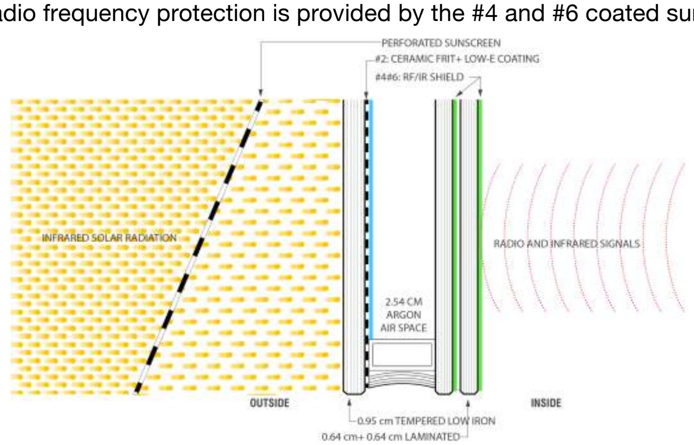
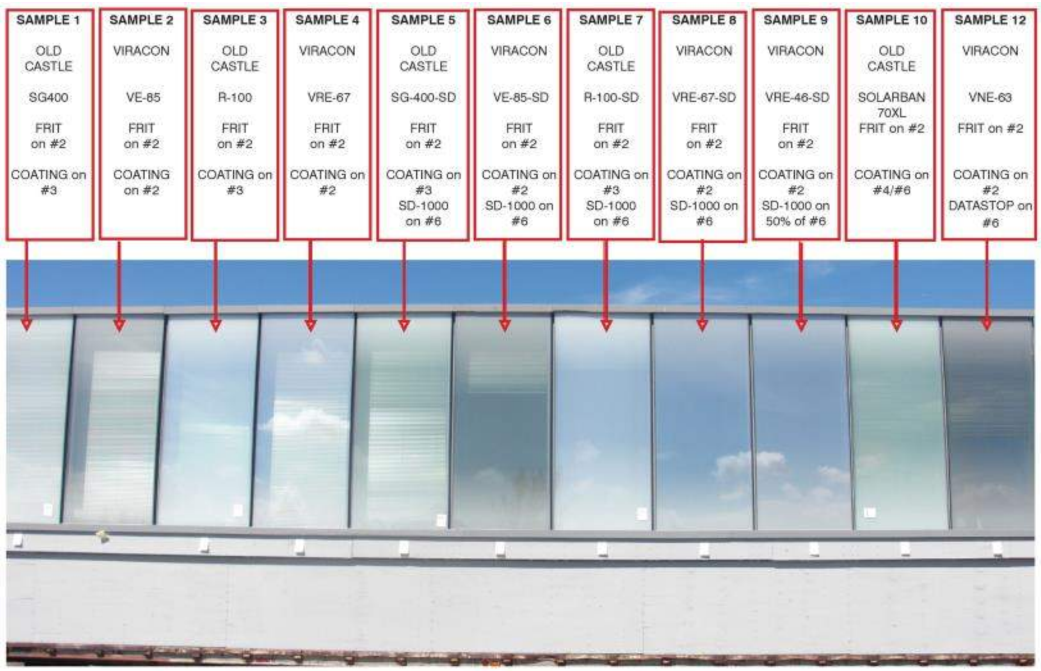


Figure 4: The unitized glass assemblage in section.

On site, the design team sampled 12 full-size glass assemblies with various combinations of low-e coatings and white frit patterns in order to understand the VLT, color, and reflectivity of different types of glass before choosing the assemblage used in the building's construction. All of the glass assemblages sampled on site achieved a SHGC in the desired .20 to .40 range, yet each had a very distinct visual aesthetic (Fig. 5). The design team chose sample #8 for its balanced appearance and color rendition.



GLASS SAMPLE MOCK-UP WITH DIRECT SOLAR EXPOSURE ON SITE ON AUGUST 02, 2011

Figure 5: The 12 unitized glass assemblages being tested on site. While the SHGCs all fall within desired range, their visual properties varied immensely.

The entire Miramar building glass assembly measures 4.76-cm-thick. This is almost twice the thickness of typical façade glass, but it is remarkably thin when the site's climatic conditions and the building's integrated security requirements are taken into consideration. Its performance is also remarkable thanks to a two-level shading system. Exterior, 30% perforated aluminum shades effectively stop the direct sun from reaching the surface of the glass on the building's south elevations—the "sunniest" surfaces (Fig. 6). Each inverted v-shaped shade blade measures 228.60 cm wide by 33.02 cm deep. The shape directly responds to the path of the sun and was determined to be the most efficient use of materials to maximize shading during peak sun times (Fig. 7). Like the glass skin, the shades are unitized with no shade-to-shade connection in order to address the structure's differential defections.

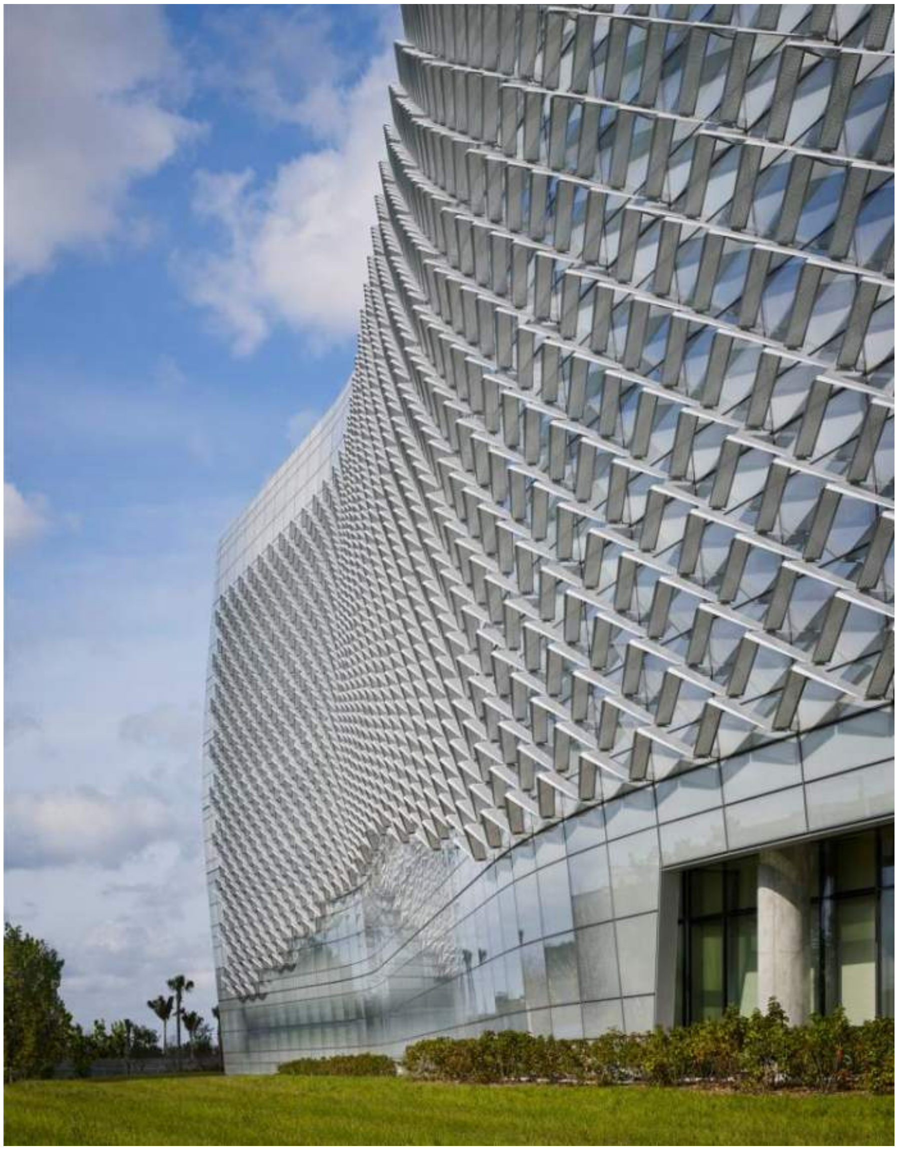


Figure 6: The aluminum sunshades help protect the south façade of the building. Image © Hedrich Blessing.

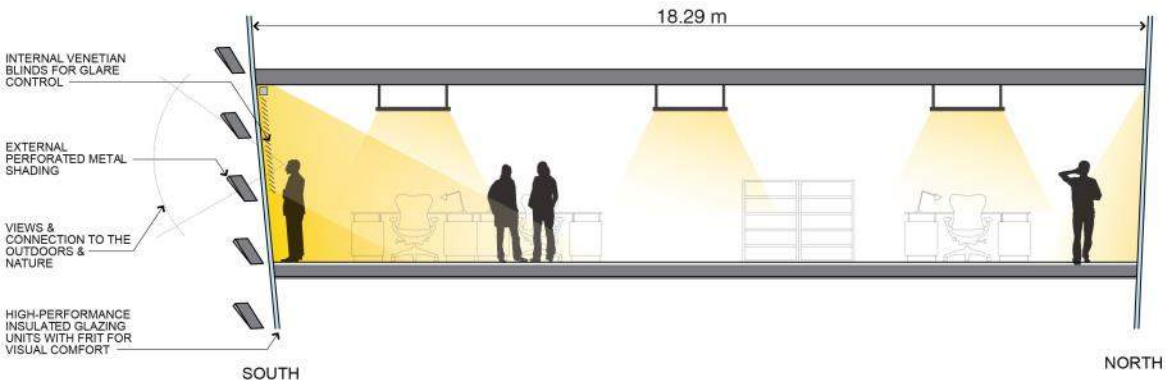
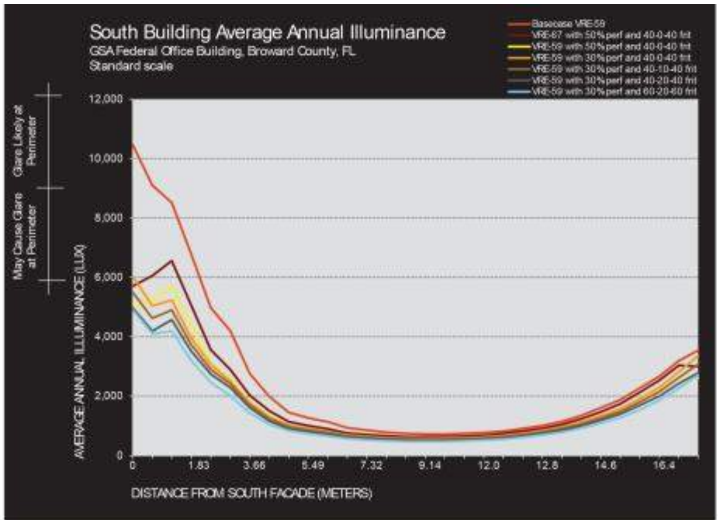


Figure 7: The sunshades help control for VLT and SHGC. They are located on the south side of the building, the surface that receives the most direct, intense sunlight throughout the year. Image © Atelier Ten.

The design team also fine-tuned the ceramic frit applied to the #2 surface of the assemblage. The frit fades from a 60% opacity at the spandrel to a 20% opacity at the center of the occupant vision area, effectively managing solar heat gain and glare without obscuring views to the exterior. The results of the frit working in tandem with the south façade solar shade system are impressive: together, they reduce the building's overall SHGC from .26 to .17 and allow a balanced VLT, meaning that energy performance is drastically enhanced without sacrificing interior comfort or views to the Everglades
(Fig. 8).



	South building						
	VRE-59, no frit, no perforation	VRE-67, 40-0-40 frit, 50% openness	VRE-59, 40-0-40 frit, 50% openness	VRE-59, 40-0-40 frit, 30% openness	VRE-59, 40-10-40 frit, 30% openness	VRE-59, 40-20-40 frit, 30% openness	VRE-59, 60-20-60 frit, 30% openness
glass SHGC	0.34	0.32	0.29	0.30	0.29	0.28	0.26
% solar radiation admitted through shading	100%	71%	71%	65%	65%	65%	65%
Combined SHGC	0.34	0.23	0.20	0.19	0.19	0.18	0.17

THE GLAZING SHGC MULTIPLIED BY THE PERCENTAGE OF SOLAR RADIATION ADMITTED THROUGH THE SHADING GIVES THE COMBINED "EFFECTIVE" SHGC (GLAZING SHGC X % OF SUN ADMITTED THROUGH SHADING = EFFECTIVE SHGC)

Figure 8: The sunshades and the frit work together to achieve optimal SHGC and VLT levels. Various combinations were tested to find the ideal solution, listed in the blue column. Image © Atelier Ten.

Security was of equal concern to environmental performance and an integral component that shaped the unitized glass assemblage's design. Per ISC's *Security Design Criteria for New Federal Office Buildings and Major Modernization Projects*, electromagnetic shielding was required in the radio frequency spectrum range of 100 kHz to 20 GHz, the general electromagnetic signals produced by cell phones and wireless networks (Fig. 9) (ISC, 2001). Shielding effectiveness—known as attenuation—is measured in dBs. The greater the attenuation, the more reduction there is in the signal strength making it less likely that electromagnetic signals will be retrieved by eavesdropping devices.

Testing glass to understand its electromagnetic shielding potential is done in a laboratory. Prior to 2014, test protocol IEEE 299-2006 Standard Method for Measuring the Effectiveness of Electromagnetic Shielding Enclosures was often utilized. In 2014, ASTM F3057 Standard Test Method for Electromagnetic Shielding Effectiveness of Glazings was released and became another test method available for testing the shielding potential of glass products. For the Miramar building, the specific testing completed is confidential.

The design team chose to test Datastop, a Pilkington glass product that is treated with an ionized coating, to attenuate the transmission of electromagnetic signals, due to its shielding performance and color neutral transparency. Datastop also has a higher VLT than other coatings and anti-eavesdropping films. This made it an intriguing option for the glass assemblages that make up the Miramar building's glass skin.

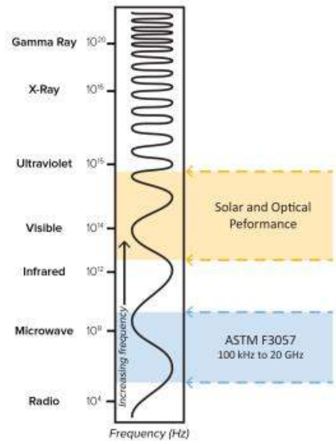


Figure 9: Frequencies found in the delineated electromagnetic fields needed to be blocked via special glass coatings.

Image © Viracon.

DATA

With building modeling and simulation increasingly driving design decisions, it was imperative for the bridging team to assess and verify the actual daylighting and visual comfort of the space. Post-construction measurements by the bridging team confirm that 72% of the office space achieves at least 200 lux or more on any given day, a level that allows for adequate ambient natural illumination. Internal corridors, entrance lobbies, elevator lobbies, public corridors, stairwells, bathroom areas, and dining areas all require a nominal illumination level of 200 lux. Normal work station spaces, training rooms, and physical fitness spaces specify a minimum of 300 lux (GSA,"2003 Facilities Standards: 6.15 Lighting," 2003). Approximately 60% of the typical Miramar office floorplates achieve 300 lux, a sufficient natural illumination level according to IESNA guidelines for office tasks conducted during occupied hours (GSA "Facilities Standards: 6.15 Lighting," 2015). Luminance was measured in key open office spaces as well as at perimeter spaces; all measurements were taken on a summer day. Field measured values fall within 10-20% of the predicted luminance levels, achieving the design team's target daylight autonomy. In terms of daily operations, this means the need for artificial electric lighting is reduced or eliminated during daylight hours (Fig. 10). Glare mitigation from external shading and light reduction levels, most notably at the building's south perimeter, outperformed the model predictions.

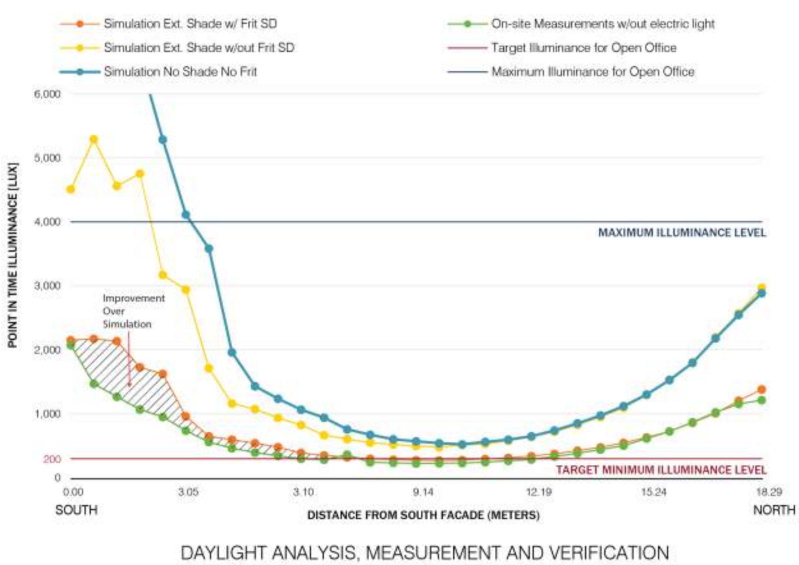
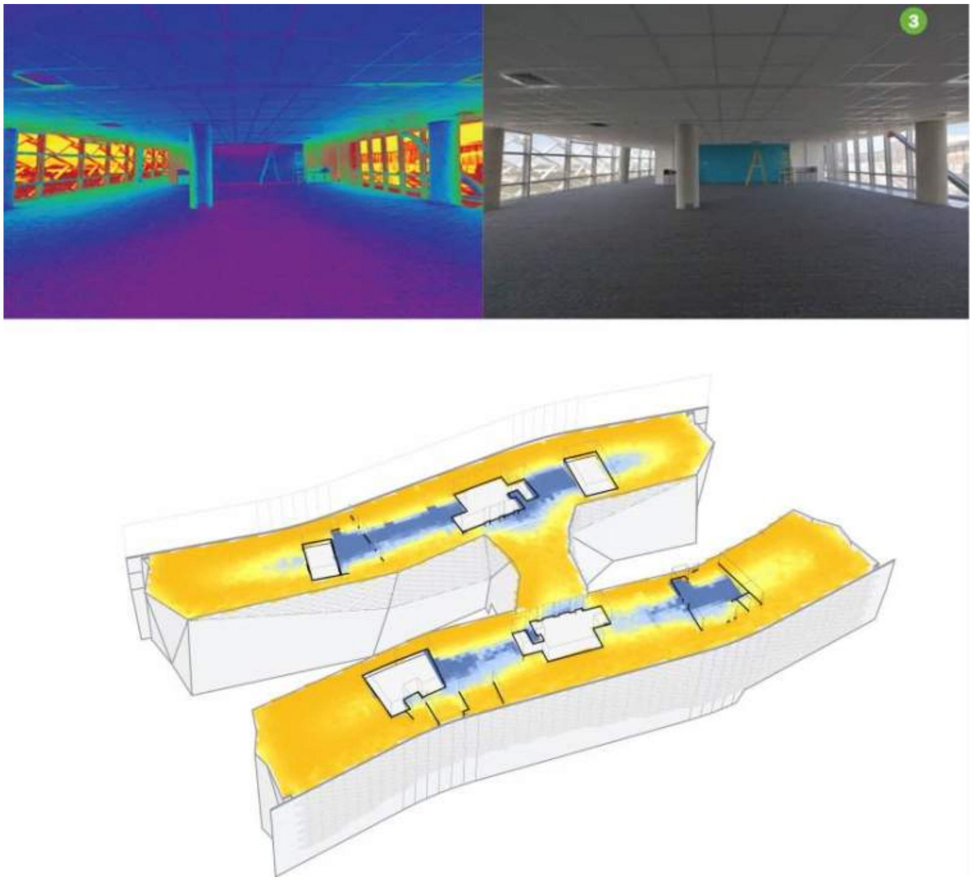


Figure 10: Daylight analyses of the built space verify that natural illumination is often possible on the office floors.

Image © Atelier Ten.

Calibrated High Dynamic Range (HDR) imaging was also deployed to determine brightness and daylighting contrast in the spaces. These photos were digitally layered and compiled into a single composite image. Analytic software uses the image and the luminance site measurements in order to calibrate the pixels in the image so that they realistically represent the relative brightness of the objects in the scene—in other words, the HDR image shows what the human eye sees and experiences. At the Miramar building, the brightness level on the south façade is remarkably in balance with the brightness level on the north façade, meaning that the façade and its shading devices are equally distributing light across the entire floorplate (Figs. 11 & 12).



Figures 11 & 12: HDR imaging shows that brightness and daylight are well calibrated throughout the course of the day over the majority of the typical floor's area.

Image © Atelier Ten.

The HDR imagery ultimately confirms the design team's models and predictions. As designed and built, the all-glass façade and its shading devices reduce high-contrast glare (specifically on the building's south façade) and spread daylight evenly across the building's 18.29-meter width. The result is a naturally illuminated workspace where artificial lighting is not often necessary, resulting in energy savings and increased employee productivity, health and comfort. When successfully applied, daylighting can end up paying for itself as the increased dollar value of office worker productivity can be greater than the cost of implementing daylighting technology (National Renewable Energy Laboratory, 2002).

CONCLUSION

At its dedication, the FBI Director declared the new Miramar building an inspiration—high praise for any built work (Fig. 13). After approximately 18 months of 24/7 operations, it is clear that this inspiration extends beyond platitudes. Creating a federal building that represents the vigor and stability of the United States and exceeds the highest sustainable performance expectations of its users is not a simple task. Weaving in hurricane, bomb blast, and electromagnetic attenuation requirements only makes the assignment more challenging. It would have been easy to turn to a tried-and-true architectural solution but instead, the Miramar building, with its complex geometry and transparent, unitized glass skin, introduces a new, truly integrated approach to federal architecture. It leverages one well-designed feature—an advanced glass skin—in order to resolve the project's disparate design goals, and it makes this feature the visual and performative focal piece of the entire design. The skin works with the building's other features—orientation, landscape, and exterior sunshades —in order to balance the highest levels of sustainability and occupant wellbeing. The building is light filled and inspirational, and it also attains a level of security typically not seen in other glass buildings in the United States. In this manner, the project's inherent defensiveness becomes, both figuratively and literally, light and agile.

The Miramar building marks the evolution of the federal office building, putting forth a better solution for Design Excellence projects and the next generation of high performance architecture.

Figure 13: The completed Miramar building, with its restored site and geode form.

Image © Hedrich Blessing.

REFERENCES

Building Design and Construction. "GSA Design Awards: 20 federal buildings honored as 'best of GSA.'." http://www.bdcnetwork.com/gsa-design-awards-20-federal-buildings-honored-best-gsa (accessed July 12, 2016).

Florida Climate Center. "Weather Planner: Miami." https://climatecenter.fsu.edu/products-services/data/weather-planner/miami (accessed May 3, 2016).

General Services Administration. "Design Excellence." http://www.gsa.gov/portal/category/21079 (accessed May 2, 2016).

General Services Administration. "Designing for Democracy: 20 Years of Design Excellence." http://www.gsa.gov/portal/category/21080 (accessed May 2, 2016).

General Services Administration. "2003 Facilities Standards: 6.15 Lighting." http://www.gsa.gov/portal/content/101308 (accessed July 11, 2016).

General Services Administration. "Prospectus – Design/Build Federal Building-FBI District Office Miami/Miramar, FL." http://www.gsa.gov/graphics/pbs/fy10_program__construction__federal_buildingfbi_distrct_office__miamimiramar_fl.pdf (accessed July 11, 2016).

General Services Administration. "The Site Security Design Guide." https://www.wbdg.org/ccb/GSAMAN/site_security_dg.pdf (accessed July 11, 2016).

Interagency Security Committee, *ISC Security Design Criteria for New Federal Office Buildings and Major Modernization Projects*, May 28, 2001, available on a limited-access website at [http://oca.gsa.gov].

Miami Dade Government. "Regulatory & Economic Resources: Building." http://www.miamidade.gov/building/ (accessed May 6, 2016).

U.S. Department of Justice, U.S. Marshals Service, *Vulnerability Assessment of Federal Facilities*, June 28, 1995 (Washington:1995), p.1-1.

Whole Building Design Guide. "Daylighting." http://www.wbdg.org/resources/daylighting.php (accessed July 12, 2016).

SUPER-TRANSPARENT AND COMPLEX

Cutting-edge façade technology in Doha, Qatar

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ABSTRACT

Qatar's policy for modernizing the country is to combine construction innovation with iconic architecture. The fascinating designs and the extreme climatic conditions require top-level façade engineering and design technology.

The paper features some of the most challenging envelope projects in Doha, capital of Qatar, which were engineered and designed by the authors. In terms of geometric complexity, the National Museum of Qatar (Atelier Jean Nouvel, Paris, France) is a real milestone in 3D engineering and BIM full-detail modelling and design. Two more innovative façade technology examples are the super-transparent facades of the Qatar National Convention Centre (Yamasaki Architects, Troy/Michigan, USA) with 18m tall glass fins, and the cable facades of the Doha Exhibition and Convention Centre (Jahn Architects, Chicago, USA) with their innovative support on horizontally stressed cables.

KEYWORDS

Computational Design, Glass Engineering, Building Information Modeling (BIM), GFRC, Transparency, Complex Geometry, Qatar.

INTRODUCTION

Many of the largest, most innovative and challenging recent architectural construction projects of the world are located in the Gulf states, and Qatar is home to some of the most iconic ones. The present paper describes the stunning architectural and engineering features of the envelopes of these projects, and the Gulf region façade market experience and the local design and construction conditions are explained.

NATIONAL MUSEUM OF QATAR - COMPLEX GEOMETRY AND BIM MODELLING

The National Museum of Qatar project goes back to an architectural competition won by Atelier Jean Nouvel (AJN), Paris. The design is based on the idea of a sculptural building compound in the form of a desert rose, a small crystalline gypsum object that is created by certain mineral and water evaporation conditions in the deserts of the Arabian peninsula.

The building does have a very iconic, complex three-dimensional geometry made of several hundreds of disc elements. These do have various diameters and thicknesses, up to 87m large. As in the real gypsum desert rose, these discs are intersecting each other in an irregular way (fig. 1).

Figure 1 National Museum of Qatar – bird's eye view of full project extent.

The AJN design team was engaged by the client to prepare a design-and-build contract tender package, which was awarded to Hyundai Engineering & Construction from Korea (HDEC). Their scope included, amongst other project parts, all envelope design-and-construction works.

The sculptural disks which are the envelope of the project do have a cladding made of glass-fibre-reinforced concrete (GFRC). These solid panels are irregularly shaped and all have a double-curvature coming from the curvature of the individual lens-shaped disks. They are attached in an invisible concealed way to a secondary steel substructure, which is on top of a waterproofing-foamglass-insulation-metal-deck roof buildup. All that entire buildup is supported by the primary steel beams and trusses designed by ARUP and produced and installed by Eversendai in the UAE. The GFRC panels themselves were produced by FIBREX in their plants in UAE and Qatar.

The scope of WSS involved the role as façade specialist for consulting and site supervision on the entire façade design and installation, and in particular for the optimization, engineering and 3D modelling of the entire FRC cladding substructure and related steel elements.

The key to designing that super-complex three-dimensional building compound was to combine all design files of all the individual companies involved into a giant 3D BIM model (fig. 2). That 3D BIM model is a kind of living organism, with constant data feed and updating from all parties involved, in full Level of Detail LOD400, with a permanent clash detection and design coordination process running in the background. The model was administered and maintained by Gehry Technologies in California, using Digital Project software. All details and layouts and profiles were optimized by WSS to originate from a set of common design principles, to minimize the extent of individual components and to use as many equal parts as possible. All kinds of tolerances had to be accommodated, as well as limited availability of hardware products on the local market and ease of fabrication, construction, transportation and installation.

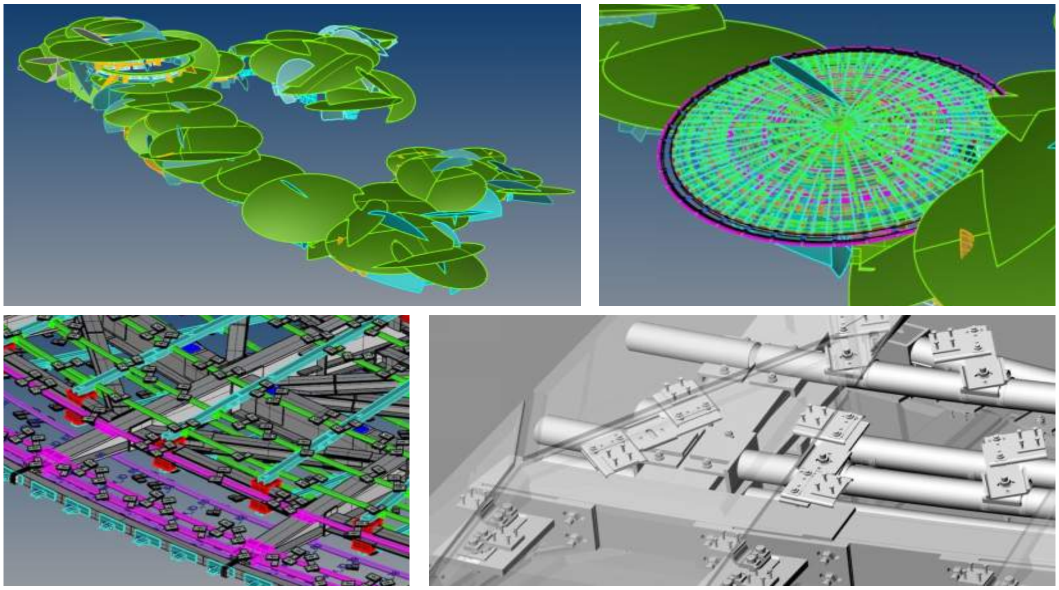

Figure 2 National Museum of Qatar – various stages of detailing of cladding substructure.

The entire secondary steel scope was divided among no less than five producers (Gulf Steel, Hanlim, Boston Steel, PSCQ, and Eversendai). These were working in parallel on different areas of the project at the same time, for the sake of construction schedule and stability of performance. The detailed WSS 3D BIM files went to these producers who derived their cutting and drilling machines input and all other related information directly from them.

The size and complexity of the project was an outstanding challenge to all parties involved. Table 1 shows the numbers of a few key components of the project; bear in mind they all were designed and tailored to suit the individual location and situation on the multi-faceted 3D sculptural disc shards cladding.

Design teams were working on three continents, the producers and site people were from everywhere across Asia, with up to 3,000 workers on site (fig. 3). WSS deployed a permanent site team of up to four engineers and 3D specialists for site supervision and design coordination. Only with the combined best efforts of Hyundai and all their subcontractors, it was possible that this bold architectural dream became reality.

Table 1 Selected Quantities of Secondary Steel Structure (SSS).

Item	Quantity
Amount of Individual 3D BIM Files by WSS	12,000
WSS 2D Drawings of SSS	4,000
BIM Data Volume generated by WSS	700 GB
SSS Beams, Weight in Metric Tons	1,800 to
SSS Beams, Total Length, estim.	50,000 m
FRC Embeds (Fixings)	500,000
Support Stubs Connectors to Primary Steel	23,500
Nose Fixings	7,700
Amount of FRC Panels	75,000

Figure 3   National Museum of Qatar – installation of panels.

SUPER-TRANSPARENT GLASS FACADES

QATAR NATIONAL CONVENTION CENTRE

The QNCC is located in Education City, a part of the city dedicated to universities, education and the like. The architecture is dominated by a very recognizable and iconic tree-shaped megastructure across the full width of the front elevation (fig. 4), reminding of the legendary Sidra tree in whose shadows the scholars used to teach and read in old times.

WSS was approached in 2009 by the architects (Yamasaki Architects, Troy/Michigan, USA) to enhance the façade design by providing engineering, design and tender documents for the super-transparent 20m tall insulated solar-control vision glass façade in between the metallic tree megastructure.

At these times, it was clear that the options to procure 18m tall glass fins in one piece were very limited, if any. For economic and competitiveness reasons, a design had to be engineered where the glass fins would be produced in several pieces and put together on site.

The usual option in that case is to connect the glass fin parts of the full-height assembly by means of metallic connectors, using drilled holes in the glass, to arrive at a bending-rigid continuous vertical glass fin beam element. The disadvantage of that approach is that the forces that can be transferred through such drillings are limited, and several large drillings in one row would be needed, and that the limited tension stress capacity of glass would require a certain distance between two individual drillings; both effects would have made the connection pieces very large and dominant.

To enhance the transparency and the clean look of the connections and to meet the highest architectural requirements, WSS took a different structural approach: The individual 800mm deep laminated glass fin pieces are only as tall as the insulated glazing bays (5m), but are connected to tiny steel profiles at the front and back of the fins, to form a vertical truss system against horizontal (wind) loads. In that truss system, the glass fins are always acting as compression diagonals, regardless of direction of wind. In case of wind pressure, there is a slender tension bar at the inward side of the glass fin assembly, to take up the tension chord loads of the truss system; in case of wind suction, the glass fins do transfer the “compression web” forces amongst themselves by compression contact force action.

By using that innovative structural system and thus exploiting the structural properties of the glass in an optimized way, it became possible to maximize architectural transparency and the aesthetic quality of the details. At the same time, the individual glass fin pieces were not excessively long and it was possible to include façade bidders from the region into the tendering process. Consequently, the façade was awarded to Metal Yapi from Istanbul, and shop design and erection were successfully made under the guidance, checking and supervision of WSS.

The opening of the building in 2012 became a huge success. In the meantime, the second stage of the National Convention Centre project is already completed, too, and does provide Qatar with one of the largest and most recognizable conference venues in the world.

Figure 4 Qatar National Convention Centre view from outside.

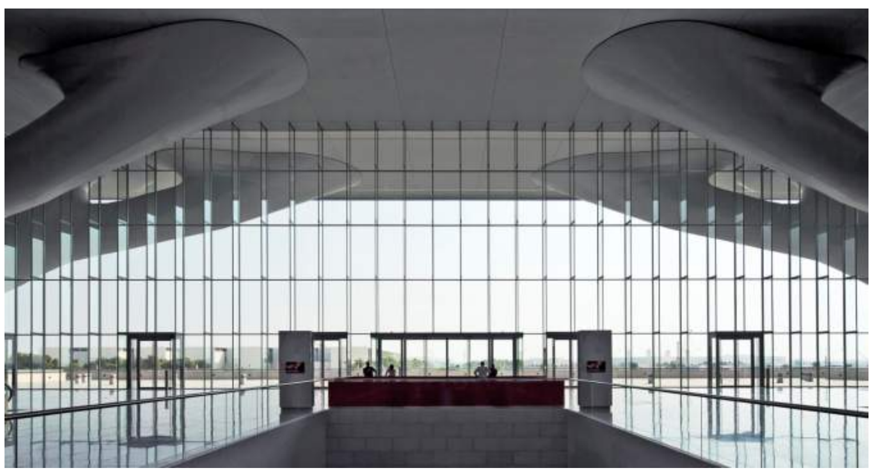

Figure 5 Qatar National Convention Centre – 20m tall glass fins connections engineering.

DOHA EXHIBITION AND ENTERTAINMENT CENTRE

The DEEC is located in the highrise business district of Downtown Doha, next to the Corniche. The building features a wide-spanning roof and two super-transparent elevations, an inclined south façade and a vertical west façade.

The architectural design intent by Jahn Architects, Chicago, was to create an appearance as transparent and generous as possible, and it was clear from the beginning that a cable façade would be the method of choice to achieve that goal.

The critical condition was that the large cantilevers of the main roof trusses were designed in a way that they were able to carry the dead loads of the 18m tall facades, but not any large additional loads such as from pretensioning of vertical cables.

Therefore, WSS invented a design where the wind loads are carried only by horizontal cables. These cables are tensioned against bow string columns at the corners of the building, and they are only laterally supported in 18m spacings at box section roof truss tiedown columns of the main roof steel structure.

The project features the first purely horizontally stressed cable façade in the world. The horizontal façade cables are up to 400m long, taking full advantage of the specifics of steel cable construction, and making the facades a stunning experience for visitors (fig. 6).

Special attention was given to all details within the cable façade scope of work of WSS. The glass clips and the cable clamps and all other connections are speaking a common design language, with curved-tapered steel plates and minimized connectors (fig. 7).

The design was continued by Jahn & WSS to detailed design and tender documents, and the installation was awarded to Josef Gartner GmbH from Germany. The building was successfully completed and ceremoniously opened in November 2015.

Figure 6 *Doha Exhibition and Entertainment Centre – 18m tall horizontal cable facade.*

Figure 7 Doha Exhibition and Entertainment Centre – a common detailing language everywhere.

CONCLUSION

Facades and building envelopes are a key feature for iconic and innovative architecture. Their customized engineering and expert consulting is the key element to make them become real, regardless of demanding environment or boldness of design. The lessons learned on parametric design, BIM modelling, glass engineering and supply chain management in the Gulf states will be of high value for future projects to come, pushing the limits of feasibility further.

Façade <> Education

AN "IDEAL" CURRICULUM

Preparing architecture graduates for a career in enclosure design

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ABSTRACT

Building enclosure systems are increasingly important components of high performance architectural design, and have been described as one of the key the places where energy savings are found during the design process. Given the importance of this building component, and its relationship to all other systems, how can we best equip architecture students with the knowledge, understanding and ability required to move practice forward as they enter the profession? What might the ideal professional curriculum look like? The background research was formative in nature and included interviews with architects, reviews of undergraduate and graduate architectural and building science curricula, conversations with representatives of AIA, AIAS, ACSA and NCARB regarding interpretation of the 2014 NAAB accreditation criteria, and an investigation of ongoing research on recent developments the design and production of high performance building facades. The findings identified several sets of core competencies that fit within and extend beyond accreditation standards. These, together with existing architecture and building science curricula, were used to develop of an "ideal" professional Master of Architecture curriculum designed to prepare students to excel in the area of building enclosure design.

KEYWORDS

degree programs, future trends, material science, codes & standards, curriculum, NCARB, digital processes

INTRODUCTION

A high performance building is comprised of four carefully integrated systems: structure, enclosure, services and interior, expressed in support of a design concept that is responsive to owner and user needs (Bachman, 2003). It should be common knowledge among building professionals that buildings consumed about 40% of the total US energy consumption in 2015 (USEIA). The building enclosure system is increasingly important and has been described as one of the key the places where energy savings are found during the design process (Dunning, 2014).

It is common practice within larger architecture firms for professionals to specialize the building enclosure, and there is also a growing community of building enclosure consultants (architects, engineers and building scientists). Given the importance of this building system to architecture as a whole, it is clear that graduates of accredited architectural programs must be equipped with the necessary technical understanding and abilities required as they enter practice. In addition, the opportunity to specialize in enclosure design during a professional education is desirable if we are to advance enclosure design. From the point of view of an architectural educator charged with developing an accredited curriculum and delivering courses, it is also important to place building enclosure design within the context of the accredited professional curriculum and architectural education, as well as to understand the forces that are influencing current and future enclosure design requirements and practice.

The goal of this research is to develop and present a proposed "ideal" curriculum for programs that are striving to educate not only future architects, but those who wish to be equipped with the knowledge, understanding and ability required to move forward the practice of building enclosure design.

METHODOLOGY

This ongoing study is best described as an effort to identify contemporary issues and areas of research related to the design, performance, production, and construction of building enclosure systems initiated in preparation for the introduction of a new advanced construction course focused on building assemblies. It included a review of print and online journals, conference proceedings and commentaries representing sources from practice, industry, government and academic research. It also included studying undergraduate and graduate architecture and building science curricula that provide an emphasis on building enclosure. Several focused interviews were conducted with architects practicing in medium and large firms, and less formal discussions were held with project managers for large building contractors. Finally, conversations with representatives of AIA, AIAS, ACSA and NCARB regarding interpretation of the 2014 NAAB accreditation criteria. The findings are presented below, along with a proposal for a professional architecture curriculum with a focus on building enclosure.

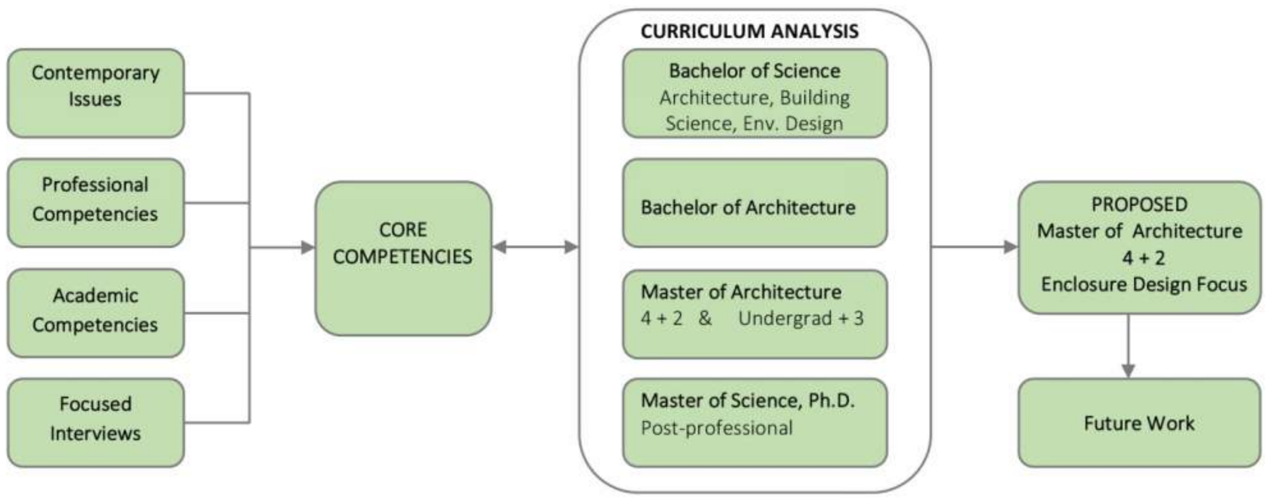

Figure 1: Research design diagram

CONTEMPORARY ISSUES

In reflecting on the question "what is the future of building facades?" at the 2013 San Francisco Facades+ Conference, Matt Elder stated "Nothing in architecture combines the issues of performance and appearance like the building facade. It presents the greatest opportunity to implement progressive change in building performance" (Elder, 2014).

This opportunity is not a simple matter and is influenced by changes with market forces and advances in materials technology to name a few. In many cases the new technologies and design proposals are well ahead of the construction industry's ability to develop accurate bids and implement the design solutions in the field. More specifically, factors contributing to the development of façade technologies include the ability to

- incorporate new materials with existing construction systems while achieving required levels of performance.
- form design teams that can collaborate on an even playing field – sharing both the risks and rewards required to develop innovative solutions.
- design enclosure systems that meet the regulatory requirements and elective goals required to produce sustainable designs (changing energy and building codes, net-zero aspirations, Living Building Challenge, etc.).
- find the balance between the advantages of digital technologies and the designer's skills and knowledge in developing form and finding solutions.
- find high performance solutions in retrofit projects.
- assure durability and longevity of material and design.
- achieve occupant comfort, health and productivity.
- develop innovative and interactive digital tools (Elder, 2014; USC, 2016; UC-Berkeley, 2016).

The issues summarized above are of particular importance in practice, and are underlain by very specific research agendas developed through industrial and academic research in building science, material science engineering, industrial production, etc. These are illuminated by the work represented in technical journals and the proceedings of technical conferences.

CORE COMPETENCIES

In addition to the importance of understanding contemporary issues and projecting future needs, it is important think in terms of the competencies required to achieve success in a professional setting. These are essential and advanced skills and knowledge about conventional and emerging materials and technologies and include the underlying theoretical principles of building science. These can be examined from two points of view: competencies required of the professional specializing in enclosure design and those required of the graduates of accredited architecture or engineering programs.

Interviews with several architectural leaders indicated that education, experience and career path would all be key factors to consider in the decision to hire (or develop from within) an enclosure design specialist. Evidence of a strong educational background, excellent digital skills, completion of the required internship and licensure are the basics. In addition, this person would demonstrate a developing expertise in and a passion for creative problem-solving related to construction technology, the ability to collaborate across disciplines and leadership skills would be indicators of potential to excel and move a practice into the future (Davis, 2016). Another telling observation with regard to digital technologies came from Karen Brandt, who said "What's been interesting about the [digital] tools is the way they can upend the hierarchy of an office. Sometimes the person who has the skill that you absolutely need to solve a problem is the youngest person in the office. That has been incredibly useful in increasing the inventiveness of the office as a whole" (Elder, 2014).

TABLE 1. COMPARISON OF CORE COMPETENCIES FOR ENCLOSURE DESIGN SERVICES

(B.C., Canada) Professional Practice Guide to Enclosure Engineering Services (BEE)	**(U.S.) Standard Guide for Building Enclosure Commissioning (BECx)**
Building Codes and Standards	
Theoretical and Technical Knowledge	Building and Materials Science
Construction Document Preparation and Design Review	Contract Documents and Construction Administration
Investigation, Assessment and Testing	Performance Test Standards and Methodology
Construction Field Review	Procurement and Project Delivery

Table 1, Comparison of core competencies for enclosure design performance and services in the United States and British Columbia, Canada. Sources: Professional Practice Guide to Enclosure Engineering Services, Assoc. of Professional Engineers and Geoscientists of BC (2012), and ASTM E2813-12 - Standard Practice for Building Enclosure Commissioning, 2013)

PROFESSIONAL COMPETENCIES

A more dispassionate view of core competencies is described in the Professional Practice Guide to Building Enclosure Engineering Services published in 2012. It grew out of the 1999 guidelines developed by the Council of the Association of Professional Engineers and Geoscientists of the Province of British Columbia. The document was developed in cooperation with the Architectural Institute of British Columbia (AIBC) in response to requirements for enhanced building enclosure services (EBES) required in the British Columbia Building Codes. In addition to establishing the basis of contractual relationship between professions, the document sets out core competencies for providers of Building Enclosure Engineering (BEE) Services. (Lawton).

The United States has taken a different approach. In 2014 the ASTM Standard Guide for Building Enclosure Commissioning (BECx) was issued. This standard grew out of the work of the National Institute of Building Science (NIBS) and ASHRAE, and is a voluntary guide. This standard identifies enforceable levels of performance testing and also establishes core competencies, listed in Table 1, for service providers at three levels of expertise (Lemieux, 2013). These competencies form the basis of three levels of certification currently in development by ASTM, NIBS and the International Organization for Standardization (ISO).

In comparing the core competencies developed in the US and Canada, the guides have a number subjects in common, but there is not a one-to-one correspondence. This is due in part to the regulatory and professional environments in which they operate. Both organizations also have requirements for professional experience that are not presented here.

ACADEMIC COMPETENCIES

In contrast, academic institutions offering professional programs in architecture or engineering are addressing a much broader range of competencies. For the purposes of this paper, professional architectural curricula are analyzed, with a focus on criteria related directly to developing knowledge and abilities related to building enclosure. The 2014 Conditions for Accreditation are the most current criteria issued by the National Architectural Accreditation Board. In Part I, five over-arching perspectives that must permeate programs are identified. Four of the five directly relate to the contemporary issues and core competencies identified above: Collaboration and Leadership, Design, [breadth of] Professional Opportunity and Stewardship of the Environment (NAAB, 2014).

Part II addresses educational outcomes. The current incarnation of Student Performance Criteria (SPC) includes 26 standards divided into four Realms: Critical Thinking and Representation, Building Practices, Technical Skills and Knowledge, Integrated Architectural Solutions and Professional Practice. Programs must demonstrate that students are minimally competent at the level of ability or understanding in all criteria within each realm; however, in reality it is rare that a program satisfies all SPCs. Programs aspiring to provide an enclosure specialty would need to be strong in areas covered by the criteria listed in Table 2.

TABLE 2. STUDENT PERFORMANCE CRITERIA RELATED TO BUILDING ENCLOSURE DESIGN		
A.1	Professional Communication Skills	*Ability*
A.2	Design Thinking Skills	*Ability*
A.4	Architectural Design Skills	*Ability*
B.3.	Codes and Regulations	*Ability*
B.4	Technical Documentation	*Ability*
B.7	Building Envelope Systems and Assemblies	*Understanding*
B.8	Building Materials and Assemblies	*Understanding*
B.9	Building Service Systems	*Understanding*
C.1	Research	*Understanding*
C.2	Integrated Evaluations and Decision-Making Design Process	*Understanding*
C.3	Integrative Design	*Ability*
Realm 4	Professional practice	*Understanding*

Table 2, Student Performance Criteria, including number and performance level from 2014 National Architectural Accrediting Board Conditions for Accreditation

Most of the learning outcomes directly related to building enclosure design come from the realms of technical skills and knowledge and integrated architectural solutions. Unlike the professional competencies listed above, understanding and ability related to design and integrated solutions are critical to the student's education, and they also relate directly to contemporary issues discussed above.

EXISTING CURRICULA

A review of architectural programs offering specialties in building enclosure design was conducted by identifying curricular offerings by member institutions of the Association of Collegiate Schools of Architecture (ACSA). In addition, a more general search of institutions identified as having programs with specialties in building technology, building science, building envelope, or related topics was conducted. Two undergraduate programs in building science were identified along with a number of graduate programs that offered post-professional studies that either directly or indirectly provided options to focus on topics related to building enclosure.

A new undergraduate degree in building science was recently implemented at Rennselaer Polytechnic Institute (RPI) where it is positioned within the School of Architecture and geared toward students entering the construction industry. It is the only non-professional undergraduate program in the school, and is described as providing "direct entry into one of the building industry's many sector…[including] façade design, building performance consulting… or an excellent foundation for advanced degrees in architecture, engineering, construction management or business" (RPI 2015-16). The building science program at Appalachian State University offers both BS and MS degrees in building science and is part of the Sustainable Technology and the Built Environment Department (App State, 2016). Both are interdisciplinary in nature and appear to have emerged from construction management studies. It is likely that similar programs exist in construction management programs elsewhere.

Other post professional graduate programs with a focus on building science or building technology are offered by University of California at Berkeley, University of Southern California (USC), Harvard Graduate School of Design, and Massachusetts Institute of Technology, among others. The USC Architecture School's MS Building Science has a specific focus on building envelope and is the home of the Façade Tectonics Institute.

While programs with a focus on building enclosure exist in architecture programs at the pre-professional undergraduate and post professional graduate levels, none have been identified within NAAB accredited professional programs. Why is this? It no doubt has much to do with the requirements of architectural accreditation and the length of time required to complete the programs. However, it seems there is room in the 4 + 2 (4 year undergraduate pre-professional + 2 year professional) or undergrad + 3-plus year M.Arch. models for specialization to be developed by the motivated student. What follows are several strategies for developing this specialty within a professional architecture program, and a model of what a 4 + 2 curriculum might look like.

CRAFTING THE IDEAL PROFESSIONAL CURRICULUM

The contemporary issues, core competencies and examples of non-accredited programs outlined above can be used to develop an accredited professional graduate architectural curriculum that not only meets the accreditation criteria, but provides students with opportunities to build a strong academic foundation that will help lead to a future in building enclosure design. One "obvious" option is to earn an undergraduate degree in building science or a related program (perhaps engineering or material science) and follow that with a 3 plus year professional degree in architecture. A graduate with this combination of knowledge and skills could move directly to a professional position as an enclosure specialist within an architectural firm or as a consultant. This option would require 7 ½ - 8 years of study. This is similar in time to a path that involves earning a B.Arch. and MS Building Science. Another option that could prepare a student for this technical specialty, and involve about 5 ½ - 6 years of study could be developed within an accredited professional architecture program. This would be a valuable program for highly capable students who for a number of reasons – including the accumulation of debt – believe they need to graduate with an accredited degree as quickly as possible.

What would this 4 + 2 curriculum look like? The typical professional M. Arch curriculum must include at least 45 semester credits of courses that are not required, and which typically include about 36 university-required general education courses earned as an undergraduate, along with elective (options) offered outside or within the architecture course offerings. The remainder of the credits may be delivered from within the professional program in the form of required and elective courses. There are typically opportunities for experiences such as service-learning, internships, research, design/build and international travel. If a program approaches the design of the educational experience from first semester to last, one can imagine a curriculum that, along with internship and licensure, would prepare an aspiring enclosure specialist to enter directly into the architecture profession.

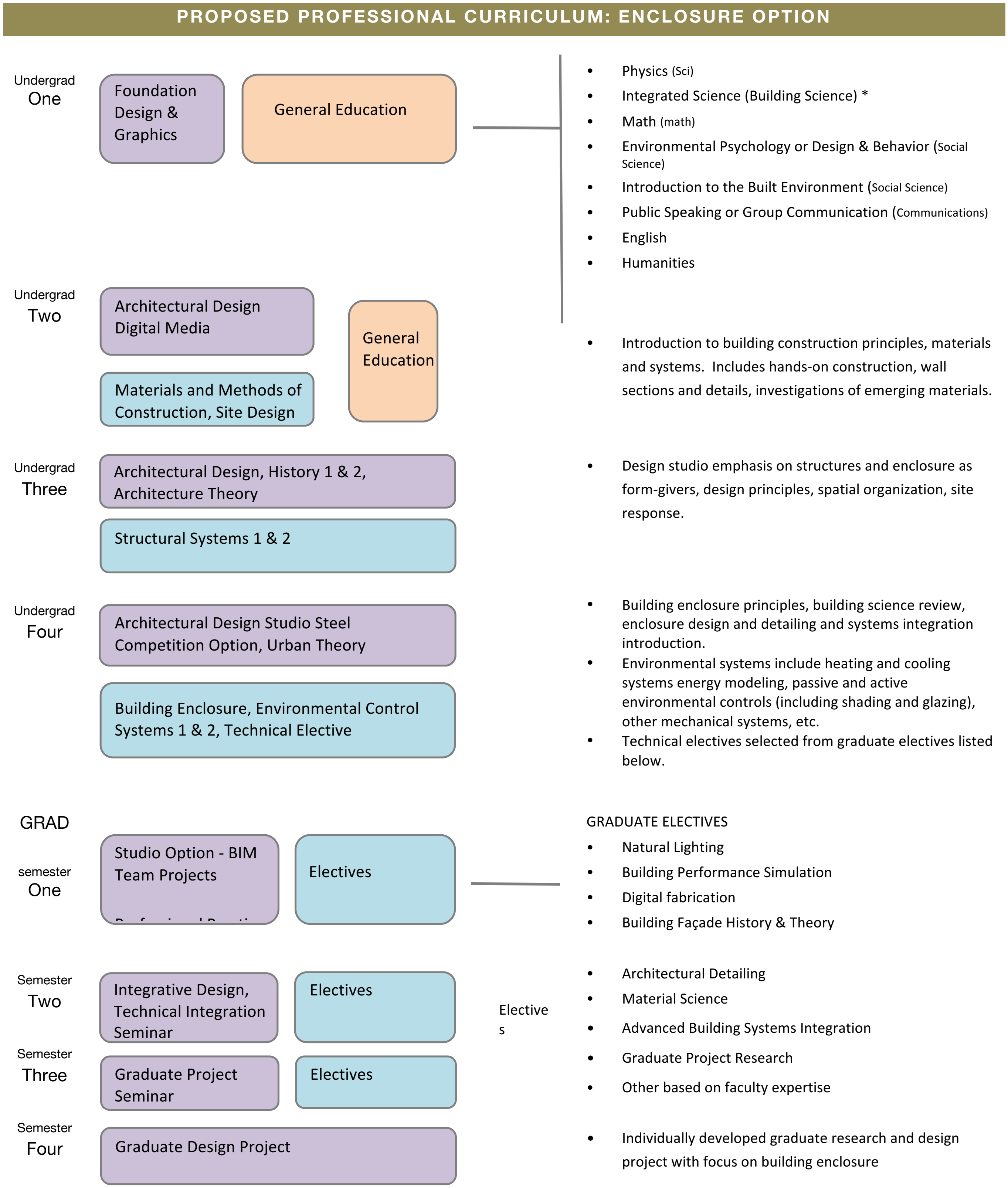

Figure 2. Diagram of conceptual NAAB accredited architectural curriculum with specialty in building enclosure design.

RE-IMAGINING GENERAL EDUCATION OPTIONS

General education courses exist outside the architecture program and typically require coursework in natural sciences, social sciences, humanities, math, communication and small topical interdisciplinary seminars. There are various models for general education studies at universities in the US, and the 36-credit University of Idaho program was used here. Architecture programs can require students to take specific general education courses that also satisfy disciplinary needs – thus "double-dipping". They could also advise students who desire to develop specialties to seek out general education courses that would provide preparation in specific areas. For the enclosure focus, general education courses would include:

- Interdisciplinary topical humanities/social science seminar 3 credits.
- Natural Sciences (7-8 credits, 2 courses):
    - Physics (required)
    - Building Science (recommended). By definition, this area of study explores factors that come into play in the relationship between a building (at all scales) and naturally occurring phenomenon including weather and sub-surface conditions. This is a course that rarely exists in an undergraduate program – but rather as topics within in a number of sciences. Developing an interdisciplinary course of this kind could be welcomed as a general education course due to its integrative nature.
- Humanities (6 credits, 2 courses)
- Social Sciences (6 credits, 2 courses)
    - Environmental Psychology or Design and Behavior.
    - Introduction to the Built Environment

- Communications (6 credits, 2 courses)
    - College Writing and Research (required)
    - Communications: Public Speaking, Interpersonal and group communications
- Mathematics
    - Calculus and/or statistics and/or computer science

REQUIRED ARCHITECTURE COURSES

- Design Foundations
- Design Studio. Courses offered every semester. These courses address design at various scales in different levels of the curriculum and should include: design principles, site design, architectural design in response to natural forces, spatial composition including a focus on design of building elevations/facades, tectonic opportunities of structures and enclosure, sustainable urban design, and integrated building design studio.
- Optional design studios would allow students to develop a focus on enclosure design, and might include BIM and high performance buildings, digital fabrication, advanced materials and systems, advanced exploration of passive and active solar design for heating and cooling and natural lighting design, design/build, detailing.
- Building Technologies. The building technology sequence should build upon rather than repeat building science principles. Design-oriented structures would include physical and digital modeling and simulation, basic principles and calculations. Integration with at least one design studio would be included.
- Beginning and advanced construction technology courses build upon building science principles would be linked with both structures and design studio. The advanced course(s) would focus on building assemblies and enclosure systems and explore conventional and advanced materials and systems of building enclosure and façade construction
- Environmental technologies would build on principles of building science and explore passive and active methods and technologies of environmental controls, lighting, plumbing, acoustics, etc., and building performance simulation. This can be directly tied to both design studio and advanced building construction courses.
- History and Theory. Many of these offerings could be broad in interpretation and include the evolution of technology and performance. For instance, courses like The Façade, of The Detail could address these topics from multiple viewpoints.
- Integrative (Comprehensive) Design Experiences. These experiences have traditionally been built around a comprehensive design studio and may also include a co-requisite integrated design technology capstone course. Many programs also conclude with an independent undergraduate capstone or graduate project. This again an opportunity for a student to define a problem specific to his/her interests in enclosure systems, work with a committee of experts and develop in integrative solution to problems with local, regional, national or international impact.
- *ELECTIVE OPTIONS*
- Transformational Experiences. Opportunities for experiences that stretch students beyond the boundaries of the academy exist in many programs. Substantive internship opportunities architectural, construction management or similar firms would be very desirable for the aspiring enclosure specialist. National or international travel programs

that investigate subjects like green architecture, high performance design or new materials could also be a good opportunity.

- Elective studios might could include interdisciplinary projects that simulate integrated project delivery or high performance design, and collaborators might include students from engineering, environmental science, building science, business and other disciplines.
- Specialty Electives. Depending upon the depth of faculty expertise and program resources, electives can be developed in the areas of digital tools (building performance simulation, building information modeling, digital fabrication, new materials, advanced enclosure design and technology, occupant comfort, natural lighting, building evaluation).

CONCLUSION AND FUTURE WORK

This paper posits a conceptual accredited architectural curriculum based on the contemporary practice of building enclosure design. It provides one model for academic programs seeking to develop a focus in this area and prepare students for a career that involves pushing the limits of the possible as an architect and enclosure designer. It is clearly the first step in a much longer professional path that may include becoming a licensed architect, pursuing advanced studies in building science, working in progressively more advanced settings with teams of experts, and gaining leadership positions in professional practice. The model is also intended as a point of departure for critique and discussion of curriculum development in the area of building technology specializations within professional programs.

Future work includes developing detailed descriptions, core competencies and pedagogical approach for proposed courses, and implementing and assessing the specialization within an existing program. Another opportunity is to examine M.Arch. programs that exist in tandem with post professional graduate building science or technology programs to determine if students are devising their own specialties. There is also potential to examine curricular opportunities within professional engineering programs.

REFERENCES

Appalachian State University Catalog (App State), BS in Building Science. http://buildingscience.appstate.edu. Accessed 7/18/16.

Association of Professional Engineers and Geoscientists of BC (APEGBC). Professional Practice Guidelines: Building Enclosure Engineering Services, October 2012.

ASTM E2813-12 - Standard Practice for Building Enclosure Commissioning, 2013.

Bachman, Leonard R. Integrated Buildings: The Systems Basis of Architecture. New York: John Wiley & Sons, 2003.

Davis, Allan, Project Manager, NBBJ Architects and Colin Okada, Project Manager, Hoffman Construction. Panel discussion regarding design and construction of IRIC building at University of Idaho, February, 2016.

Dunning, Adin, Principal, The Miller Hull Partnership. Conversation on the role of the enclosure system in achieving net-zero at the Bullitt Center, October 2014.

Elder, Matt. What is the Future of Building Facades?, SkinTec, January 2014, Advanced Technology Studio of Enclos (@Enclos-Insight03-Chapter09-WhatisTheFutureOfBuildingFacades.pdf) accessed 4/13/2016.

Lawton, Mark, P.Eng., FEC Morrison Hershfield Limited David Ricketts, P.Eng. RDH Building Engineering Ltd,. Guidelines for the Practice of Building Enclosure Engineering. Proceedings: Building Enclosure Science & Technology, Atlanta April 2012.

Lemieux, Daniel J, AIA, Chairman-ASTM E06.55. Performance of Building Enclosures. Presentation at 21st National Conference on Building Commissioning, 2013.

National Architectural Accreditation Board (NAAB), Conditions for Accreditation, 2014.

Rensselaer Polytechnic Institute (RPI) Catalog, BS in Building Sciences. http://catalog.rpi.edu/preview_ zprogram.php?catoid= 14&poid=3039&returnto=331. Accessed 5/16/16.

US Energy Information Administration (USEIA), http://www.eia.gov/tools/faqs/faq.cfm?id=86&t=1, accessed 5/22/16.

University of California Berkeley Catalog, Architecture, MS in Building Science and Sustainability, http://ced.berkeley.edu/academics/architecture/ programs/master-of-science/, accessed 5/16/16.

University of Southern California Catalog School of Architecture, MS in Building Science with focus on Building Envelopes. https://arch.usc.edu/programs/master-building-science. Accessed 5/16/16.

ANALYSIS, SENSORS, AND PERFORMANCE

Closing the loop with post-occupancy data analysis

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ABSTRACT

There is a historic disconnect between the design and realization of high-performance facades. Despite rigorous analysis, simulation, and best-practice design approaches, we don’t fully understand the long-term performance of installed enclosures. A critical unknown is how a space is used once occupied. Relatively low-cost sensors allow us to collect data, test assumptions, better understand occupancy, ensure proper installation, learn from previous efforts, and build lessons learned into subsequent designs.

The authors have taken a multi-faceted approach to closing the loop between analysis, design, and realization.

We have deployed a network of environmental sensors throughout our current office space. These sensors collect data on environmental metrics such as temperature, humidity, light, sound, and air quality. We then correlate these metrics to occupant use and comfort to evaluate the performance of mechanical systems. This will also highlight the relationship between the interior environment and the exterior facade. These post-occupancy data will be evaluated against the assumptions and simulations that informed the design.

We have also built relationships with other industry experts and academics to pursue related research. We recently concluded a research seminar at a prominent architecture program. In this seminar we are studying how environmental sensors can be integrated into the design of high-performance responsive facades. We have also engaged engineers and data scientists to discuss possible futures of façade/building design.

Together, these efforts have enabled us to create a set of recommendations on how to move forward, to better understand the relationship between space use and façade performance, and ultimately help close the loop between analysis, design, and realization.

KEYWORDS

Façade Futures, Systems and Technology, Open-source hardware, Adaptive Façade Systems, High-Performance Façade Applications, Health and Comfort

INTRODUCTION

As the primary mediator between the unpredictable exterior conditions and the controlled interior environment, building facades play a critical role in the comfort, wellbeing, and productivity of the occupants of a building. Therefore it is essential that the enclosure systems perform at the highest level. High performance means effectively working with the building mechanical systems to control the objective measures of comfort such as light levels, temperature, humidity, and indoor air quality. High performance also means allowing occupants a certain level of control of natural light and ventilation to affect their subjective comfort. A guarantee of this high level of performance is particularly challenging since most large scale modern building facades are custom designed, developed and built.

Traditionally, design teams attempt to reach performance goals by employing industry best-practices and subjecting designs to rigorous analysis and simulations. As a design progresses, mock-ups are built to reveal and rectify deficiencies prior to final construction. However, as will be elaborated upon later, there are a variety of reason why this process can fall short.

Low-cost environmental sensors provide an opportunity to create better performing building enclosures. They promise to allow the building façade to more actively participate in controlling interior conditions and to give occupants knowledge and control of those conditions. Additionally, the data gathered with these sensors can provide invaluable insight to building management, occupants, company leaders, and the design team into how spaces are being used (Babsail et. al., 2006).

The authors have taken a multifaceted approach to understanding the role of analysis, simulation and data collection in the design and realization of high performance facades and the role of environmental sensors in ensuring comfortable interior environments for users. First and of primary interest to the efforts, we have designed and implemented an in-house data collection effort intended to shine a light on how we use our self-designed space, our variable levels of comfort – measured subjectively and objectively. This effort has been underway for approximately four months and is beginning to return results. By examining these results we have developed a set of recommendations about how and why environmental sensors can be employed as part of a comprehensive design approach. Second, we have partnered with other industry experts, ranging from façade engineers to data scientists, in a series of related research initiatives. Third, we led a group of students at a preeminent school of architecture in research, investigating the role of data collection in the design of responsive façade systems. These partnerships and relationships have fortified our primary in-house data collection effort and helped inform our recommendations.

Our research has been focused on two streams. The first, endeavors to strengthen our understanding of the role of analysis and simulation within a conventional design process. We've investigated the appropriateness of analysis and simulation and different phases. We've critiqued the scale and resolution of the results and the types of analysis and simulation employed by different members of the design team. We've also analyzed the reliability of the results. The second topic of our study has been the role of environmental sensors in illuminating the performance of an enclosure and the space therein. Through research, prototyping, and testing, we've sought to build an understanding of what these data can tell us about how a space is being used and how the enclosure systems are performing.

Taken together, this research has enabled us to develop a set of recommendations for how environmental sensors can be integrated within high performance enclosure systems to maximize user comfort, and health.

PART 1 - ANALYSIS AND SIMULATION

In a conventional approach to architectural design, the architects and engineers work through a linear process. They begin with an idea which is enriched through analysis and simulation. That idea is refined, developed, documented and if all goes well, it is eventually realized as a building. While there is a fair amount of feedback in this system – which is to say that at each stage in the process, new information shapes the parameters and constraints of the project – that feedback ends once the project is complete, thus completing the linear process.

Further, despite all the analysis, simulation, and best practices available to the design team, there is still no guarantee that the building will perform as anticipated once completed. This uncertainty is the result of the following issues:

- No guarantee that the building systems will be built as intended
- The assumptions underlying the analysis, simulation, and best practices may be flawed
- Lack of clarity/understanding about how the occupants will ultimately use the space

The introduction of low-cost environmental sensors empowers the design team to rectify the shortfalls listed above and in so doing close the loop between analysis, design, and construction. By equipping building systems with these sensors we can: ensure that buildings systems are installed as intended, verify or reject the underlying assumption that informed the design, and gain a window into how the space is ultimately being used. Taken together this approach will allow the design team to learn through its efforts and build better over time.

As practitioners in an industry where the underlying principles of our industry were laid out thousands of years ago, we find ourselves presented with an increasingly complex set of modern demands and parameters. We therefore call upon a complex system of analysis tools that help us understand everything from pedestrian flows to energy demands using solar radiation analysis. We use a wide range of tools in the design process but, in particular, analysis tools that help us understand environmental impacts is one area where we are presented with information and data that quantify our design decisions. How do we effectively use these analysis tools within the practice of design?

Often a design approach is taken, which may carry with it specific aesthetic sensibilities and agendas, and we engage analytical tools to help us understand the impacts of that approach. The resolution or scale at which we utilize environmental analysis tools is important to understand from the perspective of the design process continuum. We deploy different analysis tools at different times to match the progress of the design. In this way, the environmental analysis tools used at any given point in the design process will match accordingly to the scale of the design decisions being considered. Simplistically, we take a “right tool for the right time” approach to using these analysis tools. A sampling, but not necessarily an exhaustive list, of typical environmental analysis tools illustrates this move from large-scale to small-scale analysis tools (Fig. 1).

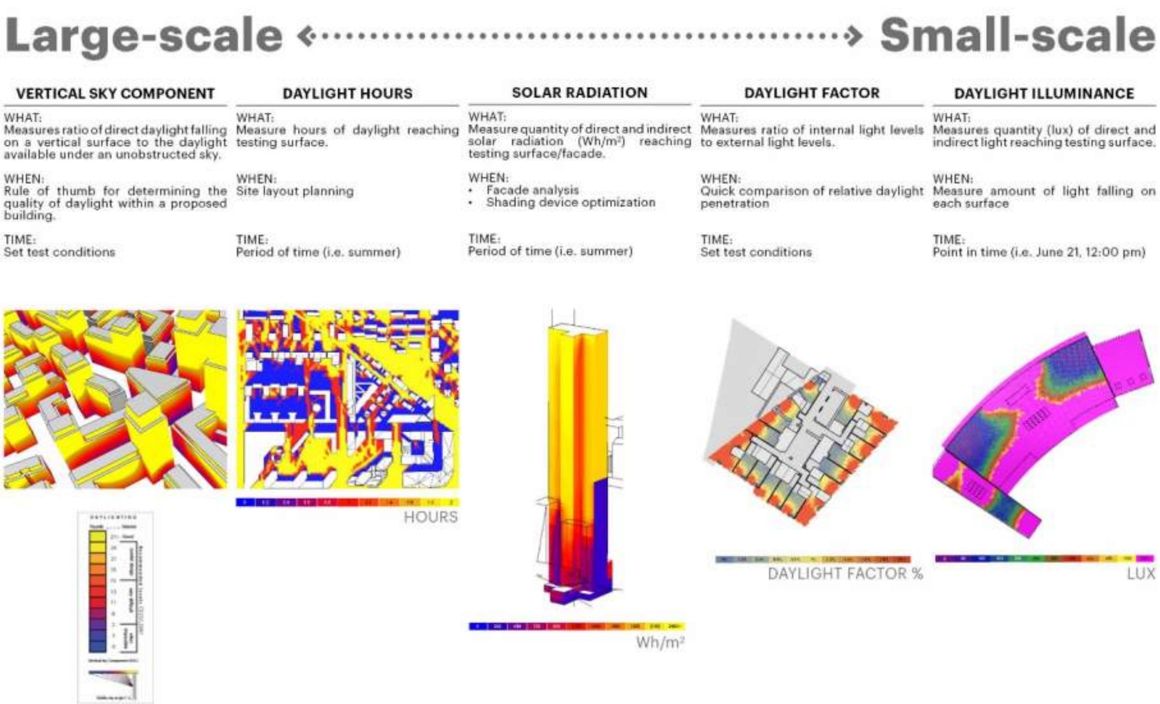

Figure 1: Analysis tools

In the early stages of design, higher-level decisions and outcomes are our main concern so accordingly we first strive to understand the design from a large-scale perspective so our efforts are focused on understanding context. Analysis tools that operate at a large scale are used to help us understand how surrounding buildings might impact the qualities of the proposed design and vice versa. At this urban scale we are using analysis tools like shadow studies and daylight hours analysis to understand the impact of existing buildings on the social function of the surrounding spaces. Since site layout and planning are of primary concern at this stage we can use analysis outcomes to inform our decisions, being mindful to avoid overly specific examinations.

As the design progresses we begin to move to examining specific characteristics of the proposed design. At the building scale, we are specifically interested in how our decisions about things like building form and orientation might be impacting sustainability and performance goals. Conducting a solar radiation analysis is a common first step at gauging the thermal performance demands that might be placed on the façade system as well as the internal mechanical systems.

As we move into later phases of design and our design decisions begin to focus on smaller-scale issues and according, our analysis tools operate at a finer resolution. The tools begin to examine finer level conditions like the qualities of individual spaces, shaping our decisions about programming, layout, and even shading strategies with louver design. As an example, daylight factor and daylight illuminance analysis inform us, at a room-scale about the light qualities in the space, which affect occupants on a more intimate level. It is at this point where we find ourselves shifting our efforts from thinking about exterior to thinking more in terms of interior spaces and human comfort considerations. This is typically the lowest level that we will follow an analysis tool to make decisions because below this threshold lies the domain of a more specialized professional like a façade consultant, mechanical engineer, or lighting designer.

Aside from considerations of analysis scale and resolution, our work as designers often involves evaluating options. The environmental analysis tools often serve as a means by which to conduct a comparative analysis. That is to say, we are less concerned with examining the quantitative outcomes as much as we are interested in benchmarking them against one another by way of ranking them to get a relative comparison. We may assemble and propose a range of options for building form and conduct several different environmental analysis across those options to give a sense of their relative performance in each of those analysis. The quantified results simply become a method to benchmark different options. As an example, a solar radiation analysis can be conducted to predict quantifiable levels of radiation on the entire building envelope but in a scenario where we are evaluating design options we are less concerned with examining and analyzing that total solar radiation number as much as we are interested in looking at where this number places that particular option in relation to how the other options have performed in the analysis. In this way we are using an environmental analysis as a means to sift through less desirable options and hone in on a final design.

The basis for this research lies with our desire to use to use technology to examine and comprehend the long-term performance of the spaces we design. We don't currently have an understanding of the long-term outcomes of our design decisions so how we can use empirical data to learn about our design interventions, and further, how we can iterate to better designs over time (Babsail et. al., 2006). Our intuition as designers and researchers needs to be augmented by technology and data analysis. In a sense, this might be thought of as the Moneyball approach to building design. In Michael Lewis' book Moneyball, the management of a major-league baseball team discarded conventional baseball wisdom and instead focused, almost entirely, on evidence-based analytics and statistical analysis to assemble a winning team. However, this is not to suggest that architects should cast aside design intuition and training but there is a more robust implementation and way forward when we combine technology, data, and analysis with good design practices. For example, in a recent study, KieranTimberlake used sensors in their office space to understand and challenge the ventilation strategy of night flushing and concluded that this strategy was not as effective as they had originally thought (Welch et. al., 2015).

PART 2 – DATA COLLECTION

Having developed a relatively sophisticated approach to analysis and simulation, we've determined that it's essential to extend that approach to environmental sensors and the data they provide. In an era in which the Internet of Things (IoT) and Artificial Intelligence (AI) facilitates the next generation of technological development, building and the spaces we occupy are becoming smarter and more intelligent (Sherbini et. al., 2004). It is incumbent of architectural practitioners and academics to determine how the field of architecture can benefit from these emerging technologies. Our goal with the seminar class and with this sensor technology is similar to Fox's statement that, "Architects and designers are not expected…to execute their interactive designs alone; they are expected rather, to possess enough foundational knowledge in the area to contribute" (Fox, 2016). Therefore, with this research we seek to advance our level of knowledge in order to be active participants in the discussion of the impacts of emerging technology and how that will shape our profession and practice.

What was once a cumbersome and resource intensive endeavor to gain insight into the characteristics of an environmental using analog tools, our research focuses on gaining insight into the performance and use of architectural space by using newly-available low-cost open-source sensor technology (Ratti et. al., 2016). We have embarked on an in-house data collection effort using an array of these environmental sensor modules distributed throughout our office. It must be stated that the environmental sensor system we have implemented here is far from the definition of intelligent building/environment by other researchers in the sense that it only has sensing capabilities and lacks an output or actuating mechanisms to provide interactive functionality (Fox, 2016) (Babsail, et. al., 2006) (Sherbini, et. al., 2004). However, we propose this work as an initial step at engaging in this area of research that holds the potential of expanding in scope and complexity to feed into a system that could be more robust and interactive in the future. We acknowledge the work of other architecture firms such as KieranTimberlake and LMN Architects who have conducted similar research with sensor modules (Welch et. al., 2015) (Katzenstein, 2013).

The office space being studied is located in a building that was completed in 1928 in mid-town Manhattan. An existing environmental analysis of the space, which was subsequently incorporated into a Leadership in Energy and Environmental Design (LEED) submission, provides a basis for which to examine the gap between analysis outcomes and collected data from a network of sensors. Additionally, researchers were interested in evaluating the stratifications and gradients that are anecdotally apparent from occupant feedback, both vertically between two different occupied spaces (6th floor and 18th floor office spaces), as well as horizontally within the depth of the floor plate. The building's existing heating and cooling mechanical zones are a starting point for the placement strategy to determine sensor deployment (Fig. 2). This research also endeavors to examine and challenge the existing building temperature sensors to accurately report and represent occupant comfort. A brief survey of the building's mechanical system sensors illustrates the problematic placement of existing sensors, which ranges from clustering of sensors (Fig. 3) to sensors located at the periphery of mechanical zones (Fig. 4).

Figure 2: Office POE sensor locations, also showing building mechanical zones

Figure 3: Existing building sensor placement - clustering

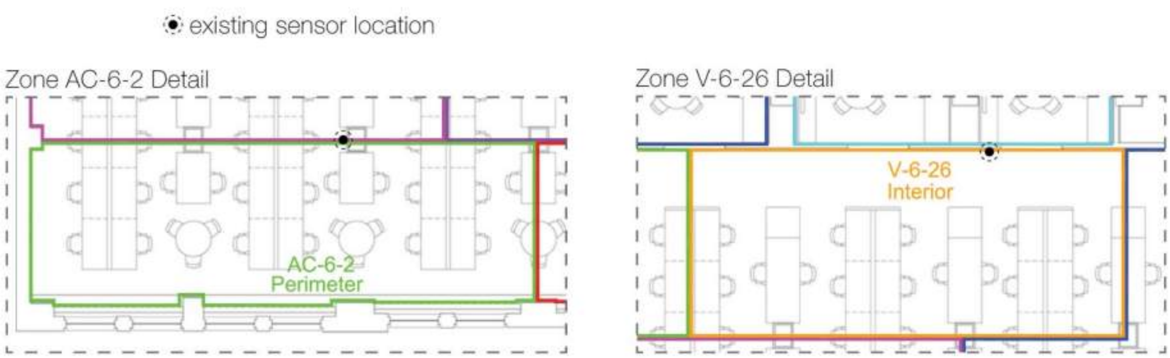

Figure 3: Existing building sensor placement – periphery locations

The method for collecting data begins by deploying a network of researcher-assembled sensors throughout the office space, locating the sensors at strategic locations. The initial deployment of sensors modules consists of four sensor modules, each measuring temperature, humidity, and light. Sensor modules were deployed in similar locations at occupants' desks by mounting them to the divider between desks, which is located approximately 42 1/2" above the finish floor or 14 1/2" above the work/desk surfaces. Custom 3D printed enclosures and mounting clips for each of the sensor modules allows them to be deployed in an unobtrusive manner and location at occupant desks (Fig. 4). Occupants often reported they often forget the sensor module is there. As Weiser and Brown conclude with regard to ubiquitous computing, that technology can achieve what they call "calm technology" by blending into its environment and this was the goal of the researchers for this study as well (Weiser, 1996).

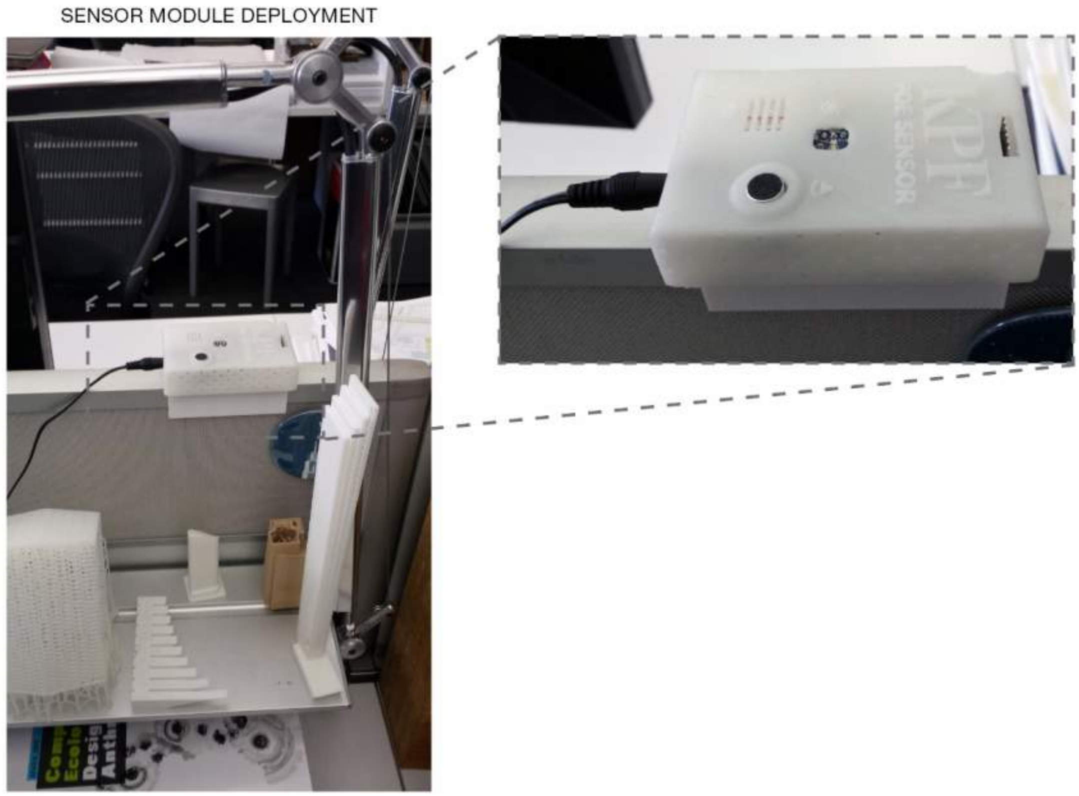

Figure 4: Sensor Module Deployment

The individual sensor modules were assembled and constructed using several parts. First, the circuitry for the sensor modules is accomplished by mounting each of the components on a half-sized breadboard and making the necessary connections between input and output pins on the sensors by using 22-gauge AWG hookup wires. Each sensor component was prepared for mounting to the breadboard by soldering a header connection into each through-hole pin on the sensor component. Power is supplied to each module by means of a USB to 2.1 mm barrel jack connection to the breadboard (Fig. 5).

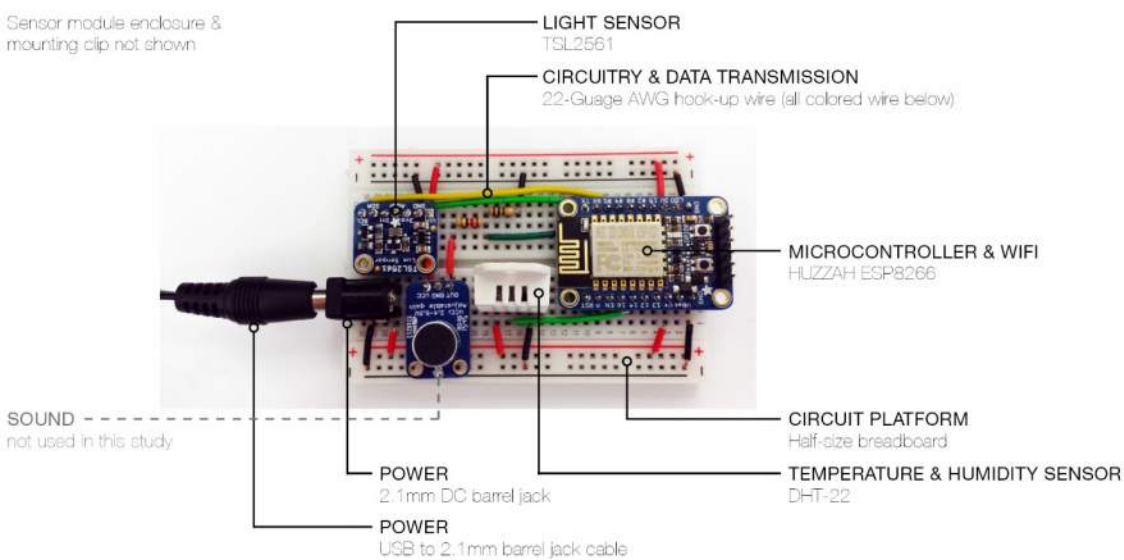

Figure 5: Sensor module layout

At the heart of the sensor module is the HUZZAH ESP8266 breakout board, which is an 80 MHz microcontroller with integrated WiFi capabilities. The board consists of an ESP8266 processor and an array of input and output pins on the board allows researchers to simultaneously collect data from multiple sensors and transmit sensor data via WiFi, through existing infrastructure already deployed throughout the office space. Custom code was uploaded to the HUZZAH ESP8266 breakout board using a USB to TTL serial cable and the open-source Arduino software. By writing custom code, researchers are able to control parameters of data collection such as sample frequency, signal conversion, and data transmission.

The individual sensors on these modules measure ambient temperature, humidity, and light levels. Both temperature and humidity readings were taken using a DHT-22 sensor. This sensor is a capacitive-type temperature and humidity sensor and communicates sensor readings with an 8-bit digital signal. It uses a polymer humidity capacitor with a manufacturer stated range from 0 to 100 percent relative humidity with an accuracy ±2 percent and a DS18B20 for detecting temperatures from -40 to 125 degrees Celsius (-4 to 257 degrees Fahrenheit) with an accuracy of ±0.2 degrees Celsius (±0.2 degrees Fahrenheit).

The light sensor component is a TSL2561 light to digital converter. The sensor integrates currents from two photodiodes, one broadband photodiode which measures visible and infrared light and a second photodiode which measures infrared light exclusively. The TSL2561 places the photodiodes on a CMOS integrated circuit, capable of providing a near-photopic response over an effective 20-bit dynamic range (16-bit resolution). The digital output is transmitted through a two-wire serial interface using I^2C protocol in fast-mode at 400 kHz (max) to the ESP8266 where ambient light levels are calculated and converted into the SI unit of illuminance, lux. The device has a manufacturer-stated range of 0.1 to 40,000 lux with an operating temperature range of between -30 to 80 degrees Celsius. Finally, the sensitivity of the TSL2561 was set to the auto-gain setting to accommodate fluctuations in light levels at different sensor module locations.

Data from the sensor modules is collected and stored in a MySQL database on a Linux machine, housed internally within the office. Since the transmission of data, from sensor module to the MySQL database, is done from beginning to end without relying on an outside platform, researchers can ensure the privacy and security of the data. The sensor modules report data on 15 minute intervals and the results of the data are then displayed and visualized using Tableau software (Fig. 6). Researchers as well as occupants have access to the data and charts via the company intranet site. In addition to the objective, empirical data reported by the sensor modules, researchers have enabled the collection of subjective data. Occupants report their comfort levels throughout the day along a number of metrics to measure overall occupant comfort (Fig. 7). The results of this data are also visualized in Tableau, resulting in a reported occupant comfort dashboard which is also available on the company intranet site (Fig. 8).

Researchers can then correlate these readings to the closest sensor reading data. In addition, to help the researchers understand factors affecting trends and fluctuations in data readings, local ambient weather data from a nearby outdoor weather station is gathered and incorporated into the data visualizations. Data is gathered from WeatherUnderground, which is a commercial service providing real-time weather information from a network of weather stations. Data is used from the closest weather station, (Weather Station ID: KNYNEWYO585) a Ambient Weather WS-1001-WiFi (Wireless) station, which has a temperature range of -40 to 149 degrees Fahrenheit with an accuracy of ±2 degrees Fahrenheit and a relative humidity range of 10 – 99% with an accuracy of ±5% and is managed by WS-1001 V2.2.9 software.

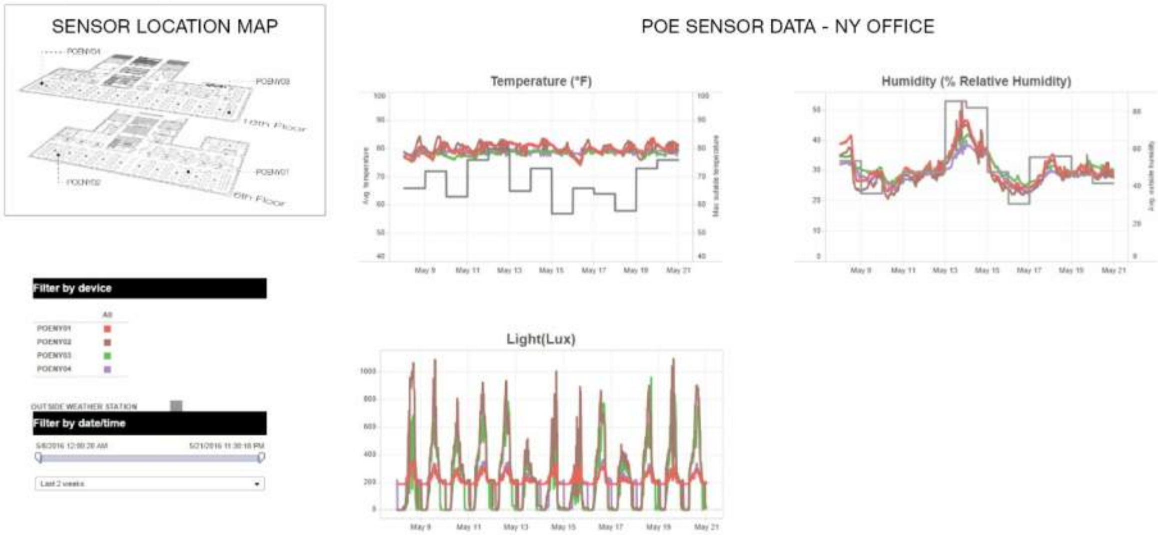

Figure 6: Sensor dashboard

Figure 7: Occupant comfort survey

Figure 8: Occupant comfort dashboard

CONCLUSION

As the Internet of Things continues to engulf the material world, data and computation will increasingly become an integral part of modern buildings. Just as with developments in advanced materials, glass, and digital modelling tools we might look to the automotive industry as a model for the direction that the practice and construction of architecture is headed (BBC News, 2016). This would suggest buildings equipped with computers and sensors capable of making the systems work more efficiently and making the user experience richer. Increasingly, we're likely to see AI and machine learning as integral parts of smart buildings systems.

In order to fully leverage the opportunities of this new paradigm, architects must develop a comprehensive design approach which is informed by data at each phase, from design though post occupancy. Already digital analysis and simulation play a vital role throughout the design process. Their value will be augmented by a sophisticated approach to data collection from mock-ups onwards.

The research presented in this paper has led to the following recommendations concerning the role of analysis, simulation and data collection as part of a comprehensive design approach:

- Designs should be subjected to rigorous analysis and simulation throughout the design process.
- Analysis and simulation assumptions should be calibrated based on real world testing results from performance mock-ups and data collected from post occupancy evaluations of previous built projects.
- Rigorously tested performance mock-ups should be used to detect deficiencies in advance of final construction.
- After substantial completion of the enclosure and in advance of occupancy, environmental sensors, thermal imaging and other field tests should be employed to ensure proper installation and performance of façade systems.
- Façade systems, or adjacent stand-alone units should be equipped with low-cost environmental sensors capable of detecting objective measures of environmental comfort such as temperature, humidity, light levels, sound levels, and air quality.
- This network of sensors should be integrated with the building mechanical systems to provide a holistic solution.
- An interdisciplinary approach involving the engagement of Engineers, Data Scientists, Electrical Engineers, Façade Consultants and other experts should be employed to ensure proper implementation of data collection systems.
- Façade Contractors need to be engaged early in order to seamlessly integrate these systems.
- Access to data must be negotiated with owners so that the design team can enjoy the benefits of comparing final performance with the analysis and simulation carried out during design and thereby refine assumptions and best practices.
- Leaders of the design team must educate owners about the opportunities afforded by these emerging technologies.

Finally, the challenges and limitations to this data collection and sensor deployment must be acknowledged. Researchers strive to accurately represent the ambient conditions of the office and as such feel that a sampling rate of 15 minute intervals is appropriate however, there are conditions where this may not accurately represent the fluctuations throughout the day. A finer resolution sampling rate and averaging those values may be a consideration for future research. Similarly, researchers realize that physical placement of the sensor modules is an ideal physical placement of the sensor modules however it is not perfect in representing certain metrics, e.g. light levels at each users' task/desk surface. In terms of duration of the study, the researchers also realize the short-term nature of the data collected (approximately four months) and acknowledge the limitations to drawing premature conclusions from a dataset without drawing observations from, at a minimum, a full year of data. Seasonal variations will most certainly affect conclusions from data analysis so the ongoing data collection will only become a more robust dataset over time. Also, there are occupant health concerns and company liability issues to consider in the ongoing work. Many occupants are interested in this study and welcome the data collection efforts however concerns have already been expressed about the company's liability to collecting and storing this data, specifically with regard to occupant health concerns. This will certainly be something that will need to be addressed as the study expands to include more sensor modules and their presence becomes more ubiquitous.

FUTURE WORK

- In-house data collection will be expanded into every corner to provide a more comprehensive and complete data field.
- Researchers will expand this sensor module deployment to other offices in different parts of the world (Europe, Asia, and the Middle East) to help understand cultural differences behind perception of comfort as well as façade performance across different climactic conditions.

- Virtual Reality and Augmented Reality tools will be explored as means of visualizing the results of the data collection spatially.
- Particulate matter sensors will be further deployed both inside and outside the space to gain a greater understanding of air quality across time and space.
- Through speculative design studies and the guided student research researchers will continue to explore opportunities for interaction and response in sensor-equipped façade systems.

Building on the work of this initial phase of research, researchers will continue to work with industry and academic leaders to open up new avenues of study. Of particular interest is engaging other research professionals across a range of disciplines, e.g. electrical engineering, computer science, data science, etc., to expand and improve this study.

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REFERENCES

Babsail, Mohammad, and Andy Dong. "Sensor-base Aware Environment: Requirements towards establishing a computational self-configuring sensing system." Arab Society for Computer Aided Architectural Design (ASCAAD 2006) Sharjah, United Arab Emirates (April 2006): 137-150.

BBC News. "How computers took over our cars." http://news.bbc.co.uk/2/hi/uk_news/magazine/8510228.stm (accessed May 20, 2016).

Fox, Michael (editor). *Interactive Architecture: Adaptive World*. Princeton Architectural Press, 2016.

Katzenstein, Erick. "Occupancy Comfort Sensors." LMN Architects, September 9, 2013. https://lmnarchitects.com/tech-studio/interaction/lmn-post-occupancy-comfort-sensors/ (accessed May 20, 2016).

Lewis, Michael. *Moneyball: The Art of Winning an Unfair Game*. New York: W. W. Norton & Company, 2003.

Ratti, Carlo, and Matthew Claudel. *The City of Tomorrow: Sensors, Networks, Hackers, and the Future of Urban Life*. Yale University Press, 2016.

Sherbini, Khaled, and Robert Krawczyk. "Overview of Intelligent Architecture". Arab Society for Computer Aided Architectural Design (ASCAAD 2004), Dhahran, Saudi Arabia (December 2004): 137-152.

Weiser, Mark, and John Seely Brown. "The Coming Age of Calm Technology," Ubicomp, October 5, 1996. http://www.ubiq.com/hypertext/weiser/acmfuture1endnote.htm (accessed Aug 1, 2016).

Welch, Ryan, Roderick Bates, Christopher Connock, and Eric Eisele. "Ubiquitous Monitoring and Adaptation of the Tempered Environment." Modelling Behavior (2015): 445-457.

Façade <> Future

ALGAE TEXTILE

A lightweight photobioreactor for urban buildings

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ABSTRACT

This design proposal aims to demonstrate how the growth of algae can be deployed at the lightweight scale of an enclosure or partition. A typical curtain wall is used to reimagine a possible future for the use of photobioreactors in buildings, and proposes an algae textile: a building–integrated photobioreactor designed as a flexible membrane. Polymeric materials are explored for their minimal dimension and flexibility, and parametric geometry is used to generate porosity and variation. These qualities introduce an ability to modulate light and view in adjacent interior spaces, rather than becoming a monolithic envelope, typical to algal façades.

By using new standards of geometry and materiality, renewable resources such as algae can, therefore, be positioned within buildings without compromising the occupant's interior experience, or expanding the wall assembly. The algae textile envisions a performance-based, next-generation algal façade—one which acknowledges both the productivity and the aesthetic of algae.

KEYWORDS

reactive building membranes, algae, energy and carbon, polymers, innovation, computational design, future trends

INTRODUCTION

THE BIOREACTOR IN ARCHITECTURE

The term bioreactor refers to any device which has been engineered to support the growth of a biologically–active substance; namely, organ tissue, fungi, cellulose or bacteria. Photobioreactors are specific to the growth of phototrophic organisms like algae. These range in design, and can be found in the form of large scale farming operations as open–pond systems, to smaller scale closed–loop systems which circulate algae through a matrix of tubing (Figure 1). While recent developments in bioreactor technology focus mainly on industrial applications, there is evident potential in translating the engineering principles of a bioreactor into the architecture of a building through material systems and claddings—making it possible for algae to act as an integral component within the envelope of urban building typologies, and turn impervious urban surfaces into productive entities which emulate the oxygenating benefits of hectares of forestland.

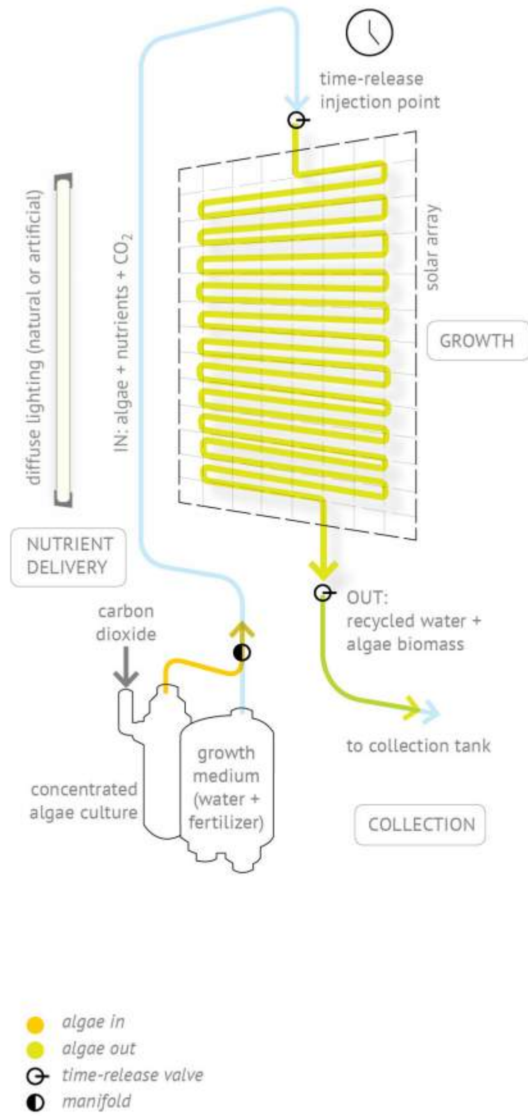


Figure 1: The basic components of a photobioreactor. (diagram by the author, 2014).

Traditional forms of the photobioreactor lack an ability to adapt to any situation or context. They are often cumbersome, robust or confined to the laboratory bench–top, making it difficult to implement the technology into urban contexts and within buildings. Consequently, it can be argued that this circumstance contributes to the difficulties which exists in making algae an integral part of city life. The cultivation of algae in an urban setting can contribute a valuable alternative energy resource, and is an advantageous method for wastewater recycling, air purification, CO2 sequestration, and nutrient recovery for the production of sellable products such as biofuels, nutritional supplements, pharmaceuticals, fertilizer or bioplastics (Oilgae, 2013). Compared to industrial scale algae production—which is focused on producing high–yields of biofuel—it is evident that urban scale algae production is, instead, focused on its distributed environmental and economic impacts. Algae is capable of producing valuable products for society, and makes it an important technology to assess when evaluating renewable resources for the built environment. However, unconventional systems require new standards. Therefore, the development of appropriate standards for algae and its use in buildings could help alleviate current difficulties associated with implementing this technology, and determine its relevance to the creation of a self–sufficient urban lifestyle. Further research in this area will help propel advancements in the technology, and strengthen the future use of algae as a closed–loop resource where it is needed most: in cities and buildings.

BACKGROUND

Spitterwerk Architects together with Arup Engineering built the world's first algae-powered building in Hamburg, Germany. Construction took three years at a cost of 5 million euros (Yirka, 2013). Named the Bio Intelligent Quotient House (BIQ), the 15–unit apartment building uses 129 algae–filled louver tanks as its outer façade, demonstrating how algae can be used to heat and cool large buildings. Using algae retrieved from the nearby Elbe River, each louver tank is filled and affixed to outside scaffolding which are mechanically controlled to orient themselves towards the sun:

When the amount of algae growth in the tanks reach a certain point, some is harvested and taken to a processing facility inside the building. There the biomass is converted to biogas which can be burned to provide heat in the winter. (Yirka, 2013)

The building now serves as a test case to be studied by architects and engineers to determine if algae power is feasible in building construction. With working mechanics, further progress can now be made on the design of the building skin—which remains monolithic. Further iterations in form are needed to make the technology's integration into construction a more prolific process. Increasing porosity and examining the possibilities of lightweight and attachable membrane systems would be beneficial to this effort.

By using algae's highly efficient photosynthetic abilities, projects like this demonstrate the benefit of reevaluating the architect's material palette. In doing so, one can begin to innovate a building skin's assembly and the purposes its material may serve within the building:

Urban façades and roofs represent billions of square metres that instead of being made of inanimate material such as concrete, could become clever photosynthetic surfaces that respond to the current state of climate warming (Griffa, 2014).

The needs for a photobioreactor in a building prove to be very different in comparison to those engineered for industrial uses. For the architect, adjusting *qualitative* parameters such as form, light or occupant comfort often take priority over *quantitative* parameters such as production yields. As a result, a set of design principles which focus on both qualitative and quantitative requirements of a photobioreactor are needed.

METHOD

The design of the photobioreactor must benefit the character of the space it surrounds. For example, its ability to modulate light and shade, or the visual interest provided by its transformation and movement between growth cycles. For this, an ease in generating a networked path within the reactor around irregular contextual conditions is required and, therefore, geometries offering plasticity are desirable (Figure 2).

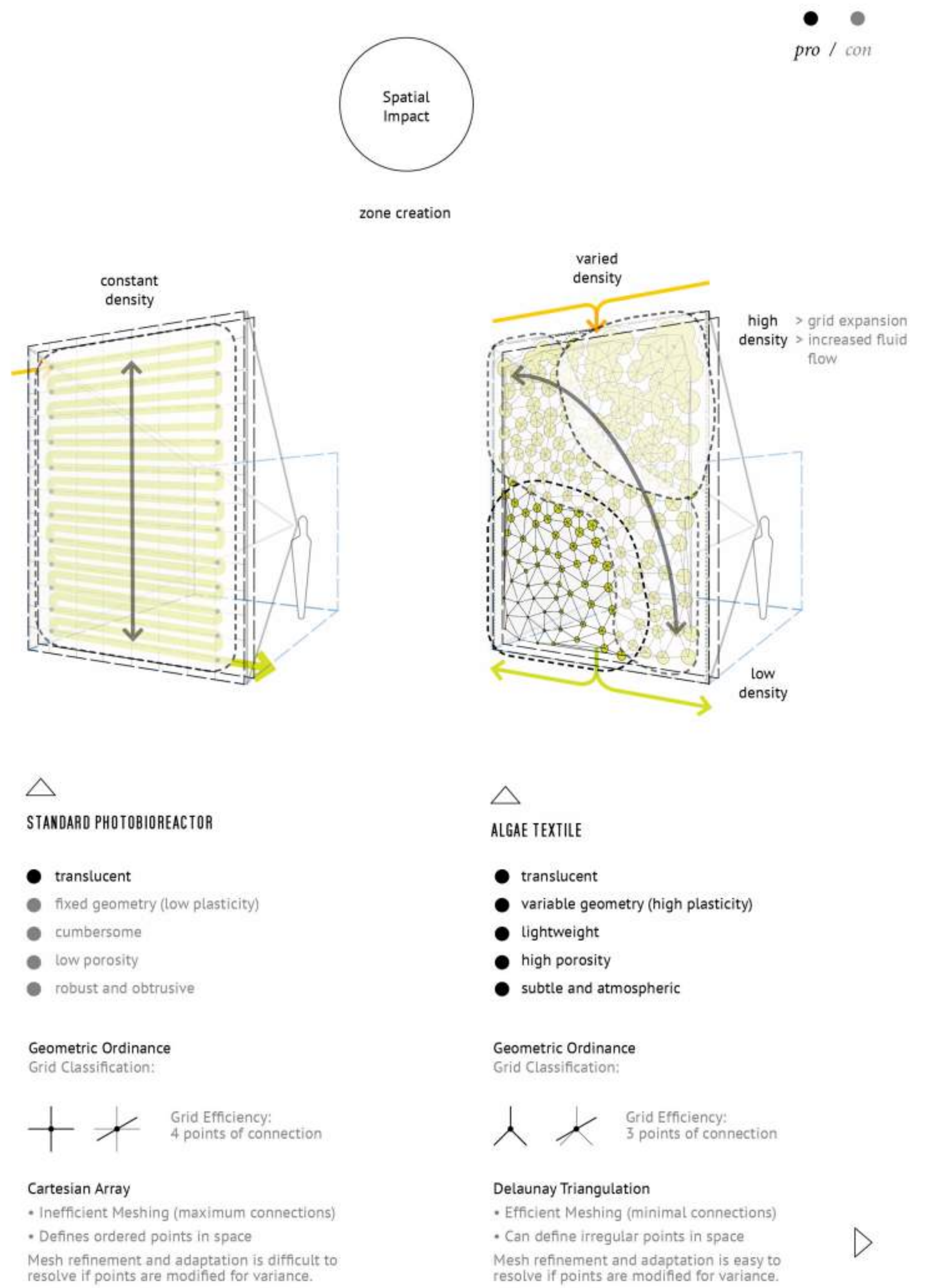


Figure 2: Comparison of the spatial impact of a standard photobioreactor vs. the algae textile (diagrams by the author, 2014).

Creating the form of the textile begins by defining the area of application and the desired density of the triangulated mesh. Using computational design, this area is represented as a series of points that can be manipulated to either aggregate around structure or openings, tailoring it to its surroundings in the building (Figure 3). In this example, the points aggregate in a downward gradient to align the plumbing services of the reactor with the floor slab and the building core. Acknowledging where structural and service lines are in relation to where the algae textile is being placed within the building will help generate the best aggregation of points for the membrane.

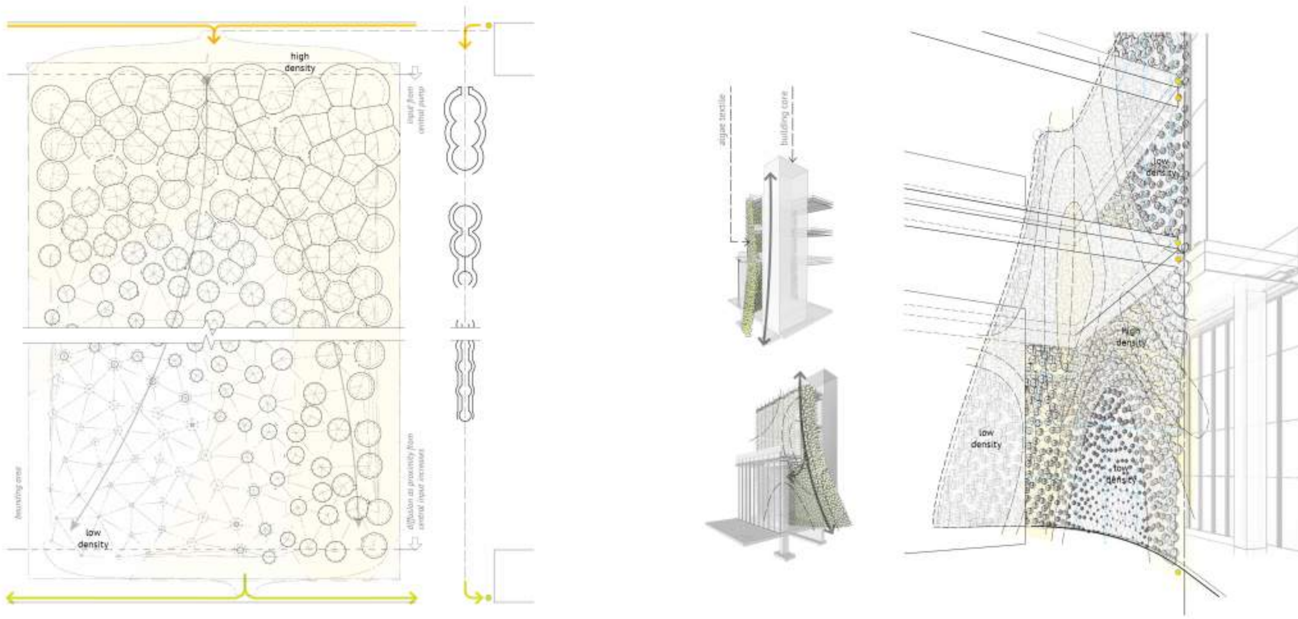


Figure 3: Creating the form of the textile begins by defining the area of application and the desired density of the triangulated mesh (diagrams by the author, 2014).

Once these points are established, locations for input and output valves are chosen. This will effect the diameter of each sphere—which is determined by proximity to the input source of algae. This results in a clumping of spherical vessels with larger diameters closer to the input, where the flow of fluid is the greatest, allowing for areas of the triangulated grid to densify: to increase fluid volume, flow and depth of section at localized areas (Figure 4).

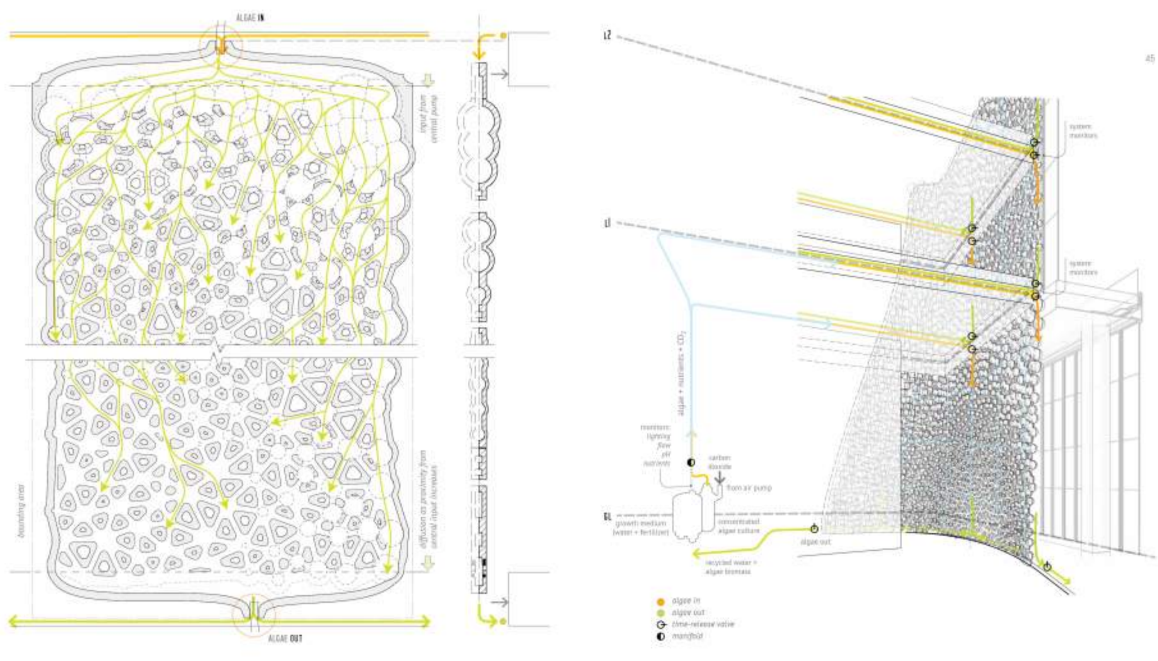


Figure 4: The aggregation of spherical voids are connected with a Delaunay triangulation, creating the circulatory system through which the algae culture flows. This interior network of voids created within the textile takes the place of the solar array in a traditional photobioreactor (diagrams by the author, 2014).

By determining where the concentration of voids lie within the membrane, the resulting density and concentration of the triangulated mesh and its spherical expansion points can be used to control matters associated with view and light modulation. During the design stage, these are important parameters of control for the architect, as they work through decisions regarding sight lines, occupancy and programme.

In this example, growth medium and algae is injected at the top of each floor slab, and harvested at the bottom of each floor slab. This arrangement dedicates a plumbing system to each floor, making it possible to control the large expanse of the textile in sections. This compartmentalization allows precise and decentralized control in: lighting, flow, pH and nutrients between levels, depending on the portion of the textile.

As illustrated, the algae textile has been developed with the interest of defining a set of desired behaviours and functions specific to the use of photobioreactors in urban building typologies such as the tower. This criteria is meant to evaluate photobioreactor design against social and environmental requirements—as they have a higher impact on architectural performance, and directly address an architect's interests. By designing photobioreactors to meet building–specific criteria such as spatial impact, the architect is able to optimize the benefits of using a photobioreactor in building construction, and evaluate their design against both qualitative and quantitative needs. These guidelines are meant to inform the architect on how to design a photobioreactor that is both effective, mechanically, and compatible, architecturally, within the design intentions of a building.

DATA

BIOREACTIVE OPTIMIZATION OF THE ALGAE TEXTILE

The importance of laminar and turbulent flows in a bioreactor (Croze, 2013), have been integrated into the design. By proposing an irregular interior path, the design aims to promote the agitation and aeration of the algae as it moves within the membrane to stimulate its growth. It can therefore be said that the network of spherical forms in the textile not only serve an aesthetic purpose, but contribute to the overall mechanical performance of the textile by addressing the importance of agitation and aeration of fluid for growth.

Environmental conditions such as light, temperature and the surface–to–volume ratio of the reactor also affect the rate of proliferation (Schenk, 2008). These diagrams illustrate how the irregular interior path of the textile takes these conditions into consideration. The textile's minimal depth places the algae in a growth environment that is thin and distributed over a large surface. This high surface–to–volume ratio maximizes the absorption of energy and nutrients (Proksch, 2013), and means an even distribution of light and temperature is available to each algae cell suspended in the fluid (Figure 6).

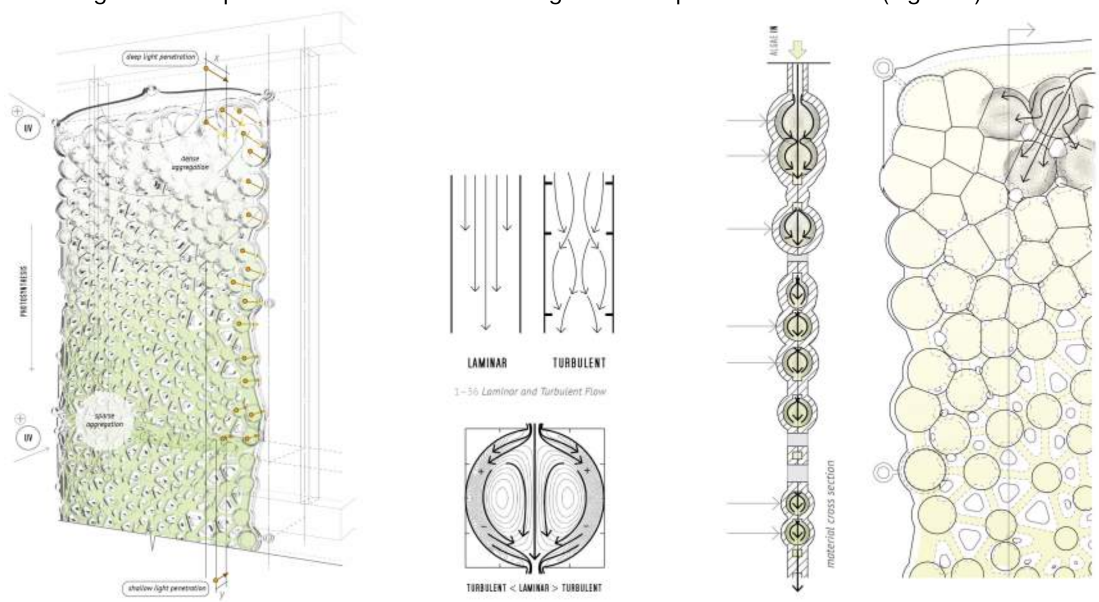


Figure 6: (Left) Three-dimensional diagram of light penetration across the textile. (Centre) Diagram of movement of fluid through a sphere and its transitions between laminar and turbulent flows. (Right) Analysis of the movement of fluid within the length of the algae textile and the effects of an irregular interior path (diagrams by the author, 2014).

Further, moments of shallowness and depth in the textile can account for the culture's change in density as it grows: a fresh culture, being less dense (translucent), can handle larger depths without loosing full light penetration, whereas, an aged culture, being more dense (opaque), needs shallower depths to ensure full light penetration. These needs can be adjusted according to where input valves are located, and will determine where the spherical vessels aggregate and dissipate. It is apparent that algae requires changing conditions along its life cycle, and therefore, variability in its path within the textile can help accommodate for this. The textile's spherical surface also allows for light exposure at all radial angles, reducing the need for solar-tracking mechanics.

MATERIALITY

To articulate variable geometric conditions within thin dimensions, the algae textile uses polymer–based materials to produce a surface which encapsulates a complex cavity on its interior, while also being elastic, water–resistant and durable. A clear polyurethane resin is specifically chosen, as it mimics the characteristics of glass, but delivers a flexible and elastic form; one which can be manipulated in a number of different ways using industrial manufacturing techniques. Polyurethane resins are available in a range of durometers, from the very hard (Shore–A 100), to the very soft (Shore–A 15), and are widely used in the manufacture of flexible and high–resistance industrial products, such as foam seating, gaskets, hoses, automotive pads and bushings, elastomeric wheels and tires, high–performance adhesives, and spandex fabrics. Unlike silicone products, polyurethane is highly durable and resistant to tear. Its molecular composition allows it to have high clarity, and UV resistance, and lends itself well to the creation of strong moulded parts. By exhibiting the qualities of glass in elastic form, the textile can therefore be placed within an existing window wall, creating minimal obstruction and installed using only a network of attachment points to tension it into place. This material characteristic is what allows the system to lie within existing building enclosures without a drastic expansion of the wall assembly, and remain in compliance with the spatial limitations of urban real estate (Figure 7a).

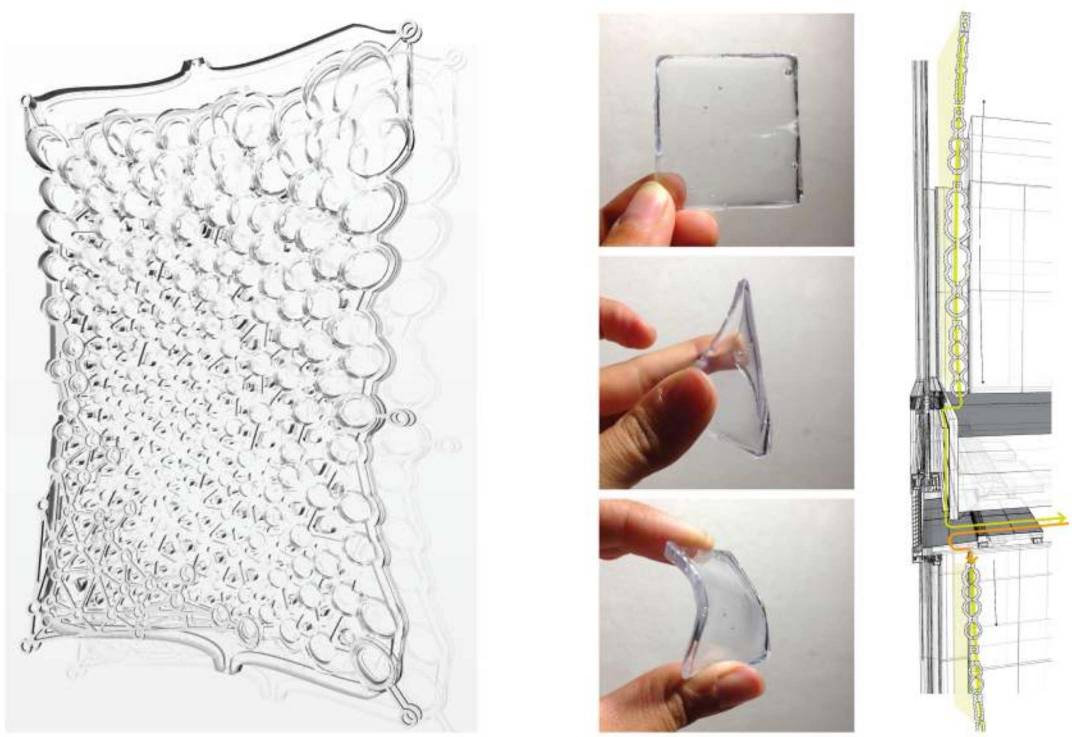


Figure 7a: Model and sample of polyurethane resin used for the algae textile (Shore-A 60), demonstrating high clarity and flexibility (images by the author, 2014).

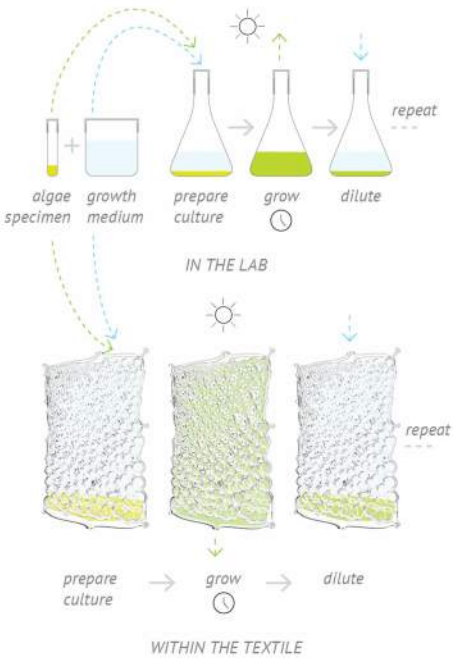
Silicone products are commonly used for building construction, but it is valuable to examine the characteristics of other polymeric materials, including polyurethane resins (Figure 7b). Displaying similar characteristics as silicone, polyurethane offers one, very important, characteristic: it is “water-clear” like glass and highly durable against dynamic movement. Silicone rubbers will never be completely clear, and have poor mechanical properties, making them less durable against movement. View the following comparison:

Material	Polyurethane	Silicone	Comments
Chemical Base	Nitril	Hydrogenated Nitrile	
Primary Uses	Static and dynamic seals, seals for high hydraulic pressure, for highly stressed parts subject to wear.	Static seals for extreme temperature applications, food, and medical applications.	
Advantages	• excellent abrasion resistance • excellent tensile strength and rigidity • low compression set • good weather and ozone resistance	• extreme temperatures • good resilience to oxidation & ozone • clean, low odour	
Disadvantages	• poor resistance to water • poor high temperature capabilities	• poor in dynamic applications due to poor abrasion resistance • not recommended for oils and dilute sodium hydroxide	*The textile is placed on the interior side of the envelope, reducing concerns of extreme temperatures.*
Transparency	transparent / water clear	translucent / milky	
Flexibility	Available in a variety of Shore-A durometers	Available in a variety of Shore-A durometers	
Durability	very good	poor	*When handling a sample of polyurethane, it is apparent that it is very resistant to tear when compared to silicone.*
Tear Strength	good	poor	
UV Resistance			
Yellowing			
Heat Aging Resistance	very good	very good	
Ozone Resistance	very good	very good	
Resistance to Oil and Grease	good	average	
Fuel Resistance	average	poor	
Water Swell Resistance	poor	very good	
Gas Impermeability	good	poor	
Abrasion Resistance	very good	poor	
High Temperature - Standard	175° C	450° C	*The textile is placed on the interior side of the envelope, reducing concerns of extreme temperatures.*
Low Temperature - Standard	-60° C	-75° C	

Figure 7b: Side-by-side comparison of polyurethane and silicone (table by the author, 2016, information sourced from Professional Plastics, 2016).

ALGAE CULTURING

A monoculture of Chlorella Vulgaris is specified for the algae textile. This strain is the easiest to grow. It is tough, resilient, and grows well in wastewater. By consulting the technical curator of the Canadian Phycological Culture Centre, valuable lessons in algae cultivation were gathered to confirm requirements specific to the spatial and environmental parameters which affect algae's growth. It was immediately apparent that the way in which environmental parameters are controlled in a lab can directly relate to decisions commonly made during the space planning of a building by an architect, including orientation, elevation, heating, cooling and lighting. Through this consultation, an algae culturing guide specific to details regarding space planning was created (Figure 8).



ALGAE CULTURING GUIDE

OPTIMAL GROWING CONDITIONS: *Changes in these conditions can be used to speed up or slow down the rate of growth*

Lighting:

- Direct sunlight is not desirable.
- Too much light will result in a culture that is not bright green.
- Direct light will kill the culture *(photo-bleaching)*.
- North facing windows are ideal.
- The textile should be setback from the window wall in other orientations, or used with frosted glass to avoid direct sunlight.
- Artificial lighting around the textile should be diffuse and evenly distributed. Hot spots should be avoided, cool white bulbs should be used and placed at least 6" away.
- Provide low-intesity light during the evening if desired. (1000–10,000 lux)

Temperature:

- cold = slow growth hot = fast growth
- Room temperature is ideal for stable growth (20–25ºC)

CULTURING BASICS

Resetting and Multiplying a Culture:

- The best way to reset a dense culture is to extract a portion of the culture and refill with the same volume of growth medium.
- Always divide the culture to maintain a back up.
- A test tube filled with the backup culture can be kept in a refrigerator for a year or longer.

WHAT TO DO IF THE CULTURE DIES WITHIN THE TEXTILE:

- Step 1: Extract the existing culture
- Step 2: Flush the reactor with a water/chlorine solution
- Step 3: Flush the reactor with water multiple times
- Step 4: Introduce new a culture

Lab-Grade Growth Medium

Growth medium is a mixture of distilled water and water-soluble nutrients.

Bold's Basal Medium (BBM): Stock Concentrate

Substance:

$Na_2EDTA.2H_2O$ (Disodium Salt Dihydrate)	10.0 g/L
KOH (Potassium Hydroxide)	6.2 g/L
$FeSO_4.7H_2O$ (Ferrous Sulfate)	4.98 g/L
H_2SO_4 (Sulfuric Acid)	1.0 mL
$CaCl_2.2H_2O$ (Calcium Chloride)	25 g/L
$MgSO_4.7H_2O$ (Magnesium Sulfate)	75 g/L
$NaNO_3$ (Sodium Nitrate)	250 g/L
NaCl (Sodium Chloride)	25 g/L
Trace Metal Solution:	
H_3BO_3 (Boric Acid)	2.86 g/L
$MnCl_2.4H_2O$ (Manganese Chloride)	1.81 g/L
$ZnSO_4.7H_2O$ (Zinc Sulfate)	0.222 g/L
$Na\ MoO_4.5H_2O$ (Sodium Molybdate)	0.390 g/L
$CuSO_4.5H_2O$ (Copper Sulfate)	0.079 g/L
$Co(NO_3)_2.6H_2O$ (Colbalt Nitrate)	0.049 g/L
H_3BO_3 (Boric Acid)	11.5 g/L
F/2 Vitamin Solution (optional)	
Distilled or Milli-Q Water	

Figure 8: Algae culturing guide (diagram and table by the author, 2014).

SUPPORT SYSTEMS

The components of the algae textile mirror those of a traditional photobioreactor, and therefore, methods of connecting necessary support systems like a water reservoir and air processor are transferable (Figure 9). The textile takes the place of the solar array—traditionally a circuit of tubing the algae travels through to expose it to sunlight and promote photosynthesis. The use of the textile as the solar array of the bioreactor allows views or light to be controlled in accordance to the surrounding context by manipulating the density of the textile's mesh. These are important parameters for an architect during the planning of a building, and why the textile is a key component for the innovation of the photobioreactor and its use within buildings.

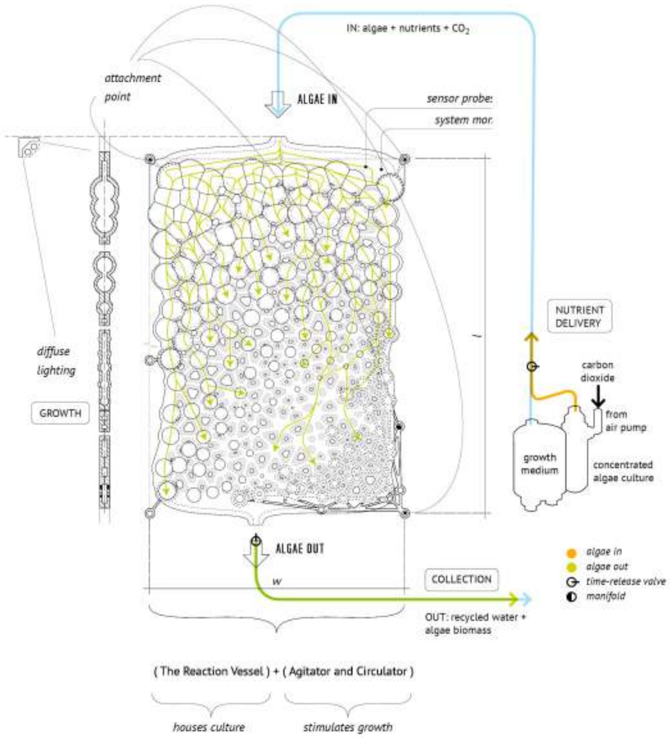


Figure 9: The components of a bioreactor incorporated into the design of the algae textile (diagram by the author, 2014).

However, the textile does not function alone, and requires the integration of various support systems within the plumbing and mechanical infrastructure of a building, including: an inoculation (culture injection) system, an air processing system, a harvesting system and a lighting system. As illustrated here, it is important to detail the ways in which these systems connect to each other and to the building to ensure the textile functions in the desired way (Figure 10).

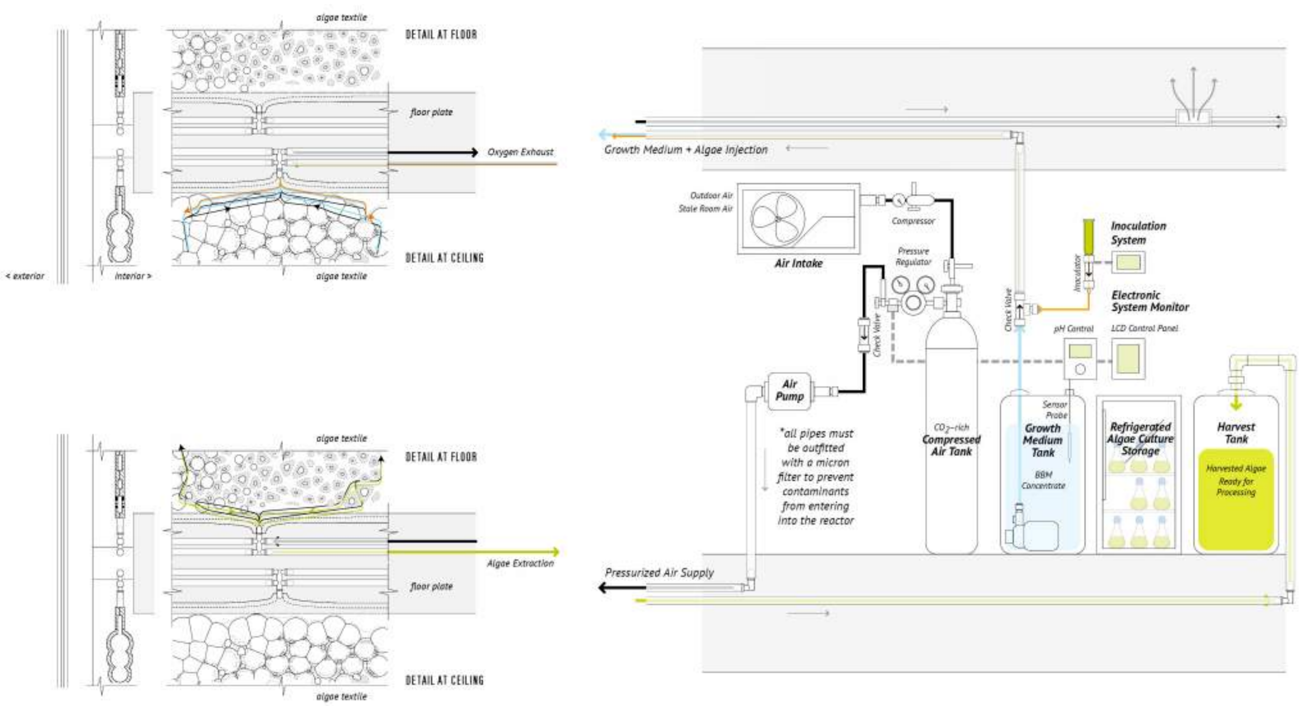


Figure 10: The schematic mechanical infrastructure for the algae textile (diagram by the author, 2014).

First, an inoculation and harvest system: (1) For starting a culture, the inoculator fills the textile with growth medium (blue line) and then injects a concentrated algae culture (orange line). This is left to grow and photosynthesize. (2) For maintaining an existing culture once it has grown, a portion of the culture is extracted from the textile and directed to a harvesting tank (green line). The inoculator then injects only fresh growth medium into the textile to dilute the culture and start a new growth cycle. Second, an air system: (1) Pressurized air is injected at floor level and travels upwards through the textile. This feeds the algae with CO_2 as it photosynthesizes and circulates the culture to promote its growth. (2) The resulting oxygen produced by the algae is exhausted at ceiling level and can be fed into the building's ventilation system thereafter.

EXPLANATION

The textile was developed to suggest a method for producing quasi–biological materials for architecture: where construction materials are not inanimate objects, but rather, are receptive and interlaced with other functions to create productive material interfaces for the built environment. The algae textile's ability to act as, (1) a perforated building skin, (2) a carbon absorbing air–purifier, and (3) a valuable energy resource, makes it a building material which offers productive functions within its form—bringing it beyond the function of a decorative skin and rationalizing the intricacies of its composition. The geometry and appearance of the textile have been developed to suggest methods of increasing its ability to cultivate algae, while also benefiting the spatial effects it has on a surrounding space (Figure 11)—a quality that is difficult to achieve with the traditionally robust nature of industrial photobioreactors.

Figure 11: View through the algae textile from the interior (images by the author, 2014).

If taken as a method rather than a definitive design, the idea of the algae textile—and the continued development of similar building materials—could transform the traditional idea of the 'decorative architectural skin' by superseding its decorative function with productive functions such as air purification, energy production, or light modulation. As such, they are designed with the additional interest of performance, together with aesthetics. Every building has its own context, program, size, view, orientation, etc., which affect the design parameters of its enclosure differently. This requires a tailored approach, and why it is important for the geometry of the textile to afford a level of alteration and plasticity; which is given through its parametric modeling. A Grasshopper definition is used in Rhino3D to generate the triangulated mesh of the textile.

The use of parametric design on enclosures can generate geometry in a prolific way to optimize the dimensions of openings or the density of a grid. If used correctly, geometric conditions can be individualized and specifically tailored to a portion of the building. This has potentials in re–skinning applications or performance–based design—where a complex façade geometry can be generated, then fluidly manipulated to control these parameters on a customized level (Figure 12). This method can already be seen in existing material systems. For example, applications of fritted glass aim to reduce the intensity of light which passes through a window wall simply by fusing varied densities and patterns of opaque ceramic directly onto the sheet of glass. This material technology provides a streamlined way of managing common problems associated with glass enclosures, reducing the effects of direct sunlight and heat gain without the need for auxiliary systems such as shading devices, or taking the place of interior drapes.

Figure 12: Implementation scenario: curtain wall section (image by the author, 2014).

The algae textile can be applied using the same logic as a frit pattern, but has the added benefit of, (1) supplying a source of ecology to purify air and uplift an occupant's wellbeing, (2) supporting the growth of a renewable resource for a self–sufficient urban lifestyle, and (3) controlling light and shade over an expanse of glass by adjusting the placement of spherical vessels within designated areas of the textile. In both these examples, the use of gradients and variation is key to achieving these subtle effects within streamlined dimensions. By embedding productive functions within material, the desire for emergent, complex and optimized qualities within traditionally rigid systems, therefore, incites a method of design where geometry is optimized and where material is machine.

CONCLUSION AND FUTURE WORK

This design proposal for a photobioreactive building membrane hopes to provide an alternative method for housing algae within buildings; contributing a view of what materials of the future might look like. If an algal–urbanism were to be implemented, the proposal envisions how material surfaces could be designed with an agency to perform productive tasks (filtration, harvesting, energy production, etc.), and introduce alternative modes of ecology in highly dense urban environments. It has been important to identify the challenges associated with algae cultivation in an urban context, and to establish what characteristics are needed for photobioreactors when used in a building. As the proposal has shown, materials developed for living organisms must not only define a form specifically tailored to the growing mechanics of that organism, but they must also satisfy demands given by architecture and design to ensure their prolific use. For algae, circulation, agitation, surface–to–volume ratio and light penetration are all important factors, and is what the textile strives to explore, challenge and test.

With additional research and development, the details of a programmable and automated pumping and reservoir monitoring infrastructure would be beneficial. These systems already exist—the BIQ House for example (Arup, 2013)—and would provide an apparatus which allows the reservoir to automatically harvest and dilute the culture as it continues to reproduce. Additionally, it could provide a method for scouring the interior of the textile for maintenance. Active monitoring systems which provide feedback and statistics on the health and growth of the algae would take the system to a higher level of sophistication, offering precise control over pH levels, lighting, nutrient levels and temperature—all of which are important factors for increasing the productivity of a photobioreactor. As a result, further research on the integration of intelligent electronic systems within the construction of the textile and its connection to a building's mechanical services would need to be explored and, in doing so, will further progress the plausibility of the textile's use in the built environment.

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REFERENCES

Arup Engineering, “The BIQ House,” (arup.com, accessed July 11, 2016) http://www.arup.com/homepage_imagining_buildings_of_the_future/biq_film

Ottavio A. Croze, et al. “Dispersion of Swimming Algae in Laminar and Turbulent Flows: Consequences for Photobioreactors,” (J.R. Soc. Interface, April 6, 2013, vol. 10 no. 81, 20121041) http://rsif.royalsocietypublishing.org/content/10/81/20121041.full

DKI Rubber & Plastic Ltd., “Materials,” (DKI, accessed July 11, 2016) http://www.dkirubber.com/materials.asp

Cesare Griffa, “Algaetecture | Expo 2015 Preview” (cesaregriffa.com, April 7, 2014) http://cesaregriffa.com/2014/04/07/algaetecture–expo–2015–preview–algae–systems–to–design–and–feed–the–city/

Oilgae, “About Algae,” (oilgae.com, accessed Dec. 17, 2013) http://www.oilgae.com/algae/algae.html

Gundula Proksch, “Growing Sustainability: Integrating Algae Cultivation into the Built Environment,” Introduction, (Edinburgh Architectural Research Journal (EAR), Volume 33, 2013) http://sites.ace.ed.ac.uk/ear/files/2013/05/147–1621.pdf

Professional Plastics, Inc., “Rubber and Elastomers Overview,” (Professional Plastics, accessed July 11, 2016) https://www.professionalplastics.com/professionalplastics/RubberandElastomersOverview.pdf

Schenk, et al. “Second Generation Biofuels: High Efficiency Microalgae for Biodiesel Production,” (Springer Online, BioEnergy Research, 2008). pg. 20-43

Bob Yirka, “First Algae Powered Building Goes Up in Hamburg,” (phys.org, April 12, 2013) http://phys.org/news/2013-04-algae-powered-hamburg.html

BIO-INSPIRED URBAN FUTURES

Designing adaptive façade networks to re-imagine the city ecosystem

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ABSTRACT

Cities can be thought of as urban ecosystems since they are composed of many interacting inhabitants and built components situated within a physical environment. Though the comparison between cities and ecosystems seems straightforward, what is often missing from the planning and design of cities is the interconnected and dynamic aspects that ecosystems in the natural world possess. The components of a biological ecosystem are interdependent and feedback on one another in response to local environmental conditions. To this end, we advocate for an eco-systemic vision of urban planning. Focusing on facades as a critical architectural link between the level of the individual building and the larger urban ecosystem can further advance this perspective. Finding inspiration in nature, our research focuses on developing dynamic building facades by taking cues from the adaptive qualities of organisms and ecosystems. The designed facades, contextually situated and responsive to local environmental conditions, take on performative characteristics. The clustering of facade systems in a network would allow for both the efficient harvesting of natural and renewable resources and the sharing of the collected resources throughout the community. Efficient and optimized façade systems should have the ability to evolve, ensuring that the way we extract, structure and transform those resources is increasingly sustainable. Sustainable bio-inspired design promotes a resilient kind of urban growth in which the city can endure change and continue to develop. For example, the specialization of an individual façade (e.g. through energy collection, air purification, sunlight filtration, etc.) would enhance the overall performance of its' shared cluster by enabling each aspect of the structure to aid in complex functions. The façades network adapts, reacts and teaches us how to go about adjusting and transforming the system through its care, repair, modification and re-use over the years. In this way façade design provides the catalyst for a neighborhood to truly become part of the dynamic urban ecosystem.

KEYWORDS

Urban ecosystems, resilience, adaptability, bio-inspired, generative, future trends, biomimicry

INTRODUCTION

Cities can be envisioned as ecosystems since they are composed of many interacting inhabitants and built components situated within a physical environment. An integral aspect of natural ecosystems is that they are resilient. They can recover from disturbances in ways that cities are not structured to do. We argue that the future of urban centers depends on resilient thinking. Humans and nature are strongly coupled to the point that they should be conceived as one social-ecological system. Due to this coupling, resilient cities will be more capable of dealing with changes. Contemporary ecological and economic stresses can be thought as shocks and disturbances. It is within this context of stress that reimagining cities as resilient urban ecosystems, via networks of Adaptive Façades, fits a sustainable vision of transformation, neighborhood by neighborhood.

BACKGROUND

Though the comparison between cities and ecosystems seems straightforward, what is often missing from the planning and design of cities are the interconnected and dynamic aspects that ecosystems in the natural world possess. An ecosystem is the community of organisms in a specific habitat and the environmental conditions under which they live.[7] All of the interacting biotic and abiotic components form an interconnected system linked by the flow and transfer of energy and nutrients. Ecosystems are constantly undergoing natural stresses and disturbances, such as fire, storms, and drought. These disturbances cause shifts in the availability of resources and changes to the physical conditions of the system. Depending on the scale of the disturbance and the biology and ecology of the organisms living in the habitat, ecosystems are resilient. The flora and fauna that make up such a system are adapted to dynamic environmental conditions, and ecological resilience comes from the redundancy of the interacting parts of an ecosystem. That is, multiple species can play the same or similar roles within an ecosystem, so stress on the system can be more easily mitigated. Using the interconnected features of natural ecosystems as inspiration, we advocate for an eco-systemic vision of urban planning. Focusing on facades as a critical architectural link between the level of the individual building and the larger urban ecosystem can advance this perspective.

METHOD

Finding inspiration in nature, the research focuses on developing and clustering dynamic building facades by taking cues from the interconnectedness of ecosystems. A cluster is envisioned as a group of existing buildings that provide the structural backbone for a network of adaptive facades, which react to environmental conditions and interact with other building systems that typically function independently. Within a cluster, building systems are reorganized and integrated into the building façade, which essentially takes on a more diversified role. The facade clusters are devised to increase robustness within a system by building in redundancy and buffering against disturbances, ultimately creating a resilient urban system.

Through the adaptive reuse of existing buildings, the clustering of facade systems in a network produces environmental benefits through the sustainable harvesting of resources, economic benefits through the net-positive production of resources, and social benefits through the creation of interconnected, shared spaces. Existing buildings are analyzed based on their proximity and structural integrity, which then are stripped down to their basic components and appropriated for specific façade systems. These include providing vital building and communal needs such as shade, light diffusion, thermoregulation, water and energy collection and water filtration. Clusters allow for both the efficient harvesting of natural and renewable resources and an efficient sharing of the collected resources throughout the community of buildings with different uses - residences, offices, commercial spaces and recreational facilities. Since buildings with different functions require resources in different proportions throughout a twenty-four hour cycle, innovative, efficient and optimized façade systems have the ability to ensure that the way we extract, structure and transform those resources is increasingly sustainable.

In the proposed model sustainability is achieved via interconnectivity. The idea of interconnectivity relies on the efficacy of systems integration shared among clusters, which focuses on minimizing repetition in equipment because each building will not require the exact same system. Instead, by linking buildings together and sharing systems and resources, the cluster model promotes a more efficient level of redundancy in order to achieve robustness. The emerged environmental and economic benefits are evidenced by the minimization of repetition in equipment and the sharing of harvested and generated resources within the community at an optimized and efficient scale. Sustainable bio-inspired designs promote a resilient kind of urban growth in which the city, by creating one net-positive neighborhood at a time, can endure change and continue to develop. Given the vastness and density of the urban environment, these are ideal conditions to interweave fields of replicated systems that are then interconnected through the central hubs, feeding resources to local communities. For example, the specialization of an individual façade would enhance the overall performance of its' shared cluster by enabling each aspect of the structure to aid in complex functions. As such, an interconnected and organic system is capable of improving efficiency to the overall system as elements would be optimally scattered and located throughout the city in order to offset the high demands of the resources. Socially, the networked facades function as inhabitable spaces that can increase social connectivity. For example, providing people with the ability to inhabit protected (e.g. naturally-shaded) outdoor areas can facilitate community interaction and transcend the conventional modes of property subdivision. This model could move the design of often flat shiny surfaces to more geometric and complex spatial inhabitation, versatile in its uses and malleable in its form. The clustering of adaptive facades allows the neighborhood to truly become part of the dynamic urban ecosystem.

Similarly to living organisms, adaptive facades, by reacting to local environmental conditions, incorporate responsive features such as dynamic shading to regulate solar radiation and daylight penetration, rainfall water collection and filtration, and wind and solar energy production. The energy to become net-zero or even net-positive is produced in a multitude of ways within the evolving urban environment, in which innovative technologies are useful tools to further aid and regulate the development of the urban ecosystem. Possible technologies, along with emerging systems, include algae growth to harvest biofuel, photovoltaics and electrocells to produce electricity, and thermal sensors, along with hydroponics and aquaponics, to provide controlled climates. Additionally, biodynamic façades can provide excellent mechanisms to filter dust and purify the air, while vertical gardens can provide vegetation and food.

Moreover, in developing the materiality of such facades, all these components can be flexible and used to manipulate the building envelope to further enhance other functions such as solar screens that can open and close, adapting to the local environmental conditions in relation to the user's needs and optimal thermoregulation. While wind is a difficult resource to harvest in a single building, the evolution of micro turbines provide great potential for the new generation of products coming to the market. The energy produced can be used immediately or sent back to the grid, which in recent years has had enormous difficulties in managing loads and requests. The development of *hubs*, places for resource redistribution and storage is a parallel critical element in this neighborhood defined strategy.

Managing run-off and providing fresh and clean water have both proven to be challenging tasks within urban settings where space is scarce and underground excavations to allocate tanks are quite costly. Therefore, harvesting rainfall is critical in building infrastructure. In order to avoid costly systems, integrated filtration systems to service water distribution can be built directly into the facades of buildings, in which water is cleaned using gravity fed filtration systems and vertically raised with solar pumps. The collected water can be used both for the building uses and, when the façade is green, for irrigation.

Adaptive facades additionally have the ability to produce collectable data from the networked systems from which inhabitants can intelligently and efficiently determine whether the systems are being used to their fullest potential or if such elements are optimally located within the cluster of buildings. This information is useful in advancing the maintenance and development of the façade system, which has the capacity to evolve as a resilient entity. As the community also grows, new clusters are developed and new intelligence is acquired, the network progresses.

DESIGN PROPOSALS

Design proposals for three urban centers have been developed to illustrate the proposed clustering strategy: 1) downtown Los Angeles, 2) Chicago's riverfront, and 3) the Porta Nuova area of Milan. Each location represents a diversity of climates, available natural resources, and environmental stresses. Each design proposal is described through a diagram proposing how inputs are transformed into outputs and networked within a selected neighborhood. Through the analysis of site-specific climatic conditions, and inspired by a particular existing building or system tested in that part of the city, the proposed clusters are located within particular quadrants to efficiently mitigate different community needs. In particular, buildings that are underutilized or could benefit from a renovation have been selected based on environmental criteria, which include sun orientation, prevailing winds directions, potential to harvest water, structural integrity, and programmatic community needs. The new dynamic façade systems are implemented by attaching the new system complimentary to the existing structure and envelope, or by dismantling and redeveloping the existing envelope to accommodate the new system on to the existing structure.

Figure 1: Inspiration from each of the three cities selected for the design proposals comes from existing buildings. From left to right: the California Department of Transportation building in Los Angeles (photo by authors), the green roof on Chicago's City Hall (photos by Antonio Vernon/Wikimedia Commons and Conservation Design Forum), and the Bosco Verticale residential buildings in Milan (photo by authors).

DESIGN PROPOSALS – LOS ANGELES

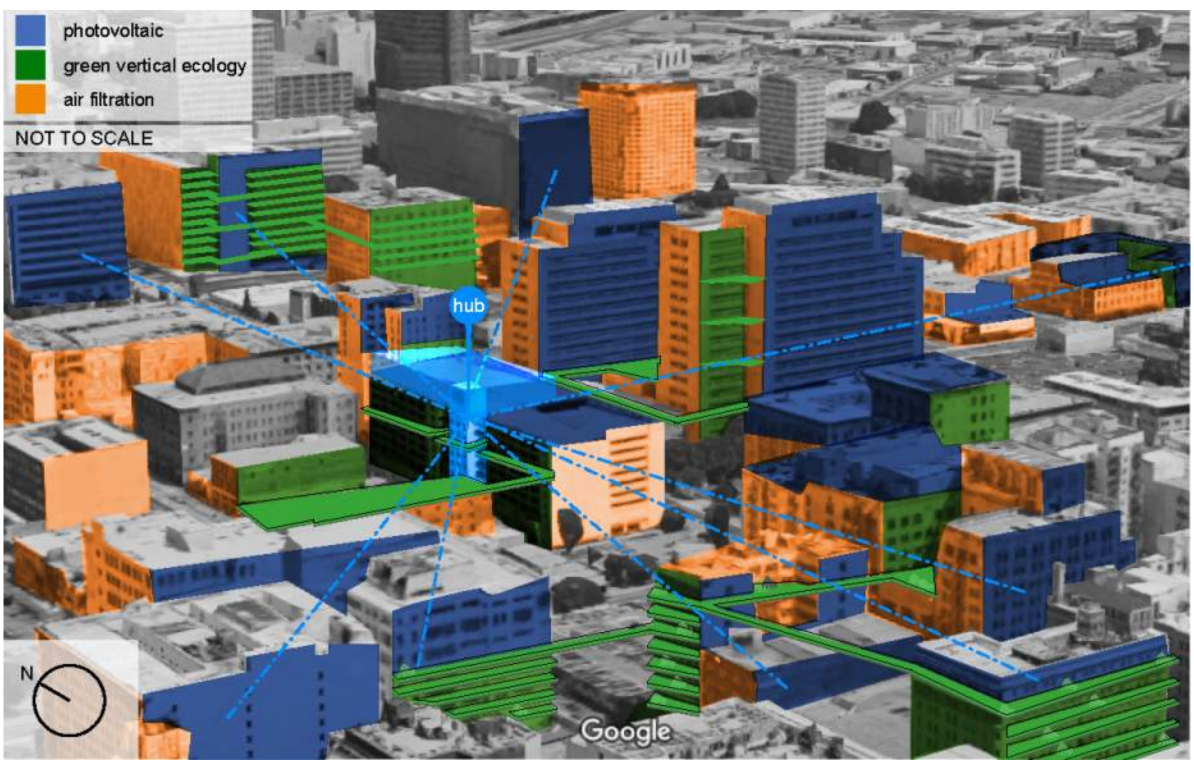

Figure 2: Design Proposal 1. Diagram showing air purification, light filtration, vertical ecology and energy collection systems for the city of LA. Diagram courtesy of Authors.

Categorized as a mild Mediterranean climate, Los Angeles is distinct in its environmental qualities. Temperatures are typically consistent between seasons, with nearly 300 days a year of predominantly clear and sunny skies. This type of climate has combined with abundant vehicular and industrial emissions to contribute to severe air pollution. Moreover, the city has recently reached 4 million inhabitants causing densification and a corresponding lack of open public spaces for public aggregation. Given these climatic and social conditions, LA is the perfect place to identify a cluster and develop adaptive façade networks. The specific location of this proposal is the eastern part of downtown L.A., in the area that borders the Little Tokyo neighborhood.

Inspiration is drawn from the nearby California Department of Transportation building, which has a south-facing solar screen made of perforated steel panels over a glass curtain wall that provides optimal views of the city. The new proposed façade systems incorporate a series of modular panels, designed with opaque insulation, photovoltaic and reactive properties, which can be distributed along the south and west envelopes of building clusters in different ways depending on their functions. Through the redesign of its building facades, the proposed façade system can sequester carbon dioxide, manage and reduce the urban heat island effect, provide shade and at the same time produce energy and filter the air. For instance, air purification technology, conceived as a combination of responsive mechanical devices and vertical vegetation screens, is a useful tool to suck up smog along with other contaminants and dust particles, especially when coupled with photovoltaic panels to compensate for the high-energy demand of the process. Additionally, these systems support in constructing desirable microclimates, which can transform typical shading devices into bridge-like linear parks in the sky connecting several facades devised to facilitate and enhance communal interactions. Learning from the current non-operational status of a building, it is proposed that a company, that over time ensures timely maintenance to all adaptive facades, operate the cluster. By networking the façades, hubs are established for storing excess energy to help solve the peak demand crisis the city periodically faces.

DESIGN PROPOSALS – CHICAGO

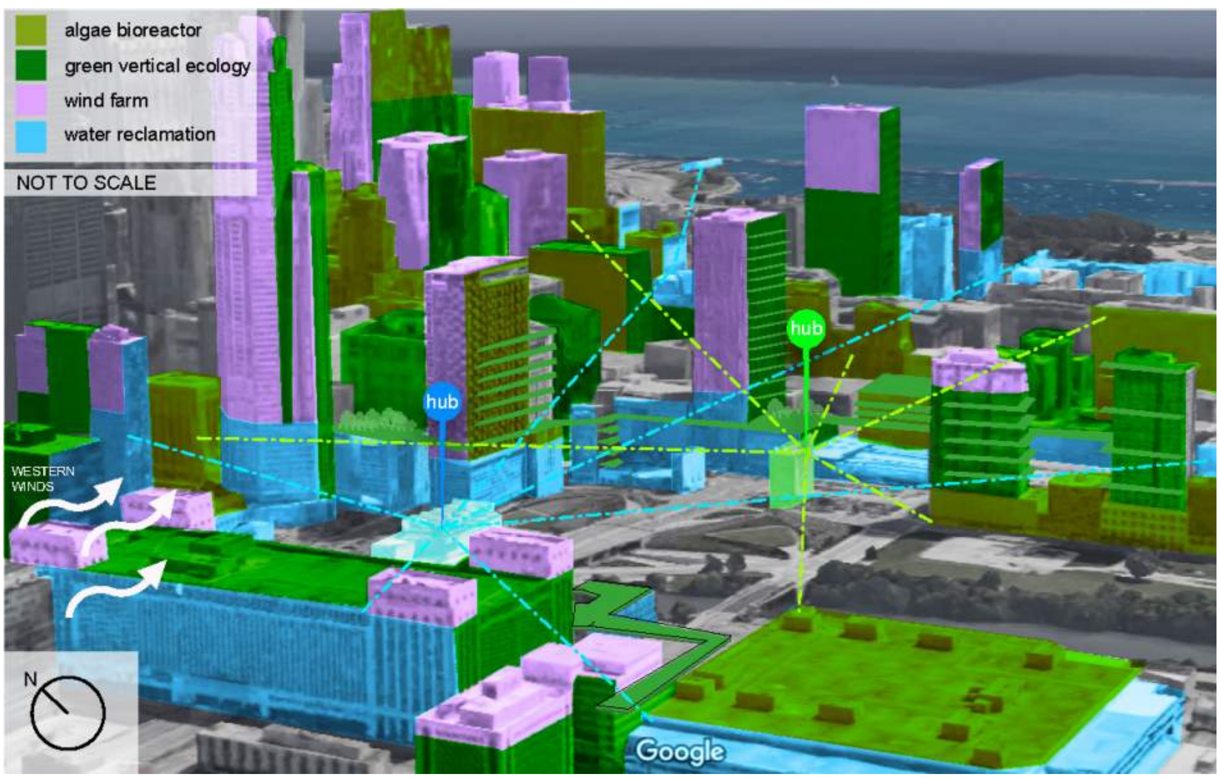

Figure 3: Design Proposal 2. Diagram showing biofuel collection, wind turbine and water collection systems for the city of Chicago. Diagram courtesy of Authors.

Influenced by Lake Michigan and named the "Windy City" for its westerly winds reaching an annual average speed of 10 MPH, and annual rainfall reaching 38 inches, the city of Chicago has abundant resources from which to draw ideas for designing adaptive facades. This design proposal selects the Near West Side and the Loop areas of downtown Chicago, defined by a mix of high-rise and mid-rise buildings bordering the Chicago River on both sides.

Sustaining fresh, clean and reusable water has been a challenge within a built environment. In recent years, Chicago has developed incentive programs promoting green roofs, because they help keep rainwater out of overburdened sewer systems, reduce urban temperatures, improve air quality in densely developed neighborhoods, and reduce building energy costs.[3] Several incentives are available for green roof construction, including the city's Green Permitting Program. Drawing from the success of these programs, the design proposal extends the strategies to facades and balconies, where water can be collected for irrigation, and filtered and recycled for redistribution. One example is to have vertically-oriented vegetation embedded within filtration systems that are serviced by water distribution mechanisms located in basements or built directly into the facades of buildings. Integration of flexible and absorbent modules into a living façade is highly useful to collect rainfall and air precipitation carried in through fog or wind. In this process, gravity becomes a critical component in cleaning and distributing collected water and other necessary resources using gravity fed filtration systems and solar pumps through structural tubes embedded within the façade.

Additional proposals for the Chicago cluster include the harvesting of wind energy and the production of biofuel. New generation of wind micro-turbines are applied to building facades. The energy produced can be used immediately to supply plug loads and lighting on the building surface or internally. Chicago's abundance of rainfall lends itself to the use of algae systems in building facades to produce biofuel. The design of this type of system produces a biofuel that could be sold directly in the parking structures beneath buildings. The benefit for the community goes beyond the fuel production; it includes the possibility to understand through direct observation how the system operates, while providing major economic advantages. The city profits at the same time the air quality improves and the climate around the buildings is mitigated. A higher population accommodated by the verticality of the buildings adds density and surface area to the building skin exposed to the sun. This would allow the community to continue live comfortably yet in a sustainable manner, reducing both carbon dioxide emissions and dependence on non-renewable energy resources.

DESIGN PROPOSALS – MILAN

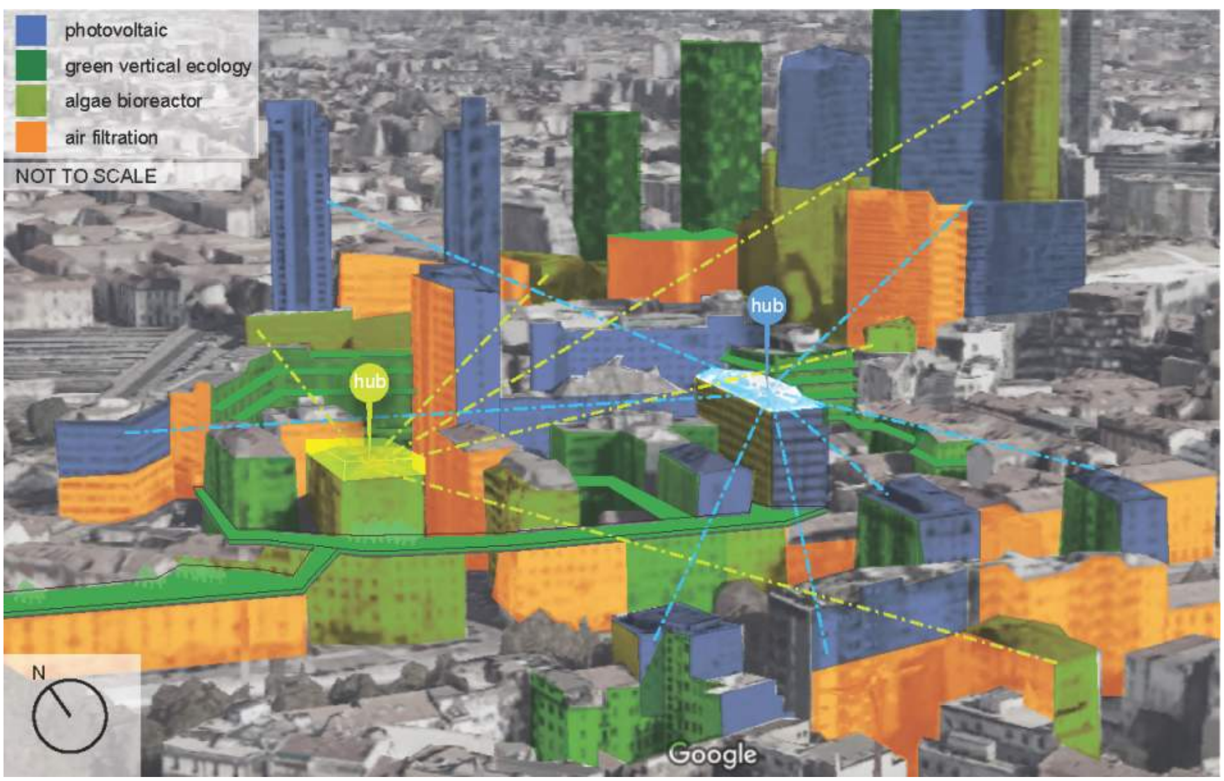

Figure 4: Design Proposal 3. Diagram showing vertical ecology, sunlight filtering, and air purification systems for the city of Milan. Diagram courtesy of Authors.

Porta Nuova is a newly redeveloped area in the city center of Milan, Italy. Several office towers have been built, but residential and commercial buildings have also been retrofitted or are in the process of being redesigned. Much attention has been dedicated to the "Bosco Verticale", or "Vertical Forest", by Stefano Boeri Architetti. The two mid-rise towers have large balconies hosting 480 large and medium trees, 300 small trees, 11,000 perennial and covering plants and 5,000 shrubs.

Within a year of completion an increase in faunal biodiversity has been recorded in the area.

Taking this development as a positive engine of renewal, this third design proposal argues for supporting more adaptive facades in the area to promote increased biodiversity levels. Considering the strengths of “Bosco Verticale”, and the Milanese tradition of multi-family housing buildings, of the large balconies, the proposal could take advantage of such strengths by allowing nature to infiltrate these extended living spaces, and flood the balconies with plants native to the region to maintain high levels of floral biodiversity and simultaneously enable the growth of fauna biodiverisity. The mechanisms to achieve this include vertical ecosystems, sunlight filters and storm water filtration. In addition to green roofs and facades, algae for biofuel production can be introduced within the facades, similar to the system described for Chicago. The abundance of water and air pollution makes this the perfect city in Europe to host a network of biofuel production since the algae are fed from carbon dioxide emissions. Harvesting algae will aid the city in working towards energy independency.

CONCLUSIONS AND FUTURE WORK

The three case studies, by using existing ideas as a point of departure, illustrate how contemporary facades are not built to maximize performance and how adaptive facades have active systems to benefit individual buildings. Urban clusters composed of a network of facades establish a community that functions better, because they optimize building functions and intelligently reorganize and redistribute facade systems to better serve the needs of the inhabitants in a sustainable way. Moreover, the responsive qualities of the proposed clusters are useful in advancing the development and maintenance of the façade system. All of these aspects of the clusters provide the capacity for a city to grow as a resilient entity. As the community grows new clusters can be developed and new intelligence can be acquired to allow the network to progress.

The ideas and cluster case studies proposed here highlight the necessity for urban design to be oriented “transversally”. The orientation should create a motivation to rethink models of building ownership to be more collaborative. New models of ownership and of maintenance and operation constitute opportunities for future work. As this research team is just starting to understand the opportunities clusters offer, more work will be done to understand how all this could be organized, expanding the team to include property lawyers and managers. Clusters offer a very different reading of existing property lines and ownership. Formally, new building typologies would arise as buildings are interconnected through their physical relationships, programming and shared resources. This new interconnected model can move forward the diffused ownership model often based on lot occupation, linking different buildings to their facade systems, which are growing and transforming, as does the city itself. The emerged new model creates an opportunity for more effective operation and maintenance of the facades through shared costs and through the inherent redundancy built into a clustered system. This model would be more intertwined and perhaps more complex, but also more appropriate to allow building components to connect to one another to perform and produce, rather than to offer simplistic and limited aesthetic solutions. The proposed facades will be expressive, in all their building systems implementations; moreover, through the infusion of innovative technological and bio-inspired systems they will be able to promote living, breathing, dynamic facades.

Inspired by nature’s ecosystems, the façades of the 21st century can be networked to develop self-sufficient, integrated neighborhoods and communities. In becoming performative, productive, and interconnected the clusters have the potential to transform the city at several levels: environmentally by assuring a net positive built environment, economically by using and sharing renewable resources, and socially by enhancing connectivity among different buildings and users. By establishing a concentrated network within the city, the facades become more efficient in harnessing, transporting and distributing resources; transforming the role of the façade from a singular entity working independently, to an ecosystem that has the capacity to take on challenges that are more responsive to the direct context and the environmental elements.

ACKNOWLEDGMENTS

Frank Chen: Los Angeles, Chicago and Milan design proposal diagrams

REFERENCES

ArchDaily. “Bosco Verticale / Boeri Studio.” http://www.archdaily.com/777498/bosco-verticale-stefano-boeri-architetti. (Accessed May 12, 2016).
Bar-Cohen, Y., (2011). Biomimetics: Nature-Based Innovation. *CRC Press*, 1st ed..
Benyus, J. M., (2002). Biomimicry: Innovation Inspired by Nature. *William Morrow Paperbacks*.
California Department of Finance. “New State Population Report.” http://www.dof.ca.gov/research/demographic/reports/

estimates/e-1/documents/E-1_2016PressRelease.pdf (Accessed May 12, 2016).
City of Chicago. "Sustainability Section." http://www.cityofchicago.org/city/en/depts/dcd/supp_info/
sustainable_development.html. (Accessed May 12, 2016).
Cleland, E. E.. Biodiversity and Ecosystem Stability. *Nature Education Knowledge,* 2(1) (2011): 2.
Daniels, K., (1999). Advanced Building Systems: A Technical Guide for Architects and Engineers. *Birkhäuser Architecture,* 1st ed.. (2000). Low-Tech Light-Tech High-Tech. *Birkhäuser Basel*, 1st ed.
DeAngelis, D.L.. "Energy Flow, Nutrient Cycling, and Ecosystem Resilience." *Ecology*, Vol. 61, No. 4 (1980): 764-771.
Folk, Carl, C.S. Holling and Charles Perrings. "Biological Diversity, Ecosystems, and the Human Scale." *Ecological Applications*, Vol. 6, No. 4 (1996): 1018-1024.
Kolarevic, B. and A. Malkawi, ed., (2005). Performative Architecture: Beyond Instrumentality. *Routledge*.
Mazzoleni, I., (2010). Involucri Biomimetici. *Disegnare Con*. (2013). Architecture Follows Nature - Biomimetic Principles for Innovative Design*. CRC Press*.
Meadows, D. H., (2008). Thinking in Systems: A Primer. *Chelsea Green Publishing*.
Purvis, A., and A. Hector, (2000). Getting the Measure of Biodiversity. *Nature,* 405(6783): 212–219.
Skilling, Tom. "Dear Tom, What are the prevailing winds in the Chicago Area?" http://articles.chicagotribune.com/
2001-04-23/news/0104230100_1_winds-speeds-chicago-area. (Accessed May 12, 2016).
Thompson, J. N., (1994). The Coevolutionary Process. *University Of Chicago Press,* 1st ed.. (2005). The Geographic Mosaic of Coevolution. *University Of Chicago Press*, 1st ed..
Walker, Brian. "Conserving Biological Diversity through Ecosystem Resilience." *Conservation Biology*, Vol. 9, No. 4 (1995): 747-752.
WeatherDB. "Wind Speed at Chicago, Illinois." https://wind-speed.weatherdb.com/l/84/Chicago-Illinois.
(Accessed May 12, 2016).
Westman, Walter E.. "Measuring the Intertia and Resilience of Ecosystems." *BioScience,* Vol. 28, No. 11 (1978): 705-710.
Wilson, E.O.. *The Diversity of Life*. Belknap, Cambridge, Massachusetts, 1992.
Zaera-Polo, A., (2008). The Politics of the Envelope: a Political Critique of Materialism. Volume.

NEXUSHAUS: BUILDING ENVELOPES

Zero net energy, net positive water, & Carbon neutral

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ABSTRACT

Developed by students from The University of Texas at Austin and The Technical University of Munich, the 2015 Solar Decathlon house, *NexusHaus*, is a modular green building that demonstrates transformative building envelope technologies in zero net energy, positive net water and an attempt at carbon neutrality. The *NexusHaus* building configuration consists of two modular rectangular structures with layers and components attached that interact with the environment to provide a resource-efficient and affordable home. The thin width of each module allows for ease of highway transportation and the shape configuration achieves energy and spatial efficiency through indoor/outdoor living, shading, cross ventilation and daylighting. A roof-mounted 6 kW photovoltaic system provides for the home's power needs, and the roof canopy collects rainwater to provide for the home's water needs. The extensive use of wood in the façade design enables the embodied energy of the home to be more carbon neutral.

KEYWORDS

building envelope, zero net energy, positive net water, carbon neutral, solar decathlon

Figure 1: NexusHaus: 2015 U.S. Solar Decathlon, Irvine, CA.

INTRODUCTION

The 2015 U.S. Solar Decathlon *NexusHaus* design form affects the energy performance of the house. The building orientation of the modules is designed to best take advantage of the southern exposure during the winter and to reduce the over-bearing intensity of the sun in the afternoon hours during the hot summer months (Figure 1). Layered onto and around the modules are a series of rain screens, canopies and arrays that either passively filter the sun's rays before they strike the building's skin, actively harvest solar energy to power the systems and appliances within the home, or harvest rainwater for all the home;s water needs and support an edible permaculture landscape. These layers also extend the threshold of the house into the landscape, providing a screen for the flow of indoor/outdoor living. Three large nine-foot-wide folding glass “Nanawalls” open up to connect the modules to a 1,000 square foot outdoor deck enhancing a spacious sensibility to the modest 784-square-foot conditioned house.

The extensive use of wood in the rain screen, decking and finish materials sequester carbon and offset the carbon produced in the embodied energy of other *NexusHaus* building materials and move the design of the house towards carbon neutrality.

BACKGROUND

ZERO NET ENERGY

Energy-efficient design procedures for the *NexusHaus*, started with energy conservation first. R-30 wall and R-40 roof insulation, weather stripping, LED lighting, Energy-Star rated appliances, a high SEER hydronic mechanical system, energy recovery ventilators and an overall building “design with climate” strategy combine to reduce the building thermal load to less than 1 ton of conditioning per 800 square feet of conditioned living space. Because the house is extremely energy-efficient, it is able to generate enough power from a 6 kW roof-mounted PV system to power the house and to charge an EV BMWi3 electric vehicle to travel 25 miles per day and to also have extra power production that is sent back into the community electric grid.

To alleviate afternoon electricity grid congestion and avoid higher-priced power, the house incorporates a stratified water thermal storage system to shift air conditioning load off-peak to the early morning hours (Figure 2). The system is an integrated thermal energy and rainwater storage system that is combined with a residential air source chiller/heat pump with hydronic distribution, *Upshaw* .

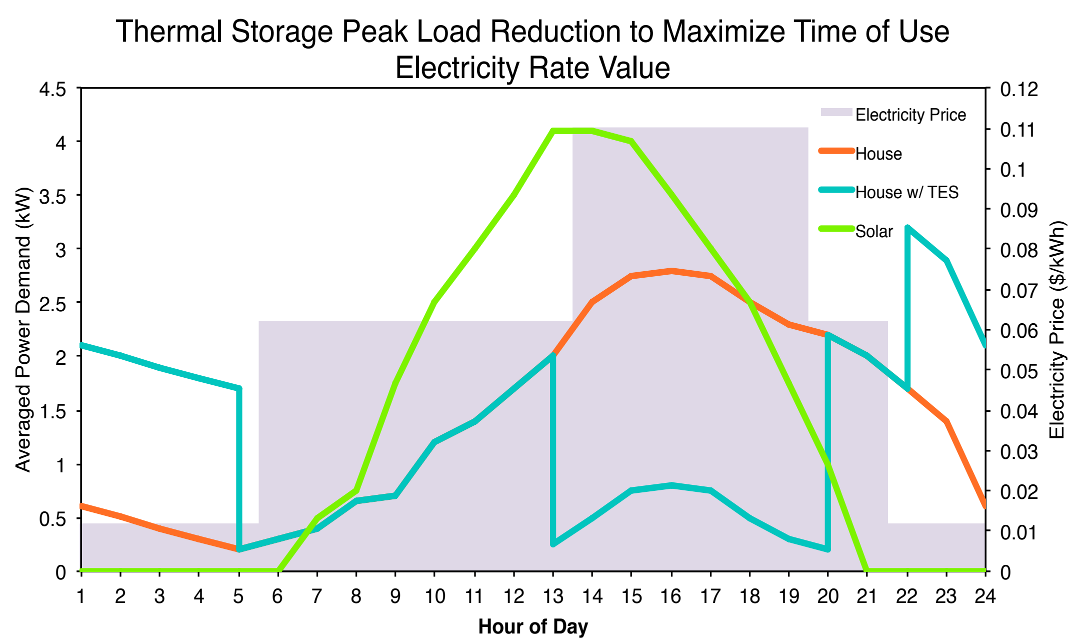

Figure 2: NexusHaus Energy Use with Thermal storage reduces the overall load from the Nexushaus to minimize consumption during high electricity price hours, and maximize the utility of

the home's solar electricity production.

POSITIVE NET WATER

Water conservation is mandatory in both Central Texas and Southern California and as such the *NexusHaus* design harvests more rainwater than necessary to meet its potable water needs. The roof of the house and the breezeway canopy are designed to collect over 17,500 gallons of water per year in Austin, Texas, *Texas Water Development Board* & . This water is stored in a 10,000-gallon polyethylene bladder tank located under the outdoor deck. The rainwater is treated using a 5-micron paper filter and a charcoal filter and is disinfected using an ultraviolet light.

The positive water system includes a potable rainwater collection system, grey water collection and irrigation system, and **an** AC condensate collection. These three segments of the water system are controlled through a series of volume balances that track the water collected, held, and consumed by the household on a daily basis. The house captures enough rainwater to supply all of its potable water needs, relying on a small city water refill line only for backup if long dry spells become even drier. A secondary thermal storage tank acts as additional storage volume for rainwater, giving the system extra capacity while also providing beneficial thermal storage and load shifting.

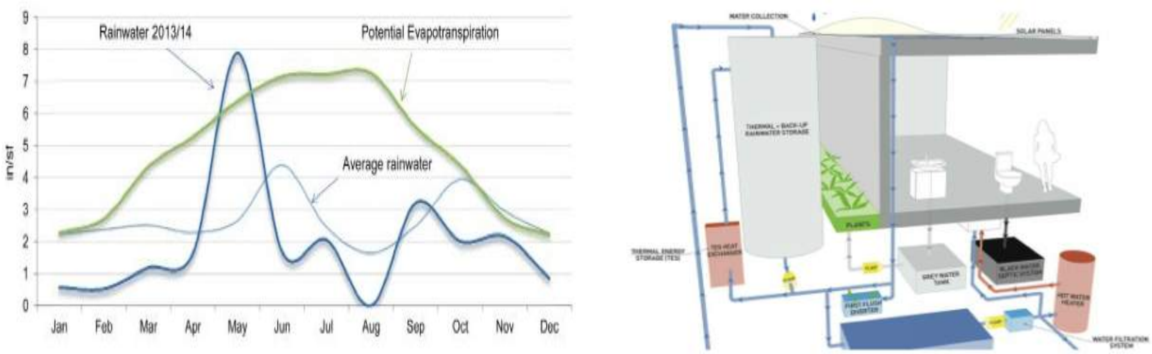

Figure 3: Comparison of the average participation with numbers from 2013/14 and the potential evapotransporiation for Austin.

Another large use of water is in the water irrigation requirements of the food a household consumes. NexusHaus employs an aquaponic garden in which fish and vegetables are grown together in a constructed aquatic ecosystem. The effluent from the fish fertilizes the water which is pumped to vegetable grow beds where bacteria convert the effluent into usable nutrients for the plants. The plants in turn absorb nutrients from the water, thereby purfying the water, which flows back to the fish.

TOWARDS CARBON NEUTRAL

The selection of building materials for the construction of the *NexusHaus* was dependent on a number of variables. The materials' strength, weight, life span, surface quality, cost and many other factors were considered from engineering, design, and economic perspectives. Adding a life cycle analysis (LCA) to this design process early enhanced the ability to make decisions based on environmental effects, with the goal of moving the *NexusHaus* towards carbon neutrality. The LCA allowed for the evaluation of different building material options, considering their overall environmental effects throughout the *NexusHaus'* 40-year lifetime, from resource extraction, construction through operation until disassembly. In each phase, an inventory of input and output of materials, energy, water etc. was calculated. The environmental impacts of these input and output values were estimated using available databases and background information.

This LCA evaluation basis was directed towards a set of environmental impacts, including acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP), as well as indicators of primary energy demand (PED), non-renewable energy demand (NED), and renewable energy demand (RED). The results were limited from eight indicators to only two: global warming potential and the non renewable energy demand. Given the limited time to convey to the public during *NexusHaus* tours the entire set of environmental impacts the focus of the investigation was reduced to only these two key indicators. These two indicators are quite popular with the mass media and commonly understood by consumers even outside of scientific communities.

The LCA comparison perfectly aligned with the objective of creating an intuitive graphic for visitors. The graphic (Figure 4) displays three baselines: miles driven equating to the carbon dioxide being prevented from entering the atmosphere (global warming potential); gallons of gasoline being saved (Non-Renewable Energy); and a percentage of renewable energy used.

Figure 4; Sample graphic (shading structure) NexusHaus LCA.

METHOD

Standard products and systems were used as a baseline to evaluate how much energy was saved or how much less greenhouse gases were emitted compared to standard solutions. For the GWP, the *NexusHaus*' impact and its savings was converted to the impact of miles driven in an average US passenger vehicle. For the non-renewable and renewable, primary energy was converted to the heating value of gasoline and the number of days to power the *NexusHaus* (by PV) was used, respectively.

Result	Amount	Unit	Comparison
Global Warming Potential (GWP)	423	g CO2 eq.	per mile driven (average U.S. passenger vehicle)
Non-renewable Primary Energy (PE nr)	137	MJ	per gallon of gasoline (heating value)
Renewable Primary Energy (PE r)	17.5	kWp	per day to power the NexusHaus

Figure 5: Conversion factors for visualizing the LCA results.

The LCA design process involved informed tradeoffs of many considerations including cost benefit ratios, efficiency, diversity and the 'sprit' of the design. Alternative models analyzed detailed alterations to the design and made it a challenge to calculate a traditional LCA. When confronted with this problem, the need for mass-information computing software to integrate LCA into the design process arose. In this particular design process several design possibilities were first created in 3D modeling software then judged against other iterations based on drawings, renderings and structural feasibility. The concept was to integrate LCA at the conceptual phase by using the 3D modeling software's quantity take off calculators that easily extracted the volume of many different components. Ideally, the tool would use these 3D-generated quantities to run LCA studies of the different iterations and quickly indicate the implications of the latest iteration.

The tool used for used the LCA evaluation is a plug-in software application called Tally , which was developed in 2008 by KT Innovations partnered with Autodesk Sustainability Solutions and PE International in response to a growing industry awareness of life cycle considerations. Its methodology is consistent with the latest LCA standards ISO 14040-14044 .

Tally was able to extract quantities from 3D models in Autodesk Revit and calculate environmental impacts of these values using its database. During the studies of LCA and research into different information sets, an inclusive database in ökobau.dat was identified that provided the detailed information needed and provided the option of hundreds of different material types. To be able to incorporate these massive amounts of data in the same way as Tally, a program definition had to be made that would mimic Tally but allow the team to easily add and vary the material choice palette. To do this, the team switched to Rhino3D and Grasshopper (an information processor for Rhino3D) and created a definition that would analyze 3D solids and evaluate them based on excel information compiled in a separate file, which was information extracted from ökobau.dat. The definition allowed for the selection of any 3D solid material properties. Then the life span, coatings or combination of materials to be tested could be fine tuned. The team's definition returned environmental impact sets and graphs that were used to evaluate the different iterations. At the conceptual phase, the environmental implications of even minor architectural considerations like beam type were revealed. This provided the flexibility the team needed to easily incorporate LCA into the design process.

In order to enable a comparison between materials, a functional unit had to be defined. The functional unit is the indicator of the product's performance under defined circumstances . The scope in this case was in identifying the best material for a residential home from an environmental perspective. Figure 6 shows the three different materials that were analyzed for the *NexusHaus.*

MATERAL	**ATTRIBUTES**	**THICKNESS**
concrete	Concrete, 4000 PSI = 30 N/mm^2; 12% cement, 40% fly ash, 40% gravel, 37% sand, 7% water reinforcement: common unfinished tempered steel	4"/10 cm
masonry	Brick, 2000 kg/m^3: stoneware tiles unglazed Mortar type N: 77% aggregate, 12% cement, 11% water	6"/15 cm
wood	Softwood, 420 kg/m^3: lumber sawn, planed, dried and cut	4"/10 cm

Figure 6: Material details of the function unit 1 m2 of wall

DATA

Typical construction materials for residential homes are masonry, concrete and wood. Their performance is indicated by the amount of material needed to guarantee safety in a wall construction. While running meters and height remain the same for all materials, the thickness has to be adjusted according to the material performance in a solid wall construction. Consequently, the functional unit for the material LCA evaluations was "1 m^2 of wall with the minimal thickness needed to provide safety in load bearing walls" .

To start the analysis, the team first built three simplified Autodesk Revit model versions of the original design to designate the materials and construction systems to compare and analyze with Tally. Then an analysis was conducted of the main material for the construction of the building: wood, brick or concrete. A comparison was run based on an assumption of 40 years building service life, which is reached by all compared materials under normal circumstances without replacements .

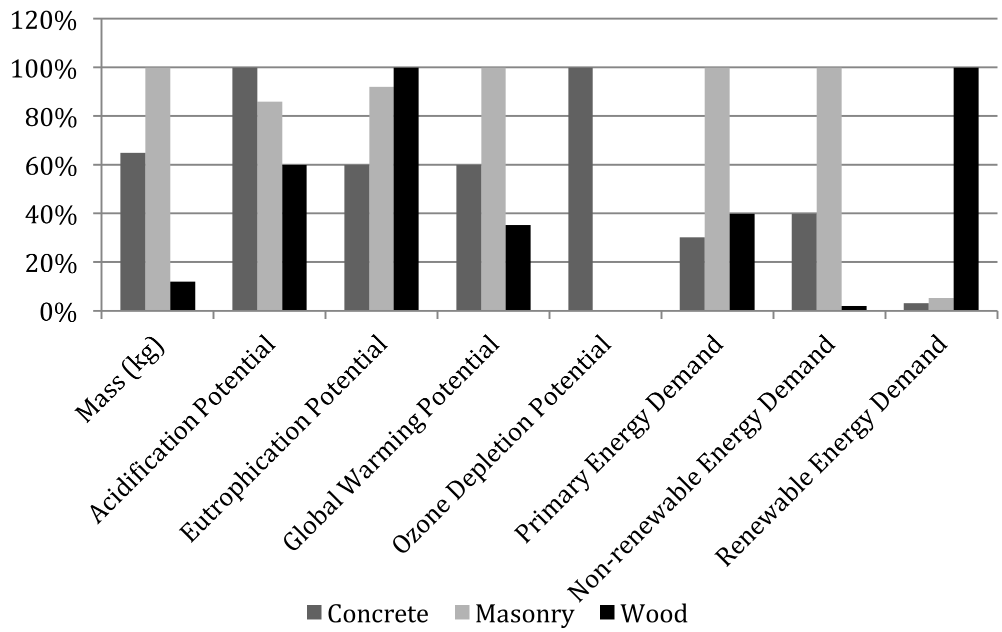

Figure 7: LCA analysis for concrete, masonry and wood building materials

Consequently, the team did not consider any maintenance or replacement efforts. Figure 7 shows the results obtained for the different materials for performance indicators and impact.

Wood weighs much less than brick or concrete and this grants major benefits for transportation in case of prefabrication. It also outperforms both brick and concrete in the impact category of global warming potential and the input category of non-renewable primary energy demand. By scaling up the results for NexusHaus LCA, the team found that the amount CO2 saved compared to masonry is the same amount as is caused by driving 11,900 miles. Also, the non renewable primary energy saved equals 889 gallons of gasoline. The calculated savings result from a total finish wall area of 840 square feet.

Figure 8; Tour Graphic Equivalents for Material Type

After using Tally to help determine the primary building material, the team used Tally for a LCA evaluation to compare three different wood construction assemblies: standard timber frame, advanced timber frame and cross-laminated timber (CLT).

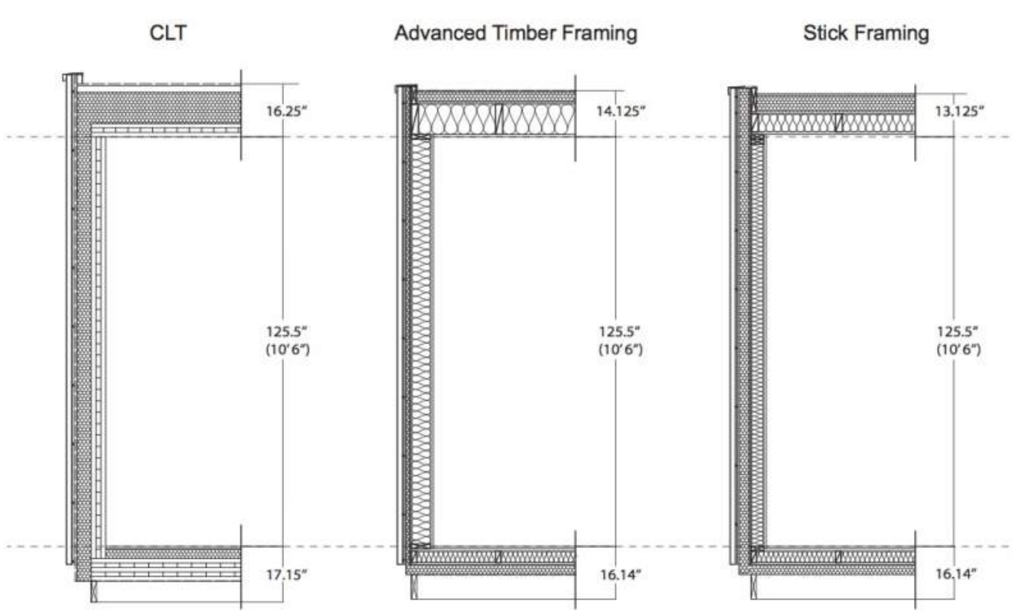

Figure 9: Thickness of CCLT vs. Advanced Timber Framing vs. Stick Framing.

In the LCA evaluation of wood framing comparisons the team assigned to each framing system, the amount of material, life expectancy, manufacturer and thickness to be analyzed. When Tally produced the results, it was possible to filter which system was the best LCA option and the team could pick and choose materials and construction systems with more precision. For example one of the main goals for this building was to use the lowest U-value feasible for the roof, floor and wall systems. Tally reported that cork is a very good insulator with a low carbon footprint. With the help of Tally the team also realized that yhe best option for the construction was advanced timber frame. In the end an optimized version was developed for the *NexusHaus*, that consisted of wood as the primary construction material, advanced timber framing as the structure with cork as rigid insulation and Icynene as fill insulation.

EXPLANATION

During the LCA evaluation, the teanused Tally to evaluate tradeoffs between the extensive amount of wood used as a finish material in the rain screen, decking and wood interior finishes to offset the use of light gauge steel as a support for the shading canopy and for deck railing, (Figure 10).

Figure 10: NexusHaus features extensive use of wood

The wooden structure was made of 6”x 6” columns (12’ tall/tributary area of 49 square feet) with 4”x 8” beams (spanning 14 feet) and the steel structure W6 columns (12’ tall/tributary area of 49 square feet) with 6” deep steel flange beams (spanning 14 feet). The steel structure had 1,400 kg CO of global warming potential as compared to 4.30 kg for the wooden structure. The steel structure increased the global warming potential of the *NexusHaus* the equivalent of 2,335 miles driven, but that was more than offset by extensive amount of wood used in the façade rain screen and deck and structure which saved an equivalent of 11,900 miles driven compared to another finish material like masonry.

Figure 10: LCA evaluation of steel vs. wood deck canopy

Using the amount of CO2 sequestered in the wood used in the construction of NexusHaus, the materials specified balanced the C02 generated in the manufacturing of our other building materials used in the house such that it was moved towards carbon neutrality, Tosi .

CONCLUSION

NexusHaus demonstrates an affordable completely solar-powered and water-efficient and attempts to achieve a more carbon neutral home, and the innovations of the house serve as catalysts for change, leading the residential housing industry towards more sustainable practices while addressing the need for well-designed, appropriately diverse, economically viable, and environmentally responsible housing. While the ability to achieve zero net energy through properly sized PV systems and to achieve net positive water through rainwater harvesting are well documented, the documentation of carbon neutrality represents several challenges. The building materials up stream and down stream database assumptions are based on statistical averages and the amount of the building materials is based on general sizing. A more nuisance carbon neutral analysis should be based on actual up stream and downstream environmental impacts and a more exact calculation of material volumes. Although the magnitude of the results from the case study analysis in this paper are not directly applicable to different sized houses or locations, the relative load reduction, water savings and reduction in the embodied energy of building materials could be reasonably achieved on larger, more traditional, homes given proper system sizing, water efficiency measures and the specification of low embodied energy materials.

Because the upstream and downstream embodied energy assumptions in our LCA databases are too general the team could not certify the the *NexusHaus* achieved true carbon neutrality. What the team was able to accomplish was to combine several available software programs together to develop a general tool to asses embodied energy. Great design involves tradeoffs including a balance between aesthetic concerns and performance concerns. Using embodied energy software tools the team was able to make informed decisions during the design process that enabled the *NexusHaus* to demonstrate a balance between aesthetic sensibility and carbon neutrality.

NexusHaus has been be shipped to the McDonald Observatory in West Texas to house scientists and other University of Texas staff members, where further monitoring and experimental evaluation will be carried on in order to further investigate the building performance.

REFERENCES

Nexushaus, www.Nexushaus.com, The University of Texas at Austin, The U.S. Dept. of Energy Solar Decathlon 2015 Competition, www.solardecathlon.gov, The Department of Energy, 2016.

Upshaw, C.R., Rhodes, J.D., Webber, M.E., Modeling Electric Load and Water Consumption Impacts from an Integrated Thermal Energy and Rainwater Storage System for Residential Buildings in Texas, 10.1016/j.apenergy, 2016.

Texas Water Development Board. The Texas Manual on Rainwater Harvesting. Technical Report, Texas Water Development Board, 2005.

Texas Water Development Board. Rainwater Harvesting Potential and Guidelines for Texas Report to the 80th Legislature. Technical Report, State of Texas Rainwater Harvesting Evaluation Committee, 2006.

United States Environmental Protection Agency. 2014. Green-house Gas Emissions from a Typical Passenger Vehicle. http://www.epa.gov/otaq/climate/ documents/420f14040.pdf, 2014.

Office of Air Quality Planning and Standards, Office of Air and Radiation U.S. Environmental Protection Agency, January 1995: Compilation of Air Pollutant Emission Factors, Appendix A: Miscellaneous Data and Conversion Factors.. http://www.epa.gov/ttn/chief/ ap42/appendix/appa.pdf

TALLY. Computer software. Http://choosetally.com/. Vers. 2014.12.10.01. KT Innovations, PE International, and Autodesk, n.d. Web.

Environmental management – Life cycle assessment – Principles and framework (ISO 14040:2006).

REVIT. Computer software. Http://www.autodesk.com/pro- ducts/revit-family/overview. Vers. 2015. Autodesk, n.d. Web.

ÖKOBAUDAT, Informationsportal Nachhaltiges Bauen: Baustoff- Und Gebäudedaten, http://www.nachhaltigesbauen.de/baustoff-und-gebaeudedaten/ oekobaudat.html, 2014.

RHINO 3D. Computer Software. Https://www.rhino3d.com/. Vers.5Mcneel, 2015.

GRASSHOPPER. Computer software. Http://www.grasshop- per3d.com/. Vers. 0.9.0076. Scott Davidson, 2015.

Lund, E., M. Nowak, and J. Crandell. Building Concrete Masonry Homes: Design and Construction Issues. Malboro: National Association of Home Builders Research Center, 1998. pages 5-6.

Weidema, B., H. Wenzel, and C. Petersen. The Product, Functional Unit and Reference Flows in LCA, Environmental News 70/2004 (2004): page 13.

Cross Laminated Timber: A Primer. FP Innovations. January 1, 2010, https://fpinnovations.ca/media/publications/Documents/clt- primer.pdf.

Tosi A., Hanisch, C., Maia, I., Park, J., Maric, M., Recher, M., & Urena, M., “Building Systems: Life Cycle Analysis of the NexusHaus, Materials, Photovoltaic’s, Construction & Transport, Integrated Life Cycle Analysis of NexusHaus,” Technische Universitat Munchen, Institute for Energy Efficient and Sustainable Planning and Building, Munich Germany, March 2015.

INTELLIGENT TENSEGRITY SYSTEM

An autonomous adaptive facade

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ABSTRACT

The Intelligent Tensegrity Structure (ITS) is an autonomous and adaptive system building on a computation driven design-to-installation workflow, enabling the efficient automated design and deployment of differential-geometry active structure with potential uses as part of an active façade system. The system employs Rapidly Deployable and Assembled Tensegrity (RDAT) workflow integrating parametric and solid-modeling methods with production by streamlining computer numerically controlled (CNC) manufacturing through novel detailing and production techniques to develop an efficient manufacturing and assembly system. The RDAT system focuses on computationally produced full-scale performative building systems and their innovative uses in the building and construction industry.

The Intelligent Tensegrity Structure leverages recent developments in machine learning, specifically reservoir computing neural-networks, allowing for the structure to analyze real-time contextual and environmental conditions and to learn and react to the conditions based on a set of parameters and target goals to improve the performance of the structure through the potential for the system to take on a multitude of geometric configurations. Additionally, incorporating sensors and mechanical actuation into the assembly allows for user controlled as well as responsive system. Eventually, this input also feeds back into the machine learning parameters applied to future configurations, and optimal techniques for interaction with the environment as well as the user preferences.

KEYWORDS

Intelligent, Adaptive – Kinetic – Dynamic, Component Performance, Adaptability, Parametric, Tensegrity, Artificial Intelligence

INTRODUCTION

The Intelligent Tensegrity system along with RDAT system is focused on the invention of computationally produced, performative full-scale building systems, and how they can be utilized ad deployed in an innovative manner in the building and construction industry. The research is meant to contribute a platform for designers, consultants and manufactures to incorporate active systems to building envelopes that can be useful when the need for environmental sensing and response is a performative goal. The manuscript traces the fundamental research into tensegrity design, analysis and production through the RDAT process and projects future possibilities with the ITS to produce automated and autonomous building envelope components.

Currently, the research is at the stage of full-scale production of tensegrity masts and plates with variable geometric configurations, including the necessary design, analysis and production workflow. The goal of the RDAT program is to enable rapid design and deployment of a wide variety of differential-geometry tensegrity structures through computational driven design to installation workflow at the scale of architectural building systems. The project incorporates the integration of parametric and solid-modeling methods to enable computer numerically controlled (CNC) manufacturing of components, and the efficient assembly of this complex system in the field through innovative design detailing and production methods.

The goal of the developing ITS program is to embed intelligence through machine learning data systems into the structures, allowing for active systems based on performative requirements.

BACKGROUND

In 1975, Buckminster Fuller coined the term "tensegrity" as a conjunction of the two words tension and integrity. The term describes a structural system of compressive and tension members that yield mechanical equilibrium, established when a set of discontinuous compression components interact with a set of continuous tensile components to define a stable volume. Recent research in tensegrity has expanded to include those biological systems such as bone and tendon configurations, as the study of forces and indeterminate structures through computational analysis has allowed the science in the field to open considerably.

Although contemporary architects and designers now have access to computational tools that could potentially solve the indeterminate structural forces associated with tensegrity structures, very few tensegrity systems are developed within the architecture profession. This is partially due to some of the inherent features of the structural system. The systems tend to be difficult to precisely form, have flexibility under load beyond normative architectural structures and require materials and detailing that are more advanced that what is the trend in the building industry. Renewed interest in deployable structural systems, cable façade systems, and fabric tensile structures demonstrate the need for an interface that architects can use to efficiently develop tensegrity designs prior to completing the cumbersome calculations traditionally associated with indeterminate form-finding.

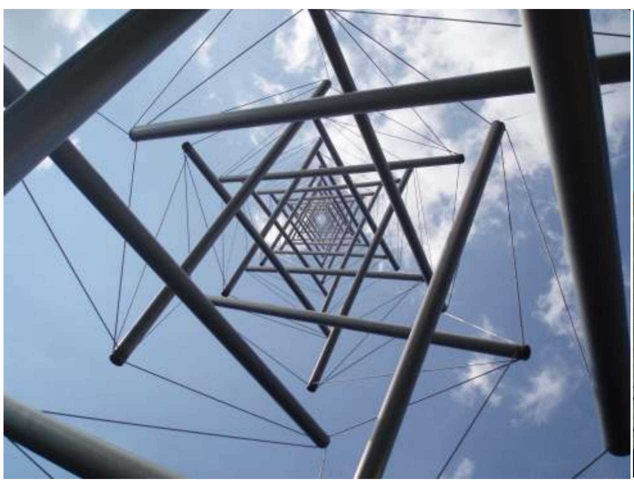


Figure 1: Keneth Snelson's Needle Tower II, a static tensegrity structure.

Figure 2: NASA SUPERball, and active tensegrity robotic lander.

Kenneth Snelson's tensegrity sculptures are the embodiment of the definitions of tensegrity. His methodology is based upon physical model building, numerous measurements, and iterative refinement of tension cable lengths on the final unique piece - a process is typical in the construction of tensegrity structures as well as most networked systems. Contemporary analytical form-finding methods require the designer to predefine parameters such as cable length in order to calculate the ratios of other components directly without involving the iterative process. Contemporary numerical computation tools and powerful computers can be harnessed to bring about a more efficient integration of digital and physical production in the creation of indeterminate structures through the use of physics engines that are part of advanced software packages.

Tensegrity structures offer numerous advantageous properties. As three-dimensional self-stressing cable systems, while they offer a relatively small number of disjoint compression members, they are self-erecting in that tensioning the final cable transforms them from a compact group of members into a large three-dimensional volume. As such, tensegrity systems are extremely lightweight, materially efficient, embody resilient properties, allow for greater tolerance, and are composed of primarily standardized linear elements. Within the RDAT System, tensegrity structures are now calculable, easy to assemble and are reconfigurable, offering potential uses as structural reinforcement; i.e. infrastructural elements, reusable or left-in-place formwork, scaffolding, and other flexible building components such as roofs, curtain-walls and other similar systems.

METHOD

As a design methodology, the RDAT system integrates these properties with digital design tools, a detailed set of components, and digital fabrication technologies into a cohesive system; mitigating the interoperability issues associated with existing cross-platform design, analysis, fabrication and project delivery methods. The goal is to develop an optimized, project-dependent workflow to resolve interoperability conflicts by adapting existing solutions and proposing innovative alternatives. This method, similar to Building Integrated Modeling, leverages real-world parameters such as physics, materials properties, and allowable strengths of components to develop systems that meet the goals of the designers. Since the late 1980s, architects and engineers have used computer-aided design and manufacturing (CAD/CAM) tools to develop building projects while narrowing the gap between representation and fabrication. Researchers have argued that advances in digital design and fabrication have led to a triumph of appearance over substance and that few truly new materials, features and processes have resulted from the proliferation of digital design techniques.

The reliance of architects on craftsmen and fabricators to carry out their designs suggests that architects are disconnected from the skill of making. Research on the use of digital design tools (CAD/CAM, BIM, scripting and computational analysis), project delivery methods, and fabrication technologies, in order to synthesize full-scale case study projects lead to new proposals to develop the use of innovative materials, novel processes and ultimately to reintroduce making to architects as an integral component of digital design and fabrication.

Prototyping done within the framework of existing software is a critical method of rapidly developing a set of processes for testing, while simultaneously developing the criteria for the eventual programming of the custom design and analysis tools. The RDAT System concludes with the fabrication of a tensegrity tower derived from designs parameterized in the computational system through a customized program interface. The digital and associated physical fabricated components address pre-stressing or post-tensioning of the cable elements during the assembly process, as well as assembly tolerances while able to track each category of element for optimizing strength, assembly sequence and inventory. The RDAT detailing was developed to allow for variable parametric assembly processing with the ability to be quickly deployed, demounted and reassembled for numerous tension line configurations. The node is simple and efficient to construct, is as strong as traditional tensegrity connection methods and is quite elegant.

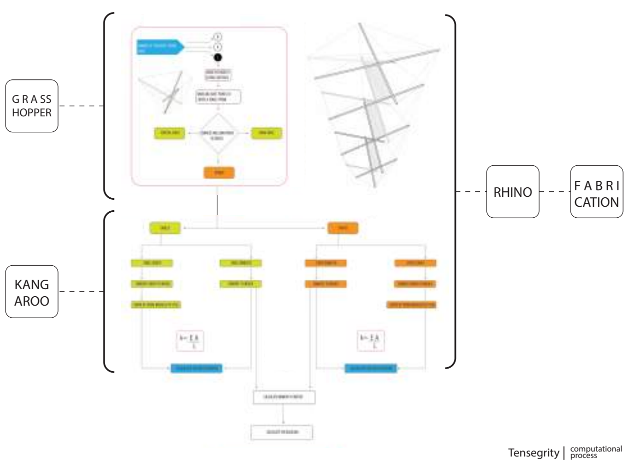


Figure 3: RDAT design-to-production workflow diagram.

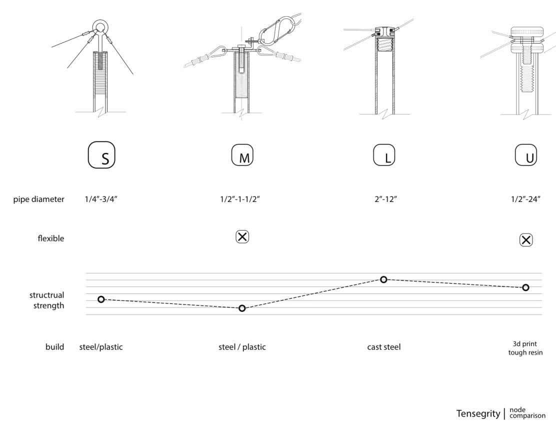


Figure 4: RDAT tensegrity node evolution.

The fundamental process relies on the inherent compressive forces on the strut at the node detail by the combination of three acute angle tension wires and one obtuse angle wire. At each node, the three-dimensional vectors combine to a resultant vector that is always directed into the node, thus preventing the separation of node and strut. This allows for rotation to relieve internal stresses from system flexing, and struts easily engage and disengage during assembly and demounting of the structure. The RDAT node is fundamentally composed of a cylinder of material such as machined aluminum or high-density polyurethane, designed to fit within the strut. In the case studies, fabricated high-density polyurethane foam was used to form the cylinders to fit snugly within the anodized aluminum tubes. The CNC equipment was used to tap a thread into the center of the cylinder for the attachment of the connection disk. The connection disk is a disk of plasma-cut steel that can be bolted to the cylinder as well as connected to the four tension lines at the node. The cutting of the disk is detailed with connection points radially variable to allow for tolerance at the tension connections; the load is transferred to the disk and strut simultaneously to resolve the forces imposed on the system. Once erected and tensioned, the combined forces resolved to axial compression forces on the struts closes up the tolerances and assures the nodes stay engaged within the strut.

Once all elements are produced using extracted computer model data, the process for assembling a completed tensegrity prism is 1) construction of nodes, 2) assembly of an end-prism, and 3) attachment of the remaining prism elements linearly to the end-prism. Once constructed on a horizontal surface, the structure is lightweight enough to be positioned vertically by one or two people, depending on the height of the complete structure. If the structure is to be demounted and transported, the procedure is reversed; place the assembly in a horizontal position and 1) remove the primary tensioning cable at one end-prism, 2) collapse the end-prism, 3) remove one cable from the adjacent prism, collapsing the prism, repeating step three until all prisms are collapsed, and then bind and fold each set of rods on the others until a single package of rods and cables is collected and bound together. While assembly is longer in duration than disassembly, a five-prism structure been assembled in as little as one hour.

Production of a tensegrity structure, fabrication, assembly and installation, has historically been the site of trial-and-error methods as described above. The RDAT system integrates the design, analysis, fabrication and assembly of the system through development of a seamless workflow is the step between the computational form-finding, analysis and the manufacturing of the components for physical construction. The creation of a detail that is designed from its inception to conform to the algorithms and parameters that are incorporated into the software including geometry, material properties, degrees of freedom and other aspects of the system is essential to assure that the produces components in the system have the capacity to perform as designed. Simultaneously a feedback loop is put in place to allow developments during prototyping, case studies and physical testing to integrate results into the programming of the CAD/CAE system ensures that the computational component conforms to the production component. Through a series of case studies where building scale production is realized, the system is measured against production and performance criteria.

DATA – CASE STUDIES

CASE STUDY 1: URBAN FOREST INSTALLATION, MONTPELIER FRANCE, 2012

The Urban Forest installation was assembled at the Seventh Annual Festival des Architectures Vives exhibition, and served as a test for rapid deployment of a full-scale system due to the requirements of erection within one night. The structures are composed of three six-meter tall conical tensegrity towers of anodized aluminum compression members and stainless steel tension members. Installed in the Hotel de Griffy courtyard in Montpellier, the towers suspend a network of metallic mylar “leaf” elements that reflect and colorize sunlight through dichroic action as it streams down the courtyard to the inhabited space below. The modified 5-prism tower structure incorporates an innovative nodal design allowing for rapid deployment with a minimal amount of time and labor, and folds to fit a shipping container measuring 2 meters long and 50 centimeters in diameter.

Urban Forest is a prototype for digitally fabricated tensegrity structures in the form of self-supporting towers and a means to demonstrate and test the structural strength as well as its formal capacities. Urban Forest is an initial prototype driven by ideas in the greater context of potential architectural applications, such as efficiency in materials, structural strength, and other technical benefits. Tensegrity presents a system that is easily transportable, collapsible, and has the potential to create large walls, enclosures, and structures with minimal amount of materials. The case study was used to test the ability to prefabricate the components in place within the structural configuration, collapse the structure for shipping, and redeploy with a minimal of time and labor required. One person erected this project in France over the course of an evening, proving that the design concept was sound while revealing potentials for improvement in the design and detailing that were added to later iterations.

Figure 5: Case Study 1 – Urban Forest

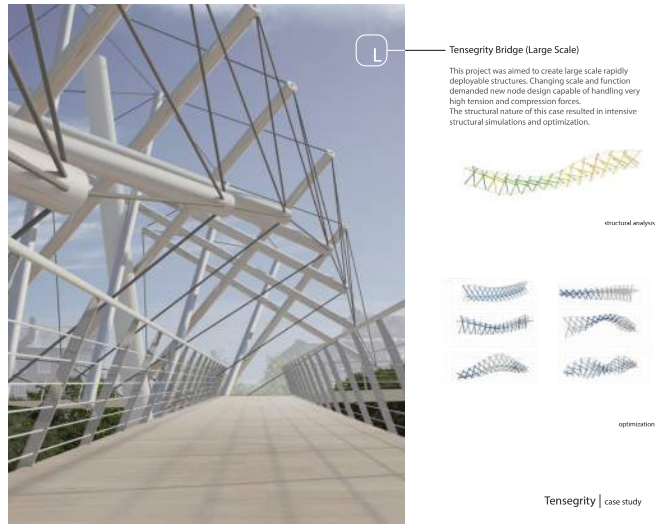


Figure 6: Case Study 2 – Tensegrity Bridge

CASE STUDY 2: SALFORD MEADOWS TENSEGRITY BRIDGE COMPETITION, 2013

The Tensegrity Bridge entry for the Salford Meadows Bridge Competition seeks to provide a needed link between Salford Meadows and the surrounding community, while simultaneously promoting an efficient and functional structure while celebrating the future potentials of Manchester. Reinforcing the rich industrial past of the local community, the innovative tensegrity structure pays tribute to the dynamic nature of the nearby Engineering Faculty of the University of Salford while acting as a catalyst to encouraging further future growth.

The Tensegrity Bridge was developed through an in-house computational program to streamline the design, analysis and production of a tensegrity system through parametric solid-modeling and computational physics simulations to envision the formulation of a sinuous shape that weaves the cable supports around a linear direct pathway. The design strategy develops the potential of Salford Meadows to create a link bringing new visitors to the site while the bridge is expressed as a physical landmark through visible configurations at the landings of the bridge.

The system is engineered to take advantage of the forces developed in a pedestrian bridge of this scale through computational sizing and configuration of the elements and the tensegrity form. The structure is naturally resilient and self-tunes to develop counter-vibration, dampening movement due to passage of pedestrians. Suspension supports for footbridge, connected with an isolating detail, reduce vibrations through dispersing the forces in the naturally resilient tensegrity system. The lightness of the structure reduces the need for extensive foundations at the embankment so that support can be focused primarily on two point loads above the river, providing a less invasive grounding condition and simultaneously expressing the gracefulness of the proposal.

This competing entry allowed for the study of a full-scale application with the collaboration of an engineer with extensive specialty structures expertise, including tensegrity structures. The Author was able to test the form-finding and analysis of his computational format in response to the program and the Engineer's advice. Further refinements in the algorithms used resulted from the application of the system at bridge scale.

CASE STUDY 3: AIA CENTER FOR ARCHITECTURE INSTALLATION, NEW YORK, 2014

The Towards a New Industry installation quietly explores the ambient possibilities of new industry, tensegrity systems, and new media with an exhibition of projects and content related to a 2014 student competition entitled Urban SOS: Towards a New Industry. Featuring video integrated in three tensegrity sculptures, the exhibition curates the four finalist projects and schemes from other program participants.

The system is a triad of self-supporting tensegrity towers where the placement of the structures allows individuals to freely circulate around each respective tower, experiencing the layering of the elastic polyester-polyurethane screen material and video projection from different vantage points. The self-supporting nature of the tensegrity towers introduced a unique design and fabrication challenge. The formal quality of the sculptures along with an intelligent use of materials required the collaboration and expertise of various designers—this integrated design approach is one which defines the success and spirit of the Urban SOS program.

The Towards a New Industry installation allowed for further refinement of the tensegrity system to include greater tolerance in the detailing to anticipate future field modifications. The addition of relatively high weight projectors to the system on-site posed a challenge to the form-finding algorithms that needed to have adjustment capabilities once installed. An adjustable node and strut system is utilized to accommodated transportation of the system to its final destination while dually allowing for adjusting of connections during deployment for projection tuning.

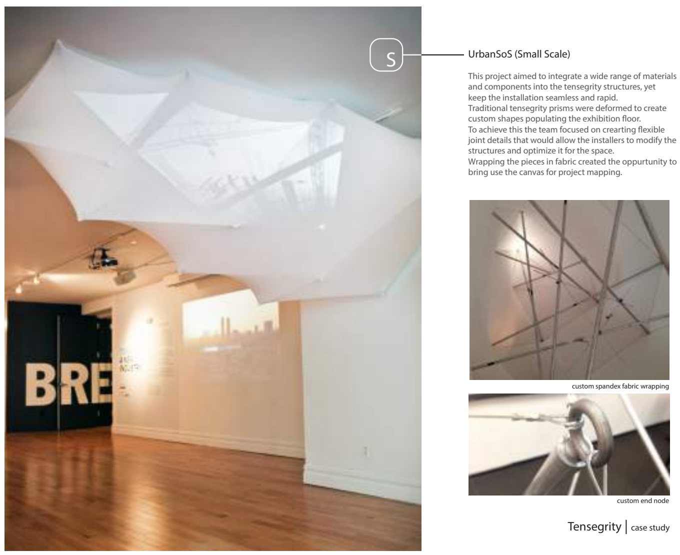


Figure 7: Case Study 3 – AIA CfA Installation.

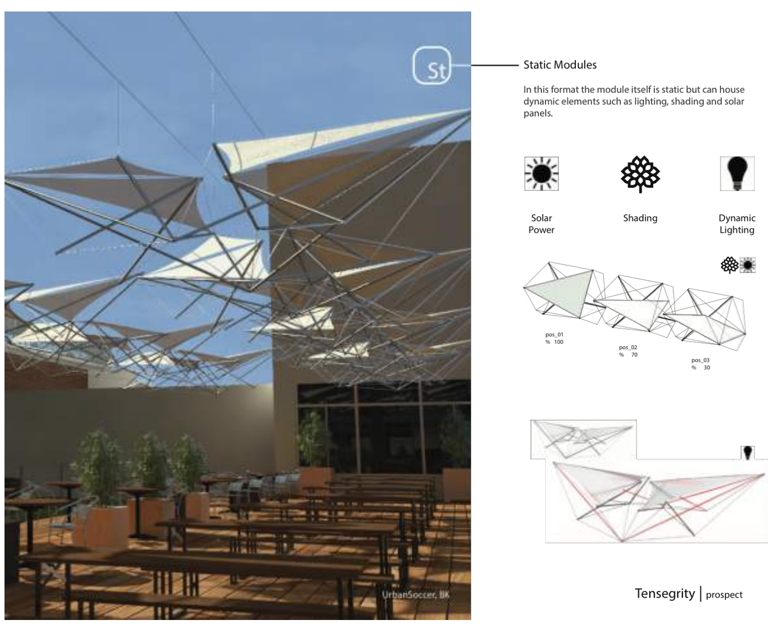


Figure 8: Case Study 4 – Urban Soccer shading system.

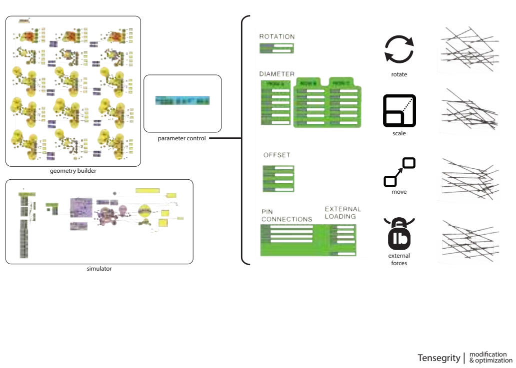
CASE STUDY 4: URBAN SOCCER SOLAR SHADING SYSTEM, BROOKLYN, 2016

The addition of solar collection devices on an external installation of the RDAT system is the goal of project to be built at a athletic training facility in Brooklyn, New York. This project, currently under design, affords the possibility of simultaneously integrating performative environmental goals such as shading the outdoor seating, with photovoltaic collection devices, energy storage technology, and nighttime lighting systems into an integrated building component. The form-finding will expand to two parameters of structural and solar performance, and the integration of electrical systems into the cables and rods will allow the development of new configurations that hold promise for active building envelope systems in development in the ITS project.

CONCLUSION AND FUTURE WORK

Initial research partially addresses digital design and fabrication issues with tensegrity systems, but more importantly, exposes the disconnect between ease of digital design and the realities of constructing complex geometric systems. In particular, the tensegrity tool provides the designer with a dependent workflow that adjusts the tensegrity structural system based upon user-inputs while also generating the necessary fabrication specifications. The successful deployment of a tensegrity structure remains in the execution of the assembly methods used outside of the digital design and digital fabrication process. Furthermore, synthetic biology research affirms the need for physical testing of prototype composite materials in order to validate the computational analysis. With the existence of an optimized digital workflow, efforts are focused on developing an interface for transitioning digital design content into manufactured objects by adapting existing fabrication technologies or designing unique fabrication solutions.

The RDAT project has performed as a research platform for the expansion into the study and integration of machine learning, data collection and intelligent systems and materials into the tensegrity structure, allowing for a more comprehensive building envelope component that in the future can provide for an active façade system. The goal of future work will be to contribute to the design, production and realization of innovative projects through continued research in digital design and fabrication technologies. Current developments include generalizing the prism geometry beyond three struts, expanding the mast structure into a planar surface and incorporating actuated sensing and programmed systems into the structure. This work is being initiated in collaboration with interdisciplinary teams to innovate in the computational algorithms and interface, developing a reconfigurable MEMS joint and strut system that will allow tuning and topology adaption and a system to research modes of automated assembly in on-site constructor conditions. Future interdisciplinary research trajectories include the incorporation of energy generating and storage strategies with a robotics industry partner as part of a building integrated system.



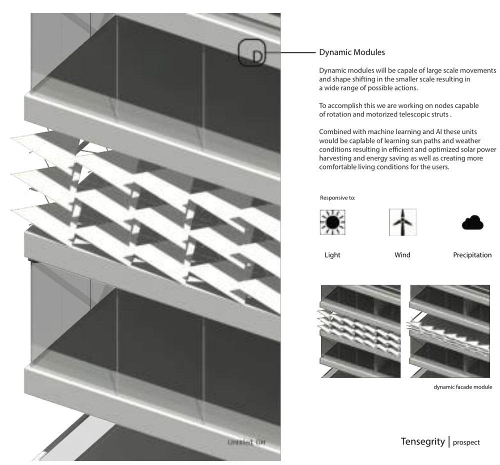


Figure 9: ITS machine learning prototype. *Figure 10: ITS building envelope simulation.*

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REFERENCES

Mijuca, D. (1997) Finite Element Analysis of Tensegrity Structures, [on-line], Department of Mechanics, Faculty of Mathematics, University of Belgrade (Serbia and Montenegro). http://www.matf.bg.ac.yu/~dmijuca/tensegrity.html Accessed August 2004.

Motro, R. (2003) Tensegrity: Structural Systems for the Future, London: Kogan Page Science.

Skelton, R.E. (1997), Deployable tendon-controlled structure, U.S. Patent No. 5,642,590, July 1, 1997

Skelton, R.E., Helton, J.W., Adhikari, R., Pinaud, J.P., Chan, W., An Introduction to the Mechanics of Tensegrity Structures. The Mechanical Systems Design Handbook: Modeling, Measurement, and Control, CRC Press, 2001.

Tibert, G. (2002) Deployable Tensegrity Structures for Space Applications. Unpublished Doctoral thesis. Royal Institute of Technology, Stockholm (Sweden) Also available in http://www2.mech.kth.se/~gunnart/TibertDocThesis.pdf

Tibert, G. and Pellegrino, S. (2001) “Form-Finding of Tensegrity Structures—A Review”, Accepted by International Journal of Space Structures, 2001. Also availabe in http://www2.mech.kth.se/~gunnart/NSCM14.pdf

Maintenance <> Lifecycle

COMPLIANT ACCESS AND MAINTENANCE PLANNING

How to increase the sustainability and minimize operational risks

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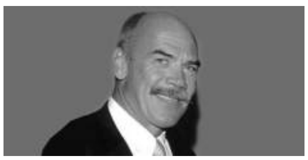

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ABSTRACT

The combination of complex geometries and exotic architecture may increase the requirements of subsequent building operation in an early stage of planning. Architects and façade engineers increasingly have to deal with aspects arising from the operation and facility management even in the concept phase. This new situation can be attributed to the increased focus on sustainability aspects by the clients and in certain countries by the government, for example China's decree of "no more weird architecture" (Rivers & Chung, 2016). As a consequence, it seems, that the design has to be changed to meet the operational requirements or to obtain authorities' approval. This case study shows how the design can be preserved and benefit from the early consideration of operational aspects and the incensement of sustainability.

The paper sets out strategies to analyze the actual maintenance needs resulting from client's requirements, environmental influences, warranty aspects etc. and the associated working processes and access systems. Based on the results, critical areas with regard to feasibility, costs, and operational disruptions can be displayed in a proper way. Within this procedure, the subsequent building operation with the related access technic can be planned, optimized, and integrated in the design concept. In addition, the importance of a work-process related documentation, which is often not a component of building information modeling (BIM) or computer-aided facilities management (CAFM) systems, will be displayed, in order to ensure the sustainability and a smooth subsequent building operation.

ABSTRACT

Das Paper „Compliant Access and Maintenance Planning" legt den Fokus auf den Approach komplexe Geometrien und anspruchsvolle Architektur mit den Anforderungen aus dem Gebäudebetrieb bereits im frühen Planungsstadium zu vereinen. Architekten und Fassadeningenieure müssen zunehmend bereits in der frühen Konzeptphase auf Anforderungen des späteren Betriebes und des Facility Managements reagieren. Diese neue Situation ergibt sich aus dem gesteigerten Nachhaltigkeitsanspruch von Bauherren und Regierungen (bspw. China's decree of „no more weird architecture"). Folglich scheint es so, als ob das Design sich unterordnen und anpassen muss, um den Anforderungen zu entsprechend oder behördliche Genehmigungen zu erhalten. Im Rahmen dieser Fallstudie werden Möglichkeiten aufgezeigt, wie das Design erhalten bleiben und sogar von der frühen Berücksichtigung der betrieblichen Aspekte profitieren kann und somit die Nachhaltigkeit der Fassade steigert.

Es werden Strategien vorgestellt, mit denen der tatsächliche Instandhaltungsbedarf einer Immobilie, resultierend aus den Anforderungen des Kunden, der Umwelteinflüsse, der Gewährleistung etc. und den damit verbundenen Arbeitsprozessen

und Zugangstechniken, ermittelt werden können. Basierend auf den Ergebnissen, können neuralgische und kritische Bereiche bezüglich der Umsetzbarkeit und Kosten von Maßnahmen, sowie der damit verbundenen Betriebsstörungen abgebildet werden. Durch diese Vorgehensweise, kann der spätere Gebäudebetrieb und die dazugehörige Zugangstechnik geplant, optimiert und in das architektonische Konzept integriert werden. Zusätzlich zu diesen Strategien wird die Relevanz von arbeitsprozessorientierten Dokumentationen, welche oft nicht Bestandteil von BIM oder CAFM Systemen sind, für einen nachhaltigen und reibungslosen späteren Gebäudebetrieb aufgezeigt.

KEYWORDS

sustainability – holistic, case study, building information modeling (BIM), facilities management – operations, design optimization, Accessibility and maintenance, integral planning procedure

INTRODUCTION

Foundation Louis Vuitton (Paris, designed by Frank Gehry) and *Kö-Bogen 2* (Düsseldorf, designed by Ingenhoven Architects) demonstrate how architecture, clients, and operators can benefit from the early and sufficient consideration of access and maintenance planning.

Figure 1: Foundation Louis Vuitton, Paris (Photo courtesy of Louis Vuitton)

Foundation Louis Vuitton provides a rough insight of the key-steps which were made to develop suitable access and maintenance solutions to meet high-end demands regarding cleanness and functionality. Placed next to the Jardin d'acclimatation in the Bois de Boulogne in Paris, the light and transparent facades are exposed to flora and urban pollutions. Because of its use as a private museum for contemporary art during the day and as an auditorium at night, time slots for maintenance measures are rare. Furthermore, the unique and complex shape of the building may cause various problems with regard to the accessibility, maintainability, panel replacement measures, operational disruptions and operation costs.

Even if maintenance costs are of low importance to the operator and owner, without a smart access and maintenance concept, restrictions of the utilization and the permanent presence of access technics like platforms might be the consequence. As up to 80% of the maintenance operations to be performed inside and outside a given building are located beyond the "at reach area," it becomes obvious that access systems are necessary to carry out maintenance work at height. In order to avoid unintended and irreversible creation of "maintenance gaps," along with high operating costs in this field, all of the access systems have to be engineered in such a way that they will meet in an optimal way the architectural, operation and maintenance requirements. In a consequence, a rough and general evidence of the accessibility and maintainability without focusing on operational constraints are getting insufficient. The increased interest of clients to prevent operational problems and to keep operating costs at minimum creates new challenges for architects and façade engineers. Façade manufacturers are also affected of this new situation, as they have to ensure the maintainability of their products. For this reason, resorting to qualified consultants and engineers is well-proven practice.

However, this example shows how holistic organizational strategies and innovative design ticks can decrease maintenance requirements and operational costs, as well as how the sufficient implantation of structural provisions can guarantee and ease the accessibility and maintainability.

Figure 2: KÖ-Bogen 2, Düsseldorf (Photo courtesy of Ingenhoven Architects)

The second example in Düsseldorf, the *Kö-Bogen 2*, designed by Ingenhoven Architects, demonstrates how to deal with constraints and special requirements of external green facades. As the project was in the design phase during the development of this paper, the described solutions may be changed or adapted by project competition. The façades shall consist of 17 levels of plant boxes with hornbeam, which shall have a total length of about 2 km. Living green facades are challenging with regard to maintenance aspects and their individuality, as extensive experiences in kind and extent of maintenance of glass or metal facades are given, but the maintenance requirements of green façades vary in each case and has to be generated for the individual situation.

Besides the demands in the field of accessibility, handling, and functionality, the economic aspects play an important role for the success of a sustainable green facade. The operating expenses, which will be shifted to all tenants, should remain in an agreed financial frame. In this respect, the working processes should be defined and determined in detail at the beginning of the planning. Errors and faulty treatments during the initial grow phase and the subsequent operation may cause undesired dead plants, uneconomical operation costs and in worse-case the collapse of the entire facade.

The right approach to the maintenance plan from the beginning of the project will help to shape the design and planning process in a sustainable manner.

An insight of strategies and steps which were employed to realize a sustainable and operation optimized real estate can be organized into four categories:

- Profiling – Determination of the needs
- Compliant integral design
- Documentation - maintenance program for a procedure oriented operation
- Conclusion

PROFILING – DETERMINATION OF THE NEEDS

The determination of the actual maintenance needs of a building in a design process is essential to display and evaluate for the subsequent operation. It provides an overview of all requirements and needs to consider to bring the project to success. As building maintenance with its various requirements and facets is a complex topic, the identification of the tasks to be performed in the future needs to be captured in an organized way and be reduced to key essentials. Therefore, a holistic requirements matrix can be developed that categorize and evaluate the different tasks according to their effect on the operation, architecture, and access technic. Especially for complex buildings, a visual organization structure can be accompanying employed, in order to improve the audibility and location of the listed items.

The categorization and evaluation of the different tasks can be performed by the use of pre-defined attributes that can be tailored according to individual needs. Examples of such attributes are the following:

- Height of the installation / facade
- Regular inspection interval
- Priority in the event of damage
- Qualification of the executing staff for maintenance measures
- Requirements arising from the utilization of the area
- Cleaning intervals
- Etc.

Due to the pre-defined evaluation options like “twice a year,” “special authorized staff,” etc. the entering of data and performance of comparable audits is eased. Additional to the pre-defined requirements, the planning team, client and facility management can set out requirements for particular sections with a higher (e.g. retail or public areas) or lower (e.g. service areas) maintenance approach.

As the profiling is a continuous process during the entire design phase, requirements and constraints caused by the necessary access technic and ongoing planning have to be supplemented up on progress. Due to the smart automatically evaluation system of the matrix, the entered attributes get displayed in signal colors (green, yellow, orange, red) according to their potential influence on the subsequent operation. This procedure allows to detect restricted access possibilities and operational interruptions in an early planning stage.

The benefits of this dynamic and the planning accompanying procedure are a realistic overview of the subsequent operational effort during all planning phases and the backup of all maintenance requirements to be transferred to the facility management.

With regard to the *Foundation Louis Vuitton* (FLV), objections regarding the maintainability have been expressed in an early planning phase by the French authorities for safety and health (Ministère du Travail). As the employment of climbers for recurring maintenance is not allowed in France, it was doubtful that this project could be maintained in a safe and proper way with stationary and mobile access technics. In order to convince the authorities that the FLV is maintainable and meets all relevant regulations, an integral planning approach considering all requirements was needed.

Therefore, the identification of all those relevant requirements and constraints of the subsequent building operation were necessary and performed by the deployment of the above described holistic requirements matrix. This requirements matrix was used as a reliable discussion basis and organization tool in order to find suitable access and maintenance solutions for each constraint.

At least equally important is the identification and evaluation of the requirements of a living green façade. For such façades, it is an essential to know the exact requirements of the plantingin an early design stage in order to develop a holistic façade concept, which considers among the green care aspects a sufficient media supply, access to the hydration system, and pipes, plant exchange concepts, etc. During the development phase of the plants it might be necessary to control the plant growth and health once a week. With high green portion in the façade a sufficient number of access possibilities must be created to be able to keep to that rhythm. Moreover, an accessibility by hand must be ensured in any case, as trimming as well as maintaining the irrigation system etc. work only with direct access. Furthermore, the access technology must be designed in such a way that the gardener’s broad equipment find place as well as waste cuttings and the executors.

All requirements need to be considered in the overall planning, as even the neglect of a single aspect could cause expansive damages to the facades. As the most standard glass facades may tolerate a temporarily suspending of cleaning and maintenance measures without major losses, the damage for green facades could be massive.

A further benefit of the early identification of the requirements is the ability to roughly estimate the subsequent operation / maintenance costs and to simulate different strategies and boundary conditions.

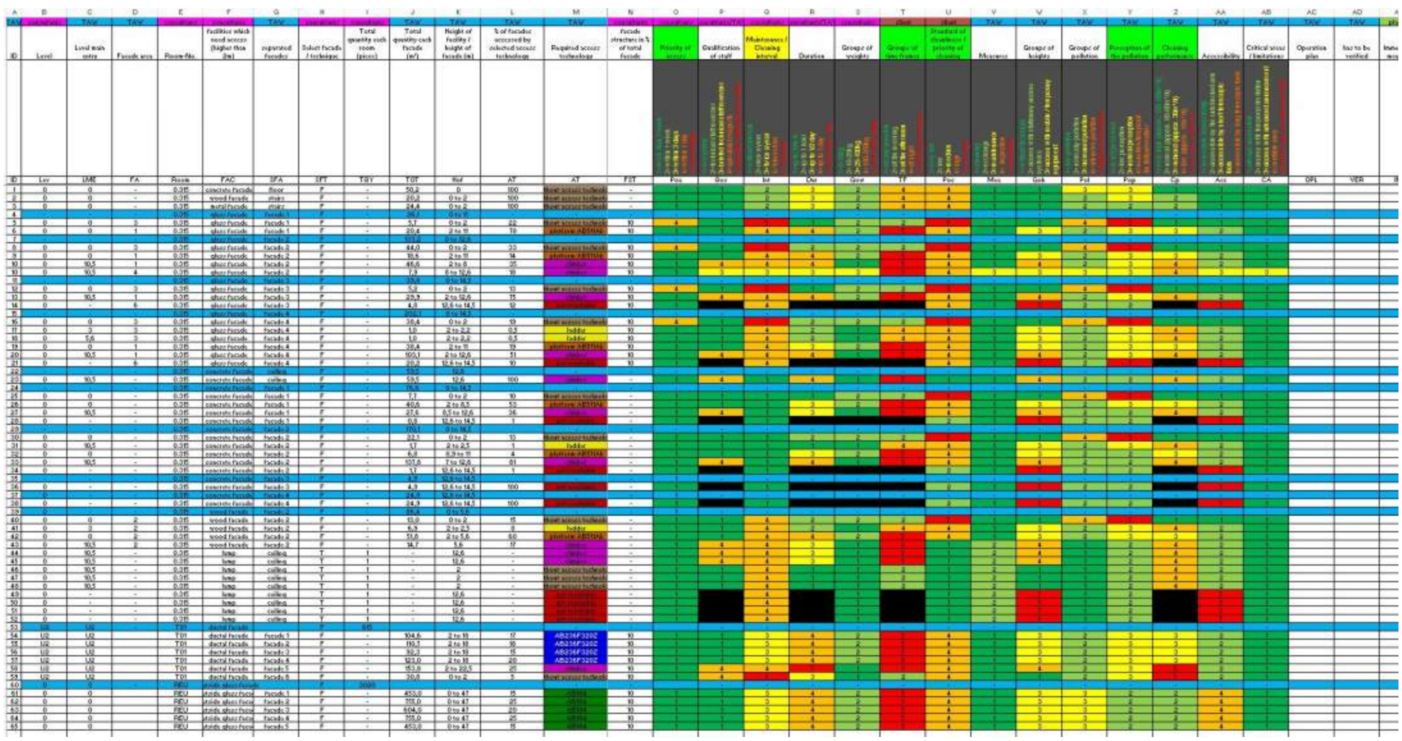


Figure 3: Requirements matrix (image by the author)

COMPLIANT INTEGRAL DESIGN

For projects like the *Foundation Louis Vuitton*, with its unique appearance and the demanding operational requirements, standard access technic is insufficient to perform recurring maintenance tasks in a proper way. Therefore, an integral planning approach was needed to optimize the structural conditions and to develop smart and compliant access solutions. The term “integral access and maintenance planning” covers the following aspects:

- Reduction of maintenance intensity (frequency, simplification etc.)
- Compliance of access technics with the architectural concept and operational belongings

REDUCTION OF MAINTENANCE INTENSITY

Provisions are taken during the planning phases in order to reduce the maintenance frequency. This is an essential step to exploit the maximum optimization potential to ensure a suitable and sustainable subsequent building operation. Therefore, the architectural concept, structural conditions, and the building service equipment (BSE) concept were analyzed according to their operational influence and optimization potential.

For the *Foundation Louis Vuitton*, it was clear from the outset that it wouldn't be possible to keep all facades clean according to the desired quality level without having the access technic around all the time. This situation is caused by the large surface areas, restricted accessibility, high pollution intensity in the air, and the limited time slots for maintenance measures. As a consequence, it is necessary to disguise the pollution to suggest a clean surface to the visitors. This effect is ensured by a light serigraphy on the glass sails, which hides the pollution on the glass and back structure. The right serigraphy intensity was tested on mock-ups on site to evaluate which one suits best to the on-site conditions and architectural concept. Furthermore, the serigraphy provides benefits with regard to sun protection and artistic effects like colored illumination.

Another problem, which often occurs, are traces on the surfaces caused by the water flow along the facades. In order to prevent such traces, the water flow is managed along the inclined alignment of the glass sails. Specialized joints with sharp and protrude edges ensure the controlled water flow. The same problem would have occurred at the white Ductal "icebergs." To prevent such traces on the ductal surfaces, the elements were arranged with a small negative inclination to guide the residual water behind the façade elements.

Not only the optimization of the facades with regard to the cleaning intensity is essential to reduce the maintenance requirements. The BSE has an important role, as it is responsible for an unrestricted operability of the building. To ensure a smooth accessibility to these installations, especially to safety relevant installations, the intended location have to be analyzed and approved during the planning process.

Therefore, a planning accompanying access map (figure 4) was develope, as a guideline for the BSE engineers. A separate layer was created in the BIM that displays the accessibility of all areas simplifies the communication between the access engineers and all other trades. Nevertheless, the location of the installations has to be double-checked to guarantee the accessibility taking into account the related utilization and requirements of the relevant area. In case of a restricted accessibility due to the utilization (retail area, rented to third parties, etc.) or other reasons, alternate strategies like oversizing of capacities or providing redundancies have to be employed. This procedure ensures the functionality till the next regular maintenance interval.

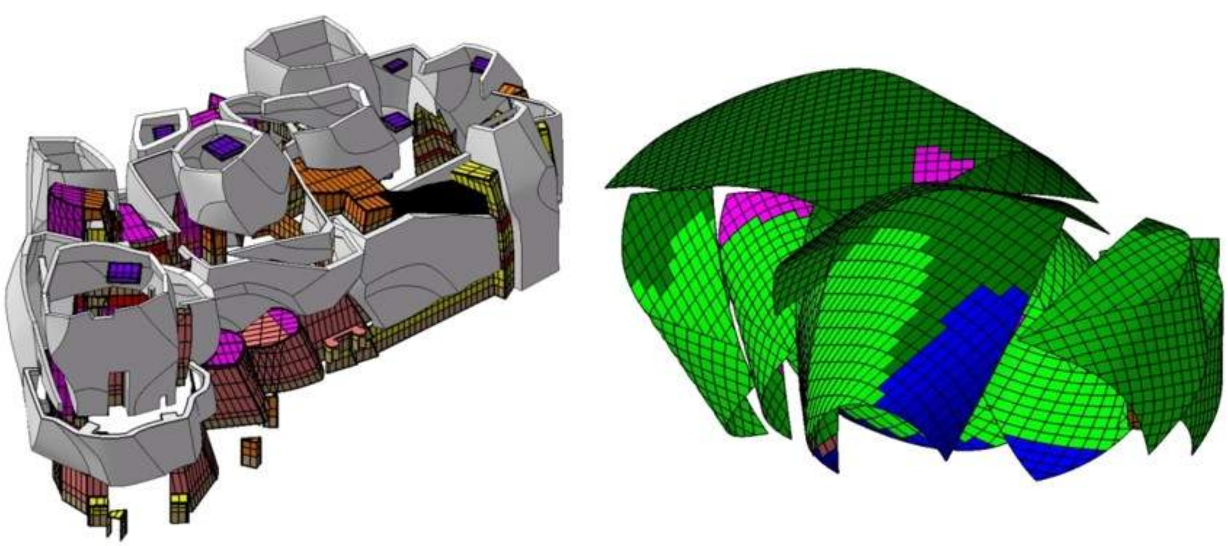


Figure 4: Rough accessibility map (image by the author)

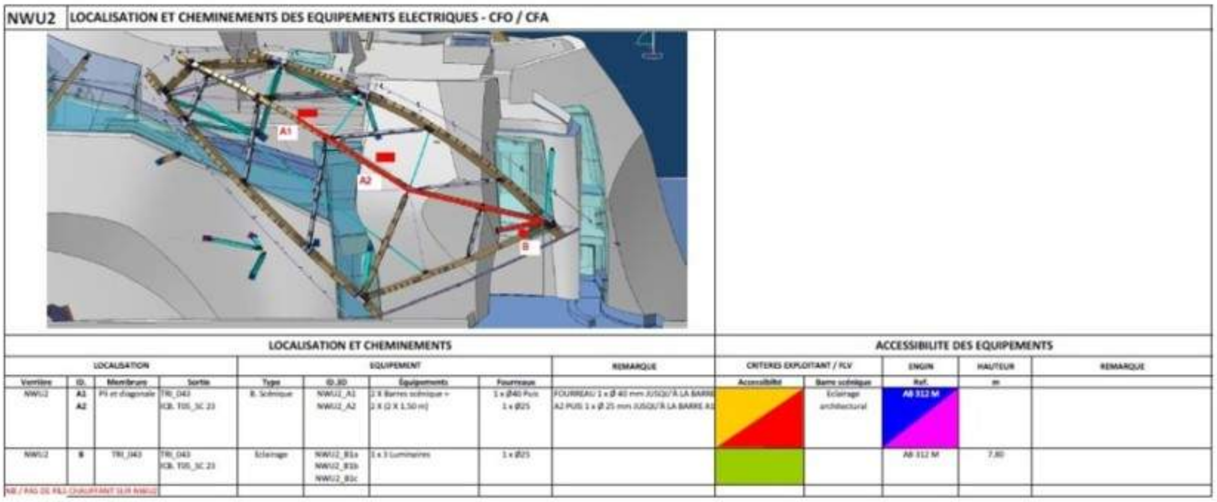


Figure 5: BSE validation document (image by the author)

After the completion of the maintenance profiling for the project *Kö-Bogen 2*, all requirements of the green (hornbeam) were determined and categorized in collaboration with experts for urban green. Based on the results, simulations with different parameter were analyzed in order to define the best boundary conditions for the plants and consequently for the operation.

In order to ensure the permanent removal of leaves and to prevent uncontrolled accumulation of leaves between the green and back structure, that could increase the fire load, the back structure should be designed smoothly with an inclination. This design should ensure that the leaves will fall down and slip down to a special leave collector. The fallen leaves could slip down by them self or could be blown frequently with air pressure to remove them from the façade.

Another aspect which should be taken into account by designing a living green façade is the maintenance of the hydration system and the permanent functionality check of those systems, as the plants could get damaged quickly (within round about 3 days for the hornbeam) by over-watering or dehydration. In order to make sure, that the functionality of these systems could be checked without long lead times or with lots of preparation and effort, they should be placed in the “immediate reach area” and not for example behind or inside the plant boxes.

COMPLIANCE OF ACCESS TECHNICS WITH THE ARCHITECTURAL CONCEPT AND OPERATIONAL BELONGINGS

Based on the results of the profiling and the reduction of the maintenance intensity, the planning process of a compliant accessibility solution can be started. In general, there are two kinds of access technics: permanent access systems like BMUs and monorails and mobile systems like truck mounted aerial platforms, vertical lifts, etc. Both kinds of technics allow for modifications to meet the projects requirements, while tailor-made mobile platforms are rare due to high development costs.

However, the complex geometry of the *Foundation Louis Vuitton* and the restricted load capacity of the glass sails excluded the employment of permanent access systems without crashing the architectural design. Therefore, the use of mobile systems was favored which produced benefits by reason of design, handling and working efficiency. In order to provide greatest possible accessibility of the glass sails with mobile lifting systems, a 100-meter truck mounted aerial platform had to be modified. Within the planning procedure, the first 100-meter lifting platform with small lateral supporting was developed to meet the requirements of landscape planning with its restricted space capacity. The planning of the access to the outer facades with this system was prepared in the 3D model (figures 6 and 7).

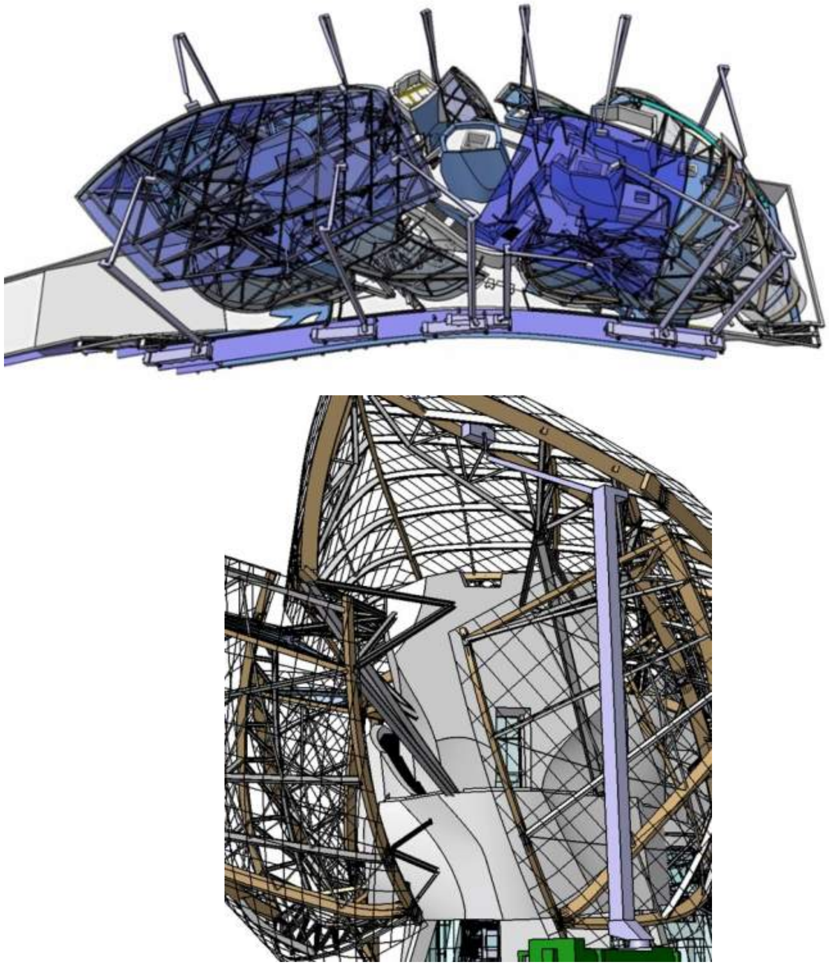


Figure 6 and 7: 3D Access analysis and determination of transport routes and set-down positions (images by the author)

During this procedure, the best transport routes and set-down positions were determined and the structural requirements (loads, widths etc.) were considered in the over-all planning. This is one of the main reasons to consider the access and maintenance planning in the early planning stages. As a special assistance in finding the right set-down position during the operation, the GPS location was determined in the 3D model.

Beside the huge tailor-made truck mounted aerial platform, two smaller lifting platforms (approx. 35m lifting capacity) were customized to access the inner glass sails and icebergs. These platforms park permanently on the terraces in small garages and have special supporters to fix firmly into the ground to ensure stability with a minimum footprint. The exact set-down positions and the structural requirements were also displayed as well in the BIM.

As it was not possible to access all relevant facades for recurring maintenance measures without disproportionate effort and massive effects on the design and utilization, the employment of climbers was unavoidable. In order to convince the authorities that the use of technical access systems will cause higher risks due to mishandlings of complex technic or the illegally climbing without sufficient safety measures, the TSCP rules (Technic Supported Climbing Procedure) were developed. The TSCP rules define exactly the structural requirements like sufficient anchorages (12 kN, max. 70 cm apart from each other.) to provide a best case environment for climbers.

Furthermore, the rules consider a safe exit procedure from lifting platforms to provide easy access to the relevant areas. Due to the exit of the basket of lifting platforms, the climbers don't have to climb against gravity and can smoothly work downwards. During the planning procedure, the exact position of temporary anchorages, rope guiding, and reinforced façade elements was developed and the climbing process was planned and documented in detail (figure 8). If all these guidelines are considered in the over-all planning, the employment of climbers could be the safest solution in certain areas. The French authorities for safety and health (Ministère du Travail) accepted these rules and allowed climbers for max. 30% of the entire façades. This was the first time, that it was officially allowed to leave a platform basket and to employ climbers for recurring maintenance measures.

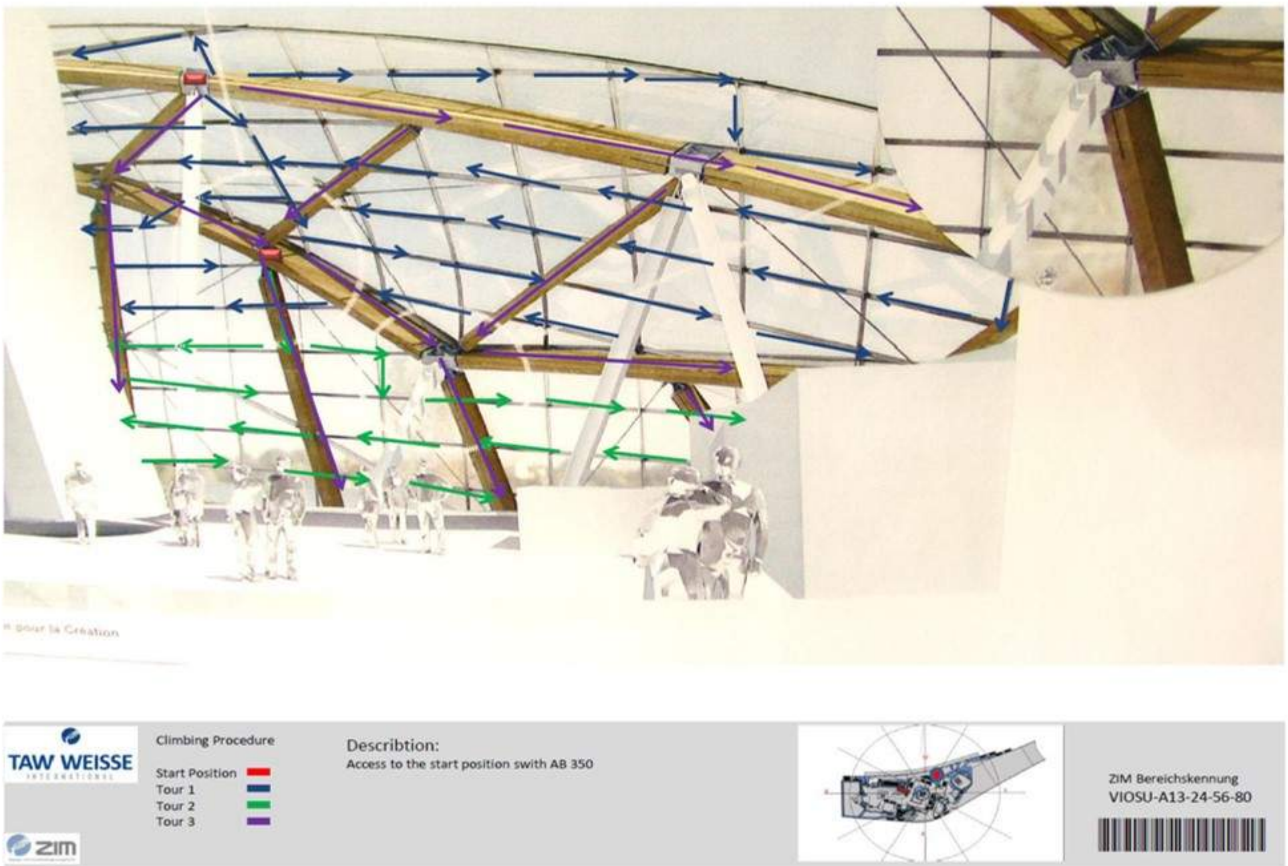
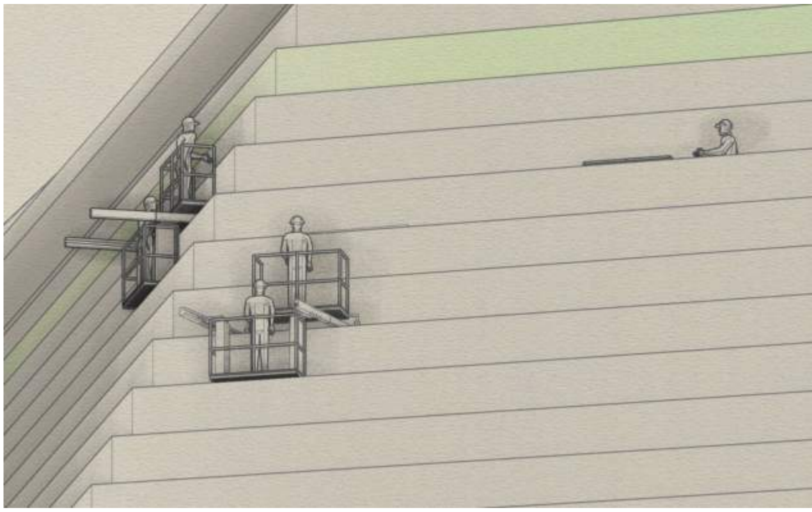


Figure 8: Documentation of climber routes according to the TSCP rules (image by the author)

Parallel to the optimization of the boundary conditions of the *Kö-Bogen 2* and the development of the maintenance concept for the green facades, a compliant access strategy was developed. The special requirements to perform maintenance measures like cutting the hedge, checking the health of the plants and the hydration system, material transport, plant replacement measures, etc. had to be taken into account. Due to these requirements and the demanding inclined geometry with limited space, aerial work platforms and standard permanent access technics were inappropriate to perform the required tasks in the desired quality level or duration or regarding the lack of.

Therefore, a tailored stationary access system was developed, which provides the required access and harmonizes with the architectural concept. The tailored system consists of foldable working baskets which were electrically driven and guided by a rail, placed directly under the plant boxes (figures 9 and 10). Furthermore, the systems provide sufficient media supply to support the working process and has an interface to install an automatic plant cutting machine, in order to achieve straight cuts. The working platforms are only visible during the working process and can be folded when parked. Due to the employment of this suitable access system, which supports the executors, the annual operational costs to maintain the green façade could be reduced by more than 200%, compared to the employment of aerial work platforms, according to life-cycle cost estimations. This example shows that the detailed analysis of the subsequent building operation and working processes could save the clients money and preserves the functionality and appearance of the building.



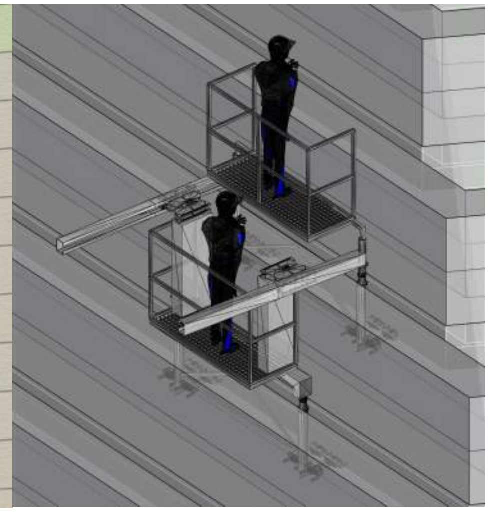


Figure 9: Rendering of the access system in action (image by the author)

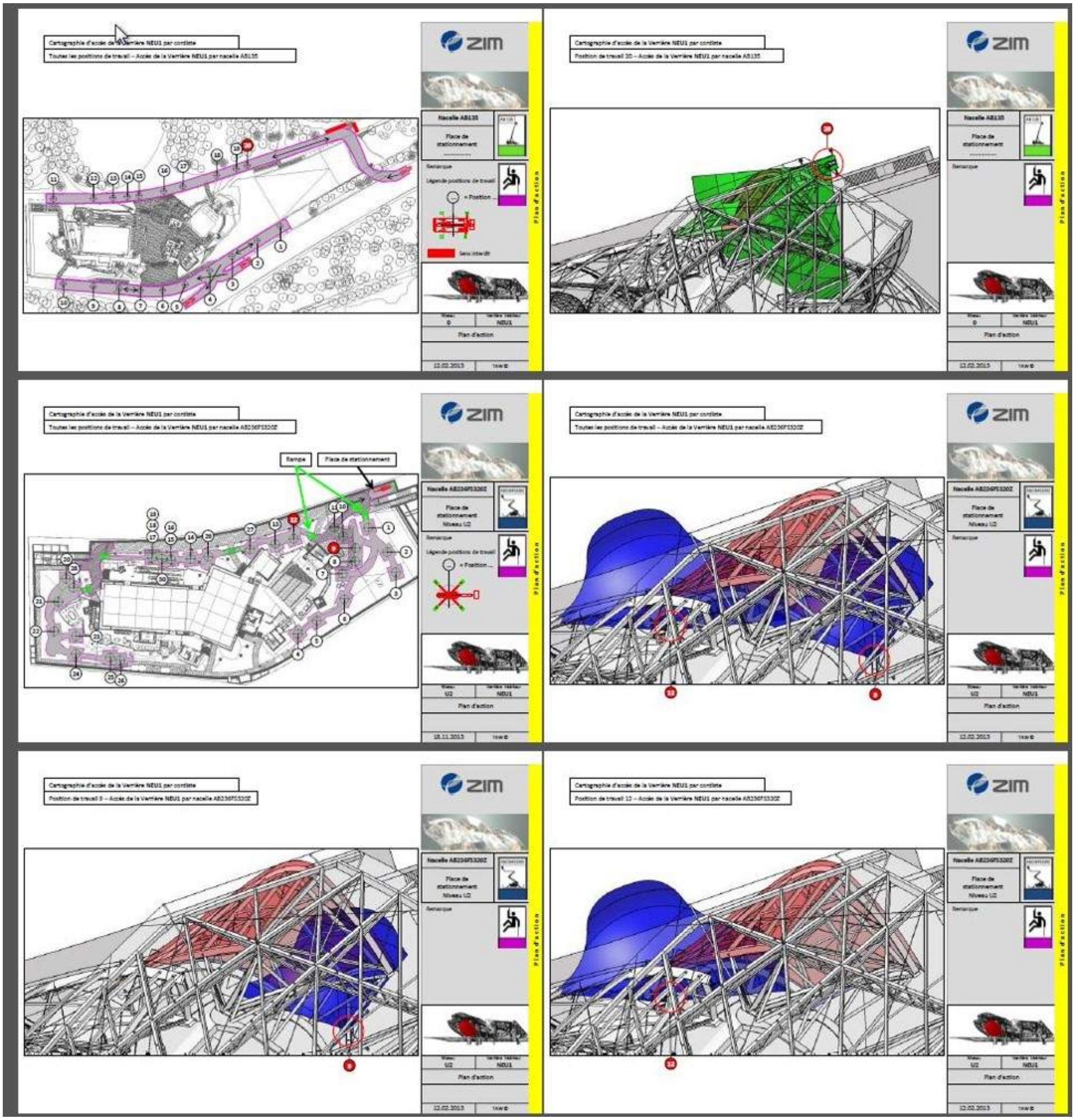
Figure 10: Kinematic of the tailored access system (image by the author)

DOCUMENTATION – MAINTENANCE PROGRAM FOR A PROCEDURE ORIENTED OPERATOIN

Systems like CAFM and BIM software are currently applied at almost all new “sculptural” buildings and are a fixed component of the building operation. The entered data refer to the used materials, quantity of installations, suppliers, manuals, etc. and allow to organize the building operation according to the administrative requirements. Essential process related information like “how,” “when,” “time schedule,” are not part of the documentation and have to be developed by the facility management individually for every maintenance task.

In order to transfer the operation related knowledge and information that were gained during the planning process to the subsequent building operator, a procedure oriented documentation was prepared. This documentation included individual working and operation instructions as well as short manuals and guidelines to support the executors at their daily work in height-access related areas. The benefits of such a documentation are the standardization of complex operations, the preservation of knowledge, the risk reduction of mishandling and related damages (operator liability) and the increased efficiency. The operation instruction for example includes the following information (figure 11):

- Type of access system / rental company
- Transport route and set-down positons with GPS assistance
- Preparatory measures for the operation
- Accessible areas
- Flow chart
- Estimated duration of the operation



Picture 11: Examples of an operation plan (image by the author)

This kind of documentation forms the basic way to transfer the planning know-how to the building operator. At the *Foundation Louis Vuitton*, an innovative access and maintenance management tool (AMM) was additionally applied to organize the documentation according to the individual areas and tasks as well as to manage the maintenance measures. All relevant requirements, which were determined within the profiling like “cleaning interval,” “regular inspection interval,” “priority in the event of damage,” “qualification of the executing staff for maintenance measures,” etc. were entered and assigned to the corresponding areas. These “active information” are adaptable according to the needs of the building operation. Through the combination of the operational requirements and the procedure oriented documentation, an innovative system was founded which complements BIM and CAFM with important and individual information (figure 12).

Figure 12: Screenshot of the access and maintenance management system (image by the author)

SUMMARY

The *Foundation Louis Vuitton* (Paris, designed by Frank Gehry) and *Kö-Bogen 2* demonstrate the employment of holistic concepts and that the early involvement of all stakeholders and requirements can be beneficial for the design, costs, and safety. The detailed analysis of requirements and the related working processes are essential to find suitable solutions. As shown, not only the employment of access technics is required to ensure the maintainability, sometimes structural amendments, for example special designed joints to guide the residual water along the façade or the oversizing of technical installations, could be helpful to reduce the maintenance needs.

At the current stage it is hard to define the actual cost savings and efficient incensements, as every building is unique and there are no studies regarding the benefits of the early, holistic, and compliant access and maintenance planning compared to a normal planning process. According to performance estimations, the average working time saving is about 40% plus the reduced intensity. However, due to this planning procedure the gap between planning, construction, and operation, could be closed in this field, and the quality and sustainability of the building could be increased.

REFERENCES

Rivers, M., & Chung, S. (2016). *Future Chinese skylines could look more uniform.* Atlanta: CNN Sans. Retrieved from http://edition.cnn.com/2016/02/22/architecture/china-weird-buildings/

FAÇADE HEALTH(CARE)

Extended envelope life spans through permanence, adaptability and de-generation

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ABSTRACT

The current industry approach to envelope performance is reaching a breaking point. Performance of façade systems, especially those composed of glass and metal has plateaued. Advances in one material are offset by drawbacks in others when combined as an assembly or system. Future façade designs need to move past the antiquated means, methods and approaches of their construction to evolve. Only a complete shift in thinking will launch envelope and building performance into the future. A holistic approach incorporating design, engineering, fabrication and operation is needed, prioritizing people, resilience and long-term functionality as well as the environment.

KEYWORDS

Case Study, Holistic Sustainability, Health, Material, Codes and Influence.

INTRODUCTION

TYPOLOGY

Envelopes for healthcare buildings may (unknowingly) hold some of the answers on how to proceed. Perceived as inherently resilient, healthcare projects present unique design problems that require flexible and long-lasting solutions. Due to their complexity and program requirements, such projects might best be understood as 'machines' as opposed to buildings. Yet most healthcare envelopes are built with expiration dates and little to no flexibility in their façade assemblies. Current healthcare design methodologies look to change this trend to achieve resilient healing environments with extended lifespans adaptable to a wide range of typologies going forward. Buildings must thoughtfully balance the human condition, the natural environment and the technological machine.

NATURE

One strategy to humanize both the building and the occupants experience in and around the site is the (re) introduction of nature throughout the design. Healthcare designs have employed the healing power of nature since the 18th century. Numerous reports substantiate the benefits of daylight, views, and direct access to nature for patients, staff, and visitors. Elements of nature act as counterpoints to technology as a way to combine both the organic and the artificial.

PROCESS

Owners correctly require facades to perform and act more as an integrated system rather than a solid barrier between outside and in. These new expectations require further scrutiny as to how a façade is actually performing. In addition, new project drivers, including multiple aspects of sustainability and efficiency, hyper-accelerated schedules, detailed life cycle cost analysis, and total cost of ownership, are influencing innovation in design and the general outcome of projects. For these reasons, a successful process is more critical to a high performance façade's success than the design or materials used.

DRIVERS

Facades are the physical manifestation of programmatic and functional requirements based on internal and external drivers. Facades typically function well beyond their lifespan and the functions for which they were originally designed. As capabilities are slowly surpassed by evolving user needs, technological advancements, and climate change, facades remain stagnant.

Static

Providing a *static* envelope solution to predominantly *dynamic* functional requirements and drivers is no longer sustainable. Basic façade functions (water/air/thermal/acoustics/security/pollution) are reacting to dynamic factors and up to now, envelopes have served as a singular barrier. The ability to measure and validate performance today and make future projections to determine long-term impacts highlight the need for more adaptable solutions for evolving requirements. Exterior and interior climates change constantly, historical weather data is less reliable and more extreme weather patterns more common. Building ownership and functions change rapidly driven by technology and user preferences. Yet the design, engineering, materials and fabrication of building envelopes has evolved very little in the last 60 years.

Flexibility in façade systems essentially does not exist. Even though one recognizes that material advancements, component upgrades and aesthetic refreshing are commonly desired or required, few solutions are available when it comes to updating façade assemblies. Tearing down and building new, re-cladding or over-cladding are extreme and less desirable options. Continued and expensive maintenance becomes the operational mandate since extensive renovation projects are too costly.

Due to their intended long lifespan, failing facades and buildings are easily identified because their cutting edge nature at the time of construction highlights the aging more clearly. Substantial completion of a project is not the end but rather the beginning of a long steady decline in materials, systems, and entire assemblies resulting in less performance and less functionality over time (*resilience*).

Figure 34

DYNAMIC

Facades today may address some aspects of functionality when they are designed but high-performance, success and resilience should be measured by evaluating functionality over time, thus including the dynamic aspects of evolution and change.

Envelopes and buildings all have an expiration date, one that is often much shorter than the industry wants to admit. Yet we continue to design and build new facades knowing that they are in part obsolete even as they are being built. The longest warranty on a façade material might be 20 years, but most, including the actual façade assembly as a whole, are much shorter than that.

When discussing projects we often refer to them in 50 or 100 year increments, as in 'a 100 year building'. But how does such a claim match up with individual components covered for a lifespan of 5-10 years, 20 years maximum?

Not knowing when a material is underperforming, or outright failing, is a problem. As operational budgets and energy usage are scrutinized, more closely monitored and efficient mechanical equipment will quickly highlight underperforming façade systems. In addition, theoretical performance metrics modelled, measured and analyzed during design will need to be validated well past completion over multiple years of occupancy.

Developments in material technology, procurement and fabrication are going to require a complete re-think as to how facades are designed, engineered, and assembled. New, singular material characteristics should drive complete system performance, while advances in the use of technology and BIM will streamline the design-engineer-document-fabricate-install-operate procedural cycle.

A functional and modern façade assembly should address more than minimum performance capabilities. It should include emerging future functions driven by programmatic flexibility, evolution in technology and building use, systems integration and the need for environmentally, economic, functionally and socio-culturally sustainable solutions.

Figure 35

CAPABILITIES

The design and construction of healthcare facades reveals six fundamental capabilities which outline developmental concepts towards achieving the 'façade of the future'. Façades must be more than a singular barrier assembly. They should be multi layered component systems to better respond to future drivers. In this way performance and positive effects of the façade will be guaranteed over a greater number of years.

PERMANENT – COMMUNITY/PURPOSE

As socio-cultural objects, buildings represent continuity and tradition as well as providing a sense of time and place. They are often judged by their facades being heavy and imposing forms made from long-lasting, solid materials to create permanent landmarks within the urban fabric.

A façade's permanence often abstracts its essential purpose.
Facades must balance elements of the past (respect, tradition and conformity) with the future (stimulation, creativity and individuality).
Imposing landmarks should not hinder a building's creation of space to serve and enhance the community.
Permanent facades should support and not stand in the way of human values. They should facilitate, not complicate, relationships between people as well as foster strong bonds between their occupants and the environment both inside and out. Permanence can be achieved with a continued connection to nature as a constant, grounding and unifying mechanism benefiting productivity and well-being for occupants and the community.

Figure 36

ADAPTABLE – SYSTEM/CONSTRUCTION

As material science has progressed, facade assemblies are now increasingly marked by their thinness maximizing glazing and minimizing opacity in an effort to visually blur the separation between interior and exterior. Glazing has been reduced to a nominal 1 inch width, held in place by 8 inch or deep structural members comprised of aluminum profiles extruded as thin as possible.

The result of this evolution is that facade assembly components are approaching limits in fabrication technology and that they remain a barrier with few performative capabilities.

Advancements to glazing, coatings, sealants, and other components will continue. In addition, the return on investment with regard to long-term benefits to these materials is marginal. High performance glazing with an R value of 15 continues to be installed into an aluminum framing assembly with an R-value of 2. Any performance gains from the latest glazing product are largely negated by the poor performing framing members yet many of these facades are still listed as high performance assemblies.

The level of integration of the façade system with other building systems is starting to improve but these systems are still being engineered in order not to hinder each other. All building systems should be supporting and improving each other and could potentially even be combined to act as one.

Facade performance through thinness and a singular barrier is increasingly difficult. A deeper, multilayered approach could allow individual layers to maximize specific capabilities and result in a long-term system capable of evolving and optimizing performance over time.

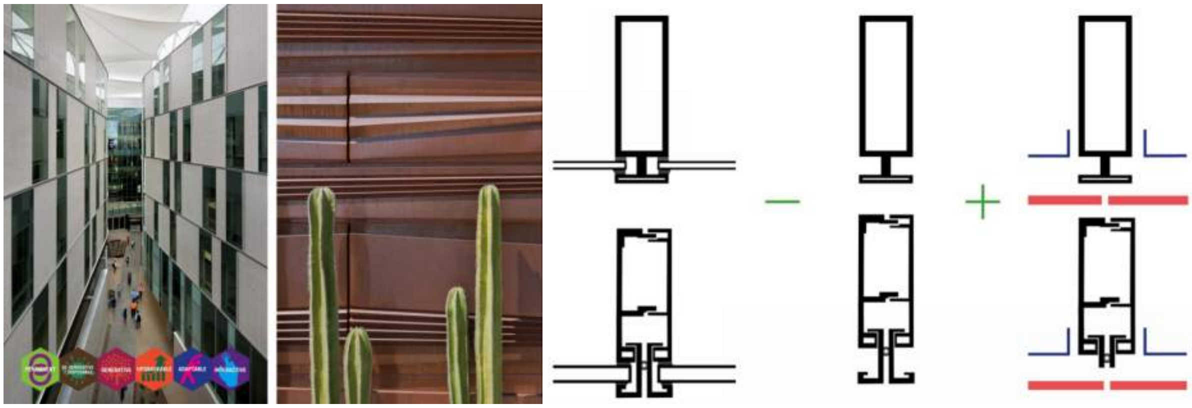

Figure 37

UPGRADEABLE – FUNCTION /ECONOMY

A building's external drivers will change over its lifespan. The majority of modern buildings, all built with the technology and design influences of their day, are meant to last well into the future. However, facades mostly decrease in performance and functionality as they age, eventually resulting in catastrophic failures.

Over a lifespan, improved functionality for facades will depend on upgrading capabilities.

Building codes will change and progress beyond mandating the lowest common denominator by dictating higher performance goals for buildings beyond the design phase well into occupancy. Accordingly, future drivers must be taken into account at the earliest moments of a building's design. The majority of facades and the larger building envelope usually are unmonitored during or after construction. Commissioning of facades post-construction is only beginning to take place with mixed results. There is no set standard, and approaches are left up to individual owners, who are often not well-informed and wary of the large economic cost for façade commissioning and ongoing monitoring. Initial capital costs are still rarely discussed in parallel with operations and maintenance cost.

Facades for the foreseeable future is a task for humans; robotic, assembly line, full scale construction is still a ways off. The majority of projects are built on a developer model, where a builder aiming to cut construction costs minimizes redundancies or cuts corners, leaving an owner/tenant to deal with problems. That reality brings the potential for a litany of mistakes throughout the fabrication, procurement, transport, and installation of facades.

Facades with end dates might stimulate a new business approach. Rather than purchasing, building owners could rent the façade under a lease approach retained by the original manufacturer/installer. Select upgrades for maintenance, improved performance as required by code, and new aesthetic expressions could be part of a lease agreement. A decline in construction defects and litigation might take place if fabricators/installers added '*Façade owner and operator*' to their title.

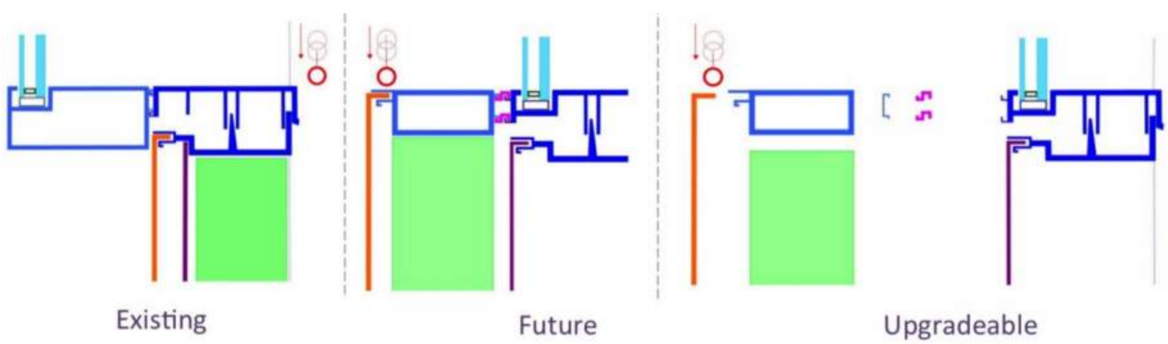

Figure 38

INTERACTIVE – COMMUNICATION/TECHNOLOGY

Facades now lag behind other industry information capabilities, but not for much longer. '*There's an APP for that*' will be commonplace when discussing façade systems.

Most people are aware that at some point in their automobile driving experience, the "check engine' light will illuminate providing a warning that a checkup is in order. Automobiles have a host of ever-growing monitoring capabilities. Tire pressure, fuel and oil gauges, MPG are now commonplace. On the other hand, self-monitoring of output, failure warnings, and external influences are hard to find in today's facades.

Nearly 70% of humankind will live in cities by 2050. Buildings will grow in height to accommodate this influx of people. Along with new density, new methods of transportation and living, working, and playing spaces--all under a single roof--will evolve. The separation between private and public will become blurred and more complex. Facades should be part of this process, so that they will relay information for interaction with individuals, the public, and one another.

Presently, typical high-rise structures rely on a prefabricated external 'skin' covered by an interior furring wall. Multi-trade installations, one group for the exterior and one group for the interior, will become past tense. New city facades are approaching a synergy where both sides will become essential contributors for occupants. Electrochromic glazing, external lighting and automated blinds are the first step towards a wired, '*dynamic*' façade. Spandrel locations, typically left unfinished with foil faced insulation, will be replaced by finish panels, LED screens, lighting, and other applications.

Facades will interrelate to their occupants and interact with each other. Instead of individual use or capacity, cities will require buildings to share energy, resources, and environmental impacts, both good and bad. The architecture of cities will move beyond a collection of individual structures towards an interconnected collective campus.

Figure 39

GENERATIVE – OUTPUT/RESOURCE

All building facades (walls and roofs) help to protect and provide comfort to their occupants but they remain largely a natural resource mitigator rather than generator.

Science fiction stories often feature a plot in which a population either harnesses or eliminates the earth's dwindling supply of natural resources. Not unlike the plots of these stories, the world's growing population, with its constant need for building and new construction, will devour energy and materials at an alarming rate.

The need for generative facades to offset and exceed a building or community's energy and water use is now paramount. No significant material or technological advances have been made in the last 15 years to make goals such as the 2030 challenge commercially feasible on a large scale. The efficiency of photovoltaic cells still struggles and strategies to collect and filter water or air are still only mostly prototypical.

The building envelope needs to contribute further in reducing the heat island effect, particularly the vertical surfaces. Over the past 30 years, the use of glazing as a primary façade material --particularly high performance glazing with reflective coatings--has resulted in buildings that direct the sun’s rays in uncontrollable ways leading to uncomfortable glare or redirecting rays hot enough to burn through durable materials.

Run off or process water destined for the water supply/sewage system should be collected, filtered and re-used with a more widespread introduction of green roof and wall installations allowing native wildlife to become an integral part of the building systems.

A return to self-sustained buildings with the ability to analyze, learn and optimize individual and collective performance is needed. Architecture designed in a vacuum with designed-in resource inefficiency simply offset by expensive technological gadgets and the impact on the immediate environment as an afterthought can no longer work.

Figure 40

DE-GENERATIVE/DISPOSABLE – MATERIAL/LIFE-SPAN

Many recently finished projects are lauded for their performance and sustainable features but they are all already in a state of constant decline with little option other than an ongoing maintenance program. Facades erected today and properly taken care of will look exactly the same and may perform the same 50 years from now. Does this approach to architecture make sense in the 21st century?

Society is ever moving towards the next thing at a faster rate; architecture should recognize that facades should be built to accept transformation and designed responsibly for change.

Perhaps facades should not be built to last ‘*forever*’; maybe 15-20 years should be the goal to match most warranties. They can then be dismantled without impacting the building occupants, disposed of responsibly and re-introduced into the manufacturing flow.

A guaranteed, build-in expiration date for facades requires an overhaul of the old with the new, allowing for innovative materials, upgraded technologies, new aesthetics and increased performance to enter the commercial arena much sooner.

This would allow for a larger material palette, varied assemblies and more environmentally friendly systems during fabrication, assembly, installation, and post removal; systems that are a truly cradle-to-cradle.

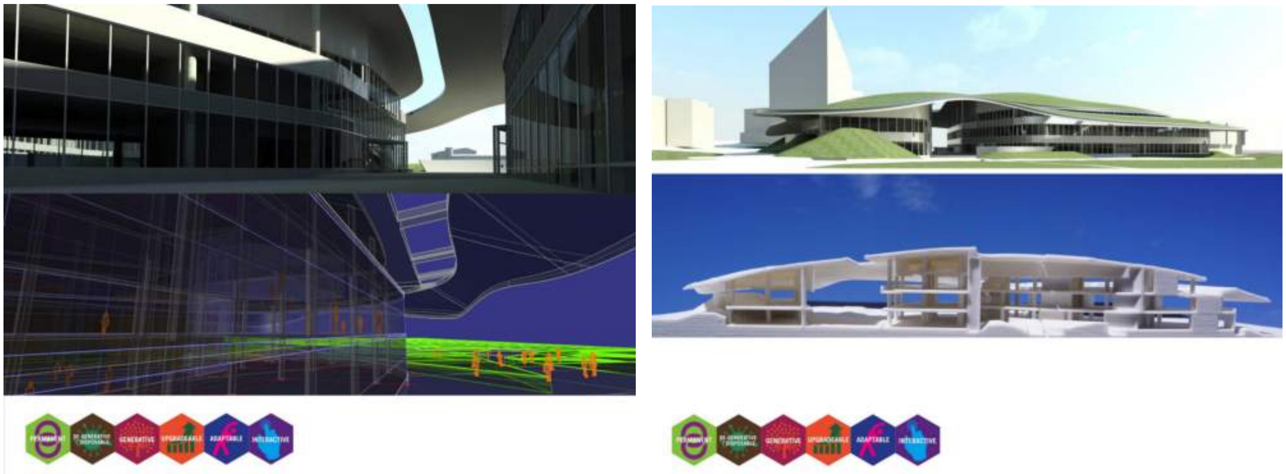

Figure 41

CONCLUSION

The building envelope must undergo fundamental and systemic change to address dynamic internal and external drivers. In addition to a building's primary functionality, the pace of technology will demand that all building components and systems continue to evolve as opposed to decline post occupancy.

Using the inherent challenges of modern healthcare projects as a guide, six individual areas of study for façade capabilities have been identified.   These capabilities are a means by which one can assess facade resilience.

The current trend towards innovation in material science resulting in better components is a valuable step but ultimately only a very small part of the overall puzzle. Façade advancements will be driven by functional necessities well beyond the latest material upgrades and will greatly impact fabrication, ownership value, economic drivers and post occupancy recyclability to name a few. This requires Architect, Engineer, Fabricator and Owners, as an integrated Research and Development Team, to be part of the development process. Even with integrated project delivery processes, these project stakeholders still operate in silos.

A true high performing façade will both meet basic performance criteria and include the appropriate blend of the identified capabilities determined by project context and circumstance.

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