# Distance daylighting and digital fabrication

**Glenn Sweitzer**[1], **Joshua Vermillion**[2]

[1]Sweitzer LLP, Muncie, IN
[2]Ball State University, Muncie, IN

ABSTRACT: In this paper we assess the use of digital fabrication for a distance daylighting course. Precise scale-model components were digitally-fabricated locally to facilitate assessment and photo-documentation of solar access and Daylight Factor (DF). The goal is to extend, globally, use of limited, local daylighting laboratory tools. If successful, a wider distant student and professional audience could be served from the limited facilities that offer physical assessments.

Based on distance introductory lectures, seven distant student teams developed digital three-dimensional model files to specify sidelighting and toplighting schemes for a school classroom project. At the local site, the files were translated into two-dimensional pattern files to digitally-fabricate architectural scale model components. Following assembly, each completed scale model was tested (also at the local site) for solar access, using an adjustable-table heliodon, and Daylight Factor, using a mirror box.

Documentation of each local assessment, returned to each distant team, included a video file (solar access), still images (solar access and DF), and a digital contour map (DF). This enabled the distant teams to compare, for example, solar access given by digital modelling vs. physical scale models. The differences engendered vigorous online review discussions. Suggested changes to improve the process are discussed.

Conference theme: Digital approaches to architectural design and education
Keywords: Daylighting, Digital Fabrication, Distance Education

## 1. INTRODUCTION

Architecture has been slow to embrace digital tools. Aircraft, auto, and ship building industries long ago replaced top-down, hierarchical, and linear assemblies of parts with integrated modules. Digital tools are now widely used to visualize, simulate, and manage the assembly of complex modules. Integration of digital technologies within design, prototyping, and production processes has helped produce products that are better, faster, cheaper - More for Less (Kieran & Timberlake 2004).

Digital tools are now gradually raising expectations for architectural education, practice, and building. Integrated Practice (IP) and Building Information Management (BIM) tasks, for example, require well-informed, competent, and team-oriented users of digital tools. Most architectural educators remain challenged, however, to use digital tools for teaching, locally or globally. Course content, sequence, teaching methods, and student progress are at stake.

Architecture curricula, specifically, have been slow to embrace the full spectrum of digital tools and their capacity to transform the design process. Initially, digital tools were used by architectural students for representing design work. Visualization and simulation advances followed.

### 1.1 Virtual Design Studios

Beginning in 1993, small groups of architectural students at different institutions around the world participated in collaborative design projects; their tools included CAD, Internet, and teleconferencing. (Bradford, Cheng and Kvan 1994). This “Virtual Design Studio” (VDS), as it came to be known, enabled team members worldwide to work simultaneously together (synchronously) or separately (asynchronously). The latest state of each design would always be available in a shared database (Kolarevic, et al 2000).

Over time, the focus, structure and scale of tasks considered - and the tools used - in these collaborations expanded. They fit in a continuum, from conceptual theory to pragmatic application (Cheng 2003). For distant partnerships, generally available communication channels were used, including e-mail, web pages, listservs; desktop video-conferencing, and text chat, with or without voice. Different tasks of a project required different kinds of support, e.g., for text vs. graphics. Most critical, the means need to fit the participants (Cheng & Kvan 2000). That is, effective teamwork is considered a process of negotiation among its members, with rapport influencing outcomes. Accordingly, individual expectations for outcomes influences what is evaluated as successful (Cheng 2003).

While these conclusions may apply to several fields, it is unfortunate that the literature reviewed for this paper focuses almost entirely on architectural education. Surely there is also relevant experience in the aircraft, auto, and ship building industries, each of which preceded architecture into the digital world.

### 1.2 Digital Technology

Transformative digital technology enables users to manage design constraints and decisions within a digital, three-dimensional model. By using a digital master model to design, each architectural component (standard or custom) can be described precisely, including instructions for fabrication and assembly. New forms of information can be extracted from this master model, to drive the digital exchange between designing and building (Mitchell 2001)—at model scale, or full scale—quicker and seamlessly. Evaluation can also become an integral part of this design process, but only when significant changes have been made in the way that information is collected, shared, and reused throughout the industry (Cohen 2000).

Advanced digital tools are now integrated with complex modelling software (e.g., CATIA, Revit, and Solid-works), and are used to derive forms in response to performance-based criteria (Kolarevic & Malkawi 2005). Digital technologies are transforming communication among agents in the building industry, by presenting opportunities for recording, managing, and distributing design information, for simulation, optimization, and production (Kolarevic 2003).

Digital-fabrication represents a pivotal transformation, between image and product and is expected to be commonplace in the near future. Accordingly, command of relevant digital tools must be integral to architectural education and practice (Cheng 2006).

### 1.3 Digital Competency

Digital competency requirements for using digital tools in accredited (e.g., US) architecture programs remain vague. Does this reflect the uneven use of digital tools among architecture students, and / or among faculty responsible for evaluating their work? The National Architecture Accreditation Board (NAAB), the sole agency authorized to accredit US professional degree programs in architecture, currently promulgates its position under Graphic Skills: “Ability to use appropriate representational media, including freehand drawing and computer technology, to convey essential formal elements at each stage of the programming and design process.” (NAAB 2004). Note, while these criteria are expected to be revised soon, precisely how is not yet clear.

### 1.4 Environmental Technology Course Potentials

Non-studio architecture courses, such as Environmental Technology (ET), can also benefit from digital tools, locally and globally. Unlike design studio, ET is most often presented in a lecture format, with up to 100 registered students per class. In addition there may be laboratory meetings when students perform exercises in smaller groups. This approach usually hinges on the availability of competent graduate student assistants. In any case, close contact with students who need it most is difficult to maintain. Following we describe use of digital-fabrication in our project-based ET course.

## 2. PROJECT-BASED ET COURSE

At Ball State University (BSU), from 2003-2007, we developed an alternative ET format for the required two-semester sequence, respectively, focused on passive and active ET topics. Each term, for ca. 80 students, 3-4 hands-on projects were assigned. Essentially, each was a short design project that required testing to meet performance-based criteria.

### 2.1 Team Projects

For each project, the students were divided into teams of two; with different students each project. Based on the prerequisite digital media course, digital-fabrication was encouraged, but not mandated, for constructing scale models for assessment. Interim and final reviews were conducted, each with a comparable weighting toward the final project grade.

For each review, each student was required to score all team projects, including their own, according to the criteria. By the final submittal of each project, each team was well aware of their standing in the class and of their impression of the project. The latter was captured in a questionnaire survey, before grading. This format gradually improved the quality of project submittals while reducing (instructor) grading time. Student feedback to the passive projects (daylighting, ventilation, and whole building energy assessment with focus on daylighting) indicated that the daylighting project contributed most to their learning, although it took the most time to complete. The students also concluded that application of the lessons learned would contribute the most, in practice, to sustainability. Indeed, daylighting is rated (e.g. in LEED) one of the most sustainable means for building (DiLouie 2007).

.

### 2.2 Daylighting Models vs Software

For the daylighting project, scale models rather than software were used for assessment, for practical and pedagogical reasons. Daylighting was given three weeks in the syllabus, that is, 7.5 hours of contact time. Solar geometry, vision, and lighting principles preceded the project introduction. The interim review was held after two weeks, with the final a week later. There was insufficient time, in addition, for the class to gain command of a high-fidelity lighting software, such as Radiance.

Pedagogically, precise scale models enable students to grasp daylighting issues more rapidly than through a series of “sweet snapshots”, even though photo-realistic. Changes in the distribution of incoming direct and reflected sunlight on interior surfaces for representative days of the year can be captured, efficiently, via short video clips. Images of violations can be isolated for study.

With each successive daylighting project, more and more student teams used digital fabrication for producing their components. The benefits were most evident in the assessments for solar access, made on an adjustable-table heliodon. The precision also improved the appearance of the photo-documentation of the assessment for Daylight Factor, made in a mirror box simulation of a uniform overcast sky

Could this method be shared with a wider audience, given the urgency to practice sustainable means (2030 Challenge)?

## 3. DISTANT DAYLIGHTING COURSE

Based on our experience with the ET courses, we were able to test our method via a distant Architectural Daylighting course for architecture students at Taiwan National University of Science and Technology (NTUST), Taipei. The NTUST architecture curriculum is decidedly more Architectural Engineering (AE) oriented than architectural-design programs in the US. In addition, the (elective) class of 14 varied considerably by age, culture, mother language, and mastery of analog vs digital tools relevant to the course.

Initially, we planned to engage the students via video-conferencing, with visual and aural channels in each direction. By show time, this system was not available, and we were reduced to two-way voice and projected images. This limitation worked surprisingly well for those proficient in English, but less so for the others.

For all students, the course was effectively launched during the three-week onsite visit at NTUST by the instructor (first author). Through live face-to-face introductions and working together on two initial analog exercises, student engagement and confidence soared.

### 3.1. Analog exercise #1

The first analog exercise challenged students, at an unobstructed rooftop site, to hand-render daylighting in a shoe-box. The side- and top-apertures (opposite the viewing port) were limited to flaps that could be opened inward or outward or taped closed light-tight (Figures 1a – 1c). These limits enabled each team to explore alternative daylighting combinations before rendering an assigned sequence of 5 images. In addition, each team was assigned a different solar orientation, to provide varied outcomes of direct vs diffuse daylighting. Grey-scale tones were rendered to represent the brightness distribution on the (uniformly finished) interior surfaces (walls, ceiling, and floor). A stool was provided to support each shoebox, to maintain its solar orientation and fixed height, while the rendering time for each scene was limited to 10 minutes.

### 3.2. Analog exercise #2

The second analog exercise was to design and assemble hand-built sidelighting and toplighting components for a shared template model of a school classroom (Fig. 2). Based on the experience accrued with the shoe-boxes, each team developed a scheme to be asses-sed, subjectively, outdoors. As with the shoebox exercise, visual adaptation was critical to appreciating each interior view, this time, via a porthole large enough for photographic documentation. Note that the lighting criteria for this classroom model was the same as for the digital models that followed.

**Figure 1a:** Unobstructed rooftop shoebox rendering site; **1b:** Example shoebox interior with left, right, and top apertures; **1c:** Shoebox rendering for same.

**Figure 2:** Analog Classroom Template Model.

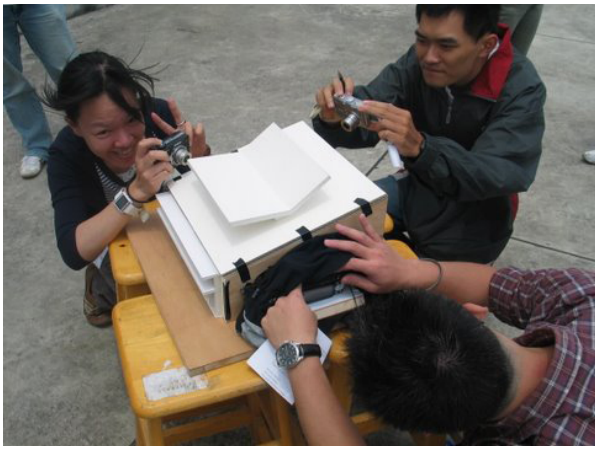

**Figure 3:** Rooftop model assessment.

### 3.3. Performance-based daylighting criteria

The assigned daylighting project involved a rectangular school classroom, with a sloping ceiling, extending upward from the south-facing window wall (Fig. 2). Any part of the south-facing window wall could be used for sidelighting, although at least one light shelf, extending outdoors and / or indoors, was required. East and west walls were blank, as well as the north wall up to the height of the south wall. The north wall area above could be used for sidelighting. Any part of the roof / ceiling area could be used to admit toplighting.

The student desk area, the horizontal workplane, was designated by a continuous raised rectangular platform. A whiteboard, a vertical workplane, was located on both the east and west walls. The challenge was to prevent direct incoming daylight on either the horizontal or either vertical workplanes throughout the year, from 09:00 – 15:00. Each student team was assigned a different latitude, to generate varied solutions.

**Figure 4:** Sketchup digital model.

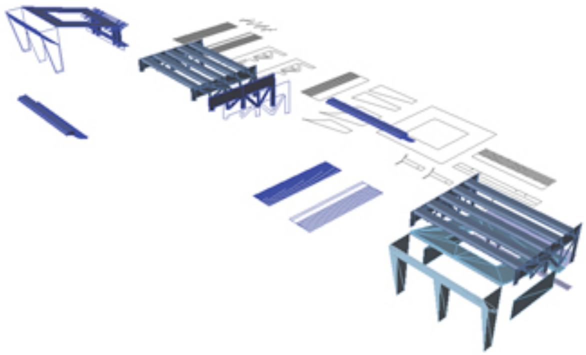

**Figure 5:** Preparing the digital files for laser cutting.

### 3.4. Digital modeling

Based on the results from the analog models, each NTUST student team constructed a digital model, using Sketchup (Fig. 4). Upon completion, the files were sent to the BSU student fabrication consultants for review prior to fabricating and assembling the models.

Component structural integrity, scale, geometry, and tolerances were reviewed to ensure light-tight fits with the BSU classroom template model. Once deemed adequate for fabrication, the BSU consulting team used Rhino, a 3D modeling software that facilitates the extraction and translation of surfaces into lines and curves, to prepare the files for CNC laser-cutting. Each scheme component was translated into vector-shape information to guide the laser cutter (Fig. 6 and 7). Nesting of the shapes within a standard size of material sheet stock minimized material waste from fabrication (Fig. 7). Assembly of each model was straightforward. Tolerances were tested beforehand to ensure a precise, tight-fitting model.

The two daylighting assessments followed.

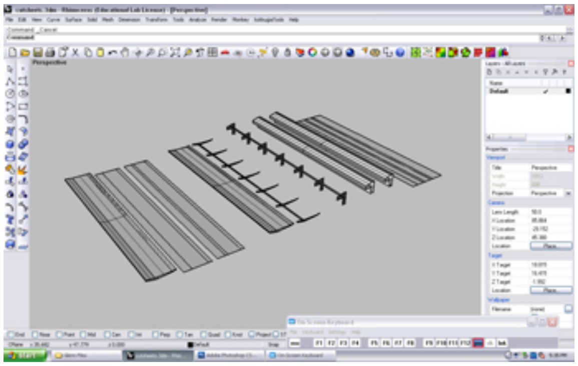

**Figure 6:** Preparing light shelf details for laser cutting.

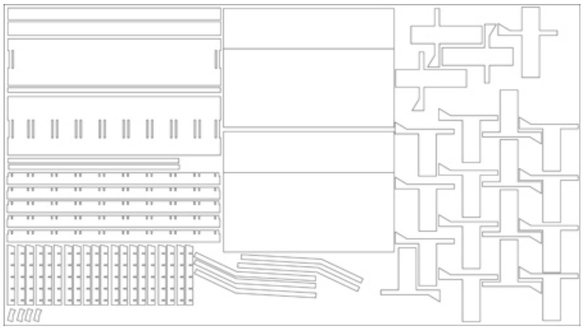

**Figure 7:** Nesting patterns for CNC laser cutter.

### 3.5. Solar Access Assessment (BSU)

Solar access (sun only) was assessed for each model using an adjustable-table heliodon (Fig. 8a). The (hinged) north wall was lowered to position a fixed video camera, to take in the full scope of the room and all three workplanes (Fig 8b). The play of incoming direct light was captured from 09:00-15:00, for the summer and winter solstices and the equinox(es). Through replay, any violations could be detected and remedies proposed (marked red in Fig. 8c).

### 3.6. Daylight Factor Assessment (BSU)

Daylight Factor, which assumes a uniformly overcast sky, was assessed for each model inside a mirror box (Fig. 9). Interior views were photographed with the horizontal workplane in place (Fig. 10). To measure horizontal illuminance at 25 positions throughout the classroom, however, the raised platform was removed. Five sets of measurements were made, each with 5 sensors aligned N-S on a paddle (Fig. 11) yielding a 5 x 5 matrix. The graphic output was a software generated Daylight Factor contour plot (Fig. 12), based on the ratios of the interior illuminances compared to the unobstructed exterior reference illuminance.

For each assessment, exterior and interior still photo-documentation was provided to each team for use toward their summary report. Written and graphic explanations were required, of 1) project intent; 2) project outcomes, and 3) explanation of the differences between intent and outcome, and what the team would do differently given another opportunity.

**Figure 8a:** Adjustable-table heliodon assessment; **8b:** Video documentation of solar access; **8c:** Proposed changes (shown red) for light shelf & top.

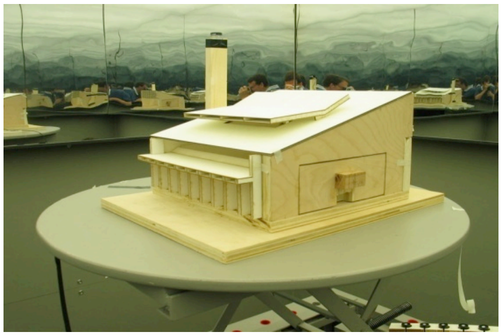

**Figure 9:** Mirror box assessment site.

**Figure 10:** Interior under overcast sky from student perspective in NE corner.

**Figure 11:** Illuminance measurements using five-sensor paddle.

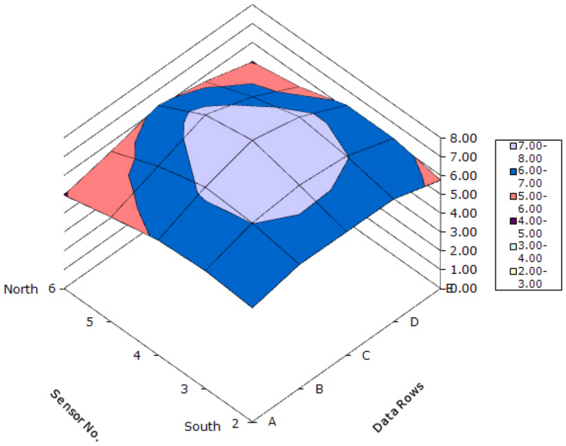

**Figure 12:** Daylight Factor Contour Plot.

## 4. DISCUSSION

Digital tools hold untapped potentials for ET in architectural education. Our first distant ET course was based on recent BSU courses that had benefitted from digital fabrication. The distant NTUST daylighting course differed from the BSU courses, however, by focus, student contact, model production, and review of outcomes. Following, we discuss these issues, each vital to improving outcomes for future distant and local ET courses.

### 4.1 References

Our literature search yielded no references that describe the use of digital fabrication for ET course projects. We found several references however that describe digitally fabricated building envelope components, including those for daylighting. In practice, for example, Foster & Partners and Grimshaw Architects are leading exponents of parametric design and digital fabrication. We consider a next step to be parametric design, crucial to understanding of optimazation, in response to performance-based criteria. (Burry 1999).

### 4.2 Course focus

The NTUST course focused exclusively on daylighting while in the BSU courses the daylighting project was one of four. The additional time in the NTUST course allowed for the two analog exercises, the shoebox renderings and the draft model. A couple of NTUST students considered the shoebox exercise to be the high point of the course: Both analog projects probably improved student understanding and confidence, critical to developing their digital models.

### 4.3 Student contact

Contact with the NTUST students was remote until the onsite period. Until then, there was little palpable chemistry among the students, and few questions. Afterwards, course interactions blossomed.

Had the onsite meeting been at the beginning of the course instead of mid-term, the students probably could have benefitted more.

### 4.4 Model production

Following completion of the analog exercises, the NTUST students relied on local digital fabrication and assembly of their models. Hands-on control was lost once they submitted their digital files. All files were edited locally, some much more than others. For example, dimensional changes were made to fit the model materials used, and, for structural connections necessary to realize their intentions, as shown in the digital files, but not adequately detailed to work in a physical model.

Materials are critical to the production and performance of scale models as well as real buildings. Errors were made by the BSU consulting team, in editing the files, and in fabricating vs. assembling the components. All three tasks may have been done by a single consultant, or independently, for example, by more than one. This points to the need to carefully organize digital fabrication, so that accountability is maintained throughout. For example, a lightshelf, which included exterior and interior components, was installed backwards. As a result, the scheme violated the criterion for solar access. The error was flagged during the final review. Following correction, the scheme was retested; and the lightshelf worked as intended.

This example echoes what needs to happen in practice, from digital files to fabrication of full-scale elements. A two-way feedback loop, including materials and production logistics, is essential.

### 4.5 Final Review

The final review was online, via popular video chatting software (Skype). Each team had received in advance visual images of their project assessments, documented locally. This included video clips for the heliodon assessment of solar access and still images of the solar access and sky assessments. The video provided arguably the most telling and challenging images. It allowed comparison of the digital Sketchup shadow studies done initially by each team, with the physical assessments. The differences between these, flagged by the distant student teams, proved most informative, for the local team as well. These differences showed the need for better coordination between the editing / preparation, fabrication, and assembly phases. It also showed the need to provide allowance for error between digital and physical models. It follows, that allowance should be provided in practice, between the precision of a digital model vs. the building.

## 5. CONCLUSIONS

### 5.1

The use of digital fabrication in ET courses is not widely reported. Further research and development of this potential could lead to improved integration and outcomes in studio and actual projects that include physical assessments of scale models.

### 5.2

Analog tools can yield valid bases for comparisons with digital outcomes. Analog exercises should not be dropped from architectural education, but rather taught along with digital tools.

### 5.3

Digital fabrication tools can save time (for iterative fine-tuning,) and resources (contributing to sustainability goals).

### 5.4

The daylighting project proved ideal for testing model performance, especially for solar access. The next logical step is the use of more advanced, parametric design tools to generate components that can be more readily optimized for daylighting performance. Parametric design would allow for easier and quicker fine tuning and reconfiguration of envelope components.

### 5.5

Video-conferencing is ideal for distance lecture courses that require continuous visual and aural contact. Alternative free communication channels meanwhile can prove worthy for focused meetings, including those that involve images.

### 5.6

Sketchup, free for downloading and used worldwide, is an ideal program for creating basic digital files by students with beginning digital design skills. The shading option is a useful reference for comparing assessments of solar access for physical models. For preparing digital fabrication information, advanced modelling software (such as Rhino) can be used to post-rationalize Sketchup geometry into the appropriate information for laser cutting.

## ACKNOWLEDGEMENTS

The authors wish to thank Professor Eddie Chiang and course assistants Ling-Mei Liao and Charles Sanchez Jimenez, in the Department of Architecture at the National Taiwan University of Science and Technology, Taipei. At Ball State University, we thank the Department of Architecture, the Institute for Digital Fabrication, and the Center for Energy Research/ Education/Service (CERES). We also appreciate the critical comments received from the anonymous reviewers.

## REFERENCES

2030 Challenge. Online source: http://www.architecture2030.org/2030_challenge/index.html.

Bradford, J.W., Cheng, N. and Kvan, T. 1994. "Virtual Design Studios". The Virtual Studio: Proceedings of the 12th European Conference on Education in Computer Aided Architectural Design. Glasgow, Scotland), 7-10 September 1994, pp. 163-167.

Burry, M. 1999. "Paramorph: Anti-accident Methodologies". in *AD: Hypersurface Architecture II*. Parella, S., ed. Wiley: London.

Cheng, N. and Kvan, T. 2000. "Design collaboration strategies". Timmermans, H. (Ed.), *Fifth Design and Decision Support Systems in Architecture and Urban Planning - Part one: Architecture Proceedings*. Nijkerk, the Netherlands

Cheng, N. 2003. "Approaches to Design Collaboration Research". *Automation in Construction.* Volume 12, Issue 6

Cheng, R. 2006. "Suggestions for an Integrative Education". Chapter 5 in *AIA Report on Integrated Practice*. Friedman, D., ed. Online source: http://www.aia.org/SiteObjects/files/5_Cheng.pdf Last accessed 9 January 2009.

Cohen, J. 2000. *Communication and Design with the Internet: A Guide for Architects, Planners, and Building Professionals*. New York: Norton.

DiLouie, C. 2007. "Sustainable Technology: Lighting". ARCHITECT, July/August 2007. Online source: http://www.architechmag.com/articles/detail.aspx?contentID=4843 Last accessed 1 January 2008.

Kieran, S. and Timberlake, J. 2004. *Refabricating Architecture*. McGraw-Hill: New York.

Kolarevic, B., Schmitt, G., Hirschberg, U., Kurmann, D., and Johnson, B. 2000. "An experiment in design collaboration". *Automation in Construction.* Volume 9, Issue 1, 2000

Kolarevic, B. 2003. *Architecture in the Digital Age: Design and Manufacturing*. Spon Press: New York.

Kolarevic, B. and Malkawi, A. 2005. *Performative Architecture: Beyond Instrumentality*. Spon Press: New York.

Mitchell, W. 2001. "Roll over Euclid: How Frank Gehry Designs and Builds". in *Frank Gehry, Architect*. Ragheb, F., ed. Guggenheim Museum Publications: New York.

NAAB (National Architectural Accrediting Board). 2004. Online source: http://www.naab.org/accreditation/.

Sweitzer, G. and Vermillion, J. 2007. "Enhanced Daylighting through Digital Fabrication". In *Thermal Performance of the Exterior Envelopes of Whole Buildings X International Conference Proceedings*. Clearwater, Florida, US. December 2007.