
Enhanced Daylighting through Digital Fabrication

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ABSTRACT

Daylighting is vital to building user health, task performance, and satisfaction. Daylighting design can be enhanced through the use of Digital Fabrication technologies, for 1) rapid prototyping of precise scale models that facilitate daylighting assessment and 2) fabrication of full-scale daylighting components that can perform as modeled. This paper focuses on the former, for an introductory environmental control systems course for architecture students. Program, daylighting, model material, and digital fabrication criteria are specified for a school classroom project. Sidelighting and toplighting classroom model elements for each scheme are assessed, using an adjustable-table heliodon (sun only) and a mirror box (overcast sky). Video documentation for sun only is provided for summer and winter solstice and equinox periods. A software-generated Daylight Factor contour plot is provided for the overcast sky. Fixed-frame photo images, however, best show the improved realism provided by the digitally-fabricated vs. the hand-built scale-models.

INTRODUCTION

Daylighting is vital to building user health, task performance, and satisfaction. Access to daylight helps regulate individual circadian rhythms, essential to health (EPRI 2001). Daylight can aid treatment of sleep disorders and seasonal and chronic depression. Daylight exposure indoors varies by latitude and longitude; time of year; sky conditions (Muneer 2004); architectural interventions; and individual behaviors.

The amount of daylight can impact task performance. A widely reported study claims a positive statistical correlation between the amount of daylight in elementary school classrooms and the performance of students on standardized math and reading tests (Heschong 2001). Not reported is whether the classrooms were sidelit, toplit, or both, affecting the amount of daylight on the tasks. Additional limitations of this report are discussed in a critical review (Boyce 2004).

In addition to individual benefits, daylighting can reduce demand for electric lighting and cooling (Selkowitz, 1998), which rely heavily on non-renewable fuels such as coal, oil, and nuclear. Potential savings provided by daylighting vary

considerably, by building solar orientation; window-to-wall ratio; glazing type; and daylighting control, to dim or turn off electric lighting in response to available daylight.

To assess the energy benefits and costs in detail, various computer software models have evolved (DOE). Computer software to accurately render daylighting effects has also evolved (RADIANCE). Both tools benefit from expert users, and are most useful during preliminary design when alternatives can be considered and changes accommodated.

Few undergraduate architecture students – at least in design-oriented programs – are expected to master “expert” energy analysis or daylighting software. Most students are likely to be required, however, to hand-build architectural scale-models in design studios.

Hand-built scale models have long been part of architectural design, in education and practice. Crude concept models might precede even sketches, or evolve in concert with quick drawings for specific purposes, such as mass, circulation, structure, skin, or daylighting (Leggitt 2002).

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Alvar Aalto, the acclaimed Finnish modernist architect, cultivated daylighting design, notably in his native Finland. Aalto worked primarily with section models, presumably combining spatial, structural, and daylighting analyses (see Figure 1). Moore's studies of daylighting in selected Aalto works (see Figure 2) indicate his talent for manipulating indirect lighting paths (Moore, 1993).

Most architectural scale models, however, emphasize exterior rather than interior appearance, counter to the needs of daylighting models. Accordingly, most daylighting models represent a compromise to full-scale mock-ups, which are highly desirable but costly and time-consuming to build.

One of the most widely-publicized full-scale mock-ups in recent times is for the new New York Times Headquarters Office Building in Manhattan, now under construction.

The mock-up was built for four reasons," says Glenn Hughes, director of construction at The New York Times. "First, we needed a furniture mock-up. Second, we realized there were not sufficient tools available to model natural light admittance, glare and daylight harvesting with certainty. Third, we wanted to perform analyses on some of our interior designs such as the communicating stairs. Fourth, we were able to take hundreds of our employees through the mock-up and gather many comments (Mukerji 2004).

Apparently, these specific needs could not have been achieved with software or virtual means. Accordingly, architectural mock-ups and scale models survive, although the means and materials used to produce them are changing.

Digital Fabrication technologies are increasingly available and affordable for rapidly prototyping building components, large or small. Computer numerical control (CNC) laser cutters and milling machines can quickly and accurately produce precise components, reducing time, labor, material waste, and safety risks. Given an introductory course in digital media, students can readily compile routines for cutting, for example, complex sidelighting or toplighting design components. The time savings allow for more exploration of design alternatives. Accordingly, model scale is contingent on needs for visual assessment and / or documentation rather than on available materials or model maker skills.

Our course benefits from a prerequisite course in digital media. All of our students are thus deemed competent to digitally fabricate scale-model components. The four basic tasks are: 1) file preparation; 2) material layout; 3) fabrication; and 4) assembly. It is estimated that even on the first try, digital fabrication should save time over hand-fabrication. Additional time - and material use - savings should accrue with additional experience.

To describe the geometry of proposed components, most of our students use Rhinoceros, a 3D modeling software, and/or a two-dimensional drafting software such as AutoCAD. Rhinoceros is a nonuniform rational b-spline surface (NURBS) modeler, which allows students to draw curves and lines to create surfaces and, easily extract curve/line informa-



Figure 1 Section model by Alvar Aalto—Church of Riola, Italy.

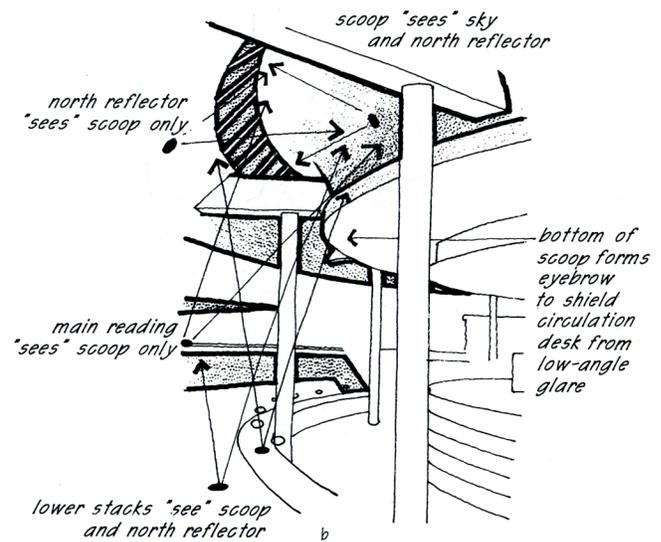


Figure 2 Daylighting analysis of Mt. Angel Library by Alvar Aalto, Mt. Angel, Oregon. Source: Moore (1993).

tion from three-dimensional surfaces. This vector-shape information is then used to precisely guide a laser cutter in 2D, where two-dimensional shapes and components are cut from flat sheet stock and then assembled into a 3D model.

This "flat" strategy can be scaled up to full-size, using building materials such as wood, metals, or even stone. Computer controlled equipment, similar to laser cutters, which are capable of cutting harder materials, already exist. These include water jet technology, routers, and plasma-arc cutters (Kolarevic 2003, Schodek 2005).

The process of preparing digital files/instructions for this full-scale equipment is remarkably similar to that of a laser cutter used for scale models. Essentially, the digital design/

fabrication information can be scaled up or down as needed, as demonstrated by Bernhard Franken (see Figure 3).

The precision of laser cutting helps students negotiate between ‘perfectly’ drafted or modeled digital forms and ‘imperfect’ material realities. Material selection is critical for laser cutting, as each requires an optimal power and speed setting in order to be cut cleanly. The shapes that are to be laser-cut can be nested within standard sheet material stock sizes, in order to minimize waste.

The greatest benefit of using CNC laser cutters, aside from gained precision, is the reduction in time to cut model components. For our classroom project, the average time to laser cut a complete set of model components fell between 20-40 minutes. Unfortunately, none of the students exploited this capability, to rapidly and accurately cut-out alternative schemes for comparison. Instead, the laser cutter was used to make perfect cuts for a single model.

In the near future we intend to require our students to use parametric, object-based modeling systems. Parametric modeling allows for component proportions to be described as numerical parameters and the embedding of geometric constraints between each component. This will help shift each student’s emphasis from guessing at possible solutions to creating a set of strategic relationships, rules, and parameters that can yield an optimal solution.

Digital parametric models that demonstrate a particular daylighting control strategy could be built as a starting point and “fine-tuned” afterwards. This process would expedite the feedback loop between the proposed digital geometry and the resulting physical scale-model and heliodon/mirror box testing. The output would be informed by daylighting criteria and augmented by computation.

Such enhanced means to design and assess daylighting could lead to improved building assessment schemes. At present, LEED (Leadership in Energy & Environmental Design) is the prevailing scheme in the US, even as it evolves. For LEED’s New Construction version 2.2, for example, 14 out of a possible 69 points can be linked to daylighting (DiLouie 2007).

Against this background, we describe a daylighting project that is part of our introductory environmental systems course (with emphasis on passive design) for architecture students at Ball State University. Our aim is to transition from textbook-based to hands-on projects supported by digital media.

DAYLIGHTING PROJECT

The project is to daylight a 30’W x 40’L x 12’H school classroom with a south-facing window wall exposure. The horizontal workplane is defined by a 20’ x 20’ area, located at a standard 2.5’ desk height in the middle of the room. The two vertical workplanes (whiteboards) are 20’W x 5’H, extending upward from the 2.5’ height of the horizontal workplane, on the east and the west walls only. The north wall is blank.

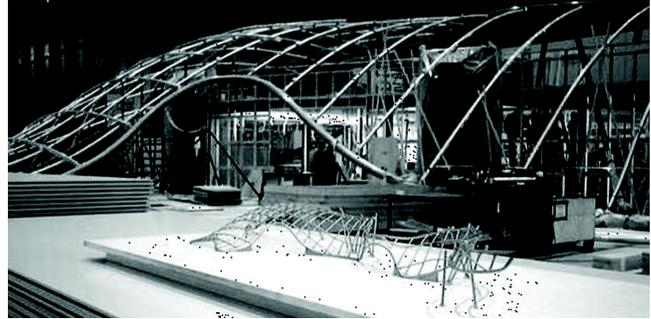


Figure 3 Scale model and full-scale BMW Brandscape Pavillion by Bernhard Franken. Source: FrankenArchitekten, <http://www.franken-architekten.de/English/level0.htm>.

Daylight is to be admitted to the classroom only via apertures in the south-facing window wall and the roof-ceiling. Termed sidelighting vs. toplighting, respectively, these apertures are defined and diagrammed in the course textbook (Lechner 2001). The sidelighting scheme is to include at least one horizontal light shelf, that extends outdoors and indoors and not below 7.5’H indoors, for clearance.

Each student, or team of two students (depending on class size), is assigned a latitude ranging from 28 degrees to 56 degrees north latitude, in four degree intervals. A solar path diagram for each is included in our course textbook. The intent is to encourage diverse daylighting solutions in response to the latitude differences.

The first required submittal is a plan and a transverse-section, each comparing relevant cut-off angles for incoming solar angles, by time of year and day. The second submittal includes draft scale-models of sidelighting and toplighting elements, handmade or digitally fabricated, according to student preference. Both elements are fitted to a shared template model, providing consistency while saving material. The heliodon assessment follows.

Based on each heliodon assessment outcome, final models are constructed, again hand-made or digitally fabricated, and assessed first on the adjustable-table heliodon.

Assessment under the simulated overcast sky in the mirror box follows. This involves simultaneous indoor/outdoor illuminance measurements, which represent the horizontal workplane height throughout the classroom vs the outdoor reference position, respectively. From these data, Daylight Factors are computed, using software that compensates for glazing and dirt depreciation. Output is tabular and graphic.

Each project is assessed and graded according to the following eight criteria, each weighted by percentage:

1. Materials (10%) - build a light-tight enclosure with fixed aperture elements, including at least one lightshelf for (south) sidelighting. Foamcore board e.g. permits bright

light to “bleed” through, while crescent board does not. Do not simulate glazing. Interior room surfaces should be highly light reflective but lightly-textured rather than smooth and glossy (e.g. foamcore board). Most wood and plastic materials, up to ¼” thickness, can be laser cut; cut edges that appear burnt should be painted to match surrounding surfaces.

2. View (10%) - provide clear view to outdoors for adults and children, standing or sitting. Slope window sills downward toward the outdoors in order to prevent reflected glare.
3. Lightshelf (10%) - include at least one lightshelf for sidelighting (the highest is most critical), to shade incoming sunlight below while reflecting sunlight above onto ceiling & upper wall surfaces. For the lowest latitudes (highest sun angles), raise the exterior portion of the lightshelf. For the highest latitudes (lowest sun angles), you may slope the entire lightshelf slightly downward toward the outdoors.
4. Horizontal Workplane (10%) - prevent access to incoming sunlight on the horizontal workplane area from 09:00 to 15:00, year-round. First, check graphically, section and plan; then test using the adjustable-table heliodon.
5. Vertical Workplanes (10%) - prevent access to incoming sunlight on either white- board 09:00 to 15:00, year-round. First, check graphically, section and plan; then test using the adjustable-table heliodon.
6. Lighting Distribution (10%) - sidelighting and toplighting together need to produce smooth lighting gradients on interior horizontal and vertical surfaces. Aim for Daylight Factors of 2 - 8%. Note: perceived brightness is dependent more on vertical than horizontal surface brightness. Avoid sharp lighting contrast; rounded, light-reflective edges will smooth lighting gradients.
7. Craft (10%) - ability to select and construct materials to achieve the above criteria.
8. Summary Documentation (30%) - 11 x 17 format, state intent, describe outcomes, and discuss what you would change for your scheme. Include graphic analyses, section & plan; four photos (interior views of each assessment will be provided); and a Daylight Factor contour map.

DISCUSSION

The project assignment is intended to introduce students to the challenges of daylighting a topical room, a standard classroom. Application of basic concepts is required: solar geometry, solar window, light shelf, workplanes (horizontal and vertical), and Daylight Factor. Most of the lighting criteria are consistent with standard practice, as specified by the current IESNA Handbook. The exception, no direct light on either workplane between 09:00 and 15:00 throughout the year, is arguably more stringent than standard practice, although we believe it anticipates more stringent requirements in future.

Few students accurately developed – in two-dimensional plan and section – solutions for their assigned latitude. The incoming morning and evening angles, summer or winter, proved problematic. By contrast, noon solar angles, those most often shown in the literature, were accomplished easily.

Locating and sizing the light shelf proved to be the most challenging element, as it can be adjusted up or down and inward or outward. Almost all students preferred to first try graphic rather than trigonometric solutions to this problem.

The “eureka” moment for solar geometry - for most students - came while assessing their preliminary models on the adjustable-table heliodon. At once, incoming side- and or toplighting that violated the workplane criteria could be tracked, and means identified to eliminate it. The violations were first assessed roughly by hand, then more exactly by extending or retracting a specific element such as a light shelf (see Figure 4). Precision-crafted models, mostly or entirely digitally-fabricated, facilitated adjustment. Most hand-built models, meanwhile, appeared less-finished, less-resolved; some included crooked, unevenly-spaced, or sagging elements that complicated adjustment(s).

Accordingly, students who departed the preliminary assessment with all problems resolved were ready to begin constructing their final model. Students with unresolved projects however left amidst uncertainty (given restricted heliodon access for rechecking) and at a time disadvantage even if they used the laser cutter for the final model.

Model precision is much less critical for the overcast sky assessment. The diffuse light does not render sharp shadows, as does the beam light onto the heliodon table. This may explain why some daylighting model guidelines discount need for precision, which is most revealing under the direct sun.

About half of all students submitted digitally-fabricated vs hand-built preliminary and final models. Among these were the best hand craftsmen!



Figure 4 Solar analysis using adjustable-table heliodon.

CONCLUSIONS

Daylighting is vital for building users and will remain so. Daylighting potentials for reducing use electric lighting and cooling loads remain largely untapped. Proven means to exploit these potentials must be emphasized and developed in architecture and engineering curricula.

Scale-models will remain vital to the architectural design process. Models will be improved, however, to facilitate lay and expert assessments that better inform project design decisions. In turn, these improvements will lead to improved daylighting criteria and more specific and reliable daylighting assessment.

Digital Fabrication techniques will help students and practitioners to improve daylighting models. Accurate, rapidly-developed models will encourage consideration of more varied, and hopefully better, alternatives. The same technologies can be used to fabricate full-scale components as well.

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