ENERGY SIMULATION IN PASSIVE DESIGN: TOOLS FOR CONSIDERING THE INVISIBLE

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ABSTRACT

This paper discusses the teaching of building energy simulation as an architectural tool in a semester-long introductory building simulation seminar for graduate architecture students. Coursework required students to propose a design parti which provided thermal diversity and delight through passive design, and then required quantitative demonstration of achievement of design intentions through use of an hourly thermal simulation program (Energy Plus with Open Studio). Therefore rather than using energy simulation to describe a project, students uses the program iteratively to develop a desired thermal performance in the proposed building. The seminar taught building simulation as a means to develop intuition about design's impacts on energy usage and user thermal experience. The requirement for specific, measurable results from passive strategies fundamentally developed the ability to conceive of and implement low-energy designs. It situated simulation not as an end in itself, but as a means to an architectural end, and as a means to energy literacy.

I. INTRODUCTION

While evolving and realizing a design, architects constantly ask questions and explore the answers by making drawings, renderings and models. This is in an effort to see design, to react to visual representations of space. Yet space is experienced with a full range of senses. Many of the invisible dimensions of architecture profoundly shape our involvement with it: a sun-warmed stone wall, a breezy portico, a brightly daylit office, a crisply echoing corridor. This sensory and bodily knowledge is essential to our understanding of architecture and place. And beyond shaping local invisible experience, a building brings about change at a distance; it uses energy generated at some unknown location, and is constructed out of resources for which extraction necessitates environmental impact. These invisible aspects of design are critical not only to our comfort and delight in the occupation of architecture, but also the ongoing coexistence of built and natural ecologies.

Juhani Pallasmaa argues that this visual domination, or ocularcentrism, while having roots in classical Greek philosophy, is entirely inappropriate to architecture, which is fundamentally concerned with questions of human experience, writ broadly, over space and time. In fact, he suggests this overly visual culture is a source of the "pathology of everyday architecture". Our devotion to a less meaningful aesthetic stems from a tendency to exclusively *view* architecture, and neglect the touch, sound, smell and indeed taste of it. (1) Lisa Heschong holds that one particular invisible domain, that of the thermal environment, provides a rich canvas for spatial design. Rather than developing mechanical systems in buildings to achieve a thermal homogeneity, these tools could be used to create a landscape of sensory experience. (2)

The architect would, in theory, engage in design in some changed way if other dimensions than the visible were present and engaged during the design process. Yet today, several "invisibles" are in fact knowable during design: each of the parameters of thermal comfort, ventilation, daylighting, acoustics, and energy or material consumption can be readily simulated with a range of different simulation instruments. However, the existence of simulation tools does not *ipso facto* result in designs which are either optimized to meet a performance target or are qualitatively desirable spaces. In fact, it means neither if the designer lacks the foundational skills to apply not only the science but also the art of analysis in the formative stages of design. The existence of technical possibility does not ensure results.

2. COURSE PEDAGOGY

2.1 Organization

The seminar course was created to test whether invisible dimensions, specifically those of energy consumption and thermal consumption, could be actionable elements for architectural students in a design-driven environment. The key pedagogical elements required for the students to accomplish this course successfully were: basic knowledge of thermal behavior of buildings, a well-bounded set of design parameters, a prescribed range of valid numerical inputs, and a clear design task.

In order to develop the necessary skills in the students to use simulation tools, the course first reviewed basic building science principles. (All students were required to take the basic building science courses as a prerequisite to the class.) The emphasis was on the building as a complex ecosystem of internal and external loads. The building was not framed as a set of loads which automatically trigger the response of mechanical system design; the qualitative consequences of the loads themselves were studied. Coursework was designed specifically to focus on load analysis and the simulation of fully passive environments. This was considered to be a realistic constraint for architecture students. While having an understanding of mechanical systems, they do not as a group have the detailed knowledge to specify and describe systems sufficiently for simulation of them. Developing this more advanced skill could certainly be done in subsequent training or coursework.

The course then covered the fundamentals of energy simulation, as well as deeper information about EnergyPlus specifically. The course met once a week for 16 weeks; half the course periods were lecture + demonstration, and half were laboratory or work sessions.

2.2 Projects

While still developing skills with the software tools in the first weeks of the semester, students researched and developed a case study from professional practice where designers used simulation to develop a building's design. Specifically avoiding projects where simulation is used for design validation or simply for code compliance, they looked at projects where simulation had been used from the early stages of a design concept to develop and refine a design. Students looked at published data and narratives, and also spoke with designers and energy modelers at each of the firms in order not only what was done, but how this was integrated with a design process. Early exposure to an integrated energy simulation approach was instrumental to their constructing an understanding of simulation as an iterative process.

The next phase of coursework was an exercise in skill building in the simulation tools. The students were asked to perform a set of bounded, parametric whole building simulations as an approximation of early design decision making. Variables and choices were severely constrained to ensure successful completion of the simulations. Students were given a design template, location/climate, a basic 10,000 ft^2 (929 m^2) building footprint, and idealized HVAC system design. They selected two design parameters to vary, from a suggested list of eleven. Typical parameters included window to wall ratio, wall R-value, window SHGC, and so on. They selected four output parameters: total heating demand, total cooling demand, and two others of their own choosing. After running their simulations, they were required to develop an 11x17 graphic matrix for communicating their key results, rather than simply creating tables of numbers. See Fig. 1 for an example of one such graphic matrix of results from this exercise.

By the next point the students were halfway through the term, and had sufficient skills to begin work with more complex models. The third and most substantial project of the course was to develop a design of a small building using simulation such that a particular thermal environment in the interior spaces was created. This project is described in more detail in the subsequent section.

2.3 Software

The course intentions required a tool which was robust in its simulation engine, graphic in its input interface, capable of early phase design analysis with multiple zones, and freely available. Based on the author's experience, conversation with colleagues, and consultation with comparative analyses of simulation programs (3), (4), the software selected for use in this course was EnergyPlus, with OpenStudio and SktechUp. Many other tools were considered and tested during the creation of the course, and

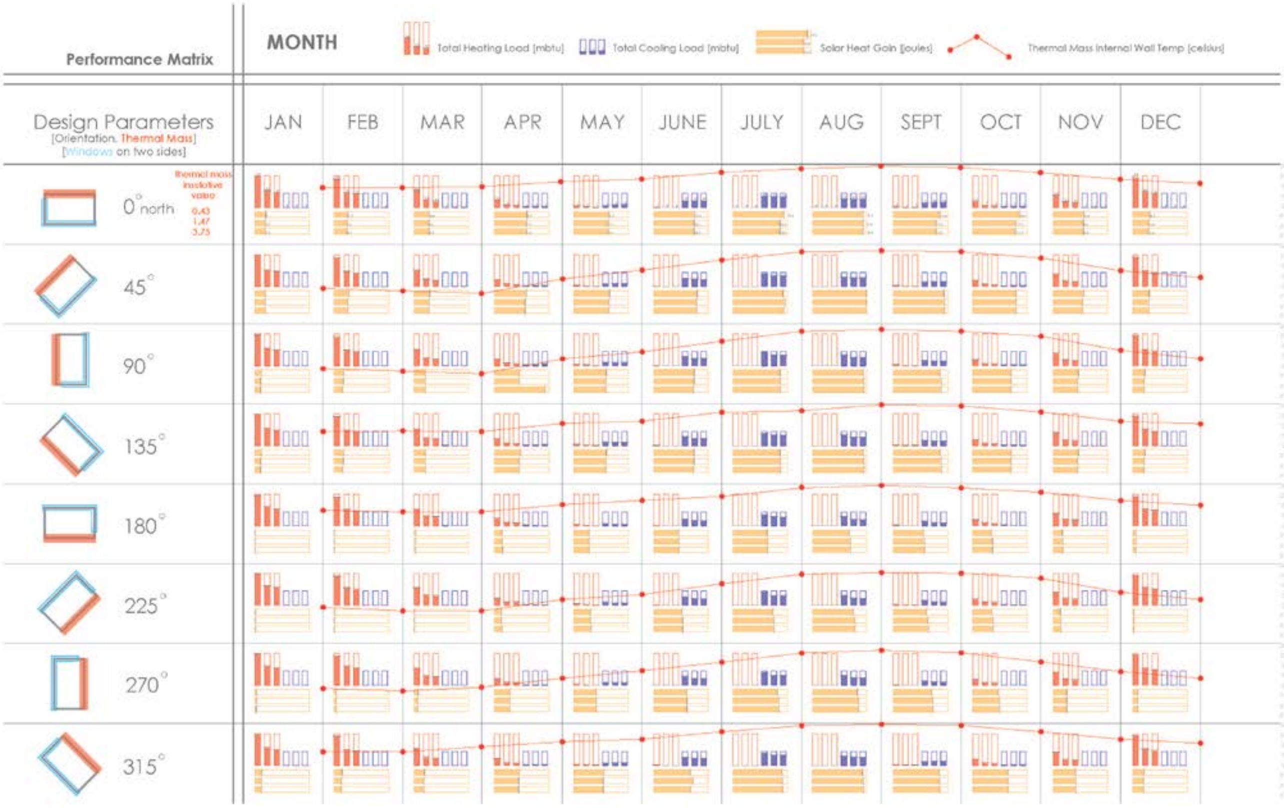

Fig. 1: Example of Project 2 matrix. The simple parametric study of orientation and thickness of thermal mass looked at heating load, cooling load, solar heat gain, and thermal mass wall temperature.

at the time it was offered (Fall 2012), this was the best fit to the course's curricular needs. This toolset uses the robust and validated EnergyPlus simulation engine with a reasonably intuitive graphic interface for both geometry input (SketchUp), simulation object definition (OpenStudio application) and numeric output (OpenStudio Results Viewer). It is also possible to use this tool for conceptual/schematic design without more detailed HVAC system specification, and to create multiple zone analyses. While this tool presented obstacles, it did offer many opportunities for the kinds of explorations desirable for the purposes of the class. Both of these will be discussed further below.

3. DESIGN PROJECT OUTCOMES

The semester design project was the vehicle through which the majority of student skill and understanding developed, and consequently the one in which students spent the majority of their work time. As with the previous assignment, students did not create mechanical systems to achieve desired thermal conditions, but manipulated combinations of envelope and interior loads to create the thermal conditions they desired.

First, working in pairs, students developed a "thermal parti" for a 10,000 ft^2 (929 m^2) architectural office building, which described how they desired the space to function thermally. This charge was intended to be interpreted broadly and creatively (perhaps even slightly absurdly) so long as it provided a thermal-spatial goal toward which they could design. Then, through development of plan and section, innovative program distribution, material selection and organization of internal loads, the students iteratively evolved their design decisions to bring about the desired indoor environment.

The design results from this project were mixed: some students were able to achieve their specific goals of thermal variety within reasonable ranges for the building, whereas some students struggled to achieve *either* variety *or* tolerable temperature ranges. While thermally comfort was interpreted liberally, it had to be unacceptable to develop interior temperature which were hot enough to be life threatening.

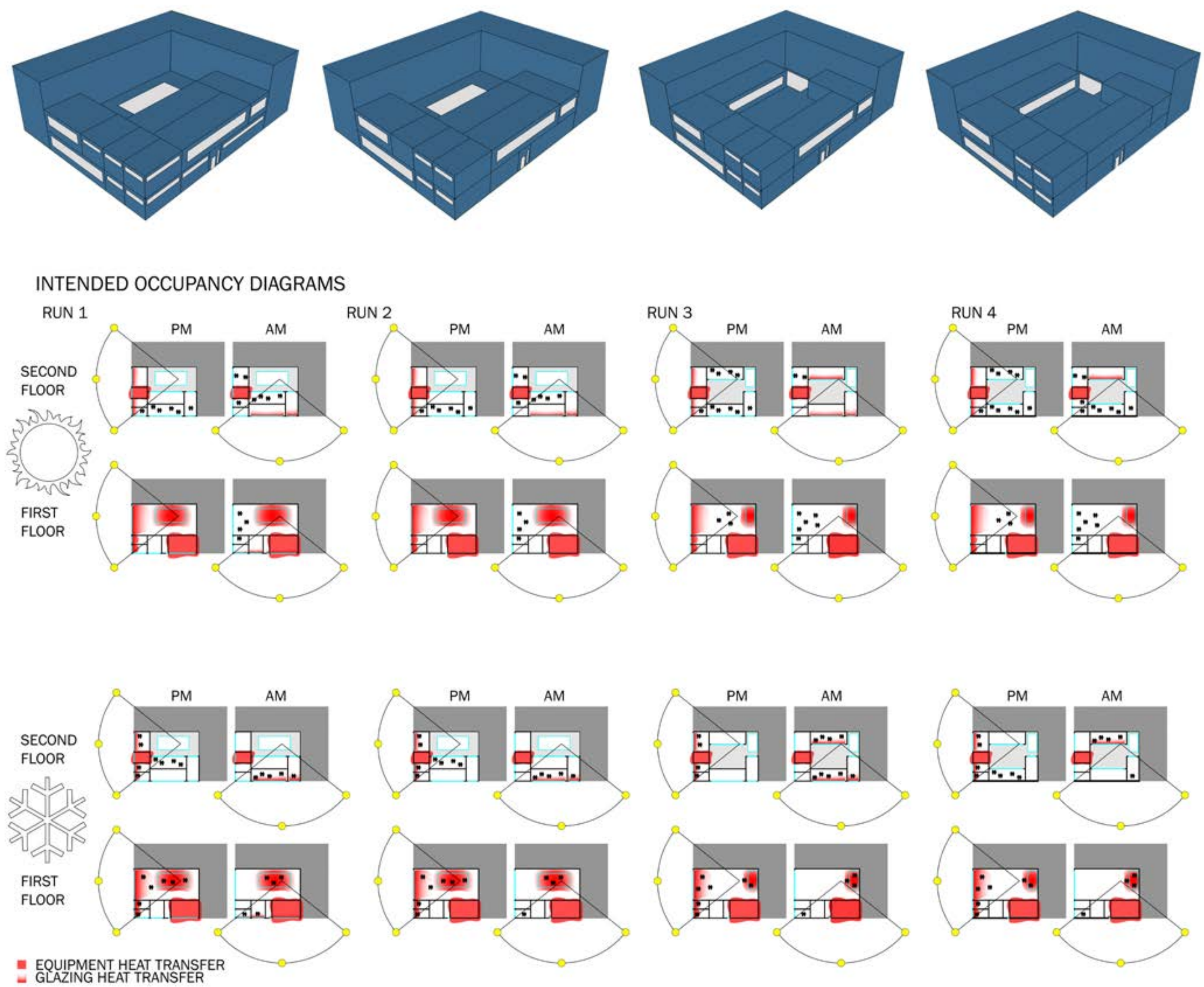

Fig. 2: Diagrams from main design project. This project experimented with daily and seasonal migration of occupants, studied through four different organizational schemes

Some projects relied extensively on large, interconnected open spaces. Because EnergyPlus treats any single zone as having perfectly mixed and thermally homogenous air, this openness obviated any temperature differentiation across the plan or section. The most successful projects tended to utilize design strategies which relied on daily or seasonal migration throughout a cellular building. See Fig. 2 for typical diagrams explaining these design intentions.

For example, pair A developed a scheme whereby the senior staff members were assumed to have left the office by mid-day for client meetings, site visits, or other travel. This meant their perimeter offices did not need to be maintained at temperature after this time period; they were located so that they were only comfortable in morning when occupied. Other members of the staff were expected to migrate, based on shifting temperature conditions as the day warmed and the sun moved around the building. The movement of the staff members was accounted for in the internal loads of these occupied spaces. The students modeled greater staff movement, indeed almost "huddling" in colder seasons, and less in warmer seasons. They found through their simulation that the office could be comfortable during all hours of the year, given the operating parameters they had constructed.

Pair B developed another approach which also relied on daily and seasonal migration. They built a redundancy of spaces into their perimeter zones; e.g. a warm and a cool conference room, a warm and a cool closed office bank, and so on. They similarly found that when the building was allowed to "float" in a larger range of temperatures, there would be a sufficient number of spaces in which the occupant population could find comfortable working conditions without any mechanical conditioning.

Both of these make rather generous assumptions about space efficiency, and this leeway was given to them freely in the interest of their developing workable schemes which were thermally engaging and passively accomplished.

4. DISCUSSION

This seminar course was ambitious in its aims to provide not only experience and knowledge of a new tool, but also to develop in students a very specific and, admittedly, contrived way of using the tool to accomplish a rather unusual task. This was intentional. The course did not set out to be a normative advanced technology seminar in building simulation. Rather, it encouraged students to consciously select the ends to which they use tools. Tools were taught in a setting where students strove to accomplish a self-defined design goal, rather than perform a set of exercises or achieve a particular performance target for a predefined building. It was fundamental to the course to link spatial decisions with performance implications. For architecture students it is particularly critical to develop technical fluency such that tools can be bent to satisfy unique design questions.

As could be expected from a newly created course, several observations were made while developing, teaching, and evaluating this course which may prove useful to others undertaking similar efforts in teaching energy simulation.

4.1 Core Concepts

Students' expertise with the concepts and terminology of building physics visibly improved quickly. While all had a latent understanding of these concepts at the beginning of the semester, the students had to move this knowledge into active knowledge in order to successfully accomplish the coursework. This development was quite evident from the ability of the students to describe and explain their projects and their processes of simulating them. However, in future semesters the course will include a pre- and post-test module to further clarify the development of this expertise.

4.2 Software-based Project Constraints

The parameters which could be explored through the designs of the projects had to be tightly constrained simply because of the capabilities of OpenStudio /EnergyPlus platform. Schemes had to be constrained to deal with conductive and radiative heat transfer, because convective-based passive systems like natural ventilation were not able to be simulated using the OpenStudio application. This created a particular barrier to the students' understanding of their projects in a "real world" context. Several times students had to resubmit their original design concepts not because of any technical improbability, or misunderstanding of building science concepts, but because the software tool could not handle a problem framed in that way. As discussed above, design concepts which involved large open spaces proved problematic, as the division into fewer zones meant less development of the thermal stratification and hierarchy which was desired.

Schemes could not adequately address daylighting integration with thermal concerns; although several of the students had expertise with Radiance simulation from previous coursework, the OpenStudio Radiance interface was not sufficiently developed at the time of this course to integrate with their work.

Perhaps because of these constraints, students ended up experimenting with occupancy and program often, as well as organization of internal loads, and material selection. Interestingly, while experimenting with their design, students did not often attempt to undertake formal exploration though their simulation studies. Perhaps taking the requirements of the assignment to heart, they treated the facades as elements which influenced the interior thermal conditions, rather than as visual design elements. Similarly, plans and sections were conceived as thermal progressions rather than tools for organization of visual sequence. This was admittedly a difficult step for visually-trained architects; some found it helpful to imagine they were designing a space of thermal delight for visually impaired occupants.

4.3 Course Size

The course worked well as a seminar class with 17 graduate students. While for most this was their first course in simulation, it went beyond the basic concepts of simulation, and asked the students to develop a design methodology. This approach may be more challenging with any but the most advanced undergraduate students, who may not have as much experience defining design processes for themselves, and would likely need more methodological guidance as a consequence. It may not work as well with a class much larger than 20 students, where individual help and critique would be much more difficult. If running a similar course for a larger group, streamlined and constrained projects focusing on skill-building rather than design exploration may be more appropriate.

4.4 Quality Control

The course required extensive quality control and troubleshooting of all simulations until the very end of the semester, when the students were fairly experienced had developed sound intuition within the specific project they were working on. It takes significant time to develop an intuition for results, and to methodically check inputs when an unexpected output occurs. The students cannot develop this intuition except with experience over time, and therefore the instructor must provide this quality control for the students throughout the semester. It was an intrinsic part of the course pedagogy to troubleshoot models and results as a group, in an effort to more quickly develop students' intuition and ability to check credibility of results. Also, the experience of this rigorous process encouraged them to develop better simulation habits.

Working through individuals' models works well in classes which run like laboratory sections, with individual machines for each student. However, as the models develop complexity, it becomes more unwieldy to try to unravel curious simulation behavior, and this begins to take more and more of class time. It is critical to establish good simulation habits at the very beginning of the semester in the introductory / skill-building exercises. Also, in future, it will be helpful to have more senior students who have completed the class available to help the newer students get up to speed and check their results.

4.5 Tool Selection

It was challenging to use the OpenStudio software platform while it was still in the development process. Great strides have been made in the development of the tool since its initial release, and it is unquestionably the right tool for the kinds of projects to be attempted in this class. However, the course structure and schedule did not adequately anticipate the kinds of instabilities the group would experience when running large numbers of complex models, and significant time was lost. That said, the development support team was responsive to questions and helpful. I would teach with the tool again.

4. CONCLUSIONS

This seminar course ultimately provided architecture students a tool with which they could productively grapple with design parameters they had not previously had means to explore. To be able to make such an exploration of thermal design in a building they had shaped required a steep learning curve of building science, simulation principles, Energy Plus logic, and OpenStudio workings. The struggle they experienced, while mighty, was a useful one and valuable to their education and work as architects. It enabled them to envision an architecture which is defined by concepts of thermal experience, or of energy consumption, and to iteratively pursue these concepts through to the development of a building. The ability to engage with issues of energy or comfort as designers, not just as analysts, is critical to architects continuing to take on the challenges of high-performance buildings as an ongoing pursuit worthy of study and attention.

There is an even steeper curve ahead to develop a completely fluid design process for architects to reconcile their visual ideas with their thermal or energetic ideas within one coherent process. Until the development of that ideal tool(s), this current working process builds and refines intuition about the principles of building physics as a complex set of interactions which can be evidenced through simulation. This moves beyond using a set of rules-of-thumb which may, be difficult to reconcile one to another. Thus simulation encourages designers to think of buildings as ecosystems, as complex interactions between living and nonliving things. The engagement with this complex behavior is a step toward more energy-literate architects.

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