From Tangibility to Complexity: Integrating Analog Analysis Techniques and Building Performance Simulation in Architectural Design Process

Jihun Kim

School of Technology and Design, New York City College of Technology, City University of New York, New York City, United States of America

Abstract

The paper presents a pedagogical approach to teach building's environmental performance by using tangible architectural analysis techniques combined with complex computer simulations. The aim was to enhance the learning process for simulation-illiterate architectural students. Through interpreting and translating information from one mode of analysis to another, students prioritized what may have affected energy flow, therefore, they could strategize how to assess the given system, helping them to design high-performance buildings.

Introduction

Recent studies on teaching building performance simulation, henceforward interchangeably called BPS, in the US, UK, Australia, and India laid out some important aspects (Hopfe, 2016; Hopfe, Soebarto, Crawley, & Rawal, 2017). They showed that a large portion (87%) of the architects were desired to incorporate BPS in practice, even if most of them (74%) did not currently use it. This was a meaningful message for the industry as a whole in that architects are the ones that typically have the earliest access to the project development when the most potential is poised to be harvested. On the other hand, the study showed two interesting aspects of BPS in higher education: 1) BPS was taught mostly to postgraduate students (50%) significantly more than to undergraduate students (12%), even if undergraduate programs were recognized more suitable, and 2) interpreting the simulation results were more challenging than learning the simulation tools. These aspects were particularly revealing in that data literacy, being recognized as a soft skill, is a more critical skill than simulation tools themselves, confirming our own observations in both design studios and seminar courses for the past 5 years.

The approaches to teach BPS to architecture students are diverse, yet they can be divided by a simple question: whether the performance assessment is outside of the design process or part of it. Considering the most typical practices, it is understandable the prior approach can be found more often, being outside design studio courses. Hence, the pedagogical focus has been on data interpretation and a general understanding of building performance (Reinhart, Dogan, Ibarra, & Samuelson, 2012). In this approach, grouping with engineering students became an evident method to enhance how architects' practices in studio settings (Charles & Thomas,

2010). On the other hand, the performance assessment can be regarded as a part of architects' design practice so that BPS is taught as a design tool. With this approach, architectural students learn BPS in design studios, quantitatively assessing building performance, integrated with qualitative design explorations (Kim, Phillips, & Braham, 2013; Morbitzer, Strachan, Webster, Spires, & Cafferty, 2001). It is an open discussion, which approach may be the more suitable, yet it certainly shows how diverse the role of BPS can be in architectural education systems, resembling the various types of practice models.

Defining the role of BPS may have been started in architectural education. National Architectural Accrediting Board (NAAB), one of the most influential institutions since it grants and accredits professional degrees in the US, addressed the needs of assessment tools by describing environmental analyses in one of the student performance criteria in "Environmental Systems" (NAAB, 2015). It would not be unrealistic that the assessment tools would refer to BPS and other numerically-oriented methods. On another side, the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) have laid out the standards and methodologies to conduct building performance simulation throughout the design processes. Relevant to the architect's interest, it included conceptual design modeling, design refinement, and design integration and optimization (ASHRAE, 2018). This set of standards shall be helpful to establish and solidify the role of BPS in professional practices. What NAAB and ASHRAE laid out can be significant precursors in architectural education toward a sustainable environment and perhaps move educators forward to find a more suitable and effective pedagogical framework for their needs.

In this context, the investigation presented in this paper introduces a pedagogical approach for undergraduate students with architecture majors who were previously not educated with BPS. Notable is we adopted analog analysis techniques in architectural design, including physical model making and diagramming, for tangibility and familiarity to the students. This is aligned with an existing approach in that tangible mediums may promote learning effectiveness for engineering education (Stone & Mcadams, 2000). The analog analysis techniques were considered a bridging mechanism to learn how to model and assess the environmental performance of buildings with computer simulations.

Materials and Methods

The pedagogical methodology in the paper was investigated by the instructors' observation and student surveys of a class in two semesters. As a background, the class has been evolved over the past 10 consecutive semesters by the same instructors. The two most recent semesters in fall 2018 and spring 2019 were focused on their major change with the newly-introduced analog analysis techniques that students were already familiar with through their prior courses. After introducing the course, the author will elaborate on the findings relevant to the subjects.

The overall process began upon students' selection on a building from a provided list, each of which contains exterior shading elements in the envelope system. The envelope system was analyzed in a sequence with 4 modes of analyses: solar tracing diagram on section drawings, physical model making for daylight, computer simulation for daylight, and computer simulation for thermal performance (Fig. 1). Solar tracing diagrams were done solely relying on the student's intuition, approximating what would happen at the building's geographic information. Climate analysis was conducted in advance with the weather data to inform seasonal solar locations. Climate analysis also helped to set up the light source for photographing of the physical model, which led to visual analyses for daylight.

Figure 1: Overall Workflow.

The results from the analog analysis techniques were compared to the result of computer simulations. The point of the comparison was to observe how the shifting among different analysis modes would have helped students to learn the inheritance assumptions in all engaged analysis techniques. At the same time, students were expected to gain a critical understanding of the role of building design components so that they can further apply them to another climatic condition.

- Demography: 35 undergraduate architecture students in a U.S. college, 2:3 gender ratio of female to male, a balanced mix of juniors and seniors, in 9 groups

- Buildings of interest: Siemens HQ in Masdar City UAE, New York Times Building in New York USA, IAC headquarters building in New York USA, Jockey Club Innovation Tower in Hong Kong China
- Simulation tools: DIVA-for-Rhino 4 for daylight, DesignBuilder/EnergyPlus 5.5 for thermal, and Climate Consultant 5.0 for climate analysis.

Simulating Unit System

A small portion of the building was modeled in isolation for analytic simplicity, establishing a unit system that was composed of the envelope and its adjacent indoor space in one structural column bay of a building. An example unit system was shown in Figure 2. This isolated approach was adopted in almost all analysis modes, except for the very last one with the whole building, being situated at an urban site. It was assumed that in the last part of the semester, students had gained confidence and technical skills in running computer simulation, understanding the subject design, and the correlation between the design and its performance.

While switching to another mode of analysis in the sequence, more information was added for increasing complexity and the more required input. Following the solar tracing diagram and physical daylight analysis, the information on building materials was added in the daylighting simulation. For thermal performance, other types of information were added such as occupancy, construction systems, HVAC system, lighting control.

Figure 2: Unit System in Section of the New York Times Building.

Establishing the Base Cases

Two base cases were established as a point of comparison to understand the certain building components and their role in environmental performance. The first base case was in the unit system. Students identified the shading components, which then were hypothetically eliminated and became the base case in Figure 3. This process occurred earliest in the semester, using solar tracing diagrams that later in the process informed computer modeling of daylight and thermal analyses. Notable was that the base case was modeled as a single zone for both daylight and thermal simulation, same as the “Shoebox” model as often used in building simulation practices.

Figure 3: Envelope System of Interest (Left) and Unit System Base Case (Right) of the New York Times Building.

The second base case was in the whole building system that was provided to students at the end of the semester. All team was given with the same building so that the change that each team had made on envelope could be compared to the change of other teams. As shown in Figure 4, an urban context was situated as a design constraint that the student had to respond with the envelope system they studied. The key characteristics of the building are below and in Table 1. For both the unit- and whole-system, the same set of aforementioned simulation tools were used to maintain the capabilities and assumptions.

- 4 story residential row house
- Located at Brooklyn New York (US)
- 20 feet wide and 50 feet deep
- Shared walls on the long sides
- Annual Source EUI: 86.31 kBtu/ft²
- Construction Cost: USD 671,174

Table 1 U-values and Window-to-wall Ratio (WDW)

Walls	Windows	Roof	WDW
1.633	6.121	2.857	23%

Figure 4: Whole Building Base Case.

Physical Model Construction and Visual Analysis

A physical model was constructed by each team for the unit system of envelope design as shown in Figure 5. The base information came from the prepared solar tracing diagrams. Students were asked to consider envelope, interior, and structure, together which constitutes a unit system as a whole. Envelope components, in particular, must have included glazing, mullions, substrates, and shading elements that control heat and light. The model scale was 1”=1’ (=1/12), which was determined for its suitability to study the penetrations of diffuse and direct daylight (Bodart, Deneyer, De Herde, & Wouters, 2007).

Upon the completion of a physical model, students were asked to conduct a visual analysis for daylighting. Students chose a light source that they positioned and angled to emulate solar location at the solstices and equinoxes of the building location. The task was to evaluate how the natural light, being modified by the envelope system, may positively or negatively contribute to the light requirement of the space, considering the building use and the seasons. Comparing back to the solar tracing diagram was another task, rectifying it if needed.

Figure 5: The New York Times Building Unit System Physical Model on Summer Solstice Solar Angle.

Computer Simulation

The unit system of envelope design was further assessed with computer simulations. The goal was to validate the visual analysis of its physical model while expanding the evaluation criteria. The identical geometry was digitally constructed and more information was added such as construction materials as shown. The evaluation criteria for daylight simulation included glare and light level, adopting Daylight Glare Probability (DGP) and Daylight Autonomy (DA) as shown in Figures 6 and 8. For glare evaluation, a set of workstations was provided and situated near a window, which guided students to focus on the influence of the envelope.

The evaluation criteria for thermal simulation included energy use intensity (EUI), heat balance as well as thermal comfort with indoor temperature and humidity. These criteria were applied to both the unit envelope and the whole building system. Notable was that during the geometry modeling for daylight simulation, students were able to identify the missing components in the physical model and added them in for their potential role in daylight performance.

Figure 6: Daylight Simulation Result for the New York Times Building in Daylight Autonomy.

Architectural Design Optimization

In the last process, students were given a task to optimize the envelope design. The goal was to improve the environmental performance of the base case building while applying the envelope that they studied. Due to the given location, Brooklyn, New York, which was in the heating-dominant climate, students immediately identified the obvious, such as the shading components in the envelope may not positively contribute to the overall energy use, even if it may be beneficial for daylighting and for reducing the cooling load. At the same time, the surrounding buildings may cast shadows, limiting solar exposure to the building, adding another challenge for

heating seasons. Therefore, more realistically, minimizing the negative impact was the performance goal of the optimization, while keeping the design integrity.

For the simulation literacy level at this point, having passed the three quarters in the semester, students became somewhat familiar with the tools in that they can independently model with the available resources from the tool developers. Hence, students held responsibilities to implement a simulation strategy on how to assess the performance of the optimized building with regards to effectiveness and computational efficiency in mind. Since they were very familiar with the subject design systems and had already simulated in an isolated domain, assigning the modeling responsibility was considered reasonable.

In the process of optimization, it was very interesting that students had to propose a very significant change in the envelope system design. Responding to the drastically different climate of the site, a team that analyzed on the Siemens Building in a Desert Climate changed its open external shading system in the envelope (Fig. 8) to a closed double-skin envelope system, of which cavity shall work as a thermal buffer for the heating dominant location in New York (Fig. 7). They also proposed to add thermal mass walls inside the cavity to minimize temperature extremes and to make use of stored heat for night time. Some teams showed modest changes, by responding to solar exposure in the microclimate. A team that worked on the NYT building that was already in New York adjusted the spacing of the external shading system to correspond to the varying sun exposure by height. This demonstrated their understanding of the surrounding buildings as constraints before they proposed and simulate their final proposal.

Figure 7: Solar Tracing Diagram of Double Skin Façade for Summer (left) and Winter (Right).

Results & Discussion

Shifting Analyses and Inventing Simulation Methods

During the shift to another mode of analysis, students identified and prioritized the crucial elements in the subject design. This process was crucial for students to investigate capabilities and limitations in each analysis

mode, leading to invent their own assessment methods for the design specificities. Particularly for computer simulations, the student-invented methods were tested for the effectiveness prior to adding more details. One of the common discussions was whether to use internal functions of a simulation tool or to construct elements for a physics-based assessment, especially regarding shading components.

For the physical model of the IAC building as an example, a fritting pattern on the envelope was made by sanding a clear plastic sheet to emulate diffusion of light. In part, students recognized the difficulty to model a large set of micro-scale elements: a numerous circular disk in 1/12-inch diameter in the scaled model. Hence, they explored and discovered the material and technique that could make a similar light effect. This discovery informed how they approached in computer simulations, using translucency for daylight simulation and visual transmittance for thermal simulation. Another group of students, modeling the NYT building, discovered a limitation of the simulation tool. At a certain size, shading elements were not accounted for in DesignBuilder, even if they were visualized properly with shadows. Hence, students decided to switch to one of the internal functions that would emulate the shading effect. Window louvers were adopted and angled to emulate the shading effect of the circular cross-sectional tubes that would work in both winter and summer. These simplified modeling methods would have not generated the most accurate solution, but they were reasonable to approximate the heat balance from solar exposure, allowing them to explore various design options.

Students' Recognition of Analog Analysis

After completing physical and computer simulation of a unit system, students were asked to identify the advantages and disadvantages of using physical model making and its analysis. Below were the responses.

- Advantages: quick assessment once it was modeled; limited types of assessment; once established quick and easy to change the solar angle for different seasons; more realistic and aesthetical ambience due to scale, physical, and 3-dimensional nature.
- Disadvantages: imprecision in light projection from the source; inaccurate solar ray tracing; hard to create material diversity; inaccurate characteristics of the material for daylighting due to the typical material choices; takes longer time in model making.

It was notable that they recognized solar tracing would not be reliable due to the light source and its diverging angle in the photographing. They valued more computer simulation for it was relatively easy to change materials and its potential parametric study.

Another set of questions focused on whether students recognized the role of the analog analysis techniques and their effectiveness in performance assessment and learning of computer simulation.

- Physical modeling and its analysis were useful to strategize how to model in a computer simulation.

54% of students indicated it was very useful and 25% of students useful. 20% indicated neutral, and no students said it was useless.

- Solar tracing diagram was chosen as the most preferable analysis. 42% of students indicated as most preferable, yet physical modeling and computer simulation was in 25% and 23%, respectively.
- Solar tracing diagram was helpful to assess building performance. 29% indicated it was very useful and 58% useful. 11% indicated neutral, and no students indicate it was useless.
- Interpreting computer simulation results became less challenging with physical modeling and solar tracing diagram. 49% indicated that they were "very helpful" and 38% indicated "helpful". 12% indicated neutral and no student indicated "not helpful".

Daylight Analysis to Thermal Analysis

Students were asked in surveys what types of information they would acquire from daylight analysis for being useful in thermal simulation. This question was asked after they completed both analyses to see if they may have been able to approximate it with analog techniques, especially solar tracing section diagrams with their knowledge on the local climate. Below were the three main answers. Understanding the first and second answer, it would not be too far of a stretch that the analysis may further influence their design decision to control the heat gain.

1. Indoor solar exposure and its heat gain
2. Heat storage with building materials
3. Seasonal temperature variation

Building Performance Simulation in Design Studio

Another set of questions were asked for the general usability of BPS in the design process. The first question was whether adopting building performance simulation could be beneficial in design studios. These questions asked twice at the beginning and the end of the course work. As a result, 36% of students strongly agreed and 37% agreed at the beginning, showing the level of the initial interest of students. However, 82% of students strongly agreed and 18% agreed in the end, showing the stark increase in their interest. Notable was there was 27% did not agree at the beginning all turned positively. Potentially, they have come from a lack of prior knowledge and experience.

- 100% of students thought that adopting building performance simulation could be beneficial in design studios.

The second question was on students' own opinions of what features in a BPS were important. Responding to this multiple-choice question, more students chose the knowledge base for decision making (80%) over tool usability (40%) or interoperability with their familiar design tools (13%). This was particularly interesting that they have consistently complained to the instructor about the difficulty and complexity of computer simulation throughout the semester, till the end, yet they thought the capabilities BPS was more important than what could facilitate modeling tasks.

The third question was what types of computational analyses were important to assess the carbon footprint of a building, out of climate analysis, thermal simulation and daylight simulation. This was a multiple-choice question asked at the beginning and end of the semester. There were increases in thermal and daylight simulation by 19% and 23% respectively. All students, in the end, thought the thermal simulation was important. On the other hand, there was a decrease in climate analysis by 14%, not very significant, but it may suggest students had recognized the gap between climate assessment and building performance assessment with it.

Collaboration Challenges in Thermal Simulation

At the beginning of the thermal simulation process, the instructor observed that students identified it was particularly challenging for collaboration as a group. The challenge was inherent in that a thermal zone has to be defined in relation to all other ones. Hence, students recognized thermal simulation as a single-person task, leading to appoint a lead student for modeling, for which others had to wait and take other subsequent tasks, such as visualizing and interpreting the results. The author believed it was not uncommon for any analysis task that may engage in complex tasks. However, it may be very helpful that the thermal simulation tool would have been developed to allow distributing the workloads in modeling given it was found the most time-consuming.

Later in the process, the design optimization with the whole building system, using thermal simulation became less challenging and every student in a group was able to

work independently to analyze a new solution that each student came up with. This observation showed the presented approach worked appropriately even if it seemed very challenging at the beginning of the thermal simulation.

Conclusion

The proposed pedagogical approach was in line with a trend in architectural education for the past 10 years in the US and internationally. It aimed to enhance the learning experience of students who had a diverse educational background. Analog techniques were adopted for its tangibility and familiarity in the architectural design practices. The study showed that the analog techniques helped to build up students' intuition to approximate the building performance, especially by switching back and forth from computational analyses. The proposed approach uncovered the necessary challenges in how to teach performance simulations for design studios, considering the counter-intuitive results and time constraints.

Another aspect of the approach was to incorporate what was typically taught in studio teaching: design exploration. After going through the learning cycle from simple diagramming to complex simulation, the major building component of interest, the envelope system design, was further exploited and optimized for another building. In this process, the value of diagramming was reinstated for its readiness and flexibility for the expanded scope with the performance approximation.

Figure 8: Section Diagram, Physical Model, and Daylight Simulation of Siemens HQ.

The proposed approach increased the overall learning effectiveness through the combined use of the tangible medium and the persistent intuition refinement. The conducted survey showed that the confidence of students was significantly improved in the result interpretation and intuitive approximation for daylight. More students recognized the connection between design and performance, while most students identified the more need to use performance simulation. It was important to note that the students' approximation showed noticeable discrepancies from their thermal simulation results. As a remedy, students and the instructor examined the relationship between the input and output of the simulation and identified what would have caused them. The main causes were identified to warrant further developments in the approach: 1) complexity in the whole building analysis and its simulation and 2) whole year weather data that disproportionally affected heating and cooling load, 3) inhomogeneous thermal conditions in the building.

As future work, it seemed logical to expand the application of the combined analysis method to other design areas than the building envelope, for its demonstrated effectiveness in student learning. This may include building morphology studies and site analyses, for which physical models and solar tracing diagrams were among the common exercises in university teaching and professional practices. Yet, considering the time constraint in 15 weeks a semester, it would be better to have them in another course in the sequence.

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