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LEARNING BY PLAYING – TEACHING ENERGY SIMULATION AS A GAME

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ABSTRACT

Being able to read thermal simulation results and to adapt one's design accordingly has become an essential skill for graduating and practicing architects. This paper proposes and evaluates an innovative way of how this skill can be taught via a 90-minutes in-class exercise or 'game' based on DesignBuilder/EnergyPlus. The game was tested in a class of 47 architecture students who competed to generate the lowest Energy Use Intensity (EUI) for an office building in Boston. Design upgrades were associated with a cost premium and the overall upgrade budget was capped. The EUIs of the ten final submissions were 22 to 31% below the base variant. While student essays revealed a clear preference for game-based learning vis-a-vis conventional teaching methods, the authors further propose that the game nourishes the emergence of an energy modeling 'culture' within schools of architecture that may lead to enhanced communication between architects and energy modelers.

INTRODUCTION

Following the rising market uptake of green building rating systems such as LEED (USGBC 2009), the use of energy simulation tools to support the design process of a building is becoming increasingly common. Unfortunately, the cost and time effort required to conduct and document energy simulations tends to delay the use of simulations to later design stages at which point they serve more as a post-rationalization of a design. This practice diminishes the effectiveness of energy models, as there is a widely shared believe within the modeling community that the early use of simulation tools yields to more cost and energy effective design solutions (Samuelson *et al.* 2011). However, even architects who are committed to 'building green' and who are thus commissioning energy simulations during schematic design, often face the impediment that they do not know how to read and act upon the outcomes of energy simulation. As a consequence the dialogue between architect and energy modeler/consultant frequently pivots around a single number, namely the percentage of energy saved according to ASHRAE 90.1 Appendix G (ASHRAE 2007). The significance of this number is that it translates directly into the amount of points for which a project is eligible under the LEED Energy and Atmosphere Credit 1. However, this may not be the best metric for choosing the best performing design. Instead, other simulation results such as monthly and hourly fuel breakdown and heat balances have to be considered as well if a design team wants to *improve* the energy performance of a design variant. One might rightfully argue that it is the energy consultant's role to translate simulation results and their significance to the rest of a design team. However, such a hands-off attitude on behalf of the architect, who directly or indirectly pays for the energy model, bears the risk that the architect either ignores the consultant's advice because he or she does not fully understand it or the energy consultant effectively takes over key design aspects of the building. Both scenarios seem less than desirable for the architect. The message, which the reader should hence take from this, is that it truly is in the interest of the architect to develop a working knowledge of typical energy simulation outcomes. This does not suggest that the architect should carry out the energy simulations him or herself or otherwise 'take over' the role of the engineer, but rather that the decision-making members of the design team should learn how to *read* basic energy simulation outcomes and how to *adapt* their design accordingly.

In the authors' opinion, these two skills nowadays constitute a key marketable ability that any graduating (and practicing) architect should possess. Reading the outcome of simulation results is rather easy to teach using a traditional lecture format. Applying this knowledge requires a more hands-on educational approach. This paper hence proposes and evaluates an innovative way of how the use of energy simulation results to modify design choices can be taught to architectural students in a playful but effective manner via a 90-minutes in-class 'building optimization game'.

The game approach differs from previous approaches of teaching building performance simulation (BPS) to architectural students. According to standard building science textbooks and course syllabi, introductory environmental technology courses for architects tend to cover BPS in passing if at all. Architectural students typically learn that building energy models exist, what the names of widely used BPS programs are and how simulation outcomes "look like" (pretty picture approach). Most of these students probably feel afterwards that BPS is the exclusive domain of consultant engineers and does not require their intellectual involvement. For the small percentage of students who show more interest in the topic, some schools offer specialized, semester-long BPS seminars. A literature review of these seminars by Charles and Thomas (2009) yielded that such courses typically focus on physical principles and equations rather than on the use of BPS in the design process itself. In order to fill this gap, some instructors have linked their BPS class to an architectural studio, asking the BPS seminar students to act as "consultants" for the studio students (Charles and Thomas 2009). These architecture-engineering collaborations are laudable but time consuming. They also only reach a few architectural students with a strong interest in environmental design. In contrast, the role of the game approach promoted in this paper is to emphasize that even though architectural students do not necessarily need to know how BPS programs work in detail, they should *all* understand what type of information these programs can generate and that their design might have to react to the simulation results. Given that architectural colloquia are already saturated with content, the challenge for the authors was to effectively communicate this message in a single lecture.

During spring 2011 the game was tested in a class of 47 professional degree architecture students at the authors' home institution. The initial inspiration for the game came from an educational session at the GreenBuild 2010 conference taught by Kim Shinn of TLC Engineers and Kirk Teske of HKS Inc. During that session, participants (mainly engineers and energy consultants) competed in two groups to design the more energy efficient office building in Chicago, IL, USA. Teams were given the choice of five building shapes, three building orientations, five envelope modifications, and two internal load options. The game consisted of four distinct rounds, and after each round, session helpers simulated each team's design in eQuest (Hirsch et al. 2011).

Building on this idea, the authors further developed and adapted the game for a university level course. Following a detailed description of the modified game, the resulting student designs are presented below along with essays written by the students on how they used the simulation results and how they perceived the game as an educational method. The discussion section describes how the game could be improved over time, what its educational merits and limitations are, and how it could be used by other building science educators.

METHODOLOGY

Game Description

As mentioned above, the game was introduced as a 90 minutes exercise as part of a semester long required introductory class on *environmental technologies in buildings* for first year architectural students in a three and a half year professional degree graduate program. The class content included basic phenomena of heat flow, lighting and acoustics and largely resembles what is being taught across North American schools of architecture as part of the NAAB requirements (NAAB 2010). The objective of the game was to reduce the simulated Energy Use Intensity (EUI) of an office building in Boston, MA, USA with a floor area of 2940m^2 (31,600 ft^2). The students were divided into ten groups and the group that submitted the design with the lowest EUI after 90 minutes was awarded 10 extra credits on their final course grade. The students could choose between eleven buildings massings (Figure 1), eight orientations (rotated in 45 degree increments), a large variety of building envelope configurations and multiple electric lighting and control systems for a total of over 400,000 possible design choices. Table 1 summarizes the choices for roof and wall insulation, window-to-wall ratios, glazing types, exterior shading, lighting power densities and automated electric lighting controls. The values for the base variant were mostly selected according to ASHRAE 90.1-2007. Differences were that Table 3.1.1.A in ASHRAE 90.1 requires VAV system 6 or 8 for non-residential building above 2.300m^2 whereas DesignBuilder version 2.4 only supports one air handling unit per building. Given that LEED also uses ASHRAE 90.1 as a baseline for its energy credits, the simulation results somewhat emulated what one might see within the context of a typical LEED project. The eleven building massings are supposed to represent "realistic" choices that architectural students might make for the investigated office building. The design choices from Table 1 were selected because (a) they can be quickly altered using the DesignBuilder interface and (b) they represent core choices that design teams are typically confronted with.

Table 1: List of Design Choices

Description	Properties	Cost Premium [GSD$]
Roof Insulation		
R-value R20[#] (base)	U-value=0.284W/m^{2}K (continuous above deck)	0
R-value R30	U-value=0.187W/m^{2}K	$
R-value R40	U-value=0.131W/m^{2}K	$$
R-value R60	U-value=0.091W/m^{2}K	$$$$
Exterior Wall Insulation, Nominal		
R-value R11.4c.i. (base)	U-value=0.551W/m^{2}K	0
R-value R19.5 c.i.	U-value=0.346W/m^{2}K	$
R-value R28.5 c.i.	U-value=0.193W/m^{2}K	$$
Wall-To-Window-Ratio (WWR)		
Punched Openings	WWR20	-$
Punched Openings (base)	WWR40	0
Punched Openings	WWR60	$$
Curtainwall	WWR80	$$$$$
Glazing Type		
Double-Pane, no coating, Argon (base)	VLT=0.7; U=0.55; SHGC=0.57,	0
Double-Pane, Low-εs2 Coating, Air-Filled	VLT=0.75; U=0.35; SHGC=0.63,	$$$
Double-Pane, Low-εs2 Coating, Argon-Filled	VLT=0.65; U=0.24; SHGC=0.38,	$$$$
Double-Pane, Low-εs3 Coating, Argon-Filled	VLT=0.65; U=0.24; SHGC=0.27,	$$$$
Exterior Shading		
None (base)		0
Shallow Overhang	0.5m deep	$$
Deep Overhang	1m deep	$$$
Electric Lighting Power Density (LPD)		
Base	12Wm^{-2} during business hours	0
Low	9Wm^{-2} during business hours	$
Photocell Controlled Daylight Sensors		
None		0
Installed	Dimming in 0 to 45m perimeter zone; target level = 300lux.	$
Occupancy Sensors		
None		0
Installed	Reduce LPD by 10% during all occupied hours (ASHRAE 90.1-2007, Table G3.2).	$

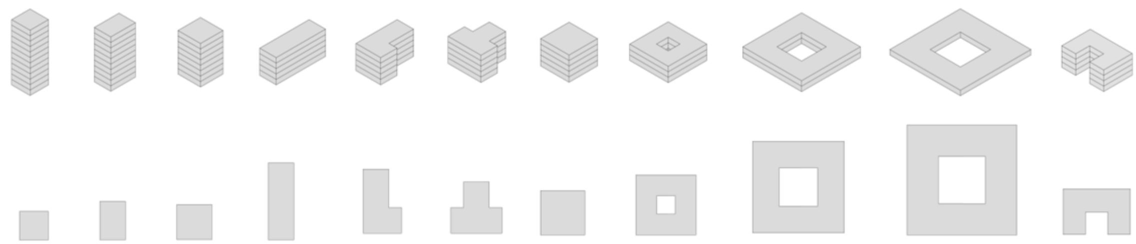


Figure 1: Eleven building massings.

In order to add further realism to the game and to avoid participants simply picking the most advanced alternative for each design variant, construction costs were introduced as an additional design restriction: Valid submissions were only allowed additional construction costs of up to nine “GSD$” (Graduate School of Design $), which reduced the pool of admissible design variants to 88,440. The idea behind using a fictional currency was to give the students a general feeling for the relative cost implications of the various design upgrades without going into overly complex detail. The cost premiums were chosen as follows. Building massing and orientation were assumed to be cost-neutral. Roof, exterior wall and glazing type were given premiums between one and four GSD$. The base window-to-wall ratio (WWR) was 40% and game participants got some ‘money back’ if they went with a 20% WWR or had to pay a premium of up to five GSD$ for an 80% glazed WWR curtain wall. Exterior shading systems that spanned the whole facade were priced between two and three GSD$ and various electric lighting upgrades could add up to three GSD$. Although extremely simplified, the authors intended these costs to have some real world meaning relative to one another. Therefore, the cost premiums (in GSD$) were loosely based on cost information found in Leach et al, 2010. For simplicity, the cost premiums remained static even though in reality, one design choice, such as window-to-wall-ratio, would affect another cost premium such as glazing type. The critical reader might rightfully accuse the authors of grossly oversimplifying actual cost implications by e.g. pricing all massings equally even though they had significantly different total facade areas. The reasons for this choice were to motivate the architectural students to first explore building form, which is their original domain, and to then develop a feeling for the pros and cons of various energy upgrades.

In order to avoid the need for separate primary conversion factors for electricity and gas, it was assumed that the office building was fully conditioned using a packaged single zone heat pump system with separate mechanical ventilation. This also helped to surmount the limitation of DesignBuilder to model more than one AHU per building when using a VAV system as required by ASHRAE Table G3.1.1A. Ground temperatures were manually calculated using the SLAB model in EnergyPlus for all building forms. Window assembly properties were calculated using Window 6.3 (LBNL 2011)).

Simulations

All simulations were conducted by a pool of ten 'simulation experts' using preconfigured DesignBuilder/EnergyPlus models (DesignBuilder 2011). The students were not asked to carry out the simulations themselves, not only to save time, but also because architects would typically not do this in practice either. Another reason was that the main educational goal of the game was to teach the students how to read simulation results and to adapt their design. The 'reading' of simulation results was taught to the students in a previous lecture. During the game, the students were asked to complete two page 'simulation order forms' that included their design choices from Table 1 plus building orientation and massing (Figure 1) to a pool of ten simulation experts. The experts would then set up and run the simulations in DesignBuilder and email the students the resulting annual EUI as well as monthly fuel totals and energy balances. An example DesignBuilder output is shown in Figure 2 for the base variant. The massing of the base variant was the U shaped rightmost variant shown in Figure 1 with the opening of the U facing South. The EUI of the base variant was 138 kWh/m^2 yr.

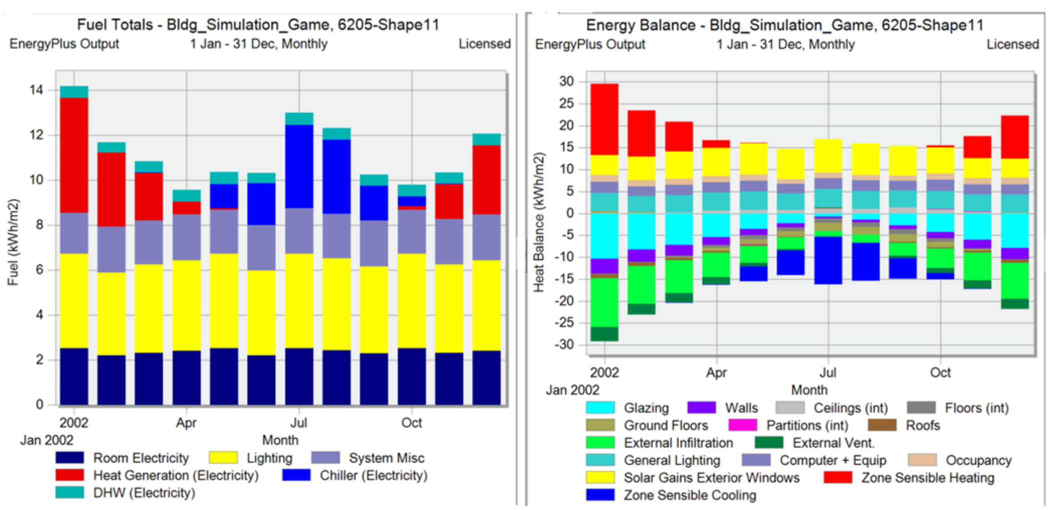


Figure 2: Simulation results for the base case.

DesignBuilder was chosen because it is already being taught in advanced classes at the authors' home institution so that a pool of individuals could be recruited for the game who could function as simulation experts. Other advantages of DesignBuilder are that it is based on a reliable simulation engine and allows the user to quickly generate graphics that can be used to interpret simulation results. For example, the graphics from Figure 2 came straight out of DesignBuilder.

The ‘simulation experts’ were volunteer students most of whom had previously taken a full semester course on energy simulations. For the sake of quality assurance and speed, the authors generated simulation templates of the eleven building forms, each with a premade library of the game’s design choices, before the game. As a result, each of the over 400,000 design variants could be prepared in less than three minutes. The simulations themselves ran for about three to eight minutes on the first author’s laptop. In order to avoid that a student group would be disadvantaged because an expert was experiencing computer problems or had a slower computer, the ten experts formed a ‘simulation queue’ to which the ten students groups could submit one simulation variant at a time on a first come first serve basis. The student teams presumably used the results from one simulation to select their next design variant. This continued throughout the 90-minute game.

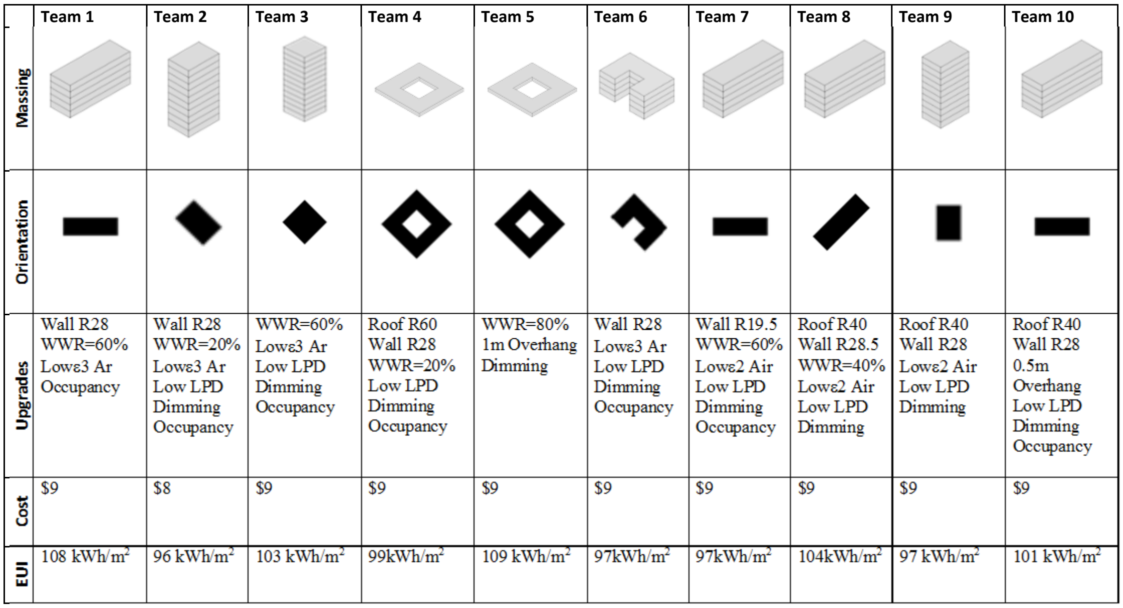
Student Evaluations

Following the game, the ten student groups were asked to prepare brief 3-minute presentations for the following class as well as an essay on the strategy that led to their intermediate simulations as well as to their final design proposal. They were further asked to reflect on what they had learned during the process, what they would do differently next time and how effective they found the Building Simulation Game as a teaching method.

RESULTS

Figure 3 shows the massings and orientations of the final designs along with the design upgrades, cost premium and EUI. It is interesting to note that the building massings chosen by the different groups diverged significantly revealing that a performance-based design analysis does not necessarily lead to converging architectural solutions.

Figure 4 shows the simulation results for all design variants explored by all groups. The groups managed to investigate between 3 and 10 design variants with an average of 7.5 variants per group. Group 9 only completed three variants because they started with a design with large external shading elements and daylight dimming controls, two choices which inherently take longer to compute than other design variants.



	Team 1	Team 2	Team 3	Team 4	Team 5	Team 6	Team 7	Team 8	Team 9	Team 10
Massing										
Orientation										
Upgrades	Wall R28 WWR=60% Lowε3 Ar Occupancy	Wall R28 WWR=20% Lowε3 Ar Low LPD Dimming Occupancy	WWR=60% Lowε3 Ar Low LPD Dimming Occupancy	Roof R60 Wall R28 WWR=20% Low LPD Dimming Occupancy	WWR=80% 1m Overhang Dimming	Wall R28 Lowε3 Ar Low LPD Dimming Occupancy	Wall R19.5 WWR=60% Lowε2 Air Low LPD Dimming Occupancy	Roof R40 Wall R28.5 WWR=40% Lowε2 Air Low LPD Dimming	Roof R40 Wall R28 Lowε2 Air Low LPD Dimming	Roof R40 Wall R28 0.5m Overhang Low LPD Dimming Occupancy
Cost	$9	$8	$9	$9	$9	$9	$9	$9	$9	$9
EUI	108 kWh/m²	96 kWh/m²	103 kWh/m²	99kWh/m²	109 kWh/m²	97kWh/m²	97kWh/m²	104kWh/m²	97 kWh/m²	101 kWh/m²

Figure 3: Final submissions.

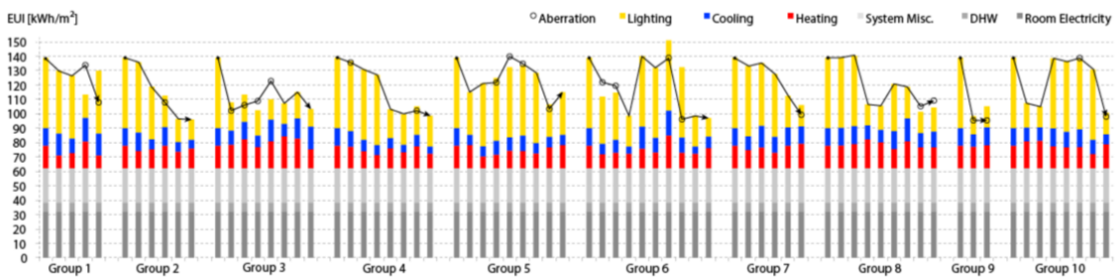


Figure 4: Simulation results for all groups. Hollow circles indicate that an incorrect simulation result was reported to the students (see Results section).

As a quality control measure, all simulation results were reproduced by one of the authors in order to detect any errors that might have happened while the experts ran the simulations during the game. It turned out that in 23 out of 62 simulations the experts reported wrong simulation results. In 5 cases the relative mean error was larger than 10%. One recurring error, that could be avoided in the future, is that an incorrect building orientation angle was entered in DesignBuilder by the experts. This happened because there was an inconsistency in the game instructions that was clarified at the beginning of the game but that still lead to confusion among some of the experts. In 14 cases the source of the simulation errors could not be identified through the quality control process. The colored bar charts in Figure 4 show for each variant the *correct* simulation result whereas the black lines show the results that were *reported* to the students. Within the context of the game, the only important errors which probably lead to misguided design decisions can be found for Groups 1 (last two variants) and

Group 6 (eighth variant). Out of these two cases only Group 1 was truly misguided in that they were made to believe that their last variant was substantially better than the one before whereas the inverse is in fact true.

Group Strategies

Based on the group presentations, essays as well as the results from Figure 4 it can be inferred that all groups did know how to read and interpret the simulation results provided to them. Recognizing that their time and simulation variant budget was limited, the groups developed a number of different strategies to interpret the simulation results and to come up with better design combinations.

A common strategy among all groups was to first concentrate on massing and orientation by exploring one or more variants that the groups expected to yield superior results. Many groups then realized that electric lighting was responsible for a significant portion of the energy balance of the office building. By living in Boston the students had an intuitive understanding that heating and cooling loads are significant as well. After deciding on a suitable massing, several groups hence first concentrated on various combinations of insulation upgrades to reduce heating and cooling loads. Finally – if their remaining budget allowed for it – they explored various electric lighting saving options. A few groups tried to ‘scientifically’ figure out the isolated effect of an individual design upgrade by running simulations with a single design upgrade at a time. This strategy proved to be rather ineffective within the context of the game since only a very limited set of simulations could be run within ninety minutes. The authors would argue that this strategy does also not make much sense in real world situations since simulations are expensive. In addition, a key strength of simulations is that they allow one to study the combined effect of various energy conservation methods (ECMs). To further the point, many students were surprised when combinations of several strategies did not necessarily provide expected outcomes. One recurring area of surprise (and suspicion) among the students was that increased insulation levels did not always improve the overall heating and cooling balance of the building. This is because an internal load dominated building in Boston may partially benefit from heat losses through the building envelope to avoid overheating. The design upgrade that caused the most confusion was the glazing option, especially the last two options with the low-ε coating placed on the second or third surface, respectively. While the theory behind window coatings had previously been covered in class, it was only through integrated simulations that the relevance of these coatings was fully acknowledged by the students. A takeaway from the exercise, that several groups mentioned, was that building massing and orientation has a sizeable effect on building energy use. This realization might seem trivial for the reader but for architectural students it can become a key motivator for engaging with energy modeling tools.

Student Feedback

In their essays all groups reported that they enjoyed the exercise and found the game to be an effective and engaging teaching method. At the same time, there was a ubiquitous feeling that the 90 minute game had been too short and hence resulted in a fair amount of guess work. In order to improve future versions of the game, the students recommended a series of smaller pre-game exercises that exposed them to only a few design variants at a time. Another idea was to provide them with a catalogue of the effectiveness of various ECMs in different building-types and climates.

DISCUSSION

The EUIs of the ten final designs were 22 to 31 percent below the base variant showing that the game succeeded in teaching students how to systematically adapt their designs based on energy modeling results.

At least eight of the student groups realized from the fuel breakdowns (Figure 2) that electric lighting use for the base variant was substantial (35% of the total energy), triggering them to invest in various lighting upgrades. In contrast, only two groups referred to results from the monthly energy balances, and none of them commented on monthly patterns specifically. The essays further suggest that the analysis of the insulation upgrades was largely driven by the students' everyday experience in Boston's cold climate rather than by a systematic analysis of how building envelope elements affected monthly heat losses and gains. The students’ choices for building massing and orientation were equally based on general rules of thumb such as that a building should maximize its South-facing surfaces. Energy simulation results were thus more used in an integrated fashion over the year instead of on a monthly basis to confirm one’s intuition. The failure to inspect monthly energy balances actually resulted in the above mentioned confusion as several groups could not accept that increasing insulation levels beyond a certain point in a building with high internal loads may have a detrimental effect on energy use.

The Emergence of a Modeling Culture

The students (and the authors) agree that the game was a success as a teaching method partly because the game itself caused an intensity and level of engagement in the classroom that is typically encountered in studio reviews rather than in a lecture course with close to fifty students. There clearly was an ‘energy’ in the room. Additionally, private communications between the authors and the students suggest that the experience of the students seeing their peers conduct the simulations sparked an interest in learning more about energy modeling software. The indirect benefit from the game is hence the emergence of an energy modeling ‘culture’ which lends new meaning to the concept of evidence based design. The authors feel that with the interest in energy simulation potentially comes a feeling of empowerment among the architects that they can start validating their own designs.

A critical reader, who is aware of the complexities of energy simulations, may cringe at the idea of an incoming generation of architects who think that they can model their buildings. These architects might even think that they do not need the engineer any more. The authors hope to diffuse these anxieties with the following arguments.

Architects have been learning the concepts of structures for centuries but there is little fear among structural engineers that architects intend to put them out of business. In contrast there is a rich history of professional friendships between significant architects and structural engineers. As we learn more about a subject we become better at understanding our own limitations. Similarly, one may anticipate a direct benefit to the energy modeler. Working with an architect who has a basic understanding of the field will allow the intellectual exchange to rise to a higher level. This is especially true because, while many energy efficiency measures such as natural ventilation and daylighting are difficult to model, the simulation output for all levels of complexity remain largely identical to the ones shown in Figure 2.

Online Tool or Modeling Experts?

One certainly disconcerting result was the high error rate of over 30% among the simulation experts given that the authors had tried to reduce the modeling effort to a minimum via a series of simulation templates. There was even a practice session a day before the game during which all experts were briefed in detail about the modeling process. Even if one blames the sobering high error rate on the ‘pressure’ that the experts experienced in setting up a simulation within minutes with several anxious ‘clients’ breathing down their neck, the fact remains that the feedback from the simulations was in some instances wrong which obviously defeats the purpose of the game.

One possible approach to reduce the simulation error rate would be to convert the game into a simple online tool for which the simulation results are pre-calculated and for which the students could enter the desired variants themselves and get instant feedback. That way the number of techniques that game participants can evaluate could be significantly widened as one could set up more complicated simulations including time-consuming natural ventilation and advanced daylighting studies. An online tool would also make the tool accessible to architecture schools that lack a group of internal energy modeling experts which is currently probably the majority. An alternative to recalculate online results would be easy-to-use schematic design stage tools such as ComFen (Hitchcock 2008), Daylight123 (Reinhart *et al.* 2007) and Coolvent (Menchaca-B and Glicksman 2008) and others.

While these are all solid arguments for an online tool, the authors ultimately feel that having a simulation expert conduct the simulation in person and in the same room as the ‘consumers’ of the simulation results adds a unique human component to the game. There is a benefit in game participants having to wait for simulation results and in talking to each other in the meantime. If they could instead carry out a very large number of simulations they might be less inclined to think about the meaning of previous simulation results and rather just investigate another variant. In that scenario game participants would learn less about building science and more about how to behave as an optimization algorithm. Another danger of an online game is that the students would probably start running many simulations in parallel trying to maximize the number of simulation variants run rather than the number of ideas exchanged among them. This behavior was in fact observed by the authors during a second simulation game that was done with the same class later in the semester. During that game the students were given a simple natural ventilation simulation program to address the problem of overheating in an office building. The results from the second game will be reported in a future paper.

A final argument for continuing the use of simulation experts is that in real life setting up a large number of simulation variants quickly becomes prohibitively expensive.

Therefore, if one decides to stick with the concept of simulation experts, better quality control is required in future versions of the game. For example, a copy of each DesignBuilder file could be saved before a simulation is run and the modeler could double-check the simulation inputs while the simulations are running.

Analysis Framework

Even if the duration of the game was extended to say three hours and if the simulation error rate was significantly reduced, students might still feel that there is a considerable amount of guesswork involved in the process. This suggests that what is ultimately needed is a framework of how to systematically evaluate simulation results and act upon them to improve a design. The lack a widely shared framework or theory to do so is somewhat disconcerting. It reinforces the fact that the building performance simulation research community has to date been nearly exclusively focused on how to model physical phenomena in more detail while rather neglecting how the results of those energy models can directly inform design. What should a designer look for in a fuel breakdown and energy balance diagram and what are suitable design measures? How much change can one expect from changing the massing or orientation rather than adding a specific technology? The authors do not want to suggest that such a framework does not exist at all, for example in the form of an intuition acquired by many professional energy modelers. In fact a provocative quote by an eminent energy modeler and consultant at the authors’ home institution is that ‘one should only simulate a building science problem unless one already knows the result'. One would not necessarily expect an energy consultant to write up such a framework as it would be a dubious activity from a business standpoint. However, the fact that no widely shared simulation analysis framework has been generated to date by the research community constitutes an oversight. If simulation games such as the one described in this document were to become common at schools of architecture, where people actually focus on the *design* of buildings, it is more likely that such a framework would emerge over time. One could argue that instead of using such a framework and carrying out a whole series of simulations, a designer could simply consult a catalogue that describes the most promising energy efficiency measures in different building types and climates. The authors feel that such a catalogue could effectively complement energy simulation models. Still, there remains an educational value for the students to experience a probing period and to discover and internalize for themselves that (for example) electric lighting plays a significant role in the energy balance of an office building in Boston.

Game Availability

The simulation instructions and DesignBuilder files used for the game described in this paper are available from the first author. As a final note it is worthwhile stressing, that if a building science educator decides to use the game in the classroom, it is of paramount importance that the instructor completely understands the assumptions underlying the simulations so that he or she can distinguish between a fundamental building science result and a simulation artifact. E.g. in the game's default DesignBuilder variants the electric lighting use was determined through schedules. This means that electric lighting energy use did not change for different massings and orientations since all variants had the same floor area and lighting power density. This is important to explain since the students might rightfully find it 'suspicious' if electric lighting use is not affected by building massing and orientation.

CONCLUSION

This paper introduced a new game-based exercise to introduce architectural students to the use of energy simulation during the design process of a building. Based on a test run of the game in a class of 47 students, the authors recommend the game as an effective teaching method that truly engages students and triggers their interest in building energy modeling. Going forward, such games could be taught in two ways: Using simple online, schematic design type software that the students can use themselves or using more advanced programs that are run by simulation experts. The former case allows students to use the programs in their studio projects. In the latter case, the students get exposed to real world design processes in which energy consultants will run simulations for them and they have to apply the results to their designs. While seeing their 'expert' peers running the simulations, they might get inspired to learn how to use the advanced tools themselves. This process can nourish an energy modeling culture within a school. In either case, quality control of the simulation results is a key factor to consider. The game has revealed that – in order to avoid students just guessing what design combinations might work – there is a need for a more systematic, theoretical framework of how to effectively use simulations to influence design choices. This task becomes of course even more challenging once aesthetic, urban, programmatic and/or other concerns are introduced that start 'pushing' back against optimal energy solutions.

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