Integrating Building Performance Simulation in Studio Teaching: A Multidisciplinary Consultancy-Based Model

PATRICK CHARLES

Roger Williams University

CHARLES THOMAS

Roger Williams University

INTRODUCTION

Increasingly, society, the profession of architecture, and the accreditation bodies demand that architecture programs deliver graduates with a demonstrable ability to design buildings with a light environmental footprint. Along with precursors in the field, we see building performance simulation (BPS) tools as a means toward that end both in the world of architectural practice and within architecture education (Clarke & Maver, 1991, Degelman & Soebarto, 1996).

Our question is how should BPS tools be integrated in undergraduate education? Our method of investigating this question has been to experiment with various teaching setups, independently at first and now collaboratively. This paper outlines the design, implementation, and outcomes of a teaching setup that we delivered during the spring of 2009. The latest in a series of experimentations with integrating BPS in architecture education is a two-component multidisciplinary collaboration. The students in an introductory course in BPS and Data Acquisition (DA) co-taught by the authors, an architect and an engineer, acted as consultants to an advanced undergraduate studio taught by the architect co-author of this paper.

The review of the literature in the field casts light on what constitutes the contribution of the outlined teaching framework. Co-teaching by architect and engineers, teaching to classes populated by both architecture and engineering students, introducing BPS to undergraduate students for analysis purposes, teaching rudiments of DA techniques to undergraduate students in post occupancy evaluation, setting up collaborations between architects and engineers in the architecture studio, or using BPS tools in the architectural design studio context are all fairly common occurrences in academia. We argue that blending all the above components along with a targeted and proactive use of BPS by consultants outside of studio as implemented in our teaching approach constitutes a contribution to the field. Also worthy of notice are the consultant-designer framework as well as the goal of grounding the BPS modeling into physical and experiential reality by means of a mix of various data acquisition activities.

The outcomes and observation section of the paper examines students' feedback and enumerate lessons that can be drawn from this teaching setup. The question of when and how BPS should be associated to a design effort are examined, The accent will be placed on reinforcing the idea that at the undergraduate level, the goal should be to use BPS to help students to develop an interest and an intuition in physical phenomena in buildings, along with an understanding of the iterative and collaborative nature of the design process. Absolutely key to the success of such a proposed multidisciplinary consultancy-based model linking a studio and introductory course in BPS is the notion that the BPS-capable students acting as consultants to the studio designer have to adopt a proactive approach. The proactive BPS consultant tests various "what if" scenarios on the basis of simplified BPS model made of just one or a few zones. The consultant introduces these ideas and results on the studio designer before he/she has began designing or committing to particular design options. Together they learn about the physical behavior of the building under different conditions and begin to frame a building concept that articulates these and the many other issues of the architectural project.

A SKETCH OF THE LITERATURE AND OF PREVIOUS WORK

Learning from past teaching and professional experiences, our approach emphasizes the collaboration between architects and engineers/consultants. This attitude is, in the case of the architecture faculty author of this paper, informed by almost a decade of design practice within the Renzo Piano Building Workshop that involved repeated interaction with BPS-fluent consultants. Our teaching setup attempts to replicate this kind of fruitful architect-consultant interaction in the academic studio environment. In contrast with the model articulated above in which the architect is not the producer of the BPS, Soebarto (2005) presents a model of design teaching in which students learn and apply various simulation tools in their design. On the subject of the role of internal or external consultants in design studios, the role of BPS in design studios, and who delivers BPS to the design studio student, we refer the reader to Charles and Thomas (2009)

The space is lacking here to address the many aspects involved in our teaching setup, and we only offer a few references pertaining to each of these dimensions. We leave aside the dimension of co-teaching and collaboration architecture/ engineering students in course and in studio (holding a role within one's area of specialization), which has been written about quite extensively. On the learning potential associated with linking and collaborating between courses and studios as well as the role student can play within an architectural design team by bringing what they learn concurrently in another specialized course, Poerschke (2007) reaffirms the need for the strong architectural design concept to act as a guide when student engage with technical systems integration.

On the aspect of content and goals of BPS courses and appropriate ways of teaching BPS at different levels, we see our model of collaborative approach to introducing BPS to undergraduate architecture and engineering student as the lower level of a three-level edifice. At this first level, BPS is used to help all architecture students gain an insight into complex physical phenomena activating buildings. Norford (2006) appropriately insists on the necessity for students to also master the first principles, in other words, students must be capable of verifying by hand calculation that simulation results make sense. We also see this level as being also concerned with developing the student's ability to operate in a BPS-rich collaborative environment. This entails having the student understand her/his role as a director in the design process. This also implies that the student must learn to interact with consultants, develop an capability to understand the BPS outputs presented to her/him and, ideally, become somewhat able to judge the validity of the modeling and outputs. We believe these goals are achievable at the B.Arch and M.Arch level.

The second level of the edifice is dedicated to teaching BPS to students so that they become effective BPS modelers /consultants. This may occur either internally, within an architecture firm, or externally, within an engineering firm. In our view, this level is likely the province of dedicated M.Sc. or Ph.D. degree programs (Hensen, 2004). At the third and highest level of the edifice, students are individuals capable of writing code with an understanding of the design process. They can translate the model of the physics that appropriately represent a design into computational language (Augenbroe et al, 2008).

On the difficulty of teaching BPS and the reliability of results produced by BPS students, Hand (1993) and Ibarra and Reinhart (2009) document both the possibility and the difficulty of training engineers and/or architects to use BPS modeling reliably.

A MULTIDISCIPLINARY CONSULTANCY-BASED MODEL OF INTEGRATION OF BPS

Our teaching setup was designed on the basis of a course and an architecture studio that run concurrently during a 15-week semester. Students in the two courses worked independently from each other at first and then the students collaborated over the course of the last five weeks of the semester (figure 1). Our goal was to provide the students with an exposure to a collaborative design environment that involves BPS. We teach with BPS more than we teach BPS, leaving the difficult task of teaching BPS modeling to more advanced degree programs. Another goal was to limit the distraction experienced by the design studio students when tasked with learning a piece of BPS software. We therefore assigned the role of "BPS-capable consultant" to the students in the Arch-Engr course. We built a unity of command and continuity of purpose between the course that was co-taught by the authors—an architecture faculty member and an engineering faculty member—and the studio that was taught by the architecture faculty co-author of this paper. The course was entitled Arch-Engr (and is referred to as such in this paper) because of its dual population of both undergraduate architecture and engineering students. Both populations were introduced to BPS and data acquisition (DA). During the collaboration phase, teams of students in the Arch-Engr course acted as consultants to teams of studio students. In the dual—Arch-Engr course and studio—setup, the responsibility of developing the design remained with the studio. We believe this dual setup placed the studio students in the position of learning their role as design leaders, including how to negotiate the collaboration, and how to incorporate and/or challenge the BPS modeling results they received from their consultant team.

We see the integration within a design studio framework as crucial element in promoting the idea that the BPS-rich collaboration should take place early in the design of the project. Our position is that an "after the fact" analysis of a "completed" design sends the wrong message as to when BPS should be used. In contrast, we see design as a synthesis, a moment of application of prior knowledge and articulation of it in the form of a building "concept" that encompasses multiple dimensions. We believe that the students can learn important lessons about the nature of the design process from operating within such a design framework. For example, an analysis exercise might reinforce the notion that one needs many detailed inputs to produce a model, in contrast, the proactive integration of a BPS modeling effort in a design problem introduces the student modeler to working within uncertainty and limited inputs. With the design problem, the student also has to adjust her/his model's scope and comprehensiveness to reflect the progress of the design. At the introductory level at which we are teaching, this typically translates into iteratively revisiting a set of simplified comparative "what if" options.

The design-problem we chose was to retrofit an existing dormitory building on our campus. Besides the fact that the students are very familiar with the building and have lived or are currently living in the building or other similar buildings, we saw five advantages to this choice of a design problem: 1) it appropriately places performance issues and understanding of physical, climatic and human comfort factors to the foreground of the design thinking; 2) it suitably limits the number of design issues the students have to deal with within the short timeframe of the design; 3) it showcases retrofits as one significant means of achieving greenhouse gas emission reduction; 4) the students can directly experience the building; 5) the cellular and repetitive organization of the building lends itself well to discussing modeling strategies and the extend of the model (one room vs. whole building model)

THE ARCHITECTURE STUDIO

The elective, advanced undergraduate studio met three times a week for three hours each. The studio had 11 enrollees, none of whom were also enrolled in the Arch-Engr course. The studio successively examined three problems centered on the central theme of the building envelope considered at a detailed construction level as well as in relationship with a building concept encompassing aesthetic, energy, environmental, and cultural dimensions. The goal of the studio was that students approach design as an integrated exercise that considers construction issues along with other issues such as systems, energy, and ventilation at a whole building conceptual level. A few practicing exterior architecture and engineering consultants participated in studio reviews.

The thematic continuity across the three studio design problems was aimed at facilitating the studio student's foray in the collaborative effort with the Arch-Engr course students. While studio students were primarily consumers of BPS modeling made by their consultant counterparts, they also were all introduced to a few other BPS tools (see section "Choice of Tools" below).

The collaborative portion of the semester was five-weeks long and focused on an existing dormitory building on our campus. The goal was to generate design proposals of how to improve the building envelope as well as how to add program and to possibly modify internal spatial arrangement to foster play, work, and a healthy community life. Each studio team of two students worked with a BPS- and DA-capable Arch-Engr team toward formulating various design alternatives and then developing one of their building/design concept further.

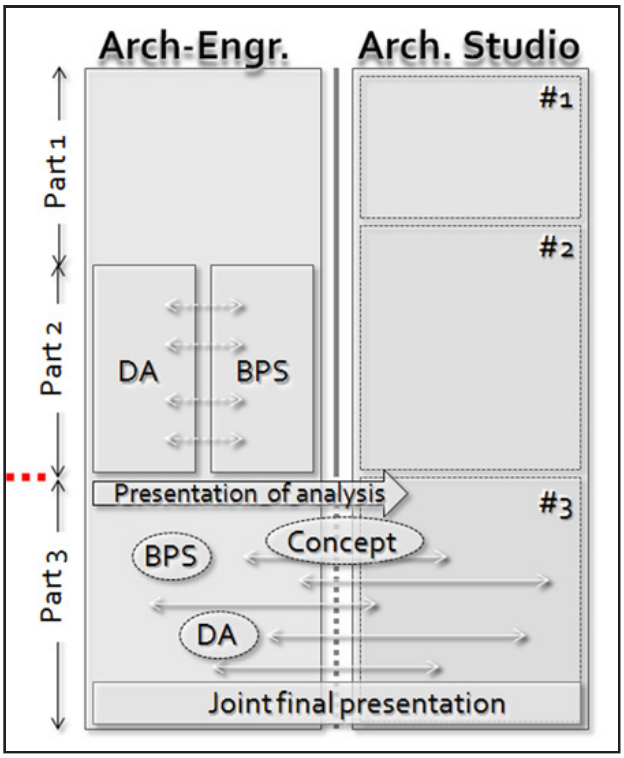

Figure1: Timelime of the concurrent studio and Arch-Engr course over the semester with indication of the collaborative key moments.

"ARCH-ENGR" COURSE

As shown in figure 1, Arch-Engr ran concurrently with the studio. The advanced undergraduate elective course met twice a week for 80 minutes. To create a multidisciplinary environment and to foster collaboration across disciplines, Arch-Engr's initial enrolment was nine architecture students and nine engineering students. The group was composed of juniors and seniors as well as two engineering sophomores. Architecture students had had a mechanical and electrical equipment course and most of the engineering students had had one semester of thermodynamics.

In terms of BPS use, the semester was broadly organized in three successive parts: introduction, analysis and design. The first part of the course lasted three weeks. It introduced and/or reviewed background material of environmental sustainability, the collaborative and non-linear design process, building physics and comfort, as well as BPS and DA. Students began documenting the dormitory building through various means including an occupants' survey, the collection of metered data, and climate analysis. Very early on, after only two introductory sessions on DA and BPS, Arch-Engr students were asked to volunteer to join one of two sections specializing in one of these two areas.

Figure 2: excerpt of the documentation of the dormitory building. Left: general layout and of the dormitory. The highlighted room was the room occupied by an Arch-Engr student in which a data acquisition system was installed. Right: documenting thermal bridges in the room.

In the Arch-Engr course, the second part of the semester lasted five weeks. Over five class sessions, students were taught in the two separate, identically sized, sections (DA or BPS) in which they received further instruction in either the principles of DA by the engineer co-author of this paper, or in the basics of BPS modeling by the architect co-author. Students completed in-class and at home labs. The DA section developed the data acquisition system for use in the dormitory room while the BPS section learned how to model the room using a transient energy simulation software and a bulk air flow software (figure 3a & b).

Through assignments and presentations, all students practiced how to interpret the data and BPS results that they and other students had generated.

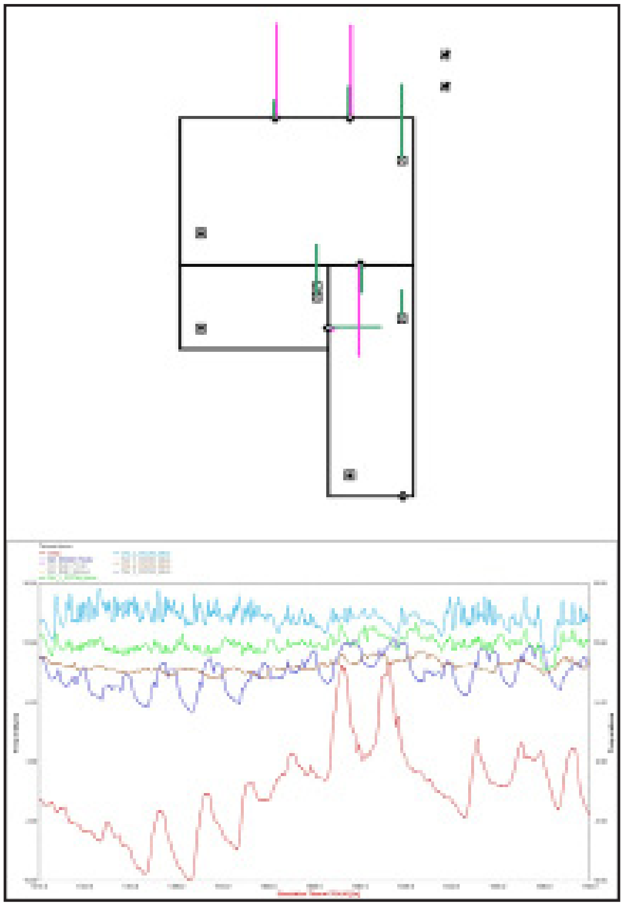

Figure 3a & b: The bulk air flow model was kept to a minimum with only 4-zones including the dorm space (largest room at the top), the adjacent shared bathroom, the entrance corridor-lobby, and the staircase above the lobby(not shown). b: Screen capture of the TRNsys model for a 12 –day period with predicted and measured interior temperatures, as well as ambient temperature from weather station.

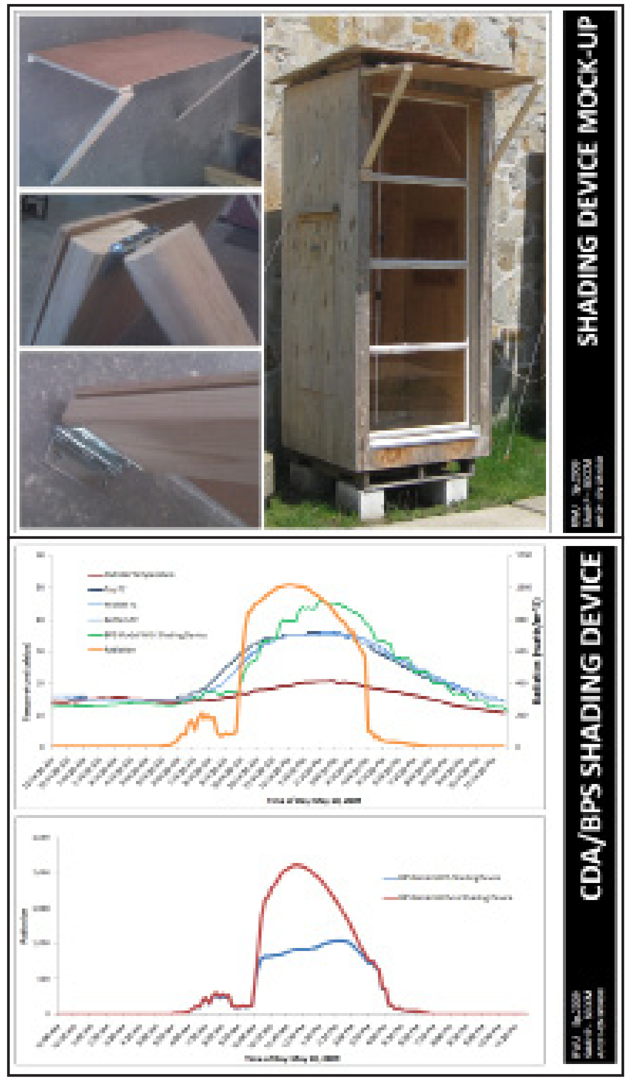

Figure 4a & b. a: a simple mock up of a shading device installed onto an existing test-cell equiped with three thermocouples (low, mid, high). b: Graphs comparing acquired data and prediction in TRNsys of the effect of the shading device

Students worked in groups to prepare an intermediate report on how the dorm room behaved from an energy flow and comfort standpoint in light of the BPS modeling results and DA measurements. A base model with the dorm room and some adjacent rooms (figure 3) was used to prepare a series of "what if" tests aimed at evaluating the impact of various parameters changes such as, orientation, building envelope composition, amount of glazing, and position of shading devices inside vs. outside, etc, on the space under study. This analysis phase culminated with the presentation of the report by the Arch-Engr students to the studio students during a joint session also attended by an external engineer guest/critique.

During the last five weeks of the semester, teams of Arch-Engr students composed of both BPS-capable and DA-capable members acted as consultants to a studio team. They met and collaborated on a regular basis as part of their homework. They first began by devising a building concept, i.e. framing a design strategy for the upgrade/modification of the dormitory building. They then analyzed ways of modeling one key aspect of the design. Here we placed the emphasis on the overall iterative approach more than on the comprehensiveness of the model itself because high-quality modeling is very hard to achieve for novice student modelers. With some support, BPS students prepared a modified version of the base model that targeted the study of one key aspect of their partner team's design. They ran "what if" scenarios through which they tested the impact of varying particular parameters in isolation. The students analyzed and discussed their results with their studio teammates who continued to develop their design. The DA "specialists" in each team analyzed their team's design proposal and devised on paper a data acquisition system aimed at adequately capturing a key aspect of the design. Some of the DA students used existing instrumented test-cells to mock up an approximation of their team's design intervention regarding the building envelope (figure 4a). The acquired data was compared with the results obtained from the BPS modeling (figure 4b). Arch-Engr students documented their process in writing in a brief report that retraced the collaborative design investigation. Arch-Engr students took part into the studio final presentation with their respective studio team.

CHOICE OF BPS TOOLS

The BPS tools were chosen to help students develop an intuition and understanding of the energy flows in a building. We have a pronounced preference in favor of dynamic tools that visually plot the condition in a space/room at every time step of the simulation as illustrated in figure 3. We used TRNsys 16, a transient thermal energy simulation software (Klein, 2000). We view this capability as a very powerful means to "place the student in the room", to have her/him relate the plotted data with an experience of the comfort. To achieve this, one must have beforehand instructed the student in the matter of relating a personal thermal comfort sensation to an actual air temperature, radiant temperature, and relative humidity measured data using hand-held devices such as non-contact thermometers, anemometers, etc.

The choice of TRNsys was also due to its capability in the area of radiatively –based means of achieving comfort (as opposed to prevailing air-based HVAC solutions). This capability provides a good entry point to connect to basic physics and first principles of comfort. The lack of 3-D visual interface in TRNsys 16 is a bit of a drawback as it does not allow for the visual inspection of a model's geometry. Conversely, we feel that the planning prior to starting the model that such a tool requires is a beneficial discipline for students to acquire.

The bulk air flow software we used was Contam (Dols and Walton, 2002). Its simplicity and adequate graphic interface make it an excellent tool to explore natural ventilation options. TRNsys's capability of linking with Contam, enabled us to investigate both thermal and airflow simulations simultaneously. Wind pressure profiles for individual openings in Contam were obtained using the web-based CpGen (Knoll 1997).

The BPS tools used by the studio students were Design Advisor (Glicksman, 2006) for general introduction. The Weather Tool (Marsh, 1996) and Climate Consultant 3.0 (Li and Milne, 2004) were used for climate analysis. A few volunteers also were introduced to Therm 5.2, a 2-D conduction and radiation heat-transfer analysis tool, (Mitchell et al., 2006) (see Figure 5). The following criteria guided the selection of the software:

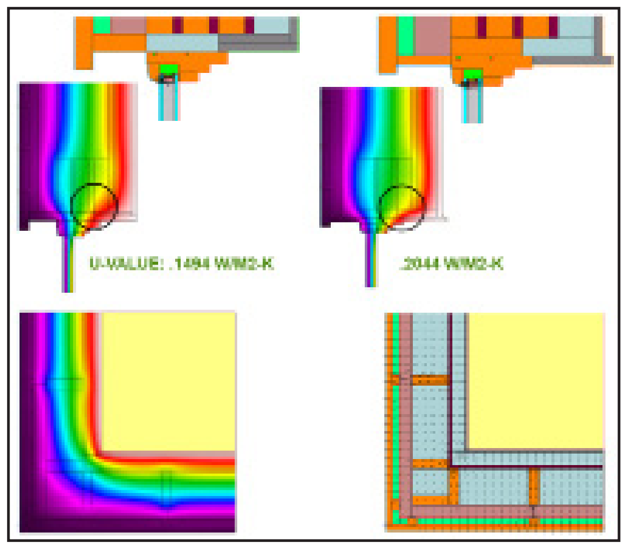

Figure 5: Thermal bridge studies with Therm 5.2 by studio students showing various envelope conditions. Window header (top), typical framing at stud with diffusion-open wood particle panel adjacent to rainscreen cavity (bottom).

- tools that help introduce general concepts and present a general picture of the room's behavior that includes energy, light, acoustics, and materials;

- ease of use so as to minimize any disruption of the design process (because the designers are still novices);

- capability of generating imagery that can be integrated in the presentation of the design (figure 5);

- thematic adequacy: the thermal bridge tool concentrates on detailed study of building envelopes which was consistent with the studio objectives.

For information on the choice of data acquisition tools and the weather station used in Arch-Engr, we direct the reader to (Charles & Thomas, 2009)

OUTCOMES AND OBSERVATIONS

Student surveys in both Arch-Engr and the Studio indicated that students were aware that they had taken part in a forward-looking teaching setup and appreciated the effort. Student mentioned that the Arch-Engr course was a considerable amount of work, often highlighting the difficulty of working in teams, accommodating different schedules, and bridging the different cultures of architects and engineers. A number of engineering students noted their unfamiliarity with the teaching style, which was different from typical engineering classes that tend to rely on textbook assignments. In the survey, students acknowledged having discovered new working styles and appreciated the learning opportunity that bridged the gap between architecture and engineering students.

A few architecture students in the Arch-Engr course expressed that they did not like having to work on two studio projects concurrently—their own, and the one for which they consulted as part of their Arch-Engr class team. A majority of the Arch-Engr students indicated that they wanted to learn both BPS and DA instead of being confined to developing skills in only one of the two areas. We argue that the latter comment shows that the students are curious and that they see the point of balancing insights gained through BPS with insights gained through DA and physical measurements.

The studio students often questioned the expertise of the Arch-Engr consultants and the validity of their findings. This was anticipated and understandable. We see that the period allocated to learn some rudiments of BPS and/or DA techniques was quite short. We also see another possible explanation. We argue that there is a mismatch between the expectations of the architecture studio students and the actual consultations received from their Arch-Engr consultants. We believe that the Architecture Studio students, who are familiar with comprehensive, (formally) synthetic 3-D models, were underwhelmed by the limitations of the small energy and airflow models prepared by the Arch-Engr students as one-issue "what if" investigations.

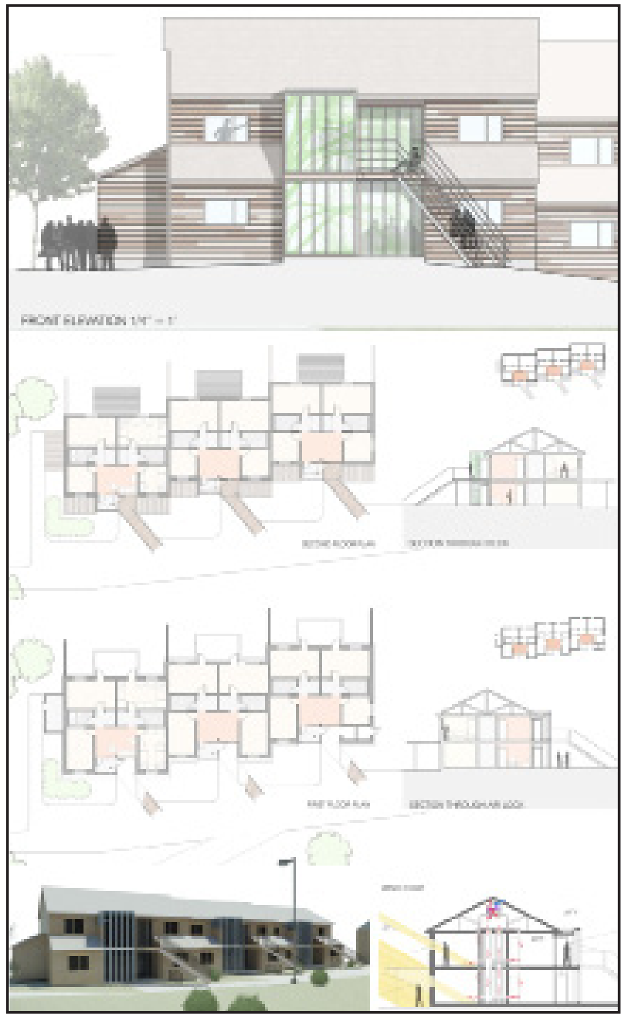

Figure 6: Project by Dan Cross, Jessica Johnson, Taylor McNally-Anderson (Arch-Engr BPS), Brittney Sullivan (Arch-Engr DA), a proposal to link units at the same level to create a greater sense of community

A number of studio students regretted that they did not learn the BPS software tools suite learned by their Arch-Engr counterparts. Sharing the view that there is a danger of overloading and distracting a studio with too much BPS tools learning in the studio, these students suggested a two-semester sequence in which student would learn the BPS tools the first

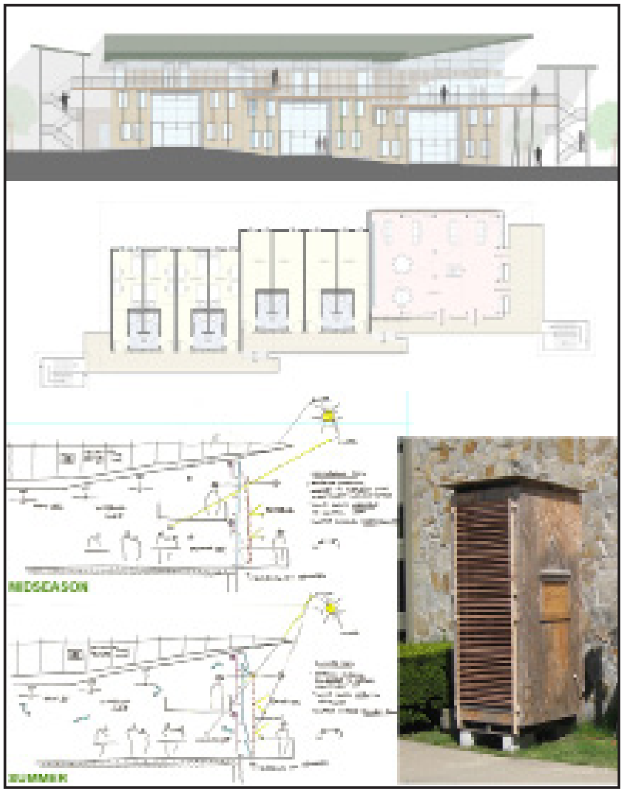

Figure 7: Project by Lauren Bergeron, Matt Dean (Arch-Engr BPS), Felipe DaSilva (Arch-Engr DA) a proposal to add a third floor with a communal lounge to the south end of the building. The BPS model and DA mock up concentrated on studying the impact of shading the lounge space at the third floor

semester, and later apply them to their design in the following studio semester. This is a fairly common formula found at several schools of architecture around the country. Although it appears to be in contradiction with our initial intention of implementing a framework that fosters collaboration between specialists that complement each other, this suggestion is worth exploring. Students are motivated to learn BPS tools to help them with their studio project design and to broaden their palette of marketable professional skills. We recognize that some might become professional BPS specialists over time, after completing an adequate course of advanced study.

Notwithstanding the points outlined so far in this section, we believe that the model we have outlined achieved some measure of success.

In terms of design quality, the proposal produced by the studio teams with the help of their Arch-Engr consultants was to our satisfaction. The way the studio was framed seemed to have influenced the design toward the "reasonable" end of the spectrum. We are inclined to think that the collaborative, BPS-rich environment with "real" issues of energy and building performance placed at the center played a role in this outcome. (figure 6 & 7)

Overall, we feel that the students have gained some insight into phenomena of energy flow in the building but we must underscore that interpreting BPS model results (and DA data) remains a difficult task for the students. Students very easily tend toward creating large model and will show a tendency to consider their work finished once they have pressed the "run the simulation" button. Output interpretation and debugging of the models must always be heavily emphasized. Our impression has been that it is not easy for students to draw accurate conclusions from the data (this is already true regarding climate data). This problem is decreased when good output graphics are available (for example, Therm 5.2 in figure 6). In this case, students have a much easier time understanding the underlying phenomenon. Similarly, the timestep -by- timestep plot of temperature in TRNsys is helpful, but we often find ourselves (instructors) having to prod the students into analyzing the plots carefully. With our goal of delivering educated consumers of BPS, the ability to properly interpret BPS results generated by a consultant is absolutely essential. We can achieve at a higher level in this area.

In terms of the depth of use of BPS in the Arch-Engr group, while the BPS user-friendliness plays a role, we believe this aspect is somewhat inflated in the discussion of BPS in the architecture curricula. Our observation is that creating a model and getting an output is not a problem for the students, however, model quality is a major problem, a point that echoes the findings of Ibarra and Reinhart (2009). Consequently, we strongly advised the students to limit the complexity of their BPS models during the collaboration phase to primarily a series of "what if" investigations of one parameter. Because making a better model is a problem, we do not hesitate to help the students with setting up the TRNSYS and/or Contam models. We do not see this as a problem. We see our focus as primarily training the students in the collaboration workflow and the interpretation of BPS results in the context of design. Furthermore, we assume that BPS tools will continue to evolve and that student will deal with improved versions of these and other tools in the future.

We see complementing the BPS computational investigation with physical means (test cells) as very valuable. Similarly, we see comparing the BPS predicted outputs (BPS) with the measured / post-occupancy evaluation (DA) in the dorm room as very essential to our approach. Experiencing the difficulty of reconciling the BPS and DA results teaches a lesson regarding healthy circumspection toward results obtained through the computer. The effort of attempting to reconcile the model and actual in-situ measurements (calibrating the model) is quite humbling. The potential explanations why the two do not coincide might be overwhelming.

We think that the teaching setup was successful in making students aware of what BPS tools can do. Some students have indicated their interest in learning more about them and have inquired about the existence of advanced courses in this area.

CONCLUDING REMARKS

The consultancy-based model of teaching, which links a introductory course in BPS and DA with an undergraduate design studio appears to be a promising method of teaching. Nonetheless, many questions as to the scalability of this model and the best ways to assess its success remain to be explored in future implementations.

Despite the growing penetration of BPS tools in architecture offices, we believe that for reasons of quality insurance and of real limitations when it comes to absolute prediction of the performance of buildings (Bannister, 2009), there is and will be room for BPS consultants in practice. We think that architects should learn to collaborate effectively with these specialists in order to increase the common ground between architects and engineers so that our concerns can meet and reinforce each other. In the debate on the redefinition of the role of the architect, we see the notion of authorship rapidly evolving towards one of a shared-authorship of the architectural design as a reflection of the increasingly collaborative nature of design. While the architect maintains her/his role of a director and of a guardian of a project's design intent, consultants such as the BPS providers will play a growing role in the early stages of the design process.

We believe architecture and engineering undergraduate students should be exposed to BPS tools. We contend that at the undergraduate level instead of teaching BPS per se, educators should teach with BPS. This distinction implies that BPS is part of the educational landscape and that the goal should be to educate a consumer of BPS instead of preparing a producer of simulation. Undergraduate architecture students should have an understanding of how buildings work from an energy flow standpoint and acquire a thermal intuition (Strand, 2000). He/she should be capable of interpreting BPS results produced by others (or himself/herself). Teaching with BPS as outlined here can be a means of promoting the collaboration between architect and engineer on design problems and preparing both to navigate a BPS-rich design environment (while not being the producer of BPS modeling).

An important learning outcome of undergraduate exposure to BPS should be a clear understanding of when BPS tools should be used and how proactively they should be associated with early ideation and problem-framing phases of design. In the implementation of the design-oriented teaching model outlined in this paper, the collaboration between consultant and designer seems to be most fruitful when the consultant proactively engages the design problem alongside the designer. Instead of waiting for a project to analyze/model in the simulation tool, the BPS-capable consultant should run simple models as a means of identifying important issues to be integrated by the designer (Olsen, 2009). Students should learn to shy away from large models with many zones and instead elect to learn all that can be learned from simplified models testing a range of "what if" scenarios. Ultimately, we would be satisfied if a student having attended Arch-Engr was able in a subsequent studio to autonomously develop a simple, reasonably accurate BPS model of one-room representative of the design to test various "extreme" cases (the variation of the operative temperature in a free-floating space under various orientation and shading strategies for example).

Teaching with BPS tools can help reinforce the notion that design is iterative and balances many different dimensions. In relation to a design effort, while the quality of BPS results is important, the mere idea and process of comparing between several different options is essential. With a strong link to design and its web of conflicting underpinnings, student can learn to be highly suspicious of any effort at an optimization of a narrow (or worse, unique) set of parameters, to conversely, engage in healthy satisficing to re-use the term cast by H. Simon thirty years ago.

The insights obtained through BPS investigation should complement insights obtained through physical means (test-cells, in-situ measurement using handheld devices) as well as basic order-on-magnitude calculations. Finally, we must take advantage of the dynamic quality afforded by transient BPS tools. At a more phenomenological and poetic level, hour per hour dynamic simulation can support a quite Bachelardian reverie or imagination of fluidity and energy flows that activates the architectural fabric. Along the same line, we believe that Pallasmaa's idea of an architecture of the seven senses can be approached through the lens of dynamic building simulations.

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