TEACHING BUILDING PERFORMANCE SIMULATION: EVER DONE AN AUTOPSY?

Ian Beausoleil-Morrison[1] and Christina J Hopfe[2]
[1] Faculty of Engineering and Design, Carleton University, Ottawa, Canada
[2]School of Civil and Building Engineering, Loughborough University, Loughborough, UK

ABSTRACT

In previous papers we have presented a continuous learning cycle that includes exposure to theories and the application of tools from the start for effectively teaching BPS and we have described the course we have developed based upon this cycle. The important role played by the *simulation autopsy* in this cycle is the focus of the current paper. This is accomplished by examining the teaching methods we use for 2 of our course's 15 topics: determining the distribution of solar heat gains to internal building surfaces, and predicting solar irradiance on external building surfaces.

INTRODUCTION

Now in its fifth decade, the building performance simulation (BPS) field offers users a myriad of tools, some targeted at practitioners, others aimed at researchers and expert users. Many have modern user interfaces and integrated performance overviews which allow users to quickly ascend the learning curve to operate the tools in order to produce simulation predictions with minimal training. User manuals typically treat applications but do not discuss default settings and data, and the underlying modelling principles upon which the tools are based.

Numerous books that treat the theoretical basis of BPS are available, for example: Clarke (2001), Underwood and Yik (2004), Hensen and Lamberts (2011), and Peuportier (2016). But much of the theoretical material elucidated in such publications is not being learnt or understood by tool users. In an earlier paper (Beausoleil-Morrison and Hopfe, 2015), we presented a series of observations on the current state of the field and argued the need for a different approach for teaching BPS, one that exposes users to the theoretical basis.

Various approaches have been used for teaching BPS. For example, Jankovic (2012), Struck et al. (2009), and Kumaraswamy and Wilde (2015) use a design/ project focused approach. Gaming methods (Reinhart et al., 2012) and assignment/ topic focused approaches (Bernier et al., 2016; IBPSA-USA) have also been used.

We have taken a different approach which involves having students actively experiment with BPS tools to support the theoretical study of modelling and simulation theory through a continuous learning cycle. The pedagogical basis of our approach as well as a description of the course we have developed have been treated in earlier papers (Beausoleil-Morrison and Hopfe, 2015, 2016).

An important part of our BPS learning cycle is the *simulation autopsy*, which is the subject of the current paper. The next section describes the simulation autopsy. We then present how such autopsies are key to the full learning cycle by presenting two of the topics of the course we have developed: modelling solar gains to internal building surfaces, and modelling solar irradiance incident on exterior building surfaces.

TEACHING WITH AN AUTOPSY

We introduced the BPS-specific recursive learning cycle in Beausoleil-Morrison and Hopfe (2015) comprising four modes of learning: abstract conceptualization (AC), active experimentation (AE), concrete experience (CE), and reflective observation (RO). The course we have developed (Beausoleil-Morrison and Hopfe, 2016) consists of 15 iterations of this learning cycle. Each iteration treats a specific topic (two are treated in this paper) and includes lectures on theory, assigned readings, a simulation assignment, and a simulation autopsy. Active participation of the students throughout the cycle is critical.

In Beausoleil-Morrison and Hopfe (2015) we observed that simulation predictions are often insufficiently scrutinized by users and that users often place too much faith in their simulation tools; evidence gathered through initial testing of teaching methods was provided to substantiate these observations. We believe that students need to be taught how to critically examine their simulation results to identify and diagnose sources of input error in order for them to develop a necessary degree of skepticism, and the skills to diagnose, repair, and reduce errors.

This is why we introduced the concept of the simulation autopsy, a working session in which the students and the instructor collectively examine the results of the simulation exercise and dissect simulation input files to diagnose reasons for predictive disagreement. We use this as a vehicle for helping students develop critical thinking skills for building upon the AE mode of learning and for relating to the theory acquired during the AC mode. The simulation autopsy takes place in the CE mode and then further blends into the RO mode of the learning cycle.

The concept is simple: the students submit their results for a simulation exercise, we compile them, and then we collectively analyze and scrutinize the results at the

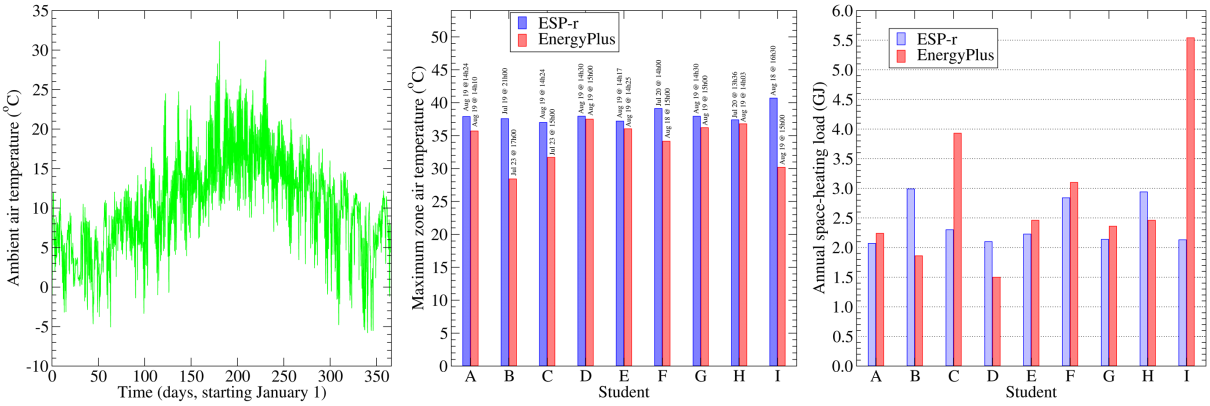

Figure 1: Ambient air temperature (^0C) from the weather file (left) against the results of the maximum zone air temperature (in ^0C, middle) and the annual space heating load (in GJ, right)

next class. The analysis phase often leads into group discussions relating the relevant theory covered in the lectures and assigned readings to the impact upon simulation predictions. As well, the simulation input files prepared by individual students are sometimes collectively examined to help diagnose causes of predictive disagreements and to identify potential input errors.

This reflective observation and diagnostic investigation is what connects the experience to the theory. As stated by Dewey (1933), reflective thought is an "active persistent and careful consideration of (..) supposed form of knowledge in the light of the grounds that support it and further conclusion to which it tends". We argue that in most literature and courses on BPS this final—and crucial—stage that motivates reflective thought is omitted, and this is key to transforming the student from a learner to a reflective learner.

We pose a number of questions to the students during the simulation autopsies to facilitate the reflection process, such as:

- Sanity check: How do we expect the building to perform?
- Can you trust the results?
- What do the results mean?
- What evidence supports your answers to the above questions?

To illustrate the above in more detail we return to the *base case* assignment introduced in Beausoleil-Morrison and Hopfe (2016) that we hand out to the students at the beginning of the course in order for them to develop a basic familiarity with the operation of the chosen BPS tools, and to develop an appreciation of the types of data required to describe a simple single zone building.

In a recent offering of the BPS course at Carleton University, each student conducted this exercise independently using both EnergyPlus and ESP-r and submitted the results in advance of the course's first simulation autopsy. All students managed to produce results with both ESP-r and EnergyPlus only three weeks after their first exposure to these tools.

Figure 1 shows a compilation of some of the results that the 9 students submitted and which were collectively examined during the simulation autopsy.

On a first glance, some of the maximum zone air temperature predictions vary significantly: Student I's ESP-r result is 12^0C higher than Student B's EnergyPlus result. Whilst the majority of all students agree on timing of this peak temperature (mid-afternoon on August 19), three students notice a different day using Energy Plus, whilst three other students notice a different day with ESP-r. There are also significant differences in the predicted annual space heating load: Student C's and I's EnergyPlus results are significantly higher than the others.

The group discussed these differences and hypothesized explanations. Following this, some of the EnergyPlus and ESP-r files prepared by the students were projected on a screen, the inputs examined, and diagnostic techniques explained for searching for potential input errors. A number of discoveries were made during this portion of the simulation autopsy:

- The annual space heating load predicted by Student C using EnergyPlus was quite high. The reason for this was that the two south facing windows were placed on the north face of the building instead.
- In student I's EnergyPlus model the constant sensible internal heat gain of 200W was specified as latent; this increased the annual space heating significantly.
- Student H's ESP-r model shows that the annual space heating load is quite high despite the maximum zone air temperature and peak heating load projections being in line with the others. Furthermore, the peak zone air temperature occurs a month earlier than expected. It turned out that this was due to using the wrong weather file.
- The cause of Student D's EnergyPlus simulation

predicting a low annual space heating load was found to be an error (not trapped by EnergyPlus) in the vertex points defining the roof: in fact, it was an incomplete surface and this resulted in an under-prediction of the heat loss through the roof.

- Student G's ESP-r results generally look okay except that the results reported the peak heating on the wrong day. This is because of using a pre-conditioning period of only 1 day. (This provided an excellent segue to return to the earlier presented theory about how numerical methods require a pre-conditioning period to eliminate the impact of the initial condition.)

Needless to say that this list is not exhaustive but does serve to illustrate the important lessons that can arise during the simulation autopsy. This concept will be further explored in the next sections, which focus on two of the 15 iterations of the learning cycle used in our course: solar heat gains at internal surfaces and solar irradiance at external surfaces.

SOLAR HEAT GAINS AT INTERNAL SURFACES

This section focuses on modelling the distribution of solar heat gains to internal building surfaces. The goal is for the students to understand the default and optional methods employed by BPS tools, and to discern the sensitivity of simulation predictions to users inputs and choices. We use a combination of lectures, assigned readings, video sequences, simulation exercises, and a simulation autopsy following the BPS learning cycle (Beausoleil-Morrison and Hopfe, 2015, 2016). The theory that is presented during the lectures is explained in the following subsection.

Presentation of theory

This lecture builds upon earlier course material that explained how BPS tools form and solve energy balances to determine a building's thermal state as a function of time. This described how energy balances are formed for each internal surface (wall, floor, ceiling), such as represented by the control volume (CV) delineated by the dashed line in Figure 2:

$$\left\{\begin{matrix}\text{energy}\\ \text{stored}\\ \text{within}\\ \text{CV}\end{matrix}\right\} = \left\{\begin{matrix}\text{solar radiation}\\ \text{absorbed}\end{matrix}\right\} + \left\{\begin{matrix}\text{convection}\\ \text{from}\\ \text{indoor air}\end{matrix}\right\}$$
$$+ \left\{\begin{matrix}\text{net radiation}\\ \text{from other}\\ \text{internal}\\ \text{surfaces}\end{matrix}\right\} + \left\{\begin{matrix}\text{net radiation}\\ \text{from}\\ \text{internal}\\ \text{gains}\end{matrix}\right\}$$
$$+ \left\{\begin{matrix}\text{net radiation}\\ \text{from plant}\\ \text{equipment}\end{matrix}\right\} - \left\{\begin{matrix}\text{conduction}\\ \text{towards}\\ \text{outside}\end{matrix}\right\} \tag{1}$$

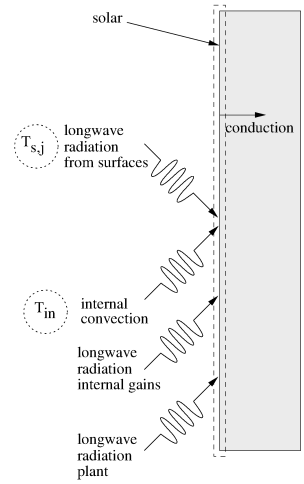

Figure 2: Energy balance at internal building surfaces

The method universally employed by BPS tools to calculate the first term on the right side of Equation 1 for each individual surface is presented:

$$\left\{\begin{matrix}\text{solar radiation}\\ \text{absorbed}\end{matrix}\right\} = \alpha \cdot A \cdot q''_{solar,int} \tag{2}$$

Where α and A are the solar absorptivity (-) and area (m^2) of the surface under consideration. The former is a parameter supplied by the user while the latter is determined from the building's geometrical inputs.

$q''_{solar,int}$ in Equation 2 is the solar irradiance incident upon the internal surface under consideration (W/m^2). This includes the beam and diffuse solar irradiance that is transmitted through windows and which directly strikes the surface, as well as the solar irradiance reflected off other surfaces towards the surface under consideration.

Explaining this theory makes the student aware that only three factors determine the prediction of solar heat gains to each internal surface: user-defined geometry, user-prescribed α values, and the models used to predict $q''_{solar,int}$. This prepares the student for the simulation exercises which allow them to explore the degree to which modelling decisions and user input data influence simulation predictions.

Simulation exercise

There are two steps to the simulation exercise, the first of which explores the sensitivity of simulation predictions to α, often an uncertain parameter for the user to quantify.

> Step 1: *Perform a simulation using the* base case *and extract the results for February 21 (a cool and sunny day). Create a graph that plots the solar radiation absorbed by the concrete floor (W) versus time for this day. Also plot the rate of heat input from the convective HVAC system.*
>
> *Perform a second simulation in which the solar absorptivity of the concrete floor is increased*

from 0.6 to 0.9. Add the predictions from this simulation to the above graph.

Did increasing the solar absorptivity of the concrete floor have the expected impact upon the amount of solar radiation absorbed by the floor surface? Explain why this significant change in the floor's solar absorptivity had minimal impact upon the quantity and timing of heat injection by the HVAC system.

The second step of the simulation exercise motivates the students to understand the default method applied by their chosen BPS tool for determining $q''_{solar,int}$ as well as to explore optional models.

Step 2: *How did you configure your* base case *to treat the distribution of solar gains to the interior surfaces? If you did not use the default method provided by your BPS tool, then configure your tool now to employ its default method. What is the default method employed by your BPS tool? Perform a simulation, extract the results for February 21, and create a graph as described in* Step 1.

Perform another simulation in which your BPS tool applies its most detailed method for determining the distribution of solar gains as a function of time. Describe the algorithm employed by your BPS tool. Add the predictions from this simulation to the above graph. Explain the differences in the solar radiation absorbed by the floor over the course of this day.

What impact does this have upon the quantity and timing of heat injection required from the HVAC system? Describe a situation in which a greater impact would occur.

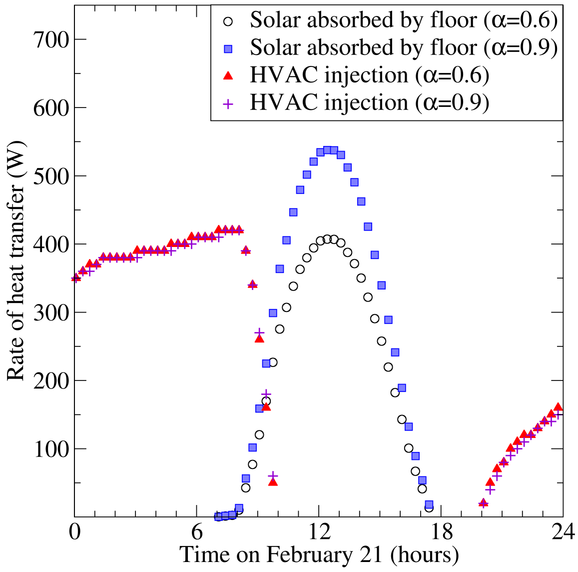

Figure 3: Step 1-*Sample results produced by a student for the simulation exercise on solar heat gains at internal surfaces.*

Student results

An example of their results for *Step 1* are illustrated in Figures 3 and 4, while Figure 5 combines some of their *Step 2* results.

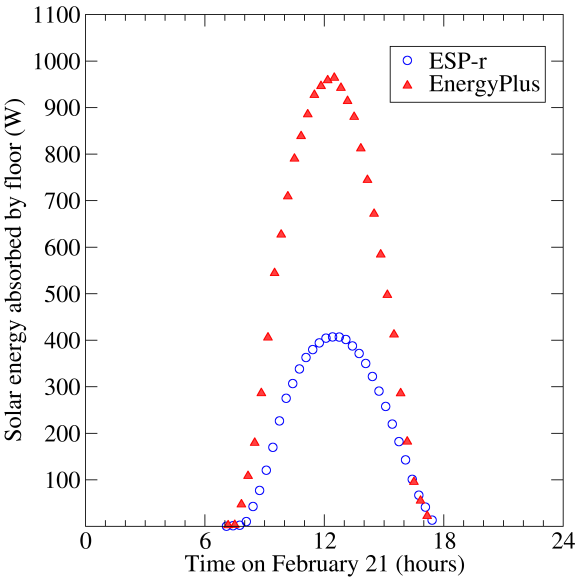

Figure 4: Step 1-*Comparison of EnergyPlus and ESP-r predictions of solar energy absorbed by floor for the* base case.

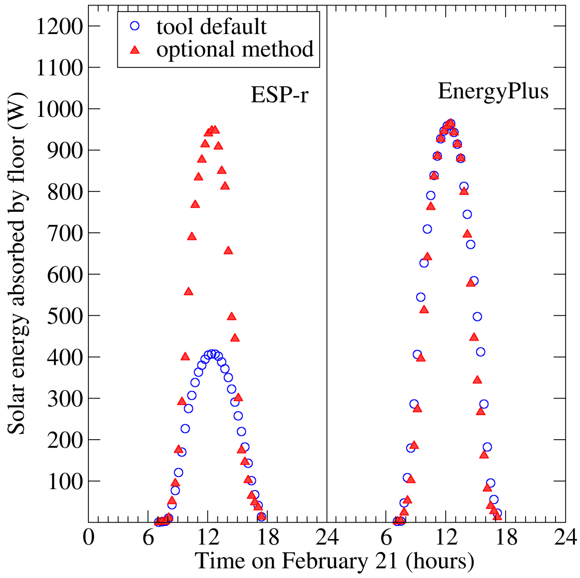

Figure 5: Step 2-*Comparison of tool default and optional methods for determining the distribution of solar gains to internal surfaces.*

SOLAR IRRADIANCE ON EXTERIOR SURFACES

This section focuses on predicting solar irradiance on exterior building surfaces. The goal is for the students to understand the models that are employed for predicting the solar irradiance on each building surface based upon the data contained in weather files, to appreciate the inherent uncertainties in these models, and to develop an appreciation for the impact of user input data and choices on simulation predictions.

The material treated during the lecture portion of the learning cycle is outlined in the next subsection.

Presentation of theory

The lecture builds upon earlier material that explained: how solar gains to internal surfaces are determined (refer to the previous section); the types of solar data contained in weather files; and external surface energy balances (similar in structure to the internal surface energy balance given in Equation 1).

The common method employed by BPS tools to calculate the solar energy absorbed by the exterior of each surface is presented:

$$\left\{\begin{matrix}\text{solar radiation}\\ \text{absorbed}\end{matrix}\right\} = \alpha \cdot A \cdot q''_{solar,ext} \tag{3}$$

Where α and A are the solar absorptivity (-) and area (m^2) of the external surface under consideration. The former is a parameter supplied by the user while the latter is determined from the building's geometrical inputs.

The lecture explains how the total solar irradiance on exterior surfaces ($q''_{solar,ext}$ in W/m^2) is predicted from the summation of three components:

$$\begin{aligned} q''_{solar,ext} = &\left\{\begin{matrix} direct\\ beam\\ irrdiance\end{matrix}\right\} + \left\{\begin{matrix} sky\\ diffuse\\ irrdiance\end{matrix}\right\}\\ &+ \left\{\begin{matrix} ground\\ reflected\\ irrdiance\end{matrix}\right\}\end{aligned} \tag{4}$$

The methods used to determine each of the three irradiance components required by Equation 4 are explained. This makes the students aware that determining the direct beam component from the data in the weather file depends only upon geometry, whereas there is greater complexity in determining the sky diffuse and ground reflected components. Specifically, they become aware of the empirical nature of anisotropic sky diffuse models and the modelling options available to the user, as well as the factors that influence ground reflectivity. This prepares the student for the simulation exercise which allows them to explore the degree to which such modelling decisions and user input data influence simulation predictions.

Simulation exercise

There are four steps to the simulation exercise, the first of which explores the sensitivity of simulation predictions to α, often an uncertain parameter for the user to quantify.

> Step 1: *Perform a simulation in which the solar absorptivity of the asphalt roof membrane is reduced from 0.85 to 0.6. What impact does this have upon the annual space heating load? Describe a situation in which such a change would have a greater impact.*

The second step motivates the students to understand their chosen BPS tool's default and optional methods for modelling sky diffuse radiation.

> Step 2: *What methods does your BPS tool provide for predicting the distribution of diffuse sky irradiance? What is your tool's default method?*
>
> *Which method did you use for simulating the* base case*? Perform one or more simulations using alternate methods offered by your BPS tool (e.g. isotropic sky model). What impact does this have upon the annual space heating load? Comment on the uncertainty of simulation predictions resulting from the treatment of diffuse sky irradiance.*

The third step is designed to make students aware of the importance of ground reflected irradiance, to appreciate the sensitivity of simulation predictions to user choices regarding ground reflectivity, and to appreciate the significance of accepting BPS tool defaults.

> Step 3: *The* base case *specifications did not include any information on ground albedo. Did you assume a constant value in your simulation and if so what value did you assume? If you used your BPS tool's default treatment, then describe what this treatment is.*
>
> *Perform a second simulation in which the ground albedo has a constant value of 0.7. Create a graph that plots the solar irradiance incident upon the exterior surface of the windows as a function of time on February 21. Use this graph to contrast the predictions from the two simulations. Also contrast the predictions of the space heating load over this day.*
>
> *Based upon these results, comment on the uncertainty introduced into simulation analyses due to ground albedo. What are some situations in which this could be a significant factor in overall uncertainty?*

The fourth step of the simulation exercise encourages students to explore methods for describing solar shading caused by surrounding objects and to develop a motivation for not ignoring such blockages.

> Step 4: *Now consider the solar shading caused by a tree located south of the building. The tree has a diameter of 2 m, a height of 10 m, and is located 10 m from the south façade and*

mid-distance between the two windows. Create a graph that plots the solar irradiance incident upon the exterior surface of the windows as a function of time on February 21. Use this graph to contrast the predictions from the base case.

Based upon these results, comment on the importance of considering shading effects by surrounding buildings, trees, and other objects. What are some situations in which the complexities of shading objects (e.g. size and types of trees, changing leaf cover) could be a significant factor in overall uncertainty?

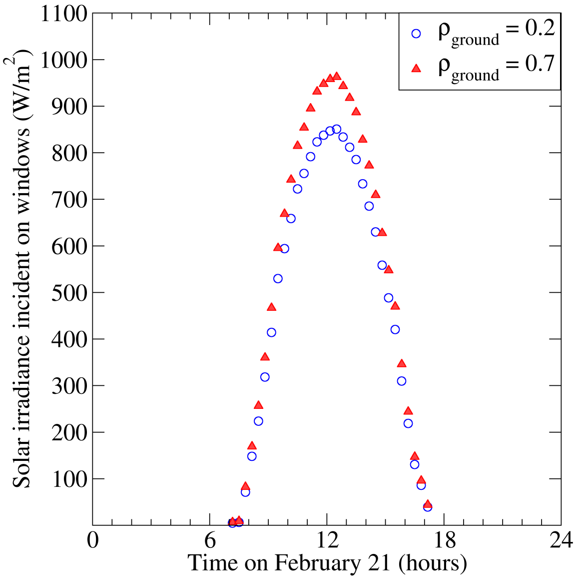

Figure 6: Step 3-*Sample results produced by a student for solar irradiance on exterior surfaces.*

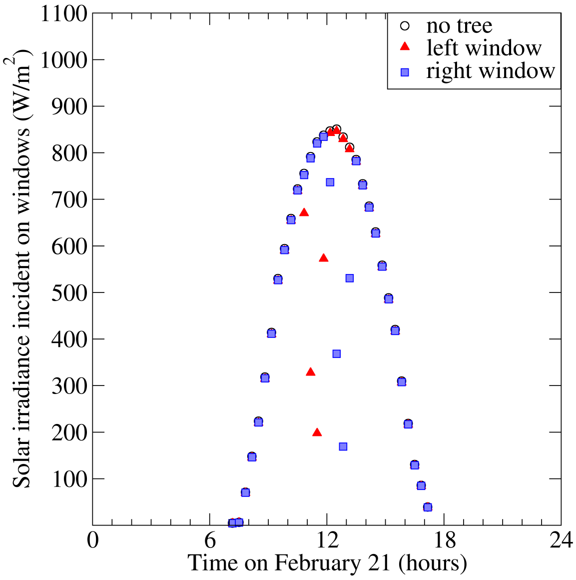

Figure 7: Step 4-*Sample results produced by a student for solar irradiance on exterior surfaces with and without a tree located south of the building.*

Student results

An example of the results generated by the Carleton University students are presented in Figures 6 (*Step 3*) and 7 (*Step 4*).

CLOSING THE LEARNING CYCLE: THE SIMULATION AUTOPSY

As explained earlier, our learning cycle uses simulation autopsies as a vehicle for strengthening the concrete experience and for transforming the student from a learner to a critical reflective learner. By focusing on the two course topics presented earlier—solar heat gains at internal surfaces and solar irradiance at external surfaces—this section describes how the autopsy takes place during the CE mode and then further blends into the RO mode of the cycle.

Solar heat gains at internal surfaces

Step 1: Each student produced and submitted graphs as shown in Figure 3, and during the following class we collectively examined these results and discussed their implications. The group observed that changing α_{floor} from 0.6 to 0.9 had the expected impact upon the rate of solar energy absorbed by the floor (refer to Equation 2 and compare the black circles and blue squares in Figure 3).

Given the influence of α_{floor} upon the solar energy absorbed by the floor, most students expected this to affect the zone energy balances (e.g. Equation 1) and consequently the heat injection required by the HVAC system. However, this hypothesis was disproved by the simulation predictions. As can be seen in Figure 3 (compare the red triangles to the purple pluses), this substantial change to α_{floor} had a negligible influence on the required heating for this day. Indeed, the impact upon the annual space heating load was only 0.4% (with both ESP-r and EnergyPlus).

The group discussed the reasons for this, referring back to the course's earlier treatment of internal surface and zone air energy balances and came to the realization that—at least for well-insulated buildings—significant changes in α_{floor} would have only minimal impact upon the required heat injection. This is an important finding because in many situations BPS tool users do not have access to precise α data, and assumptions or approximation are necessary; in this case, it is clear that significant time investment is not warranted to determine these input values.

During the collective examination of the *Step 1* results, a number of students noticed a significant difference between the EnergyPlus and ESP-r predictions (see Figure 4), and this led to a discussion of the default methods the two tools use to distribute solar gains to internal surfaces. By default EnergyPlus assumes that all solar beam irradiance entering a zone is incident upon the floor; other surfaces receive diffuse irradiance and irradiance reflected by the floor. By default ESP-r distrubutes all solar irradiance entering a zone diffusely on a area-weighted basis. (Many experienced users of these tools are likely unaware of these defaults.) Although this topic had been covered during the lecture, for many students the implications of these default methods only became clear during the simulation autopsy. This led to a discussion on situations in which these default methods may be inappropriate and could cause important simulation errors.

Step 2: Both EnergyPlus and ESP-r offer optional methods for predicting $q''_{solar,int}$. Through an exploration of the tool documentation and the demonstrations provided in class, the students discovered how to invoke the optional methods for more accurately determining the distribution of solar gains by considering building geometry and sun position as a function of time. *Step 2* of the exercise made them realize how straightforward it is to invoke these more accurate models and the minimal impact they have upon computational resources.

An example of the results produced by one student is illustrated in Figure 5, which contrasts the predictions of solar gains absorbed by the floor for the tool default and optional methods. The blue circle symbols in this figure reproduce the results previously shown in Figure 4 (tool default methods) whereas the results predicted with ESP-r's ray-tracing insolation algorithm and EnergyPlus' direct geometrical method are illustrated with red triangle symbols. Examination of these results led the students to realize that for this building geometry and for this day of the year, that ESP-r's default method resulted in substantial errors, whereas the EnergyPlus default method provided a reasonable approximation of the solar energy absorbed by the floor.

Once again, an examination of the HVAC heat injection predictions made the students realize that despite large differences between the ESP-r default and optional methods (refer to Figure 5), the impact upon the functioning of the HVAC system was seen to be negligible. The group discussed these implications and a consensus was reached that it was worth invoking the optional detailed methods as they demanded little from the user and had minimal computational demands, although in many situations (such as with this well-insulated building) the impacts upon some performance metrics would be minimal. There was also a discussion about the limitations of the optional methods and the implications this had upon abstracting building geometry. For example, EnergyPlus employs a direct geometrical method that is limited to so-called convex shaped floor plans, which places limitations how building geometry can be represented and sub-zoned.

Perhaps the most important lesson the students learnt from this exercise was that the user inputs for internal-surface material α values and choices on methods for solar distribution models have a much smaller impact upon simulation predictions (for this building) than some of the aspects explored in previous simulation exercises, such as the treatment of internal surface convection and internal heat and moisture gains.

Solar irradiance at exterior surfaces

Step 1: Given the insensitivity of simulation predictions to the solar absorptivity of the interior surface of the floor (refer to the previous simulation autopsy), the students were surprised to observe reducing the solar absorptivity of the asphalt roof membrane increased the annual space heating load by 2.5 to 3.5%. The group discussed the reasons for this, referring back to the theory of the internal and external surface energy balances, and how reflected irradiance was treated. The conclusion drawn was simulation predictions for buildings like this are much more sensitive to the solar absorptivity of exterior surfaces than to that for internal surfaces, and that users should invest more time in securing accurate data for the former.

Step 2: Both the BPS tools used by the students employ the same model (Perez et al., 1990) by default for predicting anisotropic sky diffuse irradiance. Conducting *Step 2* of the simulation exercise made the students realize that EnergyPlus does not provide any optional methods, while ESP-r allows the user to select alternate anistropic models or to treat the sky dome as isotropic. Each student chose one of these optional methods for conducting an ESP-r simulation and compared their results during the simulation autopsy. Through this, the group realized that the impact of model choice on the annual space heating load was significant: differences as much as 11% were observed.

Referring back to the theory presented in the lectures on sky models, the students realized why treating the sky as isotrpic—specifically, neglecting brightening around the horizon—may lead to significant differences in the prediction of total irradiance incident upon windows (and therefore solar gains to the building). This observation also motivated them to reexamine the structure of the Perez et al. (1990) anisotropic sky model and made them realize there must be uncertainty associated with its model form and empirical constants, and this could propagate into significant uncertainty in BPS predictions.

Step 3: An example of the *Step 3* results produced by one student is illustrated in Figure 6, which contrasts the predictions of total solar irradiance incident upon the south-facing windows ($q''_{solar,ext}$ in Equation 4). Each of the students produced and submitted such graphs which were collectively examined during the simulation autopsy. The group observed that changing the ground reflectivity from 0.2 (a common default value in BPS tools and appropriate for dry bare ground) to 0.7 (a value more representative of fresh snow) had a significant impact (compare the blue circles to the red triangles in Figure 6). The impact on the annual space heating load was seen to be approximately 18%.

Although this exercise may represent the extremes of the bounds on ground reflectivity, it served to make the students aware that the reliance on BPS tool default values may lead to significant errors, particularly in locations where snow cover is frequent.

Step 4: By conducting *Step 4* of the simulation exercise the students became aware of the facilities offered by EnergyPlus and ESP-r for representing external shading objects, including the data required from the user and the level of effort involved. An example of the results produced by one student is illustrated in Figure 7, which contrasts $q''_{solar,ext}$ on two south-facing windows.

Although this exercise prescribed an idealized shape for the tree, it motivated the students to explore the shading facilities and to realize the complexities involved in representing external shading objects, such as geometry and how opacity changes with the seasons. The group had a lively discussion on how much effort BPS tool users should invest in this task and how much uncertainty it introduces into an analysis if such shading is ignored (a common practice): in this case the tree increased the annual space heating load by approximately 9%.

CONCLUDING REMARKS

The simulation autopsy—a working session in which the students and the instructor collectively examine the results of simulation exercises and dissect simulation input files to diagnose reasons for predictive disagreement—plays a crucial role in our BPS learning cycle. We use this as a vehicle for helping students develop critical thinking skills and to connect their active experimentation with BPS tools with the theory that is taught through lectures and assigned readings.

The organization and value of the simulation autopsy was illustrated in this paper by focusing on 2 of the 15 topics of our BPS course: solar heat gains at internal surfaces and solar irradiance at external surfaces. A succinct summary of the theory we present on these topics is provided and the simulation exercises we assign the students were presented. An example of the results generated by the students was provided, and then the simulation autopsy sessions described. Although space limitations prevented an exhaustive description, we attempted to provide here some glimpses into the types of learning that were accomplished during these sessions.

We have observed that for many students the implications of BPS tool default models became clear only after the simulation autopsy and that these sessions are critical for consolidating the teachings of theory. Besides a significant reduction in user errors, the autopsies always led to discussions on whether certain methods may be appropriate or not.

The student experience also reflected our observations. Feedback surveys were administered frequently to assess the effectiveness of the teaching methods at achieving the stated intended learning objectives for each topic. The students consistently rated the simulation autopsies as the most helpful method for supporting their learning (conducting the simulation exercises came a close second).

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