What is happening? Why is it happening? –
Investigative pedagogical approach for building performance simulation education

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Abstract
This paper is based on a study that evaluates the efficacy of early Building Performance Simulation (BPS) users in critically examining their simulation model results with minimal external support. The objective of the study was to deepen the current understanding of challenges faced by early-users of BPS tools in setting up reliable simulation models. This study builds upon existing approach of experiential learning that calls upon an "autopsy" or critical examination of simulation results as an important step in creating better simulation users. We examine the stage where early-users are explicitly asked to verify their model inputs/outputs and autonomously find ways to assess the reliability of their simulation model. This self verification process requires the early-users to articulate appropriate and practical diagnostic questions before proceeding with the verification process. We evaluate the ability of early-users, in this case graduate students, to independently conduct a satisfactory autopsy as compared to matrices of questions generated by experts (in this case, class tutors). Bloom’s taxonomy was further used to assess the cognitive level at which the users chose to engage with the diagnostic activity. Most users chose to engage with the diagnosis in the "Evaluation" level where a basis of comparison had to be brought in. The "Understanding" level, that required the early-user to exhibit grasp over the underlying physical phenomenon or processes was utilized the least in conducting the autopsy. Further work shall examine knowledge gap as potential barrier to being reflective and conscientious BPS users.

Highlights
• It is perceived that BPS suffers from credibility issue as many fail to produce trustworthy results

• Pedagogic methods ("Experiential learning", “Continuous learning cycle” and more specifically, “Simulation autopsy”) present various approaches to producing trustworthy BPS users.

• This paper investigates if early users can conduct a simulation model autopsy autonomously. We further investigate barriers to reflective thinking such as a) knowledge gaps and b) oversimplification (ignoring important complexities) among early users.

Introduction
Several studies have highlighted the lack of accuracy in simulation models set up by early-users of BPS tools stemming from incomplete understanding of simulation tools, lack of awareness regarding common user-errors and credulous belief in simulation outputs (Ibarra and Reinhart, 2013, 2009). Such studies have led to development of modeling guidelines (e.g., (CIBSE, 2015)), checklists (e.g., (Reinhart, 2014)) and even new pedagogical approaches (e.g., experiential learning cycle (Beausoleil-Morrison and Hopfe, 2015)) to improve the accuracy of models set up by early-users. Beausoleil-Morrison and Hopfe (2016) suggested an “autopsy” like approach for early-users to develop healthy skepticism towards their model results.

The autopsy (Beausoleil-Morrison and Hopfe, 2016) begins with a broad objective questions like "Is the model performing as expected?" leading to more specific questions "what evidence shall I collect to know that the model is performing as expected?" and "How will I verify it?". (Beausoleil-Morrison and Hopfe, 2016) used the process of asking such reflective questions (or autopsy) as a means of active learning for the students. Autopsy was conducted collectively in-class with the following learning objectives:

• understanding the subject matter better where questions regarding the simulation outputs were used to reflect on the inputs, assumptions and modelling methods used.

• Connect experience (inputs and resulting outputs from simulation) to theory.

• Sensitize students that simulation results cannot be trusted blindly. Inputs (default or otherwise) need scrutiny.

• Learning to interpret results. The autopsy served as an in-class activity that allowed the tutor to discuss what kinds of conclusions can (and cannot be) drawn from a given simulation output.

However, conducting an autopsy independently requires the early-users to articulate appropriate and practicable diagnostic questions before proceeding with the verification process. The process of posing such questions is nontrivial as it requires understanding of modeling methods of their simulation tool and, at the same time, strategic application of fundamental knowledge of building physic-
s/lighting and HVAC to the subject building project. In this study we evaluated whether early-users (graduate students) are able to independently conduct a satisfactory autopsy as compared to matrices of questions generated by tutors.

Methods

Performing a model autopsy is an exercise in reflective thinking. It can begin with questions like - "Why should I simulate?" ("When I can calculate."). "What are the usable inputs to meet the objectives?" and if the inputs are not trustworthy, "Where can I go wrong?". The autopsy continues after these questions, requiring further reflection on what was done and as a result of it, asking questions like - "What is happening", "Why is it happening" and "Was it the correct/best possible modeling approach?".

The components of an autopsy

A successful autopsy, whether utilized for teaching purposes or as a regular practice (habit) for simulation users should meet the following requirements:

Barrier1: Articulation of a clear and tractable question that is diagnostic in nature.

Barrier2: Plan for extracting the required model data or output (as potential evidence) at an appropriate temporal and spatial scale from the simulation results.

Barrier3: Gathering appropriate reference(s) for evaluating soundness of inputs and/or outputs.

Barrier4: Finally, appropriate conclusions need to be drawn from the evidence gathered.

The questions posed (Item 1) can have varying degree of complexity. For example, both questions below are useful questions to ask:

- **Q1**: What are the default inputs for model components that have not specified explicitly (e.g., ground albedo, emissivity of shading component block)?
- **Q2**: For my building project, which components’ thermal properties matter the most? How can I find out?

Both questions above (Q1, Q2) reflect user’s concerns regarding inputs for material properties but have different intent behind them. Autopsy questions may target model inputs, outputs, both inputs and outputs or they may even be strategic in nature, focused on ensuring the best course of action for further work. To anticipate and address varying "levels" of questions that users can pose, we referred to Bloom’s taxonomy (Bloom et al., 1956) which is typically used as a framework for categorizing educational goals. A revised and action-oriented version of the bloom’s taxonomy is used in this study (Krathwohl, 2002). This revised taxonomy describes the cognitive processes which are employed when students encounter new knowledge or work with knowledge. The taxonomy has six levels. Table 1 shows example questions that a student could ask himself/herself while conducting autopsy on a given subject. It may be noted that all questions in Table 1 are example questions articulated by tutors and were not available to the students in this study. Thus for the purpose of this study, the tutors composed questions in increasing order of complexity to meet the potentially varying levels of understanding and strategic thinking that different students may have reached.

Subjects of study - the early-user group

This study’s results are based on the work-output of a recent cohort with 15 students in a two year Masters in Building Energy Performance program at xx University(name of university withheld for blind-review). Out of the 15 students, 13 have a bachelors degree in architecture, 2 students have bachelors degree in building related engineering fields. All students, while participating in this study were in their third semester, after having successfully completed two semesters (one year) of curriculum covering passive design approach to thermal comfort, HVAC system design and controls. Each of these semesters had three modules each (1) Introduction to theory and first principles (2) Measurement and verification exercises (3) Building performance simulation. Among various hands-on experiential learning opportunities, for example, students were guided to set up a weather station (first semester) or set up a heat recovery system in the classroom, operate it for a few days and measure various parameters (second semester). Several small scale ("shoe-box" style) simulation tasks and problems were also given in the later half of the first and second semester. In the third semester (the focus of this study) the students were asked to setup a detailed thermal simulation model for a whole building design (WBD) problem using a thermal simulation tool that they were familiar with (Design Builder). The required theoretical and conceptual knowledge for tackling the WBD problem had been already delivered to them in the prior semesters.

The call for autopsy

As mentioned above, no new theoretical knowledge was introduced as part of WBD module (eight weeks). The WBD module was exclusively meant for students to learn how to apply what they know, to a whole building design problem. Learning to apply knowledge is also explicit learning goal involving actions like preparing a plan of execution and implementing it. The design problem was introduced (A two storey-ed office building in a peri-urban location) with the design description from the architect, drawings and a two hour site visit (Figure 1). The students were asked to modify the existing design (Envelop design, construction materials, HVAC systems, On-site renewable) to meet ECBC 2017 (BEE, Government of India, 2017) energy performance standard. Throughout the eight week WBD module, at specific junctures, the students were ask to perform an autopsy of their work or decisions taken. For example the following directive was given as part of the first assignment in the module - "Students must present their criteria and justification for selection of the weather file (for their chosen location)".
Several students raised questions that they were not sure how to address this part of the assignment. However they were asked to reflect and encouraged come up with a criterion on their own.

Method for evaluation of Autopsy by students

The autopsies conducted by the students were evaluated by the tutors (authors) into the following possible evaluations:

1. Student did not attempt autopsy
2. Student attempted to conduct autopsy but failed. Incorrect conclusions and simplistic or “token” attempts were called failed attempts. "Token" attempts are those that fail to clearly link inputs to outputs and neither can be verified or understood. For example, investigating impact of a building element such as shading or insulation using impact on 'total cooling load' or other such "lumped" results would be considered a simplistic approach.
3. Student partially or fairly successful in conducting autopsy. An autopsy was considered successful if it managed to isolate important one or more relevant modes of heat transfer or calculation steps between two "nodes", where the "nodes" could be HVAC system components, building components or spaces depending on the scope of the autopsy.

Figures 2 and 3 conceptually show potential autopsy related exhibits that could be produced by students to demonstrate the effect of insulation and shading elements respectively in a model. Figures 2 and 3 show that the student already knows and anticipates the parameters that will be effected (e.g., air temperature, incident irradiation) and the nature of the effect (e.g., negative, positive). Figure 4 shows the overall approach towards the evaluation of various autopsies where the tutors were asked to suggest types of autopsies that could be conducted.

### Understanding barriers to reflective thinking

This study’s results are reported based on the work-output of the current student cohort (Fall semester, 2022). Work-outputs from the previous cohort (Fall semester, 2021) were used to formulate the studio requirements of this current semester. Upon repeated reflection on work-outputs of the 2021, the tutors made seven broad observations that could act as potential barriers to the students’ ability to perform an autopsy:

**Barrier1:** Thought process more likely to be driven by code compliance and itemized approach (e.g., envelope, lighting) rather than fundamental forms of energy flows.

**Barrier2:** Uni-dimensional (one variable at a time) approach towards weather data analysis and evaluation of simulation results.

**Barrier3:** Focus on reducing thermal loads without explicit thought on enhancing human-comfort

**Barrier4:** Incomplete retention of factual and conceptual knowledge from prior semesters

**Barrier5:** Inability to connect spatial / temporal observations

**Barrier6:** Deployment of inappropriate level of details (too course or too much detail)

**Barrier7:** Hesitation in adopting new, fit-for-purpose data analysis tools

Barriers 1-3 reflect a potentially simplistic view of the WBD exercise that may result from lack of awareness or active sensitization. Barrier 4 refers to potential gaps in knowledge. Barriers 5-7 reflect potential lack of data analysis skills, experience and paucity of time to do the autopsy. In this paper we shall further include work on investigating barrier 4, i.e., knowledge gaps. Blooms taxonomy’s hierarchical structure contends that in order to apply knowledge in complex ways (e.g., applying knowl-

### Table 1: Example tutor questions that could be asked for conducting autopsy on (a) choice of the weather file (b) modeling of a vegetated screen as a shading device

<table>
<thead>
<tr>
<th>Bloom’s taxonomy levels</th>
<th>(a) tutor questions on weather file selection</th>
<th>(b) tutor questions on modeling vegetated screen</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1-Retrieve</td>
<td>“How are .epw weather files generated?”</td>
<td>“What is appropriate emissivity value of plant(vegetation) material?”</td>
</tr>
<tr>
<td>L2-Understand</td>
<td>“What type of data quality issues can be expected in weather .epw files? How can they effect my simulation results?”</td>
<td>Explain how an exterior vegetated screen, that is meant to shade a façade, contributes to heat gain in the building interior?</td>
</tr>
<tr>
<td>L3-Apply</td>
<td>“How should I plot the weather data (type and scope of data plot)?”</td>
<td>How would I model a vegetated trellis as a shading device in Energy Plus?</td>
</tr>
<tr>
<td>L4-Analyze</td>
<td>“How will data anomalies manifest in the data plots? How can they be spotted?”</td>
<td>Which properties of the vegetated trellis are most important to know in order to simulate is impact on the heat gains in the building interior?</td>
</tr>
<tr>
<td>L5-Evaluate</td>
<td>“What will be my basis for selecting or rejecting a weather file?”</td>
<td>How can I compare a vegetated screen to solid opaque shading devices using energy plus when trying to shade a naturally ventilated building?</td>
</tr>
<tr>
<td>L6-Create</td>
<td>“Can I write down general guidelines/flow chart of my process for selecting weather files for my location that other people can also use?”</td>
<td>What design changes will help me make the vegetated screen more effective for my given location?</td>
</tr>
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edge and reflecting on the output), it is essential to first address the foundational aspects of the acquired knowledge, i.e., remembering and understanding. As part of this study we are also reporting results from in-class quiz scores of all study participants. These quizzes had limited scope (daylight and daylight simulation) but indicate the ability of different students to absorb new knowledge, retain and apply it, prior to the WBD module. The quizzes contained three types of questions:

- Factual questions (e.g., What is the range of horizontal illuminance (Lux) that could be found outdoors on a cloudy, overcast day?)
- Conceptual questions (e.g., Which of the following would have a higher daylight factor in a 8m x 10m room with one opening? (a) skylight of size 1m x1m or (b) a window facing south of size 1m x1m
- Strategic thinking (e.g., We examined indoor light levels in your design in a mirror box this week. Is this approach for studying daylight still relevant when we can simulate light in spaces with fair degree of accuracy?)

The quizzes were conducted over an eight week period leading up to the test period of this study and reflect (to a limited extent) on the students’ capacity to acquire, retain and apply knowledge (Barrier 4).

Results

Ability to ask the investigative questions

In this paper we are presenting limited set of results from the evaluation of autopsies conducted by students. Figure 5 (bottom) shows the tutor evaluation of two example sets of autopsies conducted by the students. The first autopsy or reflective question that was asked to the students regarding the selection basis for the weather file. For most locations (N=14) more than two weather files were available. Only half the cohort engaged with this question, and reflected on their decision. Several students found the task of conducting autopsies quite unfamiliar, were unsure how to tackle it and eventually only a fraction of the class were able to get to a point where they compiled figures and explanatory text on the topic.

Next, the students proceeded towards setting up whole
building model reflecting existing design and systems (baseline condition). Before setting up the model, decisions needed to be made regarding model level of detail and internal zoning. Students proceeded to make choices, including and excluding physical elements in the building design and context. Given that the vegetated facade (refer Figure 1 (middle and right)) is a somewhat uncommon building element, there were doubts amongst the students on the modeling approach. Students were directed in class to look into existing literature for potential modelling approaches for vegetated facades in Energy Plus. As a recap, all properties of the ‘standard component block’ in Energy Plus were also discussed in class in a question and answer format with the students. When reporting the results from the baseline model, several students specifically discussed and reported results on the effect of the vegetated facade on the building’s indoor thermal environment and thermal loads.

Figure 5 (top) shows the evaluation of autopsies conducted by the students specifically on modelling the vegetated facade. While 14 out of 15 students tried to conduct an autopsy at one or more levels (of Bloom’s taxonomy), few (2-3 students) reflected on the inputs. Most students engaged more deeply with the outputs of the simulation, indicated by more successful autopsies at the ‘Evaluation’ level (8 out of 14). While a list of inputs were included by all students in their assignments, few students actively provided justification or discussed the inputs related to the vegetated facade. ‘Evaluation’ level indicated the level at which students tried to study, report and assess the effect of the vegetated facade on the building’s indoor thermal environment and thermal loads.

Results were shown with and without the vegetated facade. Such autopsies cannot help the user identify potential mistakes nor justify the inputs. Such autopsies were thus categorised at ‘tried but failed’ in Figure 5.

Potential barriers to conducting autopsy
As mentioned earlier, in this paper we are presenting further investigation from potential barrier-4, i.e., lack of factual and conceptual knowledge. To understand knowledge related gaps that students might be facing, we collated results from quizzes that were conducted over an eight week period prior to the WBD module. Figure 6 shows the percentage of correct answers achieved by various students. The first three quizzes only contained factual questions, the next two contained factual and conceptual, and the final quiz (one week prior to WBD module) contains strategic questions as well. Large variation can be seen in the scores and could be a potential contributing factor to low engagement in conducting autopsies.

We then tried to assess if quiz scores (proxy for factual knowledge and grasp over subject matter) could indicate degree of interest and success in conducting autopsies (Figure 7). None of the low scoring students succeeded in conducting meaningful autopsies even though one of them showed significant interest in participating in the autopsy exercise. The high and medium scoring students (see pink and green streams in Figure 7) were more successful in conducting autopsies. However one student with high quiz scores did not attempt autopsy at all and one student tried but failed. It appears that other barriers may be present as well.

Discussion
A methodology for understanding student engagement with reflective thinking or autopsies has been proposed in this paper. The “levels” (Bloom’s taxonomy levels) help
characterise intent of the BPS user behind the act of reflecting. At the same time, the intent of the user behind gathering a certain type (output variable, time-step) of evidence and corresponding data plots were not clear in all instances. The current evaluation of autopsies was done by the tutors after the semester was over. They reached out to the students after the semester was over to understand the students’ approach towards the autopsies. However 10 out of 15 students responded to this request. 3 out 15 students provided further inputs and explanations.

Factors such as shortage of time and perceived incentive, during and after the semester could also be contributing factors to the participation levels. However these factors have not been investigated formally in this study so far.

**Conclusion**

Conducting an autopsy is the last step in the ’Continuous learning cycle’ (Beausoleil-Morrison and Hopfe, 2015) and is considered the most important step for new/early BPS users in closing the loop between theory, experience and learning. In this study we tried to see if early-users (graduate students) could meaningfully engage with reflective activities while setting up their simulation models. Most early-users engaged with the practice of autopsy on the ”Evaluation” level in the Bloom’s taxonomy. At this level of the taxonomy, they were conducting autopsy on the outputs only. The lower levels of taxonomy (”Remember”, ”Understand”, ”Apply”) require reflection on the inputs or question the premise of the modeling exercise. These kinds of autopsies remained large unused suggesting that the students were more sceptical about the simulation outputs than their own inputs. Fundamental knowledge and the ability to retain it, understandably were found to be contributing factors in being able to meaningfully reflect upon the work carried out, as suggested by Bloom’s taxonomy.

**Acknowledgment**

To be added after review

**References**


Figure 7: Sankey chart showing students with varying quiz scores and the level of autopsy conducted on the modeling of the vegetated facade. "Advanced" Autopsies reflect on multiple means of heat transfer or isolate multiple aspects of simulation outputs. "Basic" Autopsy is uni-dimentional. "Tried but failed" refers to simplistic Autopsies with lumped outputs that cannot help the user identify potential mistakes.


