

TEACHING BUILDING PERFORMANCE SIMULATION THROUGH A CONTINUOUS LEARNING CYCLE

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ABSTRACT

During the past decades building performance simulation tools have become complex. Alternate methods are offered for resolving many of the significant heat and mass transfer processes and energy conversion systems. At the same time, modern user interfaces allow users to quickly ascend the learning curve to operate tools in order to produce simulation predictions, although the prediction of accurate results is perhaps becoming more challenging. This paper argues that a complete and continuous learning cycle that includes exposure to theories and the application of tools from the start can be used to effectively teach building performance simulation. Examples of the application of the various stages of this learning cycle are provided and recommendations are made for the further development of pedagogical methods.

INTRODUCTION

The teaching of building performance simulation (BPS) is a topic that deserves as much attention as the development and validation of models and simulation tools. As stated by Clarke (2001): “*What is the point of developing powerful tools without putting in place the means to train and support users?*”

The challenge lies in devising approaches that teach important theoretical concepts while supporting students to develop a deep knowledge of the topic through the transformation of their experience in applying tools. In this paper we offer recommendations for a continuous learning cycle to address this challenge.

Observations on the current situation

We have made the following observations based upon our experience at delivering courses at the university post-graduate level and in the delivery of professional development training sessions:

- Obs-1* Theory underpins the application of BPS, and through experiential learning a deeper understanding of the subject is possible.
- Obs-2* It is relatively easy to train an architect or engineer to generate simulation predictions with any research or commercial tool.
- Obs-3* It is quite difficult (even for experienced users) to produce accurate results.
- Obs-4* Simulation predictions are often insufficiently scrutinized by users.

Obs-5 Users often place too much faith in their simulation tools.

Obs-6 The user is the greatest source of uncertainty.

These observations are not novel. For example, Hand and Crawley (1997) observed that novice users tend to accept initial predictions and have little concept for the need to confirm results (*Obs-4, Obs-5*).

In a study reported by Berkeley et al. (2014), 12 professional BPS users were provided plans and specifications for a commercial building and were tasked with predicting electricity and natural gas consumption using a common tool. Significant differences were observed between their simulation results; monthly electricity consumption varied by a factor of two over the range of users, while there was an order of magnitude difference in gas consumption (*Obs-6*).

In a recent empirical validation study, Strachan et al. (2015) discuss how a number of users of research-grade and commercial tools were provided with a comprehensive specification of an experimental building, including its HVAC system and controls. When comparisons were made between measurements and simulation predictions, a significant number of user-input errors were found that caused poor agreement in a number of cases (*Obs-3*).

Growing complexity

In the field's early days all users were model developers and tool programmers, and consequently they possessed an intimate knowledge of building physics and the techniques that were employed for modelling and simulating these processes. The high cost and limited access to computing resources and inaccessible user interfaces almost guaranteed that the pool of building simulationists remained small and that these few individuals possessed expert knowledge.

During the field's first two to three decades, emphasis was placed upon the development of mathematical models for representing physical processes relevant to buildings and HVAC systems and techniques for simulating these models in a computationally efficient manner (Ayres and Stamper, 1995; Kusuda, 1999). With time BPS tools became more accessible. The 1990s saw the development of the first graphical user interfaces and BPS tools began to be ported to personal computers. And in the past two decades, considerable effort has been placed upon the development of user interfaces aimed at improving the time-efficiency

of model description and results extraction.

Users today are presented with a plethora of tools offering sophisticated user interfaces. New users can quickly ascend the learning curve to describe complex building and energy systems in order to produce simulation predictions more rapidly than ever before imagined. Indeed, some vendors facilitate short courses that promise to make simulation easy and widely accessible. The attendance of design simulation programs offers architects design decisions within a day's time and an "intuitive understanding of how their design can affect light, heat, and airflow" (Anderson, 2014) (*Obs-2*).

However, today's BPS tools are complex. For example, research-oriented tools such as ESP-r, Energy-Plus, and TRNSYS offer optional models for resolving many of the significant heat and mass transfer processes. Numerous options are available—to enumerate only a few—for predicting the distribution of sky diffuse radiation, for treating convective heat transfer at internal building surfaces, for predicting air infiltration rates, and for treating cooling coils, chillers, boilers, and other HVAC components.

In many cases users are overwhelmed with these options and are ill-equipped for choosing amongst alternate methods. The training they have received—often from tool vendors—has prepared them to operate tools, but not to comprehend the underlying methods and their inherent limitations. As a consequence, many users rely upon default methods and default inputs (e.g. ground albedo, part-load-ratio efficiency curves, convection regimes) without realizing the implications of these choices.

The need for a complete learning cycle

Following (*Obs-1*), this paper argues that in order to respond to this situation, we need to teach BPS through a complete and continuous learning cycle. Moreover, it argues that the learning cycle should include guiding students on methods for interpreting, scrutinizing, and verifying simulation predictions as well as a study of the underlying models, simulation methodologies, and their inherent simplifications and limitations. It should also allow the students to become cognizant of the impact of using tool default methods and data, and the myriad sources of uncertainty. And it should encourage students to experiment with tools to investigate the impacts in a recursive manner with the formal teachings.

In contrast to the position taken by Hand and Crawley (1997), this paper argues that students should begin applying simulation tools right from the beginning of the learning cycle.

Outline of paper

The next section describes the *Experiential Learning Cycle* and discusses how it can be utilized in the

teaching of BPS. It then presents evidence to illustrate an outcome of the first mode of learning. A curriculum for guiding students through a study of models and simulation methodologies pertinent to the building thermal, air flow, and HVAC domains is then proposed. Following this, the techniques that have been employed to help students transform their experiences at applying tools and studying theory are described. Conclusions are then drawn and recommendations made for further work.

A LEARNING CYCLE FOR BPS

David Kolb first introduced the Experiential Learning Theory (ELT) in 1984 (Kolb, 2014). ELT is a theory that helps explain how experience is transformed into learning and reliable knowledge. As stated by Kolb (2014): "Truth is not manifest in experience; it must be inferred by a process of learning that questions pre-conceptions of direct experience, tempers the vividness and emotion of experience with critical reflection, and extracts the correct lessons from the consequences of action."

According to ELT, learning is defined to be the creation of knowledge through the transformation of experience. Kolb concluded that there were four distinct learning stages in the recursive cycle, and that student can begin anywhere in the cycle.

The four learning stages are as follows:

- Concrete experience (CE).
- Reflective observation (RO).
- Abstract conceptualization (AC).
- Active experimentation (AE).

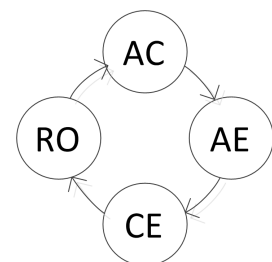


Figure 1: The Kolb Learning Cycle

Kolb argued that learning should involve all four modes recursively, as illustrated in Figure 1: CE leads to RO, which leads to AC, which leads to AE, and then back to CE in a continuous cycle.

This contrasts with other instructional methods, such as, for example, *Constructive Alignment* which is "about giving clear and consistent signals about what is important to learn (knowledge dimension) and how it should be understood (cognitive process dimension)" (Nightingale et al., 2007). Kolb's experiential learning cycle affords opportunities for creativity and ownership of learning which makes it more applicable to higher levels of studies such as learning BPS.

Figure 2 presents our proposal for a BPS learning cycle, which is based upon Kolb's ELT. Modes AC and CE relate to how we grasp experience or take in information. In the context of BPS, AC can be considered the study of theoretical underpinnings, such as the

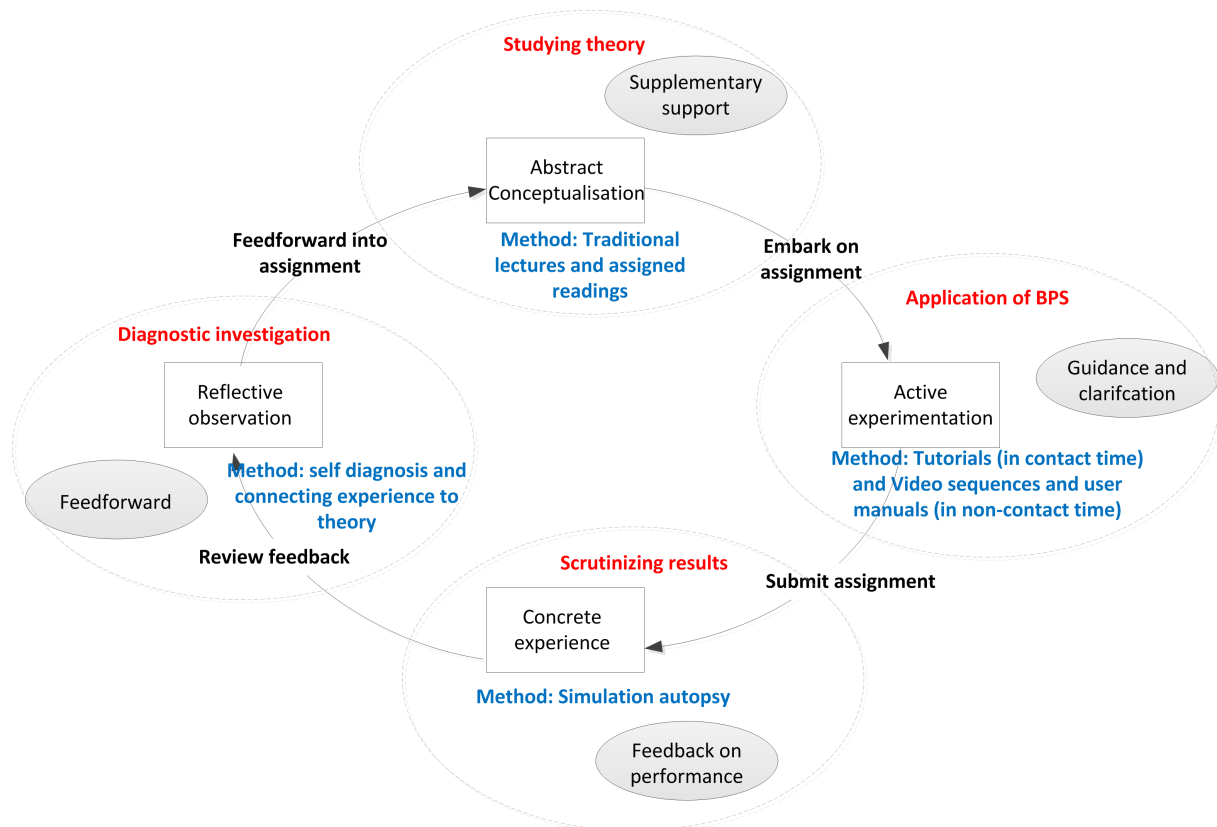


Figure 2: A learning cycle for BPS following Kolb's model that is divided into four stages: the 'Application of BPS' (AE), 'Scrutinizing results' (CE), 'Diagnostic investigation' (RO), and 'Studying theory' (AC); the dashed circles group each of the four stages with the methodology of how learning is transferred onto the student (in blue) together with the interaction the teacher has on the learning process in each stage (light grey oval circle).

structure and formulation of physical models and the mathematical methods that have been devised to simulate them. CE is the mode of learning that occurs during the examination and interpretation of simulation predictions, including their scrutiny and verification.

Modes AE and RO relate to how we transform experience, that is how we interpret and act upon the information that has been taken in through the AC and CE modes. In BPS, AE can be considered the application of tools, that is how we make choices between alternate modelling methods (e.g. methods to predict air infiltration or convective heat transfer coefficients) and simulation options (e.g. choice of time-step or methods for coupling calculation domains) or even simulation tools based upon our theoretical understanding and awareness of model simplifications and the impacts of uncertainty. This also involves the collection and input of data that describe buildings, their energy systems, occupant behaviour, and operational characteristics, as well as decisions about which inputs should be provided and which program defaults can be accepted. The RO mode of learning is how we reflect upon the scrutiny of results from CE and relate this to our understanding of the theory learned during the AC mode. It involves the transformation of the knowledge from CE into decisions about how we can and should

simulate.

We believe that the recursive application of the full cycle is required in order to develop the necessary knowledge and skills to effectively apply BPS tools, and this must be recognized in the way we teach the discipline. To echo Kolb, we believe that unduly focusing attention on one of these modes of learning at the expense of others will adversely affect the complete learning cycle.

Figure 2 also presents the methods we recommend for supporting the learning cycle (shown in blue). For the AC mode we recommend traditional lectures and guiding students through assigned readings from the literature. Tutorial sessions, self-learning through the reading of user manuals and examination of exemplars, and video sequences illustrating certain aspects of tool operation (e.g. addition of air flow networks) are utilized to support the AE mode. Simulation *autopsies* that involve collaboratively verifying and diagnosing student-created BPS models can be used in the CE mode. Finally, for the RO mode of learning, we suggest that students independently apply the techniques illustrated through the CE mode to their own BPS models in order to connect experience to theory. The sections that follow will illustrate some examples of these methods from our own teaching.

Feedback is critical in supporting the BPS learning cycle. This feedback is given through the interaction with the instructor or teacher and is shown as the light grey ovals in Figure 2. As Biggs and Tang (2007) write, “the most powerful enhancement to learning is feedback during learning”. To this end, feedback—also known as *formative assessment* or *feedback for learning*—should be provided during each learning mode and at each iteration throughout the cycle, as this provides the students with the opportunity to identify how they are performing and where they may need to improve. Importantly, this feedback should be in the form of feedforward advice, rather than concentrating on student assessment as, for example, pointed out by Glover and Brown (2006). The feedback should be considered as part of a guidance and feedback loop (Hounsell et al., 2008) in order to support the learning. Once again, the sections that follow will elaborate this with some examples.

ACTIVE EXPERIMENTATION

This section provides an example from the recent teaching of a graduate-level course on BPS. Most of the students taking this course have never used a BPS tool but all have completed engineering or architectural degrees and are studying at the master’s or doctoral level. They have all completed courses on heat transfer and thermodynamics, and some have taken courses on building physics and building services.

At the beginning of the course the students are provided with training on the operation of two research-grade BPS tools: ESP-r and EnergyPlus. This includes a demonstration of ESP-r’s *Project Manager* interface and how its *Building and Plant Simulator* and *Results Analyzer* can be utilized to create models, commission simulations, and extract results. Likewise, the students are shown how the EnergyPlus *IDF Editor* can be used to create models and how simulations can be conducted and results analyzed. Learning resources in the form of ESP-r’s *Cookbook* and EnergyPlus’ *Getting Started* manual are provided and the students are given some structure on how to acquire the necessary skills to learn the basics of operating these tools.

Following this initial training, the students are given an assignment based upon ASHRAE Standard 140 (ANSI/ASHRAE, 2007; Judkoff and Neymark, 2006). They are to create simulation input files to represent Case 600, one of the basic low-mass test cases and to predict its annual space-heating (SH) and space-cooling (SC) loads.

Generating simulation predictions is easy

Based upon their initial training, the vast majority of students are able to create ESP-r and/or EnergyPlus input files and to generate predictions of the annual SH and SC loads. This lends credence to *Obs-2*.

The students’ simulation predictions that arise from

this AE mode of learning are illustrated in the left side of Figure 3. This figure plots the annual SH and SC loads that each student predicted using either ESP-r or EnergyPlus.

Standard 140 includes the simulation predictions from 8 combinations of BPS tools and experienced users that were used to develop IEA BESTEST (Judkoff and Neymark, 1995), which is the source of Case 600. The ranges predicted by these 8 BPS tools are also indicated in the figure using dashed lines. Given that these 8 BPS tools represent a range of modelling methods and default assumptions, it would be expected that the student results should lie within these ranges.

Producing accurate results is difficult

However, the left side of Figure 3 reveals that in most cases this does not occur (evidence to support *Obs-3*). In 10 instances the student’s predictions of the annual SH load was within the expected range, while the predictions of annual SC loads were within the expected range in only 5 instances. In only 4 of 21 instances (Students 2, 7, 17, and 21) did the students predict both SH and SC loads within the expected range.

An examination of the input files of each of these 21 simulations led to the following observations:

- No errors in geometrical input were found.
- In many cases, BPS tool default values for surface solar absorptivities and longwave emissivities were employed rather than using the data provided in Standard 140.
- In a few cases students used default envelope material thermophysical properties.
- In some cases the order and thickness of materials was not correctly assigned, and there were data entry errors.
- In one case a default climate file was used rather than the one supplied with Standard 140.
- Heating and cooling systems were undersized by many students.
- At least half the students incorrectly specified window optical properties.

CONCRETE EXPERIENCE

The students were required to predict the annual SH and SC loads. In many cases it appears that these are the only simulation predictions they examined.

Scrutiny of simulation results is key

The critical examination of temporal results, such as heat injection or extraction rates, solar gains, and zone air temperature would clearly have revealed errors in some of these predictions (*Obs-4*). For example, Case 600 includes an HVAC system with idealized control. The heating and cooling capacities are 1 MW and can perfectly modulate to meet the heating and cooling set-points of 20°C and 27°C. A number of the students incorrectly input these system capacities, providing val-

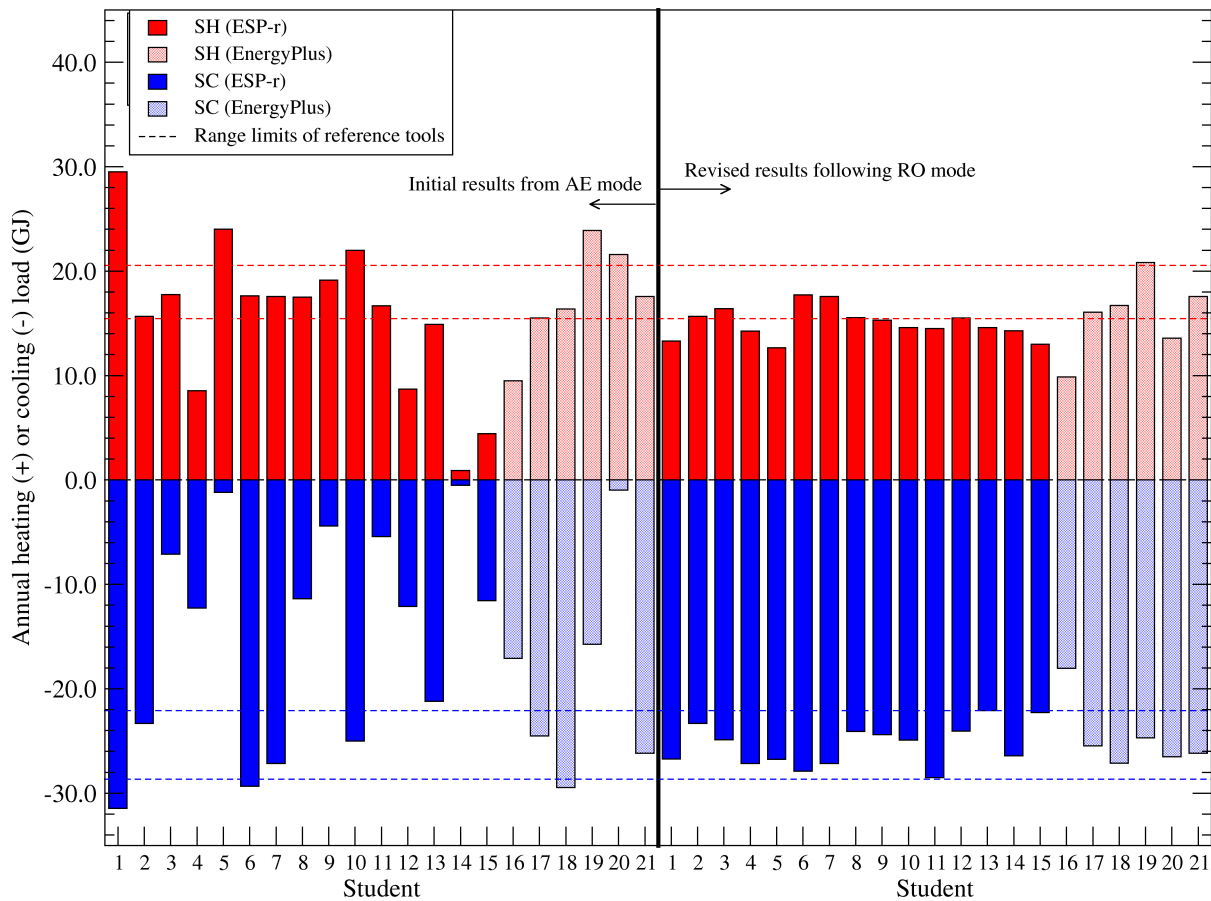


Figure 3: Student simulation predictions for ASHRAE Standard 140 Case 600: initial predictions during AE mode (left) and revised predictions following RO mode (right)

ues of 1 kW rather than 1 MW. The outcome of this user error can be seen in Figure 4, which illustrates Student 12's simulation results for two days in February. This figure clearly indicates that the heating and cooling setpoints are not maintained during the ESP-r simulation: zone air temperatures rise to over 50°C when the cooling capacity reaches its maximum, and drop below 10°C when the heating capacity reaches its maximum.

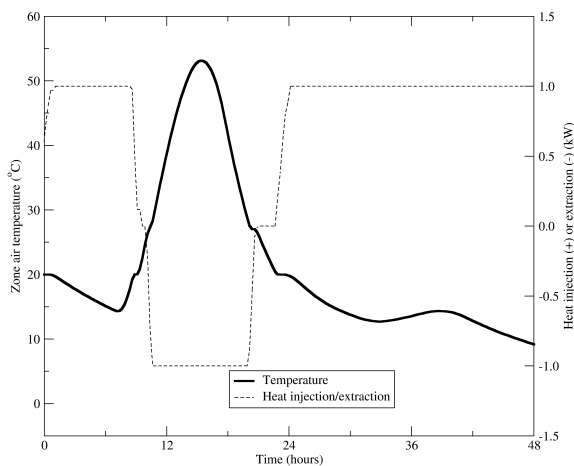


Figure 4: Student 12's predictions for two days in February

Too much faith in the tool

Standard 140 provides window optical properties for Case 600 that can be used to determine the solar transmission, absorption, and reflection of the glass layers at various angles of incidence. Student 20 neglected to use some of these provided data, leaving the inputs blank for the solar reflectance in the EnergyPlus *Window:Glazing* object. The EnergyPlus IDF Editor indicates a value greater than zero must be specified. However, the program does not issue a warning or error when this value is left blank and simulations run to completion. This user had faith that the simulation tool would flag such an omission (supporting *Obs-5*). However, this was not the case. Figure 5 plots the solar radiation transmitted into the zone over the course of 1 week in March. As can be seen, no solar radiation was transmitted through the windows during Student 20's simulation, leading to an overprediction of SH and an underprediction of SC. The figure also illustrates the predictions when the solar reflectivity values are correctly input.

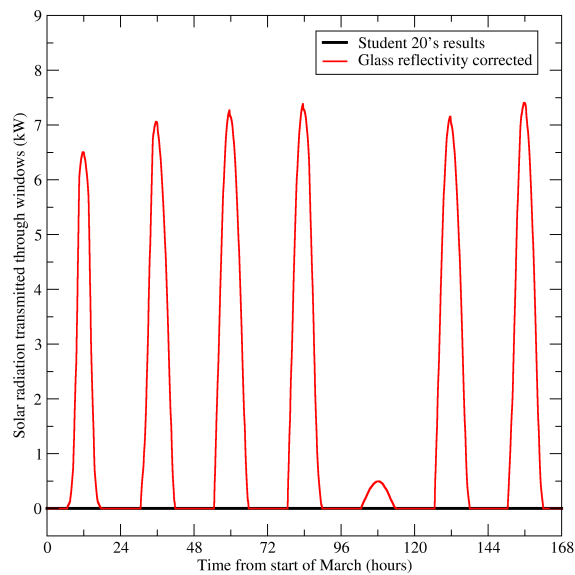


Figure 5: Student 20's predictions for a week in March

Teaching skepticism

The initial SH and SC predictions shown in the left side of Figure 3 are presented to the students and some of the input files are examined collectively. Through this exercise, the students are exposed to methods for extracting and examining temporal simulation predictions as an aid for diagnosing errors. This includes plotting the following simulation predictions over selected periods of a few hours or a few days:

- Zone air temperature (as in Figure 4)
- HVAC injection/extraction (as in Figure 4)
- Solar gains (as in Figure 5)
- Internal gains
- Air infiltration rate

Methods are also discussed for verifying the magnitude of simulation predictions using simple hand calculations. The objective is to develop a certain degree of skepticism to encourage greater scrutiny of simulation predictions before examining integrated annual results.

REFLECTIVE OBSERVATION

After scrutinizing the results, the students are then given an opportunity to diagnose their models and correct erroneous inputs via self diagnosis. This connects the experience to theory (the RO mode of learning). Through these activities the students strengthen their understanding of the models and simulation methods employed. As one student said: "As was shown during the preliminary results specifying the internal convection coefficient to a fixed value caused the annual heating and cooling loads to increase by approximately 12.5%."

The students correct their inputs following the diagnosis. The results are generally improved predictions, as can be seen in the right side of Figure 3. As stated

by another student, this reflection process has developed "an understanding that simply speaking any output is only as good as the input" and they have gained a "greater sense of how to be critical of an analysis and not just take the results as a fact".

ABSTRACT CONCEPTUALIZATION

Although Standard 140 unambiguously defines Case 600, it intentionally provides little guidance on the choice of modelling methods. ESP-r and EnergyPlus are comprehensive research-grade simulation tools that offer many alternative modelling methods. In many cases students must choose amongst these methods or accept program default treatments.

This is where 'studying theory' is important, since it allows students to make informed decisions. When students understand the theoretical implications of their research design (e.g. modelling methods, or simulation tools) they are better able to understand the uncertainty associated with their results, and thereby contextualize their findings.

In order to sensitize students to the implications of such choices, a number of these alternatives are described and a sensitivity analysis is performed to illustrate how Case 600's annual SH and SC loads react to some of these choices. This teaches the students about some of the underlying models, their limitations, and implications. Issues such as the choice of simulation time-step, discretization in the the space domain, solar insolation, etc. are examined. Each algorithm choice or input is varied in turn and the impact upon the annual SH and SC quantified. The results of these can be seen in Figure 6.

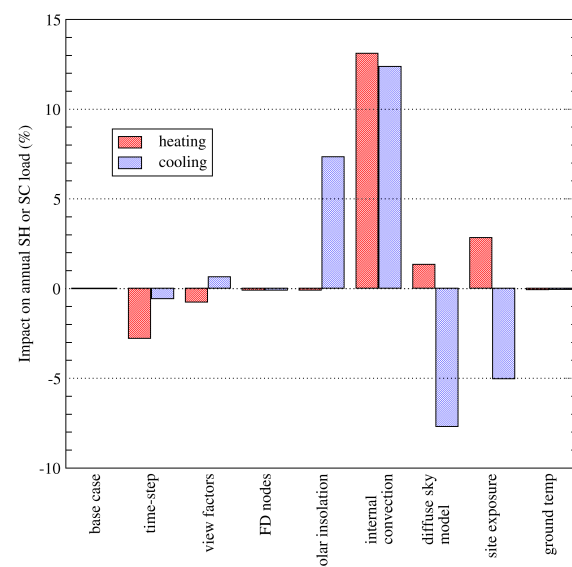


Figure 6: Case 600 sensitivity study using ESP-r

This exercise completes the first cycle through the four learning modes. This cycle can now be re-run focussing on specific topics in order to strengthen and expand student's knowledge.

COURSE CURRICULUM

The BPS learning cycle we propose in Figure 2 includes the delivery of traditional lectures and assigned readings from the literature as part of the AC mode of learning. Table 1 succinctly presents the topics we propose for a course on thermal and air flow simulation. This AC curriculum is designed with the following learning objectives in mind:

- Develop knowledge of the theories and methodologies that are utilized in state-of-the-art BPS tools.
- Create an understanding of the models employed by various BPS tools to simulate heat and mass transfers in buildings and their energy conversation and storage systems.
- Develop an appreciation of the assumptions, simplifications, and applicability of BPS simulation tools.

Table 1 presents one example of the learning objectives associated with each of the curriculum topics (space limitations prevent a complete listing and preclude the inclusion of our recommendations for this curriculum and associated learning objectives).

CONCLUDING REMARKS

Based on this interconnected learning cycle, a methodology of how students can simultaneously reinforce their theoretical and applied understanding is established. By-products of this process include both a greater awareness of the consequences of their decisions and a more critical understanding of the limitations inherent in the process of numerically modelling physical phenomena.

In many universities the following proverb, that is often attributed to Confucius, is shown: “Tell me and I forget. Show me and I remember. Involve me and I understand.” We all know that we learn best from our own personal experience. Reflection upon this learning-by-doing however is fundamental. In order to achieve this, the dynamic of the cycle needs to be driven by the engagement of the student, so that the teacher becomes solely the guide and facilitator in this process. This transition leads to an important extension of the above quotation: *Engage me, and I will become aware.*

We hope that this current paper makes a contribution towards the development of teaching and learning packages, which relates to *Proposition 15* of IBPSA’s recently commissioned position paper (Clarke, 2015).

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Table 1: Lecture and assigned reading topics for AC mode of learning

Topic	Extract of BPS related learning objectives
<p>Introduction to BPS</p> <ul style="list-style-type: none"> ● Significant heat and mass transfer paths. ● Energy conversion systems. ● Early methods for predicting energy performance. ● Major developments in evolution of BPS. ● Calibration, validation, and verification techniques. 	<ul style="list-style-type: none"> ● Understand significant physical processes and appreciate complexity in simulating them concurrently.
<p>Transient conduction heat transfer</p> <ul style="list-style-type: none"> ● Response function method. ● z-transfer function method. ● Determining conduction transfer functions (CTF). ● Numerical methods (finite difference/finite volume). 	<ul style="list-style-type: none"> ● Realize implications of model choice on spatial and temporal resolution.
<p>Zone energy balances</p> <ul style="list-style-type: none"> ● Response/transfer function methods. ● The “heat balance” method. ● Control volume methods. 	<ul style="list-style-type: none"> ● Understand and realize which tools use which methods and the reasons why.
<p>Solar radiation and fenestration</p> <ul style="list-style-type: none"> ● Predicting direct beam solar irradiance on tilted surfaces. ● Modelling sky diffuse solar radiation. ● Modelling ground-reflected solar radiation. ● Methods for treating fenestration. ● Predicting insolation/solar distribution. ● Shading by building elements and surrounding objects. 	<ul style="list-style-type: none"> ● Appreciate complexity and uncertainty related to solar radiation and fenestration (such as defaulting, data requirements, weather data) and its impact on user decisions
<p>Longwave radiation and convection heat transfer</p> <ul style="list-style-type: none"> ● Longwave radiation between internal surfaces. ● Radiation view factors. ● Longwave radiation from external surfaces. ● Newton’s law of cooling. ● Determining convection coefficients. 	<ul style="list-style-type: none"> ● Understand model simplifications and potential impacts on simulation predictions related to longwave radiation and convection heat transfer.
<p>Ventilation and infiltration</p> <ul style="list-style-type: none"> ● Single-zone methods for predicting air infiltration. ● Network air flow methods. ● Modelling natural and hybrid ventilation systems. 	<ul style="list-style-type: none"> ● To be able to undertake a significant piece of design that shows the impact of user choices and the degree of uncertainty in predicting natural and hybrid ventilation.
<p>HVAC, thermal storage, and energy conversion devices</p> <ul style="list-style-type: none"> ● Empirical vs first-principle methods. ● Steady-state vs dynamic models. ● Solar thermal and photovoltaic collectors. ● Thermal storage. 	<ul style="list-style-type: none"> ● Understand which HVAC components should be treated with dynamic methods, and the complexity this adds.
<p>Internal gains and occupants</p> <ul style="list-style-type: none"> ● Treatment of internal heat gains. ● Predicting occupant discretionary loads (non-HVAC electrical demands and DHW draws). ● Predicting occupant behaviour (light switching, blind actuation, HVAC setpoints). 	<ul style="list-style-type: none"> ● Appreciate the existence of models and their limitations for predicting occupant behaviour, and understand their impact on predicted building performance.
<p>Weather data</p> <ul style="list-style-type: none"> ● Typical meteorological years. ● Historical climate data. ● Predicting future climate. 	<ul style="list-style-type: none"> ● Understand methods than can be used to estimate urban and future climate and to be able to undertake a design that is assessed for design robustness.