Teaching the fundamentals of building performance simulation in the 21st century

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Why BPS matters

Building performance simulation (BPS) tools employs a large number of mathematical models to simulate a building's performance under a given set of weather and operating conditions. Many aspects of performance can be appraised, including energy consumption, ventilation effectiveness, thermal comfort, lighting quality, etc. The objective is to represent the significant physical processes so that the simulation provides an accurate—or at least a useful—representation of reality.

This technology provides tremendous potential for addressing some of the key challenges facing the building industry in the 21st century by improving design and operation: climate change, energy dependency, renewables integration, health/wellbeing, etc. For example, BPS can allow architects and engineers to compare the performance of innovative concepts inexpensively and to contrast design alternatives rapidly throughout the various stages of design development. This is critical as we move towards design solutions that more tightly integrate architecture, thermal and electrical systems, and energy storage.

However, much of BPS' potential remains unfulfilled. There are various reasons for this, but one important factor is a credibility gap that can only be addressed when we adequately prepare users to effectively apply tools with full knowledge of their applicability, modelling limitations, and default methods and data, and provide them the skill set to scrutinize their results.

Using BPS is easy, and difficult

Today we have access to numerous BPS tools that offer modern and intuitive user interfaces. With these, 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. **Figure 1** provides a demonstration of how easy it is for new users to learn the basics of operating BPS tools. I provided some introductory training on tool operation to students who were brand new to the BPS field. Within two weeks all were able to simulate the performance of a simple building using two different BPS tools. Their predictions of the building's cooling load are plotted in **Figure 1** and contrasted to a reference result (the expected outcome).

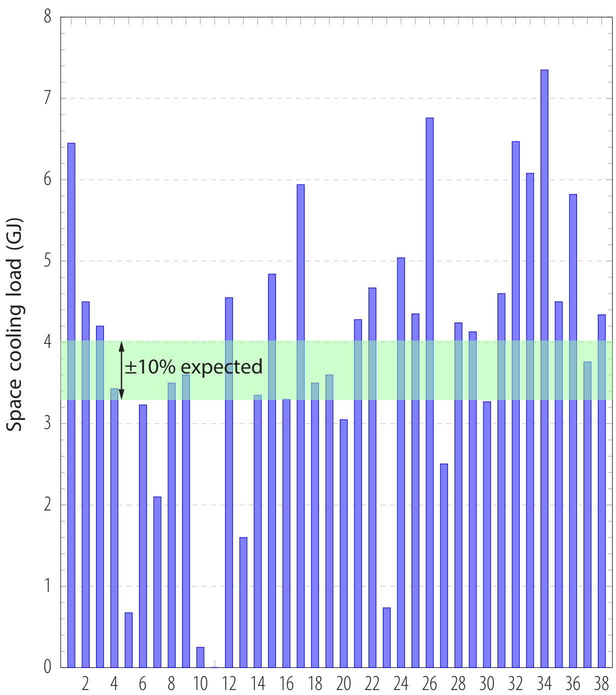

Figure 1. Simulation predictions produced by novice users trained to operate two BPS tools (38 combinations of users and tools).

Although a handful of the simulation predictions were within 10% of the reference, it can be seen that the majority are significantly higher or lower.

This is not a unique finding. The literature is full of such anecdotes, and fidelity does not seem to vary much with the experience level of the user (practicing engineers, researchers, novices) or the choice of BPS tool. It is challenging to produce accurate BPS results. Buildings are complex entities so predicting their performance requires simulating myriad interrelated heat and mass transfer processes which are excited by uncertain boundary conditions. Accurately predicting performance requires the user to select modelling options and input data to characterize all the significant processes. Deciding how to prioritize efforts on the most important and impactful parameters and modelling choices is not always easy. Should efforts be focused on geometry and zoning, characterizing air infiltration, described HVAC systems and their control, or describing convection and radiation heat transfer processes? It depends upon the building and the objectives of the analysis, so universal and simple rules cannot be prescribed.

Teaching vs training

Too often we train users to operate BPS tools – as I did in the demonstration shown in **Figure 1** – but we neglect to teach them to comprehend the underlying methods and their inherent limitations. As a result, users can easily feel overwhelmed and are often ill-equipped to operate tools accurately and with greatest impact. Because of this, 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. And they are not equipped to answer the above questions about prioritizing efforts.

To address the key 21st century challenges facing the building industry it is imperative that we develop advanced tool users who have an understanding of BPS fundamentals. These people will have the ability to prioritize efforts, decide which inputs and modelling choices will have the greatest impact upon simulation predictions, configure fit-for-purpose models, and scrutinize simulation results. This will help us to achieve the full potential of BPS.

An approach for teaching the fundamentals

I have authored a textbook to help address these needs (**Figure 2**). This book—endorsed by the International Building Performance Simulation Association—is aimed at teaching the fundamentals of BPS and can be used to support university-level courses in engineering, building physics, and architectural science. It can also be used to support professional development courses or as a self-study guide by BPS practitioners wishing to deepen their knowledge of the fundamentals. It presumes basic knowledge of heat transfer, thermodynamics, building physics, and the terminology of buildings and HVAC systems, but does not require prerequisite knowledge of BPS or experience applying BPS tools.

Figure 2. Fundamentals of Building Performance Simulation textbook.

Readers who complete all the book's learning elements (described below) will be able to:

- Understand the models that have been implemented into BPS tools for treating the significant heat and mass transfer processes.
- Appreciate the simplifications inherent in these models and the necessity for these simplifications.
- Comprehend the implications of modelling choices and default modelling methods and input data.

- Select appropriate models, simulation methods, and BPS tools for a given analysis.
- Understand which modelling choices and input data have the greatest impact upon simulation predictions.

The book employs an experiential teaching approach structured upon four interrelated modes of learning, which are illustrated in **Figure 3**. The result is a learning spiral wherein the completion of one topic's cycle through the four learning modes leads into the next topic. Most of these topics focus on an individual heat or mass transfer process, such as longwave radiation from external building surfaces, heat transfer to the ground, air infiltration, etc.

Each chapter of the book is dedicated to one of these topics and follows a common structure. Basic theories are first introduced and then the methods commonly used in BPS are described (the *Study theory* mode of **Figure 3**). This is done in a tool-agnostic manner whereby the spectrum of commonly employed techniques is outlined, and the strengths and weaknesses of each are described. Mathematical descriptions are provided where necessary to illustrate concepts, but these chapters are not meant to be a comprehensive compendium of models.

Each chapter guides the reader to experiment with BPS tools in the *Simulation exercise* mode of learning. These exercises provide instructions aimed at isolating specific algorithms, requiring readers to consult BPS tool technical documentation and to explore and experiment with their chosen tool to conduct sensitivity analyses and to extract particular results.

Student results are compared, contrasted, and collectively analyzed during the *Autopsy* mode of learning. These sessions are most effective when they are led by a course instructor and involve group discussions. By examining simulation input files and collectively diagnosing issues students develop skills in scrutinizing simulation results and learn from their own experiences and those of peers.

In the final mode of learning—*Reflect & connect*—students individually reflect upon the findings highlighted during the autopsy and perhaps revise their simulation input files and conduct new simulations to update their results. This is also an important mode for connecting the studied theory to observations derived from the simulation exercises.

This teaching approach is demonstrated by drawing some examples from a graduate-level university course and from a professional development course that I recently taught.

Teaching example—solar energy absorption by external surfaces

We'll focus on the book's chapter dedicated to solar energy absorption by external surfaces. Students commence this topic by studying some theory. This chapter of the book outlines the factors that influence the amount of solar irradiance incident upon the

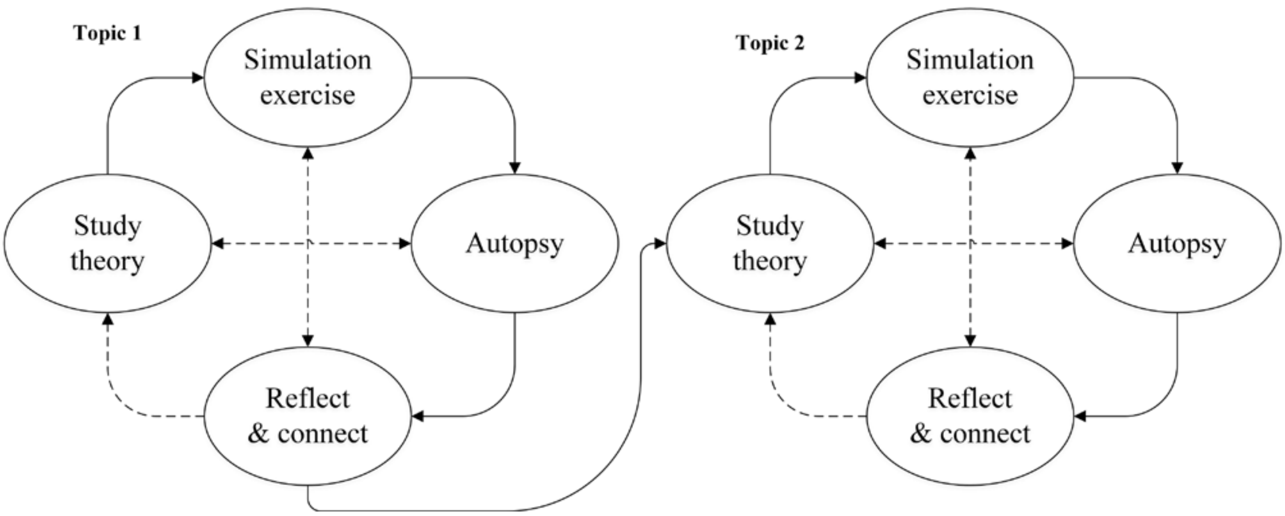

Figure 3. Two cycles through the learning spiral showing the four interrelated modes of learning.

external surfaces of the building. This includes scattering of solar radiation by the earth's atmosphere, the geometrical relationship between the building and the sun, shading by surrounding objects, and the reflection of solar radiation by the ground.

The book then explains that it is common for BPS tools to treat the global incident irradiance as the summation of three components: beam, sky diffuse, and ground reflected radiation. The algorithms that are used to derive the beam component from solar radiation data contained in weather files are explained, which develops an appreciation for solar geometry calculations and concepts such as solar declination, solar elevation, and surface azimuth. Readers then learn about the complexities and uncertainty in predicting sky diffuse irradiance and come to realize the factors that cause scattering of solar irradiance by the earth's atmosphere (**Figure 4**). They are introduced to the breadth of models that have been developed to estimate this scattering and the empirical nature of these models, and they discover that different BPS tools employ different models and provide different options to the user. Finally, they learn about the factors—such as vegetation and snow accumulation and melting—that complicate the estimation of ground-reflected solar irradiance and come to understand some of the modelling approaches available.

This chapter of the book then guides the reader through a series of four structured simulation exercises focused on solar energy absorption by external surfaces. In one exercise they alter the solar absorptivity on a single building surface and examine the impact this has upon the building's heating and cooling loads. By contrasting this result against an exercise from a previous chapter focused on the modelling of solar absorption by internal building surfaces they come to realize the relative significance of these input data. In another exercise they explore the optional methods their chosen BPS tool offers for the modelling of sky diffuse solar irradiance and the impact this kind of modelling decision can have upon simulation results. The other exercises have them discover the options for treating ground-reflected solar irradiance and solar shading.

The student's simulation results are gathered and analyzed collectively during an autopsy. **Figure 5** presents one of the graphs examined during this session, this for the exercise examining ground-reflected solar irradiance. (For illustration purposes the figure includes results from only a handful of students.) Each student independently decided how to model the solar reflectivity of the ground and their predictions are compared to their simulations performed using their tool's default approach. All students observed that their modelling choice had an important impact on the buildings heating loads, but some (students 4, 7, and 9) saw less impact that others. This led to discussions where each student explained their approach and its rationale and the theory previously studied was revisited. The conclusion of the group was that user choices for the modelling of ground-reflected irradiance can have a significant impact, so it would be unwise to casually accept BPS tool default methods for some simulation analyses.

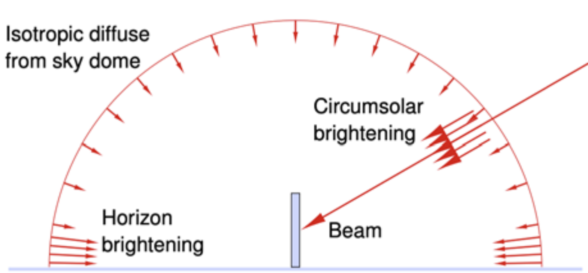

Figure 4. Methods for predicting sky diffuse solar irradiance to building surfaces.

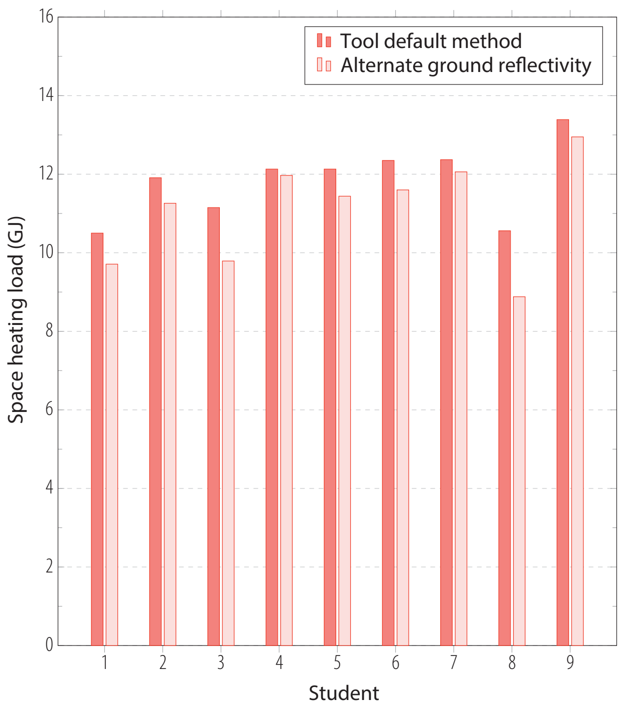

Figure 5. Student results from simulation exercise focused on modelling ground-reflected solar irradiance.

Teaching example—air infiltration

Another chapter of the book is dedicated to air infiltration and natural ventilation. Once again, students commence this topic by studying some theory. The book explains that infiltration results from pressure differences across openings in the building envelope which can be induced by wind or by mechanical ventilation systems that supply or extract air from a zone. It also describes the stack effect and explains how hydrostatic pressure differences between indoor and exterior environments can also cause pressure differences across openings. It helps the reader understand that these pressure conditions are highly variable, depending upon the speed, direction, and turbulence of the wind, and that they also depend upon the building's shape, the local terrain, temperature conditions, and the functioning of combustion equipment and HVAC systems.

The options for treating these complex phenomenon are then outlined. This includes two approaches commonly employed by users, that is ignoring air infiltration or prescribing constant airflow rates. Theories underpinning single-zone models and network airflow modelling approaches are then elucidated. Methods are described for establishing the necessary inputs for these methods, including interpreting empirical data from building depressurization tests.

This chapter also includes a series of structured simulation exercises which cause the reader to explore the facilities available in their chosen BPS tool. **Figure 6** presents some of these simulation exercise results that were examined collectively during an autopsy. (Again, the graph is limited to a handful of students for illustration purposes.) From these exercises the students gained an appreciation for how impactful air infiltration can be on the prediction of heating and cooling loads. All four students whose results are plotted in this figure predicted substantially different space heating loads using the two simplified—and commonly used—methods of prescribing constant airflow rates or ignoring infiltration. This impact was observed to be far more significant that many of the factors examined in the simulation exercises from previous chapters, such as geometrical details, transient conduction calculation methods, longwave radiation view factors, and the distribution of solar gains to internal building surfaces.

Through these exercises students discovered how to configure single-zone models based upon empirical data from building depressurization tests and they also developed an understanding of the modelling resolution that can be realized—and the associated complexity for the user—with network airflow models. By sharing their experiences with their peers through the autopsy, students understood how these models are influenced by user decisions on locating airflow openings, specifying data such as crack sizes and discharge coefficients, and choosing pressure coefficient sets. The significance of these decisions was discovered by comparing results (e.g. compare student 4 to the others).

Scope of learning

The above descriptions serve only to provide some examples of the topics covered by the teaching approach that is supported by the book, whose aim is to guide the reader through all of the significant heat and mass transfer processes.

The first part of the book briefly introduces BPS, defining what it is, how it is used, and discusses the central role the user plays in ensuring valid BPS predictions. Each of the next three parts of the book contains a series of chapters. Each distinct heat or mass transfer process is treated by a dedicated chapter appearing in one of these three sections. Part II treats the heat and mass transfer processes relevant to the building interior, while Part III focuses on heat transfer processes relevant to the exterior environment. Heat and mass transfer occurring through the building envelope

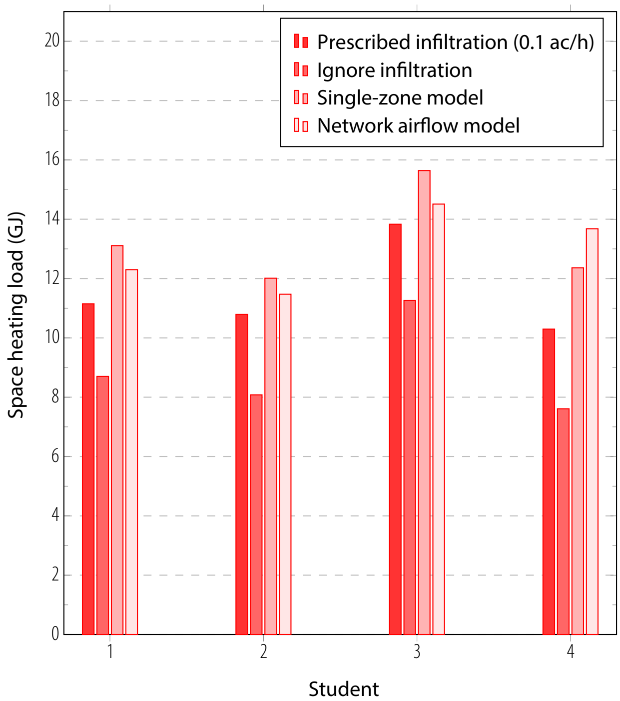

Figure 6. Student results from simulation exercises focused on air infiltration.

are the subjects of Part IV. This is followed by Part V, which focuses on HVAC systems.

The final part of the book includes a *Culminating Trial* in which the reader applies all the knowledge and skills they have developed in the preceding chapters by representing an actual building with their chosen BPS tool and by comparing their simulation predictions to measurements.

This book emphasizes depth at the expense of breadth. Its scope is limited to heat and mass transfer processes relevant to the building's form and fabric and HVAC systems. There is, of course, much more to learn—model abstraction, daylighting, occupant comfort, acoustics, electrical energy conversion and storage systems, managing uncertainty, etc.—but this book can serve as a starting point for learning the fundamentals of BPS.

Closing thoughts

I have delivered many university-level and professional development courses based upon the approach outlined in this article. The multiple iterations through the spiral's four modes of learning have been found to be effective and critical for students to concretize theoretical concepts, to help them develop techniques for interpreting, scrutinizing, and verifying simulation predictions, as well as making them aware of the impact of using tool default methods and data, and the myriad sources of uncertainty in BPS. From my experience, any shortcuts around the systematic experimentation at the heart of the approach would be detrimental. This has been validated through feedback provided by students who universally state that the course's learning objectives were fully achieved. The theory in the book, the simulation exercises and autopsies, and the Culminating Trial were consistently rated by the students as the most helpful for supporting their learning.

Understanding the fundamentals is critical but much more is required to develop the next generation of BPS users that we require to address the major challenges facing the building industry in the 21st century. It is also necessary for BPS users to develop the necessary skills for collaborating and interacting with building designers. Skills such as interpreting design questions and translating them into simulation analyses, interpreting results, and providing timely and appropriate feedback to inform design teams must also be cultivated, but this cannot happen without a solid understanding of the fundamentals.

It is my hope that the teaching methods outlined here can be borrowed, adapted, and improved by others to help move us forward. ■