TEACHING A BUILDING SIMULATION COURSE AT THE GRADUATE LEVEL

Michel Bernier[1], Michaël Kummert[1], Simon Sansregret[2], Denis Bourgeois[3], Didier Thevenard[4]
[1] Polytechnique Montreal, Département de génie mécanique, Montréal, Québec, Canada
[2] Laboratory of Energy Technologies, Hydro-Quebec Research Institute, Shawinigan, Canada
[3] rd2.ca. Québec, Canada
[4][4] Numerical Logics Inc., Kitchener, Ontario, Canada

ABSTRACT

This paper describes how a building modeling and simulation graduate level course has been implemented in the mechanical engineering department at Polytechnique Montréal. The course teaches the basic governing equations, assumptions, and solution methods used in building modeling and simulation, in order to provide students with a basic understanding of the algorithms behind the various simulation tools.

Course objectives and prerequisites are examined first. Then, course content, which for the most part had to be developed from the ground up, is presented and some of the difficult concepts to be covered are identified. Examples of assignments and exam problems are also introduced.

One conclusion from this experience is that despite being relatively mature, the field of building energy modeling does not yet have comprehensive textbooks with end-of-chapters problems that could be used in an engineering curriculum.

INTRODUCTION

The need for training in Building Energy Modeling (BEM) has increased significantly over the last decade, partly because software vendors offer tool-centric training courses that provide users with specific knowledge on using a specific tool to get results. They tend to focus on using graphical interfaces and producing eye-catching results efficiently, but typically they do not explain the assumptions or governing equations behind the software algorithms, and they do not encourage users to question their results.

The recently-created Building Energy Modeling Professional (BEMP) certification by ASHRAE (ASHRAE, 2016) goes a step further than software user training by addressing some important concepts to provide correct inputs for BEM and to analyze the results.

However, the vast majority of BEM users focus on code compliance or certifications like LEED, where the main objective is to show improvement compared to a "reference" building, rather than actually try to improve the building design in the context of an Integrated Design Process.

The American Institute of Architects encourages its members to integrate BEM into their workflow (AIA, 2012), and several courses have been developed to introduce BEM into the architecture curriculum. A successful example is shown by Reinhart et al. (2012), where a game is used to teach architects to read and interpret thermal simulation results and adapt their design accordingly, which according to the authors "has become an essential skill for graduating and practising architects". The first version of the game relied on a team of "simulation experts" who actually performed the simulations for the students. The authors have later modified their approach so that architecture students use the simulation tools themselves, with some simplifications, within the context of an introductory building technology course (Reinhart et al., 2015). The approach of a few "simulation experts" is also adopted by Charles and Thomas (2009) for a course using TRNSYS and CONTAM, although in that case some experts were volunteers from the class and not outside specialists. Kumaraswami & de Wilde (2015) describe how BEM is used and taught through classes and projects within an Architectural Technology program, relying on a mix of theory and hands-on design exercises throughout the curriculum.

The present authors think that in parallel to these efforts, a separate, and different, approach is required to integrate BEM into the engineering curriculum, to train the future energy simulation experts that will join architects in design teams, as well as to train the next generation of researchers and practitioners who will further develop BPS tools. As pointed out by Beausoleil-Morrison & Hopfe (2015), the challenge in this case is to teach important theoretical concepts while applying tools to engage the students and allow them to develop a deep knowledge of the topic.

This paper describes a course on Building Energy Modeling which was recently created within a Master's program on "Energy Efficiency in Buildings" to provide that type of training. It is a graduate level course for students with an engineering background. The course was developed and is taught by the first two authors, and external specialists (the last three authors of this article) contributed the teaching material for three lectures.

Student engagement is promoted by presenting case studies of successful BPS applications to building design, drawing on the personal experience of the teachers, and by practical homework assignments and a final project that use different tools and allow students to learn by experience.

The paper describes how this course has been implemented. It first discusses the context (how the course fits within the program) and the prerequisites. The course objectives are then presented, and the contents are detailed using the actual course structure sequence.

Some of the course assignments and past exams are openly available on the course web site (https://moodle.polymtl.ca/course/view.php?id=1753 access code: v2ene6510, password: hdF55$Nq). These documents are mostly written in French. Together with this paper, the authors hope that they will contribute to the free exchange of educational material recommended in Proposition 15 of the recently published IBPSA Position paper (Clarke, 2015).

CONTEXT

This course is part of a core of five courses related to buildings and energy systems (Figure 1).
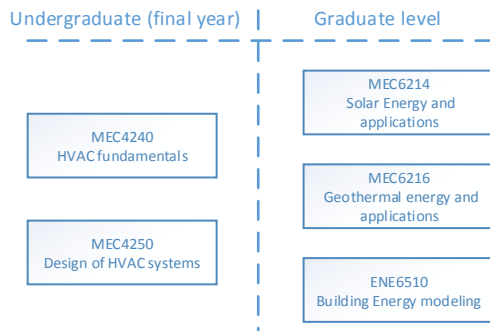

Figure 1. Position of the building energy modeling course within a core of five courses related to building systems engineering

The first two courses are senior undergraduate courses (also available to graduate students). The first of these two courses deal with HVAC fundamentals (load calculations, psychometrics, IEQ) while the second is dedicated to HVAC system design. The solar and geothermal energy courses are dedicated to in-depth analysis of these energy systems and their interaction with buildings.

PREREQUISITES

Students that have a mechanical engineering degree have all the necessary prerequisites to take the course. However, a small number of students from other disciplines (other engineering fields, architects, economists) have taken the course. Some of these students need to acquire or refresh knowledge on the

following key concepts. Suggestions are given to students on books that cover these concepts.

Energy balance: first law of thermodynamics for closed and open systems.

Heat transfer: fundamentals of the three modes of heat transfer: Fourier's law of heat conduction, transient heat conduction, convection coefficients, radiative heat transfer (short- and long-wave, transmission through glazing), and heat exchanger efficiency.

Refrigeration: basic refrigeration cycle operation, coefficient of performance (COP).

Pumps and fans: pump and fan power evaluation, electric motor and variable frequency drive.

Economics: simple/discounted payback periods, present worth factors.

HVAC Systems: as a minimum, students should know how constant volume and variable volume systems work and how they are controlled.

Numerical methods: basics of finite difference methods, notion of time step, iterations, convergence.

Site/source energy, greenhouse gas emissions: difference between site and source energy, emission factors for the various fuels.

COURSE OBJECTIVES

At the end of the course, students should be able to:

• Describe the role of simulation in the evaluation of building energy performance as well as the mathematical basis of building energy modeling.
• Select software tools and appropriate modeling strategies for a given problem.
• Model new or existing buildings and their energy systems.
• Perform parametric/optimization studies with appropriate tools.
• Analyse simulation results and ascertain their quality.
• Participate in the design of buildings and their energy systems by proposing solutions that account for the energy, economical, and environmental impacts.
• Explain and justify the modeling assumptions and analyse the results.

The course teaches the basic governing equations, assumptions, and solution methods used in building modeling and simulation to provide students with a basic understanding of the algorithms behind the simulation tools. In many instances, it is best for the students to first solve the governing equations "manually" before using a simulation tool. For example, in this course, students build their own solution for the heat balance method in a cubic room including an evaluation of transient heat transfer in walls and long-wave radiation exchange. This is a challenging problem but the authors believe that this approach helps the student understand what parameters are important in such a case.

A building simulation course would not be complete without hands-on experience to solve realistic problems using commercial software tools. TRNSYS (Klein et al., 2014) was selected as the main simulation program, and a number of specific tools are used to complement it, as described in the next sections. This choice is based on many factors. First, the first two authors are extremely familiar with this software. Secondly, TRNSYS is used in 4 out of 5 of the courses described earlier (Figure 1). Thus, a good proportion of the students taking the building energy modeling class have some background on the use of TRNSYS. Thirdly, a number of introductory lectures and examples have been built over the years so that students can perform simple simulations after only about one hour of training. TRNSYS's versatility makes it possible to add simple calculations and even simple models without a need to resort to sophisticated programming languages. Finally, most of the TRNSYS code is exposed and students can learn how others solve certain problems.

As shown in Table 1, student evaluation is based on six to eight assignments, one team project, and a final exam.

Table 1 : Student evaluation

Type of evaluation	number	weight
Assignments	6 to 8	30%
Team project	1	30%
Final exam	1	40%

COURSE CONTENT

Core mechanical engineering disciplines such as fluid mechanics, heat transfer, and thermodynamics have been taught for decades and most books in these fields follow a well-established pattern of essential basic principles with examples and end-of-chapter problems. Such books in building energy modeling and simulation do not yet exist. This is one of the major hurdles when developing such a course.

Throughout the course several guiding principles are emphasized:

1-Check assumptions and verify the source of data.

2-Find and use the appropriate simulation tool.

3-Start simple and increase the complexity of the building model as the solution evolves. Limit the number of zones in a building.

4-Perform energy balances. Use some metrics (EUI for example) to check results. Verify that the correct units are used. Also check hourly or sub-hourly values to ascertain that the building and controls are operating correctly.

5-Verify the impact of the uncertainty in the assumptions and the source of data. Which parameters have the most important influence? Calibrate the model if possible.

Following is a description of the course content in a chronological sequence.

1.0 Introduction – 3 hours

Objective: At the end of this module, students should understand the role of simulation throughout the life cycle of buildings. They should also be aware of the terminology used and the order of magnitude of the energy consumption of various types of buildings.

Content: Building energy modeling and simulation is used at various stages with various objectives in mind and for specific purposes. Students are requested to read the document by Franconi et al. (2013) which summarizes the various uses of Building Performance Simulation (BPS) tools. BPS tools are basically used for three purposes: Comparison, Compliance, and Prediction. It is also important to emphasize that different tools are used at various stages in the life of a building from the predesign phase where screening tools are used to the operational phase of the building where, for example, fault detection software might be used. No single tool does it all.

Statistics on the overall energy consumption in the US, Canada, and Québec are introduced. The percentage of the energy consumption associated with buildings is discussed. Typical grid power profiles are presented and the energy cost structure is discussed.

The Energy Use Index (EUI) is introduced (ASHRAE, 2015) to give students an order of magnitude of the energy consumption of typical buildings. Then, the definition of a zero energy building is introduced (US DOE, 2015) along with the concept of site and source energy.

Finally, the following differential equation is reviewed:

$$\frac{dT}{dt} = aT + b \qquad (1)$$

Many heat transfer processes in buildings can be reduced to Eq.1 where parameters a and b can take various forms. With constant parameters, this equation as a relatively simple and convenient analytical solution. It is important to note that the average value of T over the time step (dt) is used in TRNSYS and not the instantaneous value of T at the end of dt.

Assignment: In this assignment (Devoir #1 on the web site), students are asked to model a single-story building (50×20m) with a screening tool to determine its energy consumption (http://www.screeningtool.ca/). Then, the

students have to modify this reference building to make it a net-zero energy building. In the second part of the assignment, students have to perform a simple pre-assembled TRNSYS simulation of a residential building to check how TRNSYS solves Eq.1.

2.0 Climatic data – 3 hours

Objective: At the end of this module, students should have developed an understanding of the use of climatic information in building performance modeling, particularly for design and simulation of new buildings.

Content: It is easy for novice practitioners to take climate information for granted – the standard attitude is to use "whatever data came with the program I am running". This lack of understanding may have significant consequences since climatic conditions are one of the main drivers (if not *the* main driver) of energy use in buildings. With that in mind, the Climatic Data module of the course focuses on four main areas:

- Climatic variables
- Design conditions
- TMY data
- Spatial and temporal variability

In line with the general purpose of the course, the module focuses on the use of climate data in the design stages of a project, and does not cover the use of climate data in post-occupancy analysis.

The climatic variables section introduces the students to the various weather parameters encountered in building performance modeling: dry-bulb, wet-bulb and dew-point temperatures, solar radiation, sky temperature, sky cover, ground and ground water temperatures, degree-days, bin data, wind speed and direction, atmospheric pressure, and snow depth. The students are made aware of the various *time scales* associated with climate variables, which can range from the seconds to months; this helps situate the wide-spread use of *hourly* data into a more general context. A few climatic variables are reviewed more in detail because many students may be unfamiliar with them: this is the case of wind (log profile, wind roses, use of CFD to model wind patterns around buildings), ground temperature, degree-days (with particular emphasis on their use in defining climate zones in ASHRAE standard 169 [ASHRAE, 2013a]), and solar radiation. This last topic receives particular attention since the methods for estimating irradiance are fast changing with the recent widespread availability of satellite-derived data.

In the design conditions section, students learn about the availability and use of climatic information in the early design phases of a project. They become acquainted with simple and coincident design conditions, are shown how

these are calculated, and where to find them, for example in the ASHRAE Handbook – Fundamentals (ASHRAE, 2013b). The use of different design conditions depending upon the type of application is also covered; for example 0.4% annual conditions may be appropriate for a hospital, 1% for a commercial application and 2% for a residential building. The ASHRAE clear-sky model, which recently underwent a significant overhaul (Gueymard and Thevenard, 2009), is explained in detail.

The Typical Meteorological Year (TMY) data section is of particular importance given the widespread use of TMY data in building performance modeling. The course explains how TMY files are built by assembling individual months selected from the long-term record based on statistical criteria. The students are made aware of the benefits of the method, but also of what this implies in terms of what *not* to do with TMY files, for example not use them to calculate design conditions or wind roses. An example of file and format are shown and the students are invited to participate in hands-on exercises with the files. Finally various sources of TMY files are reviewed. Availability of TMY files has significantly changed in recent years with the use of satellite-derived irradiance, the advent of numerical weather models, and the distribution of files over the Internet. All these factors have contributed to the widespread availability of TMY files with a geographical density previously unheard of (NREL, 2016).

Finally, the students are introduced to spatial and temporal variability of climate data. Spatial considerations provide guidance in the selection of climatic conditions for a particular site; students are made aware of concepts such as the adiabatic lapse rate, and micro-climates such as those encountered in coastal and mountainous areas. The urban heat island effect is also discussed at some length. Information about changes in the climate from anthropomorphic actions is provided. Students are shown how ASHRAE climatic design conditions have evolved due to the combined effect of climate change and urban sprawl (Thevenard and Shephard, 2014), and are introduced to the consideration of 'future TMY' files obtained with morphing techniques (Robert and Kummert, 2012) to describe the climate of the future.

Exam question: (see question #1 in the 2015 final exam on the web site). In this question students are asked whether the monthly time series from a particular year was a good candidate for selection and inclusion in the Typical Meteorological Year for a given site.

3.0 Building heat transfer – 6 hours

Objective: At the end of this module, students should be able to solve the governing equations for transient heat

transfer in a room to obtain the air temperature variation based on the heat balance method.

Content: This module is subdivided into three main sections with increasing degree of complexities: i) Steady-state heat transfer; ii) Lumped-capacitance method; iii) Heat balance method.

i) Steady-state heat transfer. Before introducing transient heat transfer, students need to understand steady-state heat losses/gains from a house (Figure 1). The house is maintained at a certain temperature T and the ambient temperature is T_{ext}. Envelope losses (gains) are represented with an overall $U_T A_T$ value and internal gains from people, lights, and equipment (Q_p, Q_L, and Q_{ep}) are identified. Losses (gains) due to air infiltrating the house with a flow rate, $\dot{m}_v$, are presented. The energy required to maintain the house temperature, Q_{req}, is supplied by air at a certain flow rate, $\dot{m}_v$ and temperature T_{vent}. Finally, a certain amount of solar gains through windows, Q_{solar}, is assumed.
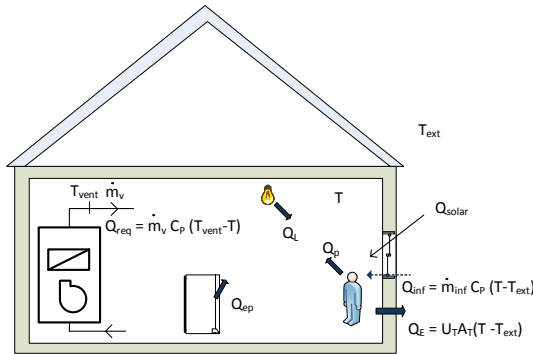

Figure 2. Steady-state energy balance on a house

A simple energy balance is established to determine Q_{req}. This equation provides a simple way to introduce many of the important factors involved in building simulation.

Then, the concept of heating degree-day is reviewed and the underlying assumptions are discussed. The degree-day method is used to do an annual "simulation" to calculate the annual heating energy consumption. The concept of degree-day is simple and, admittedly, has serious limitations. However, it gives the students a reference point on the typical amount of energy required to heat a house. Furthermore, it gives an opportunity to introduce the concept of equilibrium temperature and heating equipment efficiency, η. Finally, and perhaps more importantly, the underlying assumptions of the degree-day method are discussed. For example, is $U_T A_T$ constant during the heating season? Is the degree-day method still applicable when an air-source heat pump is used and η varies with T_{ext}?

ii) Lumped-capacitance. In this section a simple lumped-capacitance approach is used to obtain air temperature variations in a single-zone building. Steady-state heat transfer is assumed in the envelope and the internal mass of the building is lumped together in a single term, $C_p (= \sum M_i C_{P,i})$, where M_i and $C_{p,i}$ are, respectively, the mass and specific heat of the various elements (walls, air, furniture …) inside the building. The resulting governing equation can rearranged in a format similar to Eq. 1 and solve using the technique described in conjunction with Eq.1. Finally, the lumped-capacitance approach provides a good opportunity to introduce the time constant of a building ($MC_p/U_T A_T$).

iii) Heat balance method (HBM). Development is restricted to a single zone with a parallelepipedic shape shown in Figure 3. Analysis is performed on seven surfaces: six walls and a window on the southern wall. With this relatively small amount of surfaces it is possible to do "manual" calculations. For assignments or exam problems, a cube or a two-surface enclosure is typically used to limit the calculations of shape factors.
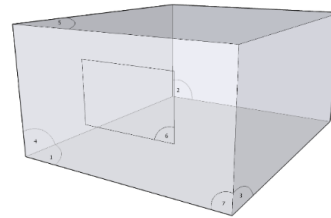

Figure 3 : Geometry used for the heat balance method

The theory on the heat balance method is taken from ASHRAE (ASHRAE, 2013c). The common assumptions used in the HBM method are discussed: i) Surface temperatures are assumed to be uniform; ii) Uniform long-wave and short-wave radiation; iii) Radiation on surfaces is diffuse; iv) One-dimensional heat conduction.

As shown in Figure 4, three heat balances are evaluated: a) outdoor face heat balance; b) indoor face heat balance; c) air heat balance. The terminology used in Figure 4 is the same as the one used in ASHRAE (2013c).
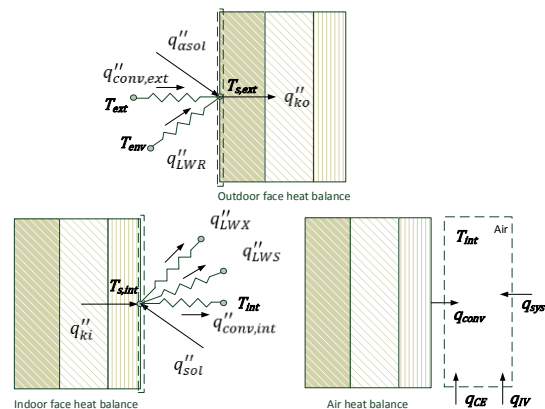

Figure 4 Three heat balances associated with the HBM method

It is important to distinguish between heat fluxes (q'' terms) and heat transfer rates (q terms). Most terms in Figure 4 can be easily understood by students except for the following: the external long-wave radiation heat flux, q''_{LWR} , the internal long-wave radiation heat flux, q''_{LWX} , and the evaluation of transient heat conduction to determine the conduction heat flux at the internal wall, q''_{ki}.

External long-wave radiation heat flux, q''_{LWR} . One of the difficulties here is for the students to realise that long-wave radiation exchange is between $T_{s,ext}$ and an environmental temperature, T_{env} . This value is typically not equal to the ambient temperature, T_{ext}. A good explanation of the equivalent sky temperature is important especially for those who are in contact with this concept for the first time.

Internal long-wave radiation heat flux, q''_{LWX}. For students, this is the most difficult part of the HBM method. First, the concept of radiosities and form factors need to be reviewed by students. Second, the evaluation of form factors becomes computationally difficult for enclosures other than a cube and a two-surface enclosures.

Conduction heat flux at the internal wall, q''_{ki}. Two main approaches can used to treat transient heat transfer in walls: transfer functions or finite volume/finite difference numerical methods. Even though Type56 (building model in TRNSYS) uses the transfer function method, it was decided to use finite volume methods in this course for several reasons. First, most students are familiar with finite difference or volume methods to predict heat transfer in walls as this subject is covered in typical undergraduate heat transfer courses. Secondly, two important building simulation programs, namely EnergyPlus and Esp-r, use such methods to predict transient heat transfer in walls. Finally, contrary to transfer function methods, coefficients developed with numerical methods have some physical meaning. The numerical method used is the finite volume method popularized by Patankar (1980). The so-called "fully-implicit" formulation is used.
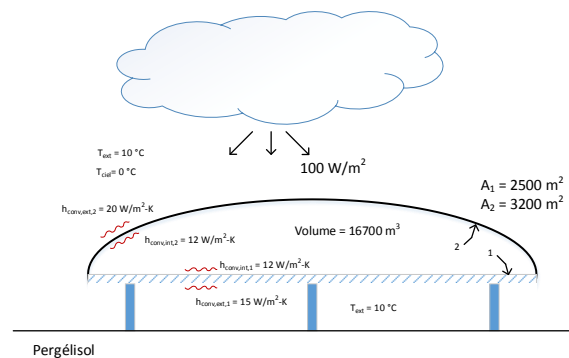
Figure 5. Schematic of an exam problem with a two-surface enclosure

Finally, it is interesting to note that the authors did not find any complete example on the use of the HBM in the literature.

Assignment: (see devoir #3 on the web site) Students are asked to evaluate the radiation exchange in the cube shown in Figure 3. The data is taken from chapter 5 of the IBPSA book (Hensen and Lamberts, 2011). They also have to perform a simple BESTEST (ASHRAE, 2014). Also of interest is question #1 of the 2014 final exam (see web site) which involves the inflated structure presented in Figure 5. Students have to evaluate radiation heat transfer within this two-surface enclosure and transient heat transfer in the floor. The problem is simplified so that calculations can be performed manually during the exam.

4.0 HVAC equipment modeling (6 hours)

Objective: At the end of this module, students should be able to understand how HVAC equipment operate and how to evaluate their energy consumption using appropriate models.

Content: HVAC equipment models are first categorized into physical-based model, grey and black box models and performance map based models. Then, techniques to model the regulation of HVAC equipment are discussed.

Wright (in Hensen and Lamberts, 2011) provides a good starting point to introduce HVAC equipment modeling. This is illustrated in Figure 6 with for distinctive parts: simulation variables ($X_{i,j}$), model parameters (A), model equations (F) which relate the input to the output variables, and output variables ($X_{o,k}$). As indicated by the symbol ♡ , it is likely that the model equations will require some iterative calculations.
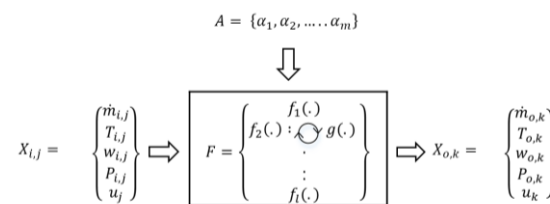
Figure 6. Schematic to illustrate HVAC equipment modeling (adapted from Hensen and Lamberts, 2011)

The HVAC model equations can either be based on physical principles, grey or black box models, or performance maps. One example of a model based on first principles is fully developed heat transfer in a pipe subjected to a constant heat transfer rate. Grey-box models are semi-empirical models based on a physically based model. The parameter estimation technique can fit in this category. This approach is illustrated in the course using the heat pump model developed by Jin and Spitler (2002).

Perhaps the best example of a black box model, is the DOE2 model for chillers. Since the energy consumption of chillers is important, a significant portion of this module is devoted to chiller models. The first important step is to understand the specific chiller terminology and how a chiller works. Furthermore, it is important to inform students about typical operational parameters and energy consumption (what does kW/ton actually mean?). The distinction between rated conditions and operating condition should also be made clear. Then, the various methods of controlling chiller output are discussed: on/off operation of compressors for small chillers; inlet vane control for centrifugal compressor; variable speed compressor. It is important to stress that each chiller output regulation mode requires a different modeling approach. Then, the DOE2 chiller model is described (Hydeman and Gillespie, 2002). It is a black box model. The governing equation of this model is given in Eq. 2.

$$P = P_{ref} \times CAPFT \times EIRFT \times EIRFPLR \quad (2)$$

Where P is the operating compressor power, P_{ref} is the rated compressor power (at rated conditions), $CAPFT$ is a capacity correction factor, $EIRFT$ is an energy input to cooling output ratio, and $EIRFPLR$ is a correction factor to account for part-load operation. $CAPFT$, $EIRFT$ and $EIRFPLR$ are typically obtained from regression analysis of experimental data. Students have some difficulty with the $EIRPLR$ concept and it should be stressed that the PLR ratio is the operating capacity divided by the capacity for the real operating temperatures and not the rated capacity.

For small refrigeration machines that operate in on/off modes, part load factors (PLF) are typically used to correct the rated COP for intermittent operation. Here again definitions are important and are not well explained in the literature. The work of Henderson et al. (2000) on PLF correlations is reviewed.

Once the PLF/PLR concept has been reviewed for refrigeration machines, it is relatively simple to apply the same concept to regular boilers. For condensing boilers, an extra parameter, i.e. the return water temperature has to be introduced into the model.

The final section on cooling towers starts with a description of the heat/mass transfer processes occurring inside the tower. Then, two cooling tower modeling approaches are discussed; i) the TRNSYS cooling tower model based on the methodology of Zweifel et al. (1995) and ii) the one suggested with CoolTools (US-DOE, 2013).

Assignment: In assignment #4 question #2 (see web site), students are asked to perform a regression analysis on experimental data to obtain relationships for $CAPFT$, $EIRFT$ and $EIRFPLR$. In question#3, they are asked to look at the TRNSYS chiller model code to report on how TRNSYS interpolates and extrapolates in the performance map.

5.0 Lighting and daylighting (3 hours)

Objective: At the end of this module, students should understand the basic lighting and daylighting vocabulary, requirements, technologies and modeling approaches available to the building energy modeler. For most mechanical engineering students this course material is new.

Content: This module has three distinct parts dealing with: fundamentals concepts; lighting energy use in buildings; and an introduction to daylighting.

About a third of the module's content deals with basic lighting concepts. Students are introduced to physics-based concepts such as the electromagnetic spectrum and optics, physiological requirements such as circadian cycles, glare and fatigue, visual adaptation and preferences to various light sources and distribution, and lighting technologies and applications including electrochemical sources, colour rendering, luminous efficacies, power/energy parameters (i.e. how we generate light through artificial means).

The module then focuses more specifically on lighting energy use in buildings (e.g. consumption, power demand, controls, costing) and current energy modeling concepts and approaches (e.g. lighting power densities or LPDs, diversity profiles, adjustment factors) one would typically encounter in current standards, codes and software. Examples comparing cross effects of reduced lighting use in cold versus warm climates are provided to illustrate the importance of assessing the energy impact of lighting systems and controls within whole building energy simulation (rather than in isolation). This allows students to explore the relationship between reductions in lighting and increased heating loads, or downsizing of cooling equipment and ventilation fans and networks. Similar examples are given to illustrate the evolution of lighting energy use in buildings over time, e.g. by comparing the impact of code-required maximum LPDs found in building energy codes from the 1980s, 1990s and today.

The final third of the module deals mainly with daylighting. Given the complexity of the physics involved, several courses would be required to fully enable graduate students to work with advanced daylighting concepts (Reinhart et al. 2006, Weinold 2009, Bourgeois et al. 2008) and state-of-the-art software (Ward & Shakespeare 2004, Reinhart 2011, Guglielmetti et al. 2011).

Given the available time, a compromise solution is instead preferred. All the while reminding students of the nowadays archaic nature of daylight factors (DFs), including their significant limitations and drawbacks (in comparison to state-of-the-art dynamic daylighting metrics), the use of analytical solutions to daylight factors can be a powerful hands-on educational tool, as an introduction to further detailed investigations using state-of-the art solutions.

There is discussion on the historical reliance on daylighting, shaping to a large degree building form and urban fabric, and its continued inclusion in various codes and standards over the centuries (e.g. UK's 19th century Right to Light, Germany's minimum requirements on daylighting levels and outside views dating back to the 1930s, LEED requirements).

Assignment: The goal of the exercise is to familiarize students with the main architectural parameters that influence a room's daylight autonomy and distribution quality (see devoir #6 on the web site). The Daylighting Factor Calculator from Minnesota's B3 Guidelines (www.b3mn.org) is an easy-to-use, helpful tool to quickly assess daylighting distribution within conventional, rectangular rooms with one-sided vertical fenestration. Students are asked to combine vision and clerestory windows in their designs.

6.0 Fenestration – 3 hours

Objective: At the end of the module, students should know how the main performance indicators for windows (U-value and Solar Heat Gain Coefficient, SHGC) are calculated from fundamental laws of heat transfer, and how they are implemented in BPS tools. They should be able to calculate these indices in simple cases, to use the WINDOW (LBNL, 2013) program to assess glazing units, and to define glazing systems and windows in TRNSYS.

Content: This module first introduces windows by presenting examples of their importance in buildings, and providing some terminology (ASHRAE, 2013d). The technical content is split in two main parts addressing the U-value of windows and the SHGC.

The notion of overall U-value of a window and its relation to the different parts of a window (center of glazing, edge, dividers, frame) are presented. The detailed methodology to calculate heat transfer through conduction, convection and long-wave radiation according to the recent ISO standard 15099 (ISO, 2012) is then presented, insisting on the center of glazing properties. Students are shown how to perform these calculations themselves and how to use WINDOW to obtain the same results. The impact of 3-D conduction in frames, spacers and dividers is briefly presented, but students are not asked to use THERM (LBNL, 2013) by themselves because of time constraints.

The Visual Transmittance (VT) and Solar Heat Gain Coefficient (SHGC) are defined and their angular and spectral dependencies are presented. The methodology to calculate the SHGC is applied manually using transmittance and absorptance values obtained from WINDOW. Students are shown how to calculate the temperature profile and all heat transfer fluxes for the center of glazing, in the presence of solar radiation.

Dedicated tools such as Resfen and Comfen (windows.lbl.gov/software) are briefly presented. Finally, the implementation of these algorithms and the use of WINDOW results in the TRNSYS Multizone Building Model (Type 56, Transsolar, 2012) are discussed.

Assignment and final exam question: Devoir #7 (see web site) asks students to implement and solve a detailed thermal analysis for center of glazing performance (U-value and SHGC, as well as full temperature profile) implementing the ISO 15099 procedure with an equation solver such as EES (Klein, 2014). They can use the WINDOW program to check their results. Question #4 in the 2014 final exam asks the students to perform a similar heat balance analysis in simple conditions (without assessing the convection coefficients), and to apply the definition of the SHGC.

7.0 Occupants – 3 hours

Objective: At the end of the module, the students should know how thermal comfort is assessed and why a minimum amount of outside air is required. They should know the importance of selecting appropriate assumptions in modeling heat gains related to occupancy and the occupants' role in building controls. They should be aware of the various sources of information to formulate these assumptions.

Content: This module is split in two main parts: what are the occupants requirements in terms of indoor comfort (limited to thermal comfort and Indoor Air Quality, IAQ), and how to model their impact on internal gains and building controls.

The fundamentals of thermal comfort and the basis for Fanger's PMV and PPD (ASHRAE, 2010a) are presented. The impact on building operation (temperature and humidity control) is discussed. The requirements for IAQ are briefly covered using ASHRAE Standard 62.1 as a basis (ASHRAE, 2010b).

The importance of internal gains and electricity use related to occupants is discussed using typical values from building codes (NRC-IRC, 2011) and standards (ASHRAE, 2013c and 2013e), as well as recent

examples showing their impact on near net-zero energy buildings (NREL, 2011).

More detailed occupant modeling is introduced by showing the role of behaviour modeling versus occupancy modeling (Bourgeois et al., 2004). Stochastic modeling is introduced by discussing the probability of opening/closing a window (Gunay et al., 2014) and the combined probability of occupant presence and different types of activities in residential buildings (Aerts et al., 2014).

The particular case of Domestic Hot Water load profiles is discussed and an assessment of different assumptions is presented for a residential case using stochastic load profiles (Wilson et al., 2014).

8.0 Calibration – 3 hours

Objective: The objective of this module is to give some principles and advice to students to help in achieving a calibrated model, qualifying the accuracy of their model and addressing its limitation. Students are exposed to the different uses of a calibrated model and the information needed to achieve it. It also presents approaches, guidelines and tools that help tuning models. Students should be aware that the number of parameters involved in a building simulation model and the lack of measured information lead to a non-unique set of solutions.

Content: This part of the course focuses on calibration of energy models for existing buildings. The calibration is a process to identify the best input parameters to the building simulation model to match simulated energy results and energy use measurement. Calibrating a model is a challenging task and clearly involves sound knowledge of building physics and simulation expertise.

The first part of the lecture exposes the numerous benefits of a calibrated model. It can be intended to assess projected or implemented retrofit measure savings. Also, it can assist in the diagnosis of operational problems through fault detection and eventually optimize the real-time building operations by predicting short time demand profiles.

The information needed to obtain a tuned model are then presented. Each of the following aspects are described in the context of model calibration:

- Adapted simulation engine (such as DOE2.2, EnergyPlus or TRNSYS)
- Audit information and detailed data entry
- Measurement information (time interval frequency, energy source, sub-metering)
- Climatic data covering the measurement period

Different calibration methods and techniques are then exposed. A discussion on iterative (trial and error) methods is presented. Mathematical approaches used to find the most influent parameters and to adjust parameters values to minimize the difference between measured and simulated are briefly covered. Also, numerous visualization techniques to compare and analyze simulated and measured data are depicted.

The content of guidelines on measurement and verification of energy savings are briefly presented. (ASHRAE Guideline 14 and the International performance measurement and verification protocol-IMPVP). These guidelines discuss the use of calibrated model to create appropriate baseline for evaluating energy measure savings. Both of these protocols propose some acceptance criteria based on statistical indices to judge the calibration level of a model.

Some of the calibration tools developed by Hydro-Québec that address specific needs are also presented (Sansregret & Lavigne, 2014; Sansregret et al., 2014) : ExcalibBEM, VizBEM and SIMEB (Interface to DOE2.2 simulation engine which include an in depth module to calibrate model using monthly billing data).

The last portion of the lecture presents a detailed model calibration case of a building.

Assignment: In assignment #8 (see web site), students are asked to manually calibrate an electrically heated office building model using the measured (15 minute intervals) annual electrical consumption. Students first evaluate the accuracy of the model based on statistical indices from ASHRAE guideline 14. Then, they analyze the measured data and propose their own methodology to select and adjust input parameter values of the model. They are asked to present the improvements of the model based on these statistical indicators. Finally, students propose an energy efficient measure and evaluate its impact using typical climatic condition.

9.0 Infiltration/ventilation (6 hours)

Objective: At the end of the module, the students should realize the significance of infiltration in building energy loads. They should know what the driving factors are for infiltration and natural ventilation, and the basic physical principles governing air movement in buildings. They should be able to implement a coupled simulation (multizone bulk air flow and thermal analysis) and analyze the results.

Content: The significance of ventilation and infiltration loads for commercial and residential buildings is first introduced to present the context of this section. Statistical data and practical examples are shown.

The driving factors and physical principles for infiltration and natural ventilation are then presented, and basic equations are introduced for wind and stack effects. The main indicators used to quantify infiltration

are discussed and compared: air changes per hour, leakage area(s), leakage rate, etc.(ASHRAE, 2013f).

Calculation methods implemented in BPS tools for residential and commercial applications are presented separately. For residential buildings, blower door test results are discussed and the Sherman-Grimsrud model is presented (ASHRAE, 2013f). For commercial buildings, a simple methodology based on the design leakage ratio is described (Gowri, 2009).

The principles of multizone (bulk) airflow calculations are presented, and practical applications are presented. The CONTAM program (Dols and Polidoro, 2015) is introduced, both in stand-alone mode, where students can experience the impact of various factors on infiltration and multizone airflow, and in co-simulation with TRNSYS (Dols et al., 2015).

Assignment: A simple hand-on case using CONTAM and TRNSYS is in the development stage.

10.0 Thermal storage (3 hours)

Objective: At the end of the module, the students should know the different uses of thermal storage in buildings, from peak shaving to long-term storage. They should understand how thermal storage devices are modeled in BPS tools, and be able to formulate and solve heat balance equations for simple cases.

Content: The roles of thermal storage, from peak-load shaving to long-term (seasonal) storage are presented with practical examples using various technologies. The characteristics of latent and sensible storage are compared. The notion of storage efficiency is presented.

Modeling of borehole thermal energy storage and thermal storage tanks is presented. The example of stratified storage tanks is used to show in detail the equations and algorithms used by a BPS tool. A complete solution, based on Eq. 1, is presented and compared to the results of TRNSYS.

Exam question: Question #5 in the 2015 final exam is dedicated to a hot water storage tank. Students are asked to formulate the dynamic heat balance equations for a 2-node tank and to solve "manually" a particular case for one time step.

11.0 Optimization (3 hours)

Objective: At the end of the module, the students should know how to formulate an optimization problem in a BEM context and should be able to select an approach to optimize their design using dedicated tools (e.g. BeOpt) or a combination of optimization software and BPS tools (e.g. GenOpt and TRNSYS).

Content: The various categories of optimization problems are presented, with a focus on multivariable

optimization of a scalar objective function. The particular problems posed by the application to BPS are presented: computationally intensive objective function, possible truncation of the calculated results, mix of integer and continuous parameters.

A simple example (building orientation which minimizes heating and cooling loads) is presented using GenOpt (Wetter, 2011) and TRNSYS – at that stage of the course students are familiar with the BPS part so they can focus on the optimization aspects. A second example is used to show the importance of selecting appropriate optimization algorithms, and the notion of local versus global optimum. This example optimizes the glazing fraction (continuous) and the window type (discrete, among preselected types). The optimization process is compared to a parametric sweep.

Practical examples of optimization for HVAC systems (e.g. hybrid GSHP system optimization) and control (e.g. peak load reduction through predictive control) are presented. BeOpt (Christensen et al., 2006) is presented to illustrate the importance of economics in optimization problems and the trade-off between on-site generation and building improvements on the path towards net-zero energy buildings.

CONCLUSIONS

This paper describes the structure of a graduate level course on building energy modeling and simulation which is part of a recently developed master's program on Energy Efficiency in Buildings at Polytechnique Montréal.

The general philosophy of the course is to teach fundamentals (governing equations, assumptions etc..) in addition to providing a hands-on experience, for which TRNSYS was selected as the main BPS tool.

The prerequisite and course objectives are presented first. Then, the paper describes the course content for each module. Areas of difficulties for students are identified and examples of assignments and exam question are provided.

As stated in the recent IBPSA position paper (Clarke, 2015): "*There is an urgent need to harmonize the disparate educational information being used within degree programmes worldwide by providing a core resource pack on BPS and by assisting with the exchange of exemplar case-study materials between regions.*" This paper and the related material openly available on the course website are the authors' contribution towards that objective.

It is clear that text books covering all aspects of the course including a thorough development of the governing equations and inclusion of end-of-chapter

problems would have made the development of this course much easier.

ACKNOWLEDGEMENTS

REFERENCES

Aerts, D., Minnen, J., Glorieux, I., Wouters, I., Descamps, F. (2014). A probabilistic activity model to include realistic occupant behaviour in building simulations. Proc. of eSim 2014, Ottawa, ON, May 8-9.

AIA. 2012. The AIA Energy Modeling Practice Guide. American Institute of Architects.

ASHRAE. (2010a). Thermal Environmental Conditions for Human Occupancy (Standard 55-2010). ASHRAE.

ASHRAE. (2010b). Ventilation for acceptable indoor air quality (Standard 62.1-2010). ASHRAE.

ASHRAE. (2013a). Climatic Data for Building Design Standards (Standard 169-2013). ASHRAE.

ASHRAE. (2013b) Chap. 14, Climatic Information. In ASHRAE Handbook of Fundamentals. ASHRAE.

ASHRAE. (2013c). Chap. 18: Nonresidential heating and cooling load calculations. In ASHRAE Handbook of Fundamentals. ASHRAE.

ASHRAE. (2013d). Chap. 15: Fenestration. In ASHRAE Handbook of Fundamentals. ASHRAE.

ASHRAE. (2013e). Energy Standard for buildings except low-rise residential buildings (Standard 90.1-2013). ASHRAE.

ASHRAE. (2013f). Chap. 16: Ventilation and infiltration. In ASHRAE Handbook of Fundamentals. ASHRAE.

ASHRAE. (2014). Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs (Standard 140). ASHRAE.

ASHRAE. (2015). Chap. 36: Energy use and management. In ASHRAE Handbook of Applications. ASHRAE.

ASHRAE. (2016). BEMP - Building Energy Modeling Professional Certification. www.ashrae.org/bemp, last accessed on 2016-01-15.

Beausoleil-Morrison, I. and Hopfe, C.J. 2015. Teaching building performance simulation through a continuous learning cycle. In Proc. of Building Simulation 2015, Hyderabad, IND, Dec. 7-9.

Bourgeois D, Reinhart CF & Ward GW (2008) A standard daylight coefficient model for dynamic daylighting simulations. Building Research & Information 36(1) pp. 68-82

Charles, P. P., & Thomas, C. R. (2009). Four approaches to teaching with building performance simulation tools in undergraduate architecture and engineering education. Journal of Building Performance Simulation, 2 (2), pp. 95-114.

Christensen, C., Anderson, R., Horowitz, S., Courtney, A., & Spencer, J. (2006). BEopt Software for Building Energy Optimization: Features and Capabilities (NREL/TP-550-39929). Golden, CO, USA: National Renewable Energy Laboratory

Clarke, J. (2001). Energy Simulation in Building Design, 2nd edition, Butterworth Heinemann, GBR.

Clarke, J. (2015). A vision for building performance simulation: a position paper prepared on behalf of the IBPSA Board, Journal of Building Performance Simulation, 8 (2), pp. 39-43.

Dols, S. and Polidoro, B.J. (2015). CONTAM User Guide and Program Documentation, Version 3.2. National Institute for Standards and Technology, USA.

Dols, W.S., L. Wang, S.J. Emmerich, and B.J. Polidoro. (2015). Development and application of an updated whole-building coupled thermal, airflow and contaminant transport simulation program (TRNSYS/CONTAM). Journal of Building Performance Simulation, 8 (7), pp. 326-337.

Franconi, E. et al. (2013). Building energy modeling for owners and managers. Rocky Mountain Institute, CO, USA.

Gowri, K., Winiarski, D., & Jarnagin, R. (2009). Infiltration Modeling Guidelines for Commercial Building Energy Analysis. Pacific Northwest National Laboratory, Richland, WA, USA.

Gueymard, C.A., and Thevenard, D. (2009) Monthly average clear-sky broadband irradiance database for worldwide solar heat gain and building cooling load calculations. Sol. Energy 83 (11), pp.1998–2018.

Guglielmetti R, Macumber D & Long D (2011) OpenStudio: an open source integrated analysis platform, In Proc. of Building Simulation 2011, Sydney, AUS, 14-16 Nov.

Gunay, H. B., O'Brien, W., Beausoleil-Morrison, I., Goldstein, R., Breslav, S., & Khan, A. (2014). Coupling stochastic occupant models to building performance simulation using the discrete event system specification formalism. Journal of Building Performance Simulation, 7(6), 1–22.

Henderson, H., Parker, D., Huang, Y. 2000. Improving DOE-2's RESYS routine: User Defined Functions to Provide More Accurate Part Load Energy Use and Humidity Predictions, In Proc. of 2000 Summer Study

on Energy Efficiency in Buildings, American Council for an Energy-Efficient Economy, Washington, DC, USA.

Hensen, J.L.M. and Lamberts, R. (Ed.). (2011). Building Performance Simulation for Design and Operation. Routledge, GBR.

Hydeman, M., and K.L. Gillespie. (2002). Tools and techniques to calibrate electric chiller component models. ASHRAE Transactions, 108(1): p. 733-741.

ISO. (2012). ISO 15099:2012. Thermal performance of windows, doors and shading devices — Detailed calculations. Geneva, CHE: International Organization for Standardization

Jin, H. and J.D. Spitler. (2002). A parameter estimation based model of water-to-water heat pumps for use in energy calculation programs, ASHRAE Transactions, 108(1): 3-17.

Klein, S. A. (2014). EES - Engineering Equation Solver. F-Chart Software, Madison, WI, USA.

Klein, S. A., et al. (2014). TRNSYS 17 – A TRaNsient SYstem Simulation program, User manual. Version 17.2. University of Wisconsin-Madison, USA.

Kumaraswamy, S.B. and de Wilde, P. 2015. Simulation in education: application in architectural technology design projects. In Proc. of Building Simulation 2015, Hyderabad, IND, Dec. 7-9.

LBNL. (2013). THERM 6.3 / WINDOW 6.3 NFRC Simulation Manual. Lawrence Berkeley National Laboratory, Berkeley, CA, USA.

Millette, J., Sansregret S., (2011). SIMEB: simplified interface to DOE2 and Energy Plus - A user's perspective – Case study of an existing building. In Proc. of Building Simulation 2011, Sydney, AUS, 14-16 Nov.

NRC-IRC. (2011). National Energy Code for Buildings 2011. National Research Council of Canada, Institute for Research in Construction, Ottawa, ON, CAN.

NREL. (2011). Research Support Facility Workshop – Session IV: Occupant behavior. National Renewable Energy Laboratory, Golden, CO, USA.

NREL (2016) National Solar Radiation Database. https://nsrdb.nrel.gov/, retrieved on January 16, 2016.

Patankar, S.V. (1980), Numerical heat transfer and fluid flow. McGraw-Hill.

Reinhart, C.F., Mardaljevic J & Rogers Z. (2006). Dynamic daylight performance metrics for sustainable building design. Leukos 3(1).

Reinhart, C.F. (2011). Simulation-based daylight performance predictions, in Building Performance Simulations for Design and Operation (Hensen J & Lamberts R, ed.). Routledge, GBR.

Reinhart, C. F., Dogan, T., Ibarra, D., & Samuelson, H. W. (2012). Learning by playing – teaching energy simulation as a game. Journal of Building Performance Simulation, 5(6), 359–368.

Reinhart, C.F., Geisinger, J., Dogan, T. and Saratsis, E. (2015). Lessons learned from a simulation-based approach to teaching building science to designers. In Proc. of Building Simulation 2015, Hyderabad, IND, Dec. 7-9.

Robert & Kummert (2012) Designing net-zero energy buildings for the future climate, not for the past. Building and Environment 55, 150-158.

Sansregret, S., Lavigne K. (2014). Spreadsheet Tool Development for Visualizing Building Performance and Simulation Data to Help Calibrating Models. In Proc. of ASHRAE/IBPSA-USA Building Simulation Conference 2014, Atlanta, September 10-12.

Sansregret, S., Lavigne, K., Daoud, A., and Leclaire, L-A. (2014). ExCalibBEM: Tool Development to Calibrate Building Energy Models. In Proc. of eSIM 2014, Ottawa, ON, May 7-10.

Thevenard and Shephard (2014) Temperature trends for locations listed in the tables of climatic design conditions in the 2013 ASHRAE Handbook-Fundamentals. ASHRAE Transactions, 120 (2).

Transsolar. (2012). TRNSYS 17 – A TRaNsient SYstem Simulation program, User manual. Volume 5: Multizone Building Modeling with Type 56 and TRNBuild. Version 17.1. University of Wisconsin-Madison, USA.

US DOE. (2013). EnergyPlus engineering reference - The reference to EnergyPlus calculations (v 8.1). US Department of Energy, Washington, DC, USA.

US DOE. (2015). A common definition for zero energy buildings, http://tinyurl.com/def-nzeb.

Ward, G.W., and Shakespeare, R. (2004). Rendering With Radiance: The Art And Science Of Lighting Visualization (revised edition). Booksurge Llc, USA.

Weinold J (2009) Dynamic daylight glare evaluation. In Proceedings of Building Simulation 2009: 11th conference of the International Building Performance Simulation Association, 27-30 Jul, pp. 1299-1305.

Wetter, M. (2011). GenOpt - Generic Optimization Program - User Manual, version 3.1.0. Berkeley, CA, USA: Lawrence Berkeley National Laboratory

Wilson, E., Engebrecht Metzger, C. ., Horowitz, S., & Hendron, R. (2014). 2014 Building America House Simulation Protocols (NREL/TP-5500-60988). Golden, CO, USA: National Renewable Energy Laboratory.

Zweifel, G., V.Dorer, M. Koschenz, and A. Weber. 1995. Building Energy and System Simulation Programs: Model Development, Coupling and integration. Proceedings of the 1995 IBPSA conference.