Teaching Commercial Building Energy Dynamics through Simplified Energy Modeling Tools

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ABSTRACT

For most people, intuition about how buildings consume energy is based on personal experience gained from living in a house. This intuition breaks down when applied to larger commercial buildings because they do not exhibit the same energy behavior as homes. To add to the confusion, commercial building energy behavior involves a host of subtle interactions that are difficult to untangle and readily understand. Building energy modelers are highly aware of these issues. They work daily with computer simulations of the various energy interactions within a wide variety of building types. However, building energy modeling is too complex and difficult to be practically accessible by most people.

But what if commercial building energy interactions could be taught using simple tools that approximate building energy models and visualize data impacts? This paper will present key concepts behind commercial building energy dynamics and outline efforts to utilize simple energy models as teaching tools to convey these concepts at accessible levels.

Three approaches will be discussed and compared: 1) the use of existing energy modeling tools within a recently developed energy modeling curriculum, 2) the use of a stand-alone simplified building energy model that provides immediate feedback to user input, and 3) a conceptual plan to transform simplified building energy models into educational game-based learning environments.

Introduction

Interest in building energy efficiency has increased dramatically in recent years, as evidenced by unprecedented growth in energy efficiency programs (Cooper, A. & Wood 2012). Within the realm of commercial buildings, a solid understanding of building energy dynamics is crucial to the cost-effective application of energy efficient techniques and technologies. Unfortunately there are many misconceptions surrounding commercial building energy dynamics - often held by such key people as building owners, energy program managers, policy makers, educators, architects and engineers. These misconceptions can lead to unrealized energy savings and even increases in energy consumption. For purposes of this paper, it is assumed that the term *commercial building* also includes institutional buildings such as hospitals, schools, and public buildings.

Many of the above misconceptions arise from assigning the attributes of residential energy consumption to larger commercial buildings. This is a natural tendency, as many people live in houses, and this is where most building energy intuition develops. Additional misconceptions can arise from the complex and highly interactive traits of commercial energy systems.

It would be beneficial for energy programs and academic institutions to possess an effective method to impart knowledge about commercial building energy dynamics. It is known that the practice of building energy modeling, or the detailed computer simulation of energy consumption within a building, conveys these complex concepts to the practitioner over time (Tupper et al. 2011). But building energy modeling is difficult, requires specialized knowledge, and takes lots of time to master (CBC 2011), making it impractical for general education purposes. However, it is possible that *simplified* building energy modeling tools could be used as effective teaching tools with less pain and effort.

This paper will first outline key concepts surrounding commercial building energy consumption, and then provide an overview and comparison of three approaches to applying simplified building energy modeling as a teaching tool.

Key Concepts of Commercial Building Energy Dynamics

Before considering methods to teach commercial building energy dynamics, it is important to outline some of the main physical processes that are frequently misunderstood. The list below is not all-inclusive, but outlines some of the major concepts.

Commercial versus Residential Energy Behavior

Commercial building energy behavior differs from residential in a number of ways for several fundamental reasons.

- **Multiple Thermal Zones, Load Diversity, and HVAC Systems.** Commercial buildings are large, and unlike residential buildings, contain areas with different cooling, heating and ventilation needs. As a result, commercial buildings are subdivided into "little buildings" called thermal zones that can satisfy different conditioning needs. These thermal zones can individually and simultaneously require either heating or cooling at any point in time. To satisfy these differing needs, commercial HVAC systems are often complex and use modulating controls. In contrast, residential buildings are a single thermal zone requiring either heating or cooling (not both) - depending upon outdoor conditions. Consequently, residential HVAC systems are relatively simple and mainly use on/off controls.
- **Internal Spaces and Heat Generation.** In contrast to residential buildings, commercial buildings contain more interior area located well away from exterior walls and roofs and isolated from outdoor conditions. Furthermore, commercial buildings generate more heat internally from lights, people and equipment. As a result, interior thermal zones are often in need of cooling during occupied times, regardless of outdoor conditions. Commercial building perimeter thermal zones behave a little more like residential buildings, being highly influenced by heat gain and loss through the building envelope and hence outdoor weather conditions.
- **Mechanical Ventilation.** Commercial building HVAC systems use fans to bring in outdoor air for ventilation during occupied times. These systems also heat and cool the outdoor air, control the airflow rate and pressure, and, during opportune times, provide "free" cooling using cool outdoor air. This later function is known as an air-side economizer. Residential buildings ventilate by uncontrolled leakage through the building envelope. Residential HVAC systems do not provide ventilation and do not utilize air-side economizers.

Because of the above differences in energy behavior between commercial and residential buildings, application of identical energy savings approaches will produce different results – for better or worse. It is therefore important to be aware of these differences and understand their nuances.

Commercial Energy Interactions and Complexity

In addition to differences with respect to residential buildings, commercial building energy systems are inherently complex and highly interactive. This is another barrier to understanding. Below are some examples of system interactions.

- **Building envelope and heating and cooling.** Heat travels in or out of commercial buildings via conduction through the exterior walls, windows or roof, causing a need for heating or cooling. The ability of these surfaces to impede heat conduction directly affects energy consumption by the heating and cooling systems.
- **Sunlight, windows, and heating and cooling.** People love windows in buildings. Windows provide a connection to the outdoors and let in sunlight. Sunlight contains a lot of heat, and while this heat occasionally helps to heat a commercial building, much of the time it produces a need for cooling. The size, orientation, and solar properties of windows directly affect the energy consumption of the heating and cooling systems.
- **Lighting, electricity, and heating and cooling.** The large interior areas of commercial buildings are far from perimeter windows and need artificial lighting. Lights need electricity to operate, and much of that electricity ends up as heat inside the building. Just like the sun through the windows, this heat occasionally helps to heat a commercial building, but most of the time it contributes to the need for cooling. Interior lighting electric consumption directly affects energy consumption by the heating and cooling systems.
- **Daylighting controls, windows, lighting power, lighting heat, heating and cooling.** One of the most complex interactions in commercial buildings occurs when daylighting controls are present. Daylighting controls reduce artificial lighting when adequate natural sunlight is available. Roughly speaking, when more sunlight is available, the lights use less electricity. More sunlight in the building increases cooling energy consumption and decreases heating. But, less lighting electricity means less light heat, which reduces cooling energy consumption and increases heating. Furthermore, window size, orientation and solar properties affect sunlight availability – which in turn affects lighting, cooling and heating energy consumption. It takes a computerized energy model to know the net energy result of these numerous interactions over the course of a year.
- **Ventilation, fan power, heating and cooling.** Outdoor air, or ventilation, must be introduced into commercial buildings for health reasons. The amount of ventilation to provide is typically determined by local codes or national standards. The time period to provide ventilated is determined by building occupancy. Greater amounts of ventilation over longer times require more fan power to move the air, and more heating and cooling to make the outside air comfortable. During certain times, ventilation air can provide some free cooling to the building. Ventilation air affects fan, heating and cooling energy – and in turn is affected by occupancy schedules.

- **Air-side economizers, cooling, fan power.** Devices called air-side economizers use ventilation air to sometimes provide free cooling. Or, at least it's nearly free – extra airflow is often needed and fan electric consumption increases to move the extra air. The net result is more efficient cooling than a standard air-conditioning system. Air-side economizers use enhanced ventilation to reduce cooling energy while producing a small increase in fan energy.
- **Ventilation heat recovery, heating, cooling, fan power, air-side economizers.** The heating and cooling energy required to temper ventilation air can be reduced through a heat recovery device. This device shares heat (and maybe moisture) between the ventilation intake and discharge airstreams, reducing heating and cooling energy. But, it takes extra energy to push the air through this device – therefore fan energy increases. Further complicating matters, the heat recovery device cannot operate while the air-side economizer is in operation, as the two "fight" each other. So the more "free" cooling that occurs the less the heat recovery device is saving energy. Ventilation heating and cooling can be reduced by heat recovery devices, but produce a fan energy penalty and are sometimes limited by air-side economizer operation.

All of the above interactions, and more, need to be considered when designing an energy efficient building. Performing a lot of energy modeling will eventually teach an intuitive understanding of these complexities, but that is impractical for most people. Other models must be explored.

Overview of Simplified Building Energy Model Approaches

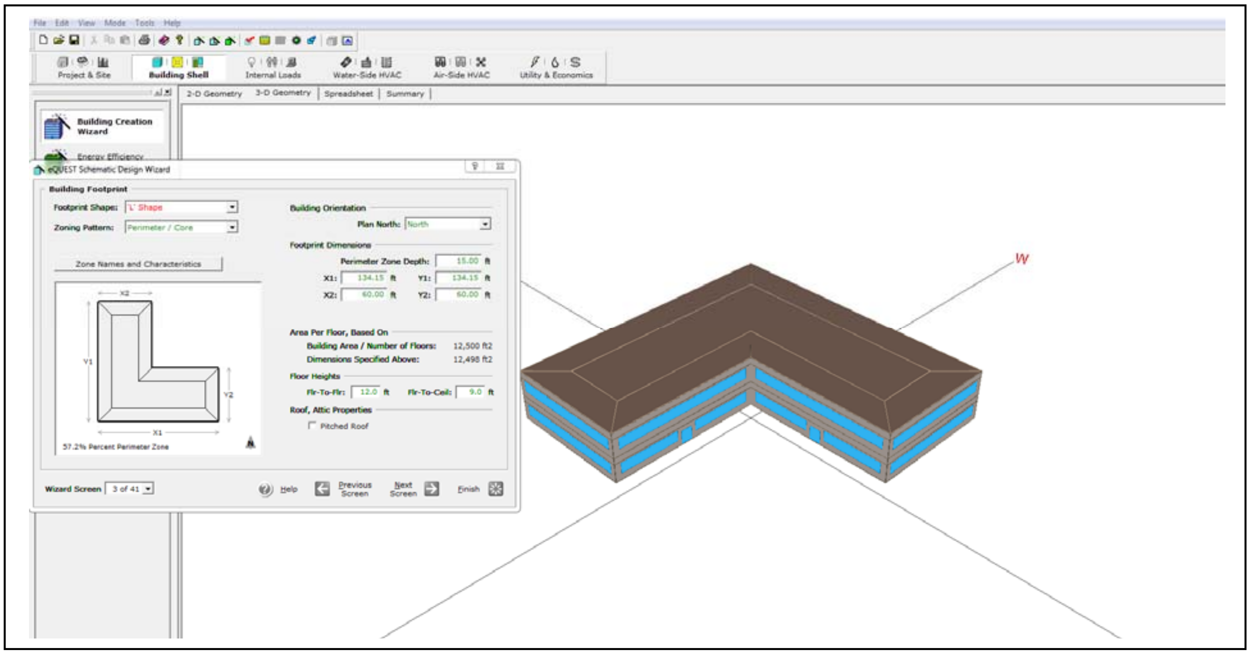
Existing Modeling Software in a Classroom Environment

In 2011 the Energy Center of Wisconsin was tasked with developing a curriculum for the Milwaukee Area Technical College to provide an overview of building energy dynamics and an introduction to building energy modeling. The first offering of this course occurred in Spring 2012. It makes use of lectures, hands-on laboratory sessions, and the eQUEST energy modeling software (James J. Hirsch & Associates 2012). eQUEST is a free graphical user interface to the DOE2.2 energy calculation engine and provides several levels of user interfaces at several levels of complexity. The most simple user interface, the Schematic Design Wizard ("SD interface") is used in the class. The SD interface consists of up to 41 screens of input data. The liberal use of default data and a linear step-by-step interface structure makes the SD interface a good first tool for those unfamiliar with energy modeling.

Course lectures are designed to deliver an overview of building energy systems, energy end-use characterization, and other related information such as energy codes and standards. The lecturer uses the eQUEST SD interface as a tool to demonstrate building energy concepts and the interactions between building energy systems. The demonstrations are conducted within the context of designing a new energy efficient building. Students follow along with their own model, entering data along with the instructor and learning how to alter model inputs and interpret the outputs.

Course laboratory sessions provide students with hands-on experience inspecting an existing building and measuring various energy-related parameters. The students then represent the building within the energy modeling software, applying the concepts learned in the lecture sessions. The final energy model is then used as a tool to evaluate energy-saving upgrades to the existing building.

Figure 1. eQUEST Energy Modeling Software – Schematic Design Interface



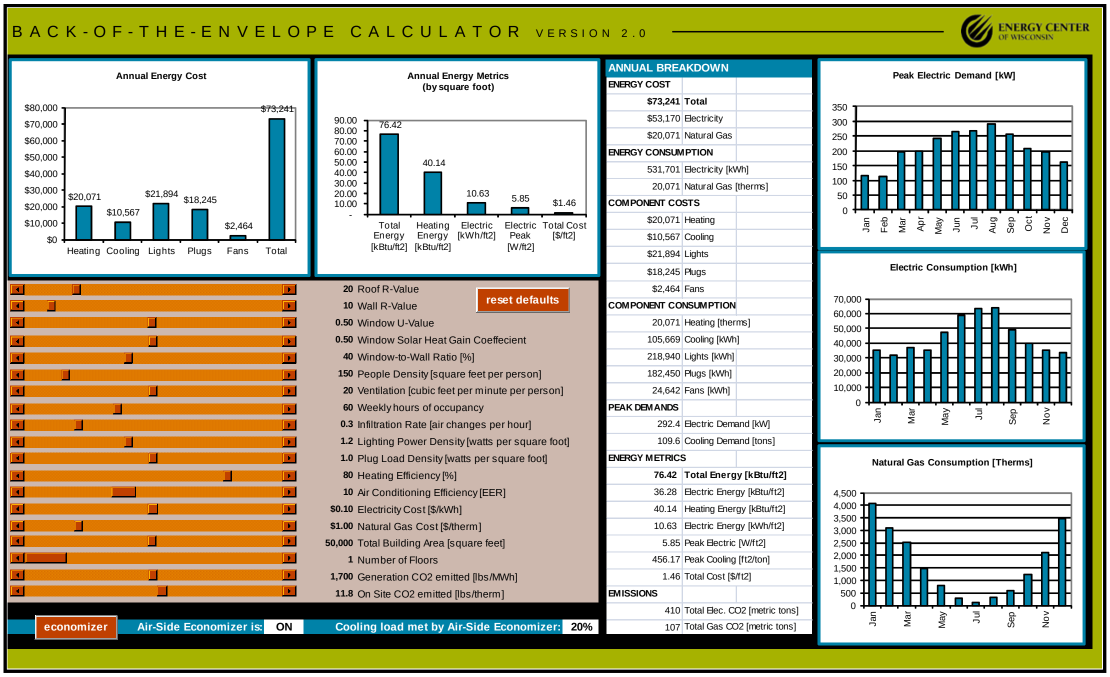
The strengths of this approach include: 1) direct instructor interaction and the flexibility to address spontaneous questions and situations, and 2) use of an advanced and flexible building energy model to explore in-depth variations in energy systems design and inter-zone interactions. Furthermore, use of an industry-standard energy model as a learning tool (even using the SD interface) has the additional benefit of providing experience with a job-grade tool.

On the downside, the simple SD interface limited energy modeling options, and using more complex interfaces was too difficult for students not seeking to perform actual building energy modeling. Additionally, this approach inherently contains a barrier to learning building energy dynamics - the lack of immediate quantitative feedback after changing model inputs. Specifically, after each change in model inputs, the model must be re-run and output reports generated and opened to observe output changes. The model complexity and lack of instantaneous feedback are major impediments to using real modeling platforms as teaching tools for a more general audience.

Custom Simplified Modeling Software

In 2006 the Energy Center of Wisconsin developed the *Back of the Envelope Calculator* (ECW 2012). Back-of-the-Envelope was an early attempt at a learning tool that allowed users to interact with a simplified building energy model. The interface was constructed using simple slider bars for data input manipulation and provides a readily understood graphical and text-based output [Figure 2]. The tool was developed within spreadsheet software and was placed on a website for free download. It continues to be reasonably popular. Over the last two years the webpage has been viewed an average of 476 times per month, with software downloads occurring 143 times per month.

Figure 2. Back of the Envelope Calculator



Both the model input and output are located on a single viewable page. In this manner, changes in model outputs can be seen immediately after moving an input slider - allowing for instantaneous feedback to model input adjustments. This is in contrast to the much slower learner feedback loop discussed in the previous approach. The Back-of-the-Envelope tool was meant to invite play, including exploring the limits of building design by pushing input boundaries.

The user interface maintains simplicity by embedding a simplified building energy model into spreadsheet software. The complexity of the model is an exercise in balance - some attributes of more powerful models (such as full 8760 hourly analysis) were developed to maintain flexibility, while many simplifying assumptions were applied to increase run speed for instantaneous user feedback. Some of the more limiting simplifying assumptions include single-zone representation of a single building-type using a single HVAC system type.

Many emails have been received from users over the years regarding Back-of-the-Envelope. Most are positive and contain constructive feedback and requests for additional features. However, the emails indicate that the overwhelmingly desired use for Back-of-the-Envelope is not as a learning tool, but as a simple building energy estimating tool. Two possible conclusions can be made: 1) there is a great need for simple building energy estimating tools in the marketplace, and 2) the Back-of-the-Envelope interface did not entice users into playful exploration of building energy interactions.

It is this second conclusion that has led to the investigation of more compelling user interfaces, including a preliminary exploration of the world of game-based learning environments.

Simplified Energy Models in Game-Based Learning Environments

The Back-of-the-Envelope calculator concept was expanded in late 2011 into an exploration study of more advanced user interface approaches. A report by Reinhart (Reinhart et al. 2011) on using classroom competitions as a method to teach building energy modeling spurred the idea of investigating the incorporation of simplified building energy models into game-based software learning environments. In fact, building energy modeling (or "energy simulation" as it is sometimes termed), is well suited for this transition, as expressed by Squire (Squire et al. 2003):

> "Perhaps the simplest way to approach the design of educational games is to take a standard simulation…and imbue it with game-like elements. Simulations and games share much in common."

Squire goes on to say:

> "Structurally, games differ from simulations in that games (usually) have an additionally narrative backstory and context, one or more goals and challenges, and various "failure" and "win" states. Students watch simulations from the outside; they immerse themselves within games, and their more immediate participation expands the opportunities for mastering the content…So, start with a simulation and then start adding challenges or goals which the player might carry out in that environment. Use those goals to motivate players to explore and map the properties of the simulated world. They will be motivated to learn the core principals and processes shaping the simulation in order to achieve their goals, overcome the challenges, and win the game. To be compelling, constraints must be added which make it difficult to achieve assigned tasks…As the students scan the game environment looking for resources to achieve their goals, they need to not only see their own roles or situations but develop an intuitive, qualitative understanding of how the system itself operates (see also diSessa, 1993)."

While still a developing concept, it appears that simplified energy modeling tools could translate well into a game-based learning environment. Following the key transition aspects from scientific simulation to games expressed by Squire above, a potential game-based environment might look like this:

> Imagine that you are an architect or engineer and your job is to design an exceptionally energy-efficient building. You are faced with constraints: your client wants a building of a certain size with spaces that serve particular functions - you are given a fixed budget and a schedule. You must select attributes of the building that affect energy consumption – shape, orientation, insulation, shading, windows, lighting, ventilation, heating, cooling and controls. As you select these attributes you are provided with immediate feedback on your level of energy efficiency, end-use consumption, budget and projected level of satisfaction of building occupants. As you attempt to balance these competing variables within your "world", you are exposed to the building energy dynamics described earlier in this paper. In fact, achieving the ultimate energy efficiency

goal within the imposed constraints *requires* learning these energy dynamics - which in the game-world are generated by a simplified background energy model.

Like many games, there would be levels of difficulty. Initial levels would be simple to allow concentration upon a few key foundational concepts. Later levels would build upon the lower level knowledge gained, and require an understanding of more-and-more complex energy interactions. Failure is allowed – you may not meet the efficiency goal within budget or schedule, future occupants may dislike working in your building (no ventilation? few windows?), or, the final building does not serve the client's intended purpose. You can be fired from the job. At higher levels, randomized events can occur – you unexpectedly win an energy efficiency grant (more budget), a new efficient lighting technology comes into production (more energy savings), the client needs to move in sooner than expected (less time available), or the client's financing falls through (game over).

Following the concept of transgressive play (Squire et al. 2003), where players receive satisfaction from the temporary suspension of societal rules, players would be allowed to design crazy buildings with absurd attributes. This helps students understand the boundaries of what is possible. Players could create really *inefficient* buildings, and they would still learn the dynamic energy concepts. The learning comes not so much from attaining an efficient building, but from pushing against the constraints and dynamics of the simulated building energy world. Optimizing an energy hog could potentially teach as much as carefully crafting an energy-sipping green showcase. In other words, you could be bad and still learn.

What can be gained by using this approach? Students could learn by exploration in a compelling and entertaining environment. Subtle building energy dynamics could be absorbed intuitively through trial-and-error approaches. Exploration of the limits of design would be encouraged. Once developed, the learning approach could be scaled-up easily through distribution of the game-based software. The downside of this approach is that a working gamed-based software environment has yet to be created. However, efforts are presently taking place to form partnerships and locate funding sources to develop a prototype of this concept.

Comparison of the Simplified Building Energy Model Approaches

A summary of the characteristics of the three approaches is shown below in Table 1. Based upon this qualitative comparison, the game-based approach provides more positive attributes than the other approaches.

Table 1. Comparison of the Three Approaches

	eQUEST in Class	Back-of-the-Envelope	Game-Based
Method	Lecture	Stand-alone software	Stand-alone software
Learner feedback loop	Slow	Immediate	Immediate
Energy model flexibility	High	Low	Moderate
Interface complexity	Moderate	Low	Low
Multiple interface levels	Yes	No	Yes
Goal-based learning	No	No	Yes
Ability to teach complex energy dynamics	Moderate	Moderate	High
Ability to teach energy reduction strategies	Moderate	Low	High
Scalability	Low	High	High

Conclusions

Teaching people about commercial building energy dynamics is important, but the ideas are complex and run counter to many people's intuition. Simple building energy models have potential as responsive learning tools to untangle and clarify energy dynamics.

Three potential approaches to using simplified building energy models as teaching tools have been discussed and compared. Each of the three approaches possess strengths and weaknesses, however a game-based learning environment appears to consistently display the most favorable features. Although conceptual at present, this approach holds great promise for making valuable knowledge available to a much wider audience within the energy efficiency world.

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