Evaluation of Energy Modeling Tools for Early Conceptual Design

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Abstract

In this project we investigate how simulation tools, specifically energy modeling tools, can be better deployed under the conditions of early conceptual design in architectural practice. We develop a method of evaluating these tools, including an experiment replicating architectural practice conditions. 5 energy modeling tools representing the range of available early design energy modeling tools are selected and assessed. Besides evaluation by experts in the domain of building energy simulations, we also solicited feedback from practitioners.

Introduction

Nearly all energy use in the commercial sector takes place in, or is associated with, the buildings that house commercial activities. The total number of commercial buildings in the USA has increased from 3.8 million to about 4.7 million and total commercial floor space has increased even more significantly from 51.1 to 67.3 billion square feet of commercial floor space from 1979 to 1999. Energy consumed in commercial buildings (amounting to 5 to 6 quadrillion Btu annually, between 1979 and 1999) is a significant fraction of that consumed in all end-use sectors. In 2000, about 17 percent of total energy was consumed in the commercial sector (EIA 2000).

The design and evaluation of commercial buildings has become increasing complex over the years. Such complexity arises from the changing perception and demands of building owners, facility managers and tenants with regard to green/sustainable developments and life-cycle operating costs (concerning energy use, in particular) as well as a growing awareness of the potential impact of buildings on human productivity, health and security.

The argument for deploying building simulations is premised squarely upon this complexity. Simulation tools enable designers to consider the performance of their designs and design alternatives in an accuracy and depth beyond that of traditional methods, as well as delivering the required information faster than external specialist consultations (Clarke 2001).

However, the use of simulation tools in the architectural practice is not pervasive, and even more so limited at the early conceptual design stage. An industry survey by Wong et al. (2000) on the use of performance-based simulation tools for building design and evaluation concluded that usage of tools remain very limited due to several factors: (1) inherent technical limitation of the software, (2) emphasis on initial of capital cost by clients, (3) a fragmented building delivery process that does not routinely include quantifiable assessments of design options by the design team, and (4) the prescriptive nature of current building codes and design guidelines do not promote analytical use of these tools.

The same study also identified most commonly deployed energy simulation tools as being developed for the purpose of design verification and to meet building code requirements at the end of the design phase. They do not necessarily provide support explicit to the requirements of design activities, particularly early conceptual design. These points are also echoed in an internal study by the Public Works and Government Services Canada (Ma, 2001).

Increasing awareness and education in the domain of Architecture, Engineering and Construction Management (AECM) and a contemporary shift in the building industry towards performance-based architecture has begun to alleviate the later 2 points mentioned by Wong et al. Similarly, developments in energy and environmental concerns such as the Leadership in Energy and Environmental Design (LEED) Green Building Rating System encourage and in certain instances require computational energy modeling.

These developments has led to more sophisticated expectations within a building project, including the formal specification of and subsequent funding for energy modeling as part of the building project. Our interest is thus in that of facilitating the development and delivery of appropriate and useful simulation tools for the design processes, especially during early conceptual design.

It is well recognized that the key to influencing the building costs and its performance standards (including energy performance) lie at the early stages of a building project's life cycle (Augenbroe 1992, Mahdavi and Lam 1991). Given the complexity involved, there is a need for effective and efficient tools to assess energy impacts early in the conceptual design phase of a new commercial building design process. Some tools currently exist in various stages of development and targeted for different types of applications and users. There is a need to assess what are currently available and where necessary, make recommendations for improvements to the tools to facilitate their use in the industry.

We begin our study by the definition of early conceptual design, the associated activities and existing tools.

Early Conceptual Design

Whilst the term "early design phase" is very commonly used in discussing the building design process, it invariably refers to the stage of work where initial design ideas are being conceptualized in tandem with the formulation of the building project requirements. It is generally recognized that this is an adaptive-iterative process (Mahdavi and Lam 1993). However, it is often not clear in practice when this phase ends and the next begins.

One essential reference to establish a professional practice definition of early design is the American Institute of Architects Contract Documents. The AIA standard form of contract (see Appendix 1) includes the provision for *Energy Studies and Report* under the category of planning and evaluation services. The description of supplementary services further describe *Energy Studies* consisting of special analyses of mechanical systems, fuel costs, on-site energy generation and energy conservation options for the Owner's consideration. The description of *Schematic Design Document* also includes electronic modeling.

Given these contractual provisions and the drive towards greener designs, it is envisaged that the use of energy modeling tools will become more pervasive in due course. The critical challenge then is to ensure the available tools are indeed effective in supporting the design process.

Many energy modeling tools have been developed over the years by research and development teams in academia, public agencies as well as the private sectors around the world. The conceptual approaches adopted and technical implementation of these tools varies significantly. Some tools employ "simplified" methods that address specific perceived needs of the early design phase while others adopt complex first-principle based engineering algorithms that can meet detailed design requirements. The potential for continuous development of any of these tools depends largely on the software engineering paradigm adopted, which should consider both data modeling and activity modeling for the entire design process.

In building performance modeling, the fundamental data required may be categorized as contextual (e.g., geographical and climatic), formal (e.g., geometric configuration and orientation), semantic or attributive (e.g., dynamic material properties), and performance indices (e.g., energy consumption targets and code requirements). Activity modeling should recognize the growing necessity to support multi-disciplinary collaborative design as building projects become more complex (Lam and Mahdavi 1995). With increasingly affordable computing power, it is argued that energy modeling tools should adopt rigorous physics and engineering-based algorithmic principles in the computational prediction of energy performance to ensure acceptable results.

The different functions within a particular design phase can be met through the user interface design which could progressively reveal different levels of pertinent information input demands with associated library support, and generate appropriate output information to assist in decision making at that particular stage. For example, at the early design phase, the architect may explore various building geometries, orientations and fenestration configurations, and be provided with recommended input parameters derived from an extensive contextual case-based library support in terms of materials, construction, performance targets, etc. The output required at this phase may just be building loads without detailed considerations of mechanical systems and actual energy consumption. As the design progresses, the design team can then be exposed to greater degrees of freedom, with commensurate application support, in modifying the input parameters, not only in terms of the data model but also in computational algorithmic options that aim towards increasing levels of accuracy and resolution as well as performance details in the results output.

Survey of Existing Tools and Selection of 5 Tools for Evaluation

We proceed to conduct a literature review of 22 well-known energy modeling tools based on three general categories of constraints or considerations. First, the tool should be affordable given the resources of the typical architectural practice. This includes both direct costs as well as resources required to operate the tool, such as hardware requirements, expertise and personnel training. Considerations such as ease of use and well designed interfaces that affect the amount of effort required to use the tool also have implications on time costs. Other issues that have an impact on the effort required to deploy the tool and thus indirectly affecting time or direct cost include well developed manuals or help-files, tutorials and customer support.

The second category of constraints relates to the conditions of design. As earlier discussed, design as an adaptive-iterative process implies certain specific functionalities as well as flexibility in an ideal tool. The nature of design as decision between alternatives also implies needs for certain features such as those that aid parametric management and comparisons. To deal with the earlier mentioned complexity of design, the ability of a tool to address multiple performance domains whether independently or in conjunction with other tools is also an important consideration. In the same category of design constraints, there is usually a time limit on simulations for the simulation results to be useful. This limit varies with the kind of design decision and different tools have adopted various methods to meet this requirement.

The third category deals with the constraints of practice. For a tool to be deployed within a professional practice, the users must be confident of the results. The degree of validation a tool has undergone, as well as transparency and documentation of the technical approaches employed thus becomes critical issues. Every industry has general or consensual practices, conventions and protocols. In most instances, conformity or compatibility is essential for effective and efficient communication and avoidance of errors. The prevalence of use of any tool in the industry is thus important when considering its deployment. More specifically, the interoperability with existing tools including both simulation tools and otherwise, file formats, data formats and other protocols have to be considered when choosing a tool. This is especially the case for geometry specifications, which has been found to be very time consuming and representative of a large portion of the effort in an energy simulation (Bazjanac 2001).

These considerations are summarized in a 15-point list that we use to review the 22 well-known energy modeling tools.

User interface
CAD interface
Ease of use
Manuals
Computer Platform
Expertise required
Input Flexibility
Output capability
Functionality
Technical approach
Validation
Audience
Customer support
Price
Usage

From the review, we select five fools that generally satisfy the constraints of practice and cost, as well as hold particular promise for use in early conceptual design. The selected tools are (1) Green Building Studio, (2) eQUEST, (3) Energy Scheming, (4) Ecotect and (5) TAS. This selection may be regarded as representative of the broad categories of tools that exist in industry, in terms of both the high-level approach to energy modeling as well as the nature of low-level technical algorithms employed. A more detailed evaluation of the performance and suitability of use of energy modeling tools in the context of early conceptual design support is then conducted with these 5 tools.

Evaluation of Energy Modeling Tools - Review

After acquiring the 5 tools, we proceed to learn the tools and reviewed them. Following the mentioned categories of constraints and considerations for applying energy modeling tools in architectural practices, we organize the points into 4 themes and develop a detailed 120-point matrix of features which is then used to evaluate the 5 selected tools.

Constraints	Themes	Matrix of Features
A. Resources B. Design C. Professional Practice	A) Usability 1. System requirements 2. Interoperability with other tools, import/export capabilities 3. User interface 4. Learning and training time required 5. Effort required in updating model / conducting parametric studies 6. Processing time B) Functionality 1. Comprehensiveness of geometric and system modeling 2. Types of energy calculations (e.g., load estimation, HVAC systems performance, etc.) 3. Types of data analysis and presentation 4. Availability of other environmental domain simulations (e.g., lighting) C) Reliability 1. Consistency of results 2. Accuracy of results D) Prevalence 1. Compliance with industry standards	A) System B) Extension C) Functionality D) User E) Modeling 1. Project Information 2. Building Modeling 3. HVAC Modeling F) Result Output

	2. Documentation 3. User support 4. Pricing and licensing	

Evaluation of Energy Modeling Tools - Experimental Testing

The experiment for evaluating the energy modeling tools are formulated in the context of the nature of informational demand the architect would have in the early conceptual or schematic design stage, as well as the expected level of technical expertise the architect would possess. Both simulation experts as well as practicing architects are included in the experiment. A survey was used to assess and objectify the experience of the participants. The focus of this survey was on how the tools would fit or complement architectural practice.

The experiment setup attempts to simulate the scenario of an early conceptual design in a typical architectural practice that presents details that would test the capabilities of the tools according to the computational design modeling themes mentioned above. A hypothetical building of 3 stories and multiple zones, with moderate complexity in geometry and construction is provided for energy simulation using each of the five selected tools.

The digital drawings of the building are initially prepared in 2-D in AutoCAD 2000 and serve as a common starting point for using each tool. This allows assessment of the interoperability of the tool with typical software us3ed in the building industry, as well as the evaluation of the usability of each tool from a neutral standpoint. Each tool will then take this basic input information for further development into a 3-D model for energy simulation. Similarly, the weather files, construction, material properties, HVAC systems, space gains and occupancy schedules are pre-determined and not taken from any of the tool's "libraries". This ensures an objective assessment of the time and effort required when using each tool.

Review and Experiment Results

In the review, most of the tools were stand-alone applications that had to be maintained and updated on local machines. With the popularity of the Windows environment and Windows-based applications, graphical interfaces that follow similar semantics and organization seem to be easier to learn and use. Similarly, documentation and help features developed in this manner were found to be useful.

In terms of the tripartite division of simulations into pre-processing, processing and post processing, most of the effort goes into collecting and defining the model as pre-processing and analyzing the results in post-processing. In the former, most of the tools employ proprietary systems of defining geometric models, which tend to duplicate efforts behind the given drawings in the first place. However, there are attempts to circumvent this by means of automatic acquisition from popular data formats.

The other obstacle commonly encountered in pre-processing is gathering all the information required for energy modeling. As previously mentioned, the designer may not have available or decided on most or all of the contextual parameters, or that the effort required to acquire specific information may exceed the available resources and time. Most of the tools employ some form of database or library of common building parameters, from material properties, construction, schedules, space loads to HVAC equipment, infiltration and utility rates. Still, the design generally has to select the appropriate conditions, though some tools have features that make recommendations or even automatically select parameters according to statistical data.

While the evaluation of the accuracy and consistency of the simulation tool, or the processing stage, was left to the experiment and a later benchmarking exercise we conducted using

EnergyPlus, most of the tools employ some form of established and validated simulation engine such as DOE-2. However, the overall quality of any simulation would still depend largely upon the pre-processing. On the other hand, we were concerned with tools that adopted highly simplified approaches such as the CIBSE Admittance method. Granted that such approaches allows fast computations and subsequently a great degree of real-time interactivity that complements the investigative activities of early conceptual design while maintaining comparative accuracy, they might not meet the objective accuracies or confidence required in professional practice.

Most of the tools seemed to be limited in post-processing capabilities. Besides the common energy graph plots, there seemed to be little features targeted at providing early design decision support. Most of the tools allow numerical results to be exported, thus avoiding the issues of post-processing. Given the nature of design and the consequent need for iterative runs informed by prior results, the lack of post-processing support to facilitate such iterations, or to manage, organize and visualize results from all the iterations to address the information demands of design decisions limits the effectiveness of tools in early conceptual design. Some of the tools features building regulation checking, but again such features are not designed to suggest design alternatives or possibilities.

In the experiment, the issues relating to geometry input are again highlighted, with emphasis on the different semantics in the tools where the geometry had to be redefined. The effects were twofold. First, significant time and effort was expended in modeling geometry, and limitations in representation were uncovered often late into the experiment. These limitations would in turn affect the accuracy of the energy models. Interoperability is still an issue, users encountered numerous problems when importing and exporting models amongst different tools.

The availability of different level-of-detail (LOD) in which to conduct simulations was found to be useful. Similarly the use of statistical data to initially help complete all the parameters required quickly for simulation was well received, as with features that make automatic recommendations. However, the concept of LOD was not carried into the latter methods; the users were not able to make changes to the automatically defined parameters. Likewise, libraries were found to be useful in quickly satisfying the pre-processing requirements, but flexibility to change the values at a later stage was deemed important. Tools with well-developed management systems allowing users to work at different LOD were found to be easy to use.

Confidence was observed to be proportional to the degree of technical documentation, explicit listing of the limitations and assumptions, as well as warning messages within the interface. This was especially the case when users had to modify input parameters due to limitations of the tool. However, there were instances when the warning messages were too general and occurred too frequently. In such cases, they distracted the user.

Our benchmark with EnergyPlus confirms that the quality of pre-processing affects the accuracy of simulations as much as the type of algorithm used. Tools that did not allow user specification at a higher LOD deviated more from the benchmark correspondingly.

Conclusions

Research by Lam et al. (2002) has demonstrated the web-based service approach to energy modeling tool design has distinct advantages of being platform independent, allowing distributed collaborations, ease of maintenance and updates, better resource support and availability and arguably lower costs. We found the same to be true in this project.

To increase usability, the user interface should be designed such that it is familiar, cognitive and compliments the concepts and processes of architectural design and energy modeling. Technical help, guidance and documentation would also affect ease-of-use. Detailed technical documentation is particularly important given the nature of energy modeling, but it might not be a dominant issue during the early design phase.

Geometric acquisition for energy modeling has traditionally been a tedious and error prone process. The development of 3D CAD model import and fully automatic geometric acquisition from imported CAD files by some software is heartening. The difficulties in delivering seamless import of models point at the benefits and importance of industry-wide standards or protocols for describing building geometry and information.

Different technical approaches have different semantic and spatial limitations. It is important that the user receives timely and detailed feedback on the correctness of the geometry that he/she has defined. This should be the case even if the geometry acquisition is totally automated.

In general, extensive library support and appropriate recommendations for constructions and materials are important for the designers, especially in the early design phase. Comprehensive weather data should also be made available.

The post processing functionalities in the selected tools are limited to conventional numerical and graphical reports of values such as loads and temperatures. It would be desirable to develop visualizations that would better facilitate a qualitative understanding of the design performance to the user and provide appropriate guidance in the context of early design decision making.

With respect to the early design phase as an adaptive-iterative process, energy modeling tools should ideally be able to support parametric studies. This is generally lacking in contemporary energy modeling tools.

The information content provided by the various tools varies tremendously. There is a need to clarify the information needs of the early design phase and to match the provisions accordingly.

For a tool to be beneficial and remain relevant throughout the building delivery process, it would be advantageous if it is developed based on comprehensive and fundamental principles in modeling the building-environment interactions. The tendency to adopt abstraction and rule-of-thumb approaches in an attempt to meet the time and resource constraints encountered in early design should be avoided. By offering different sets of user interfaces that automate and reveal parameters on different levels of granularity, it is possible for a tool to support various design phases effectively.