
A Simplified Rapid Energy Model and Interface for Nontechnical Users

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ABSTRACT

When used early in the design process, simulation can help designers reduce a building's energy demand. Early-stage simulation must allow the user to explore many options quickly. Most building simulation programs have been structured for modeling finalized building designs very accurately. Intricate detail, often including CAD models, must be entered before such simulations can take place. This can take hours or days to prepare, which is not useful for early-stage design iteration. Further, most simulation tools require a technical background and substantial user training before they may be used effectively. By simplifying the modeling process, and specifically the user-interface, it is possible to make simulation tools accessible to a wider audience. The MIT Design Advisor is presented as means for non-technical specialists to rapidly simulate and compare energy consumption of early-stage building designs. An overview of the simplified interface and the rapid energy model are given, and sample validation cases are explored. The MIT Design Advisor is available at <http://designadvisor.mit.edu>.

INTRODUCTION

In this paper a case is made for a new category of simulation tools that are appropriate for nontechnical building designers. One such tool, developed by the authors, is then presented. A description is given of the simplified user interface, which has been condensed to a single page of basic building parameters. Next, an overview is presented of the energy-load simulation procedure. Finally, validation cases are made for key components of the model, showing agreement with accepted tools.

A NEW CATEGORY OF DESIGN TOOLS

The art of building simulation is well established and experienced professionals can compute building loads with practical confidence. Building simulation packages are in no short supply. The motivation for creating yet another class of simulation tools is to combat the excessive complexity that makes many tools inaccessible to building designers, architects, and engineers for early stage design comparisons. Building simulation is typically deferred to post-design analysis.

Consequently the simple, inexpensive opportunities for reducing energy consumption in buildings are often overlooked. Simplified approaches in both interface design and modeling technique can help empower the non-technical designer to make better design choices.

Building Simulation Engines

Because of their extensive feature-set, building simulation engines such as Energy Plus and DOE-II lend great modeling flexibility to the experienced technical user. In this class of software usability is typically compromised in favor of increased ability to model complex building scenarios. Many underlying assumptions are made without being explicitly evident to the casual user. Users must have a detailed understanding of the simulation process to make useful design comparisons.

To compound the issue, most of these engines lack a pre-packaged simplified user interface. Inputs must be prepared as large text files fraught with technical jargon, physical properties, and programming constructs. Preparing input files can be

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a daunting task. Finally, simulation engines usually contain no interface for making comparisons. Raw output data must be interpreted by the user, which can take time and introduce errors. Consequently the most powerful simulation tools are used only by experienced consultants and only then to simulate finalized or near-finalized building designs.

Third-Party Interfaces

A number of third-party user interfaces have been developed for use with simulation engines. Front-end applications such as eQUEST and BLAST make the creation of input files and the interpretation of results accessible to more users. While such tools are helpful many still fail to address the need for an interface suited to the non-technical user. These interfaces often barrage the user with many questions about very fine details. While such details are necessary for simulating a finalized design, they may preclude simulation for exploring design options. The schematic design wizard feature of eQUEST, shown in Figure 1, requires some 41 screens of user-input before even a basic configuration can be modeled.

Many building certification programs require a detailed computer analysis of building energy performance to gain credit for a design (LEED, ASHRAE 2001). Although time-consuming and possibly expensive, preparing simulations once for a completed design may be appropriate. Such simulations, however, are unlikely to uncover great opportunity for significant energy reduction, since most of the design decisions will have already been made.

Simplified Engines and Interfaces

The motivation for a new design tool follows from the excessive complexity of existing design tools. Reasonably accurate results are attainable without burdening the user with excessive detail or complexity. To the designer it is more important to know the relative energy-impact of possible design options than it is to know exactly how much energy a very specific building will consume.

At the early design stages, vast time resources are typically not available. Full-scale simulations are unrealistic when few parameters have been decided upon. If architects are to use simulation, a quick, simple, and iterative exploration of the design space is required. The MIT Design Advisor offers a way for non-technical users to evaluate the energy performance of a preliminary building and to graphically compare the results of up to four buildings simultaneously. Revising a building design and re-running the simulation can be done in a moment, and in all cases, the simulation provides results in less than one minute. Results include hourly heating, cooling, and lighting loads throughout the year, thermal comfort data, and daylighting information.

The primary goal of this software package is to assist the architect in quickly discovering which design factors can save the most energy while maintaining occupant comfort. Energy savings of 15% or better may often be realized by altering a building's orientation, selecting efficient windows, or adjust-

ing the ventilation rate. By making the powerful modeling tools and techniques available to the non-technical community, it may be possible to promote better design.

MODEL STRUCTURE

We now describe the simplified user-interface and modeling technique of the MIT Design Advisor tool. Modeling is accomplished with several independent load-computing modules that are outlined in this section and covered more fully in later sections.

User Inputs—A Minimalist Approach

An interface with appropriate sophistication is critical. A simplistic and functional interface is described. When technical details must be specified, drop-down menus provide text-based clues indicating reasonable values for typical building configurations. Table 1 shows the minimum input required for a simulation.

All inputs are entered on a graphical setup page, see Figure 2. Nominal values for most parameters are pre-selected as defaults. Experience with students indicates that a new user can master the main elements of the program in less than one hour. Advanced users can modify additional options for a more sophisticated simulation. These include thermostat settings, air change rates, lighting control schemes, blind types and settings, and advanced façade configurations including airflow windows. The casual user is free to ignore these options and typical values are used in their place.

Simulation Overview

When the user has specified the basic parameters, a fast energy simulation is conducted. See Figure 3 for a software logic diagram. A library of Typical Meteorological Year (TMY2) weather data files have been generated using the METEONORM software. A weather data file is retrieved based on a user-specified city. Outdoor temperature, wind velocity, and solar data are read for each hour of the year. Using solar data and geometry, a daylight module is used once per hour to compute light intensity levels throughout the room. The required amount of artificial light is then computed based on the user-selected lighting control system. Multiple reflections of daylight are considered between interior surfaces. A new algorithm (Lehar 2004) was developed to allow accurate solutions to be obtained an order of magnitude faster than programs like the Lawrence Berkeley National Labs (LBL) Radiance software.

Energy exchanges occurring from internal loads, façade heat exchange, ventilation, and thermal mass effects are used to compute heating and cooling loads for each zone. Results are compiled, normalized by floor-area, and returned graphically to the user. Monthly and annual heating, cooling, and lighting loads are reported, and sample output graphs are presented in Figure 4a. Levelized annual energy costs are generated by specifying the cost of electricity and heat, and a

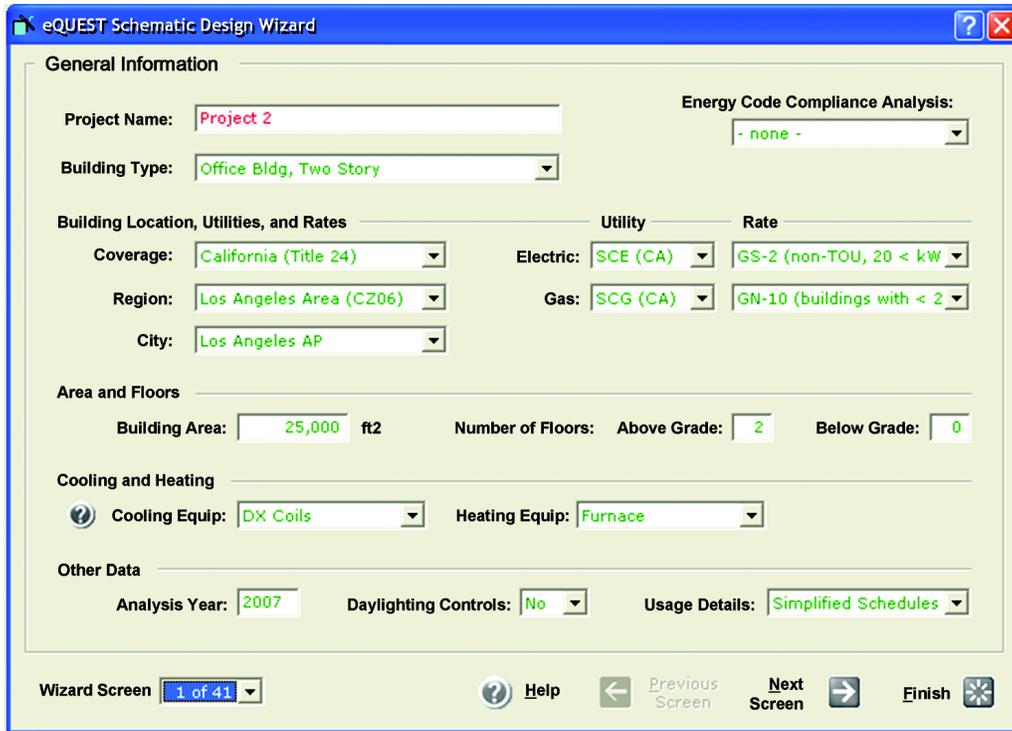


Figure 1 Page 1 of 41 in the eQUEST schematic design wizard. A daunting amount of information is required to prepare a simulation for even the simplest designs.

Table 1. Basic Input Options

Inputs	Description
Zone configuration	One zone confined to a single-side of the building; Four-sided building with well-mixed air; or Four-sided building with air unmixed between zones
Building	Location: select the nearest city for climate data Building dimensions: NS and EW lengths
Room	Primary façade orientation: N,S,E, or W Room dimensions: depth, width, and height
Window	Type: single-, double-, triple-glazed or double-skin façade Coating: clear, low-e, etc. Glazed area: as percentage of wall area
Wall	Specify: low, medium, or high insulation
Thermal mass	Specify: low, medium, or high thermal mass
Occupancy	Occupant density: # people per floor area Equipment load: watts per floor area Min. lighting req.: lux Occupancy schedule: hours of occupancy
Ventilation	Mechanical system; Natural ventilation only; OR Hybrid mechanical and natural ventilation

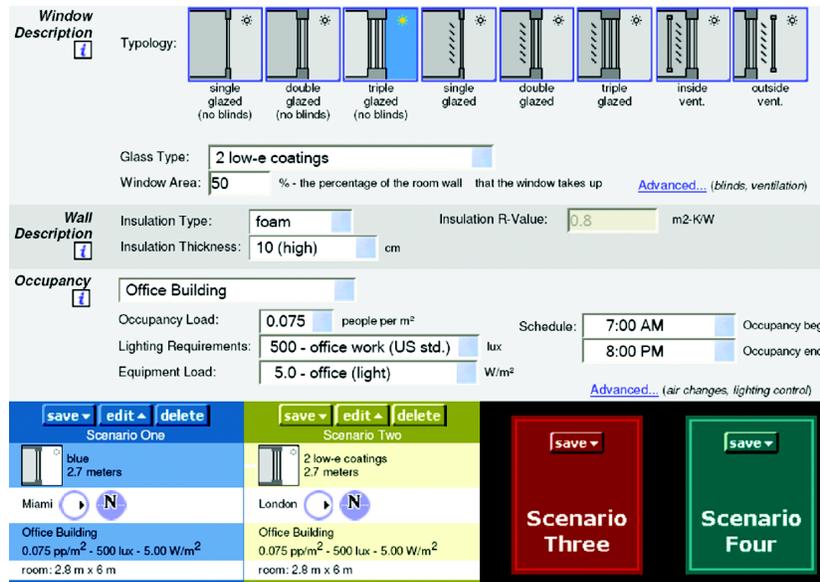


Figure 2 A portion of the single-page MIT design advisor graphical interface. Up to four building scenarios can be saved and retrieved quickly from the scenario boxes.

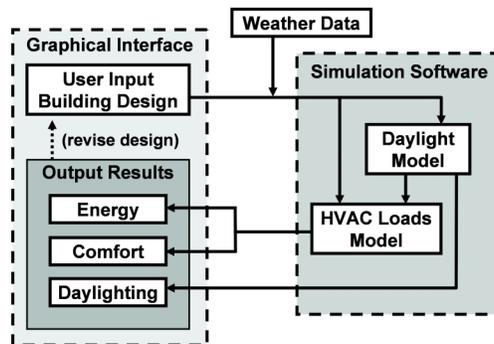


Figure 3 Block diagram of software logic.

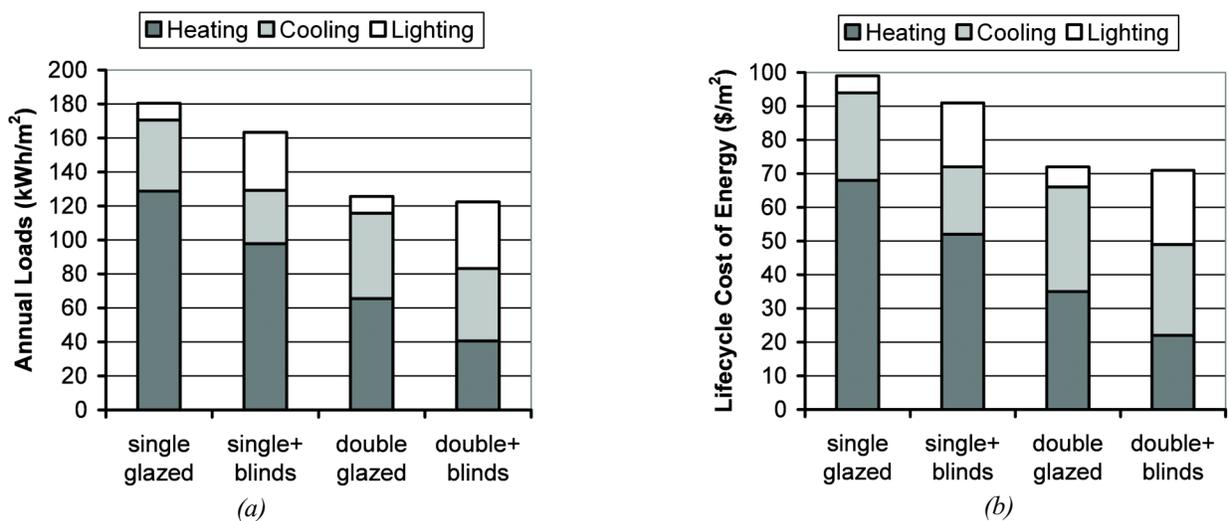


Figure 4 Sample load comparison and energy cost for four building designs.

suitable cash discount rate, see Figure 4b. Thus, a financial case can be made for installing more efficient components.

Computing heating and cooling loads independently of lighting loads can produce incorrect results since artificial lights contribute heat to the space. When blinds are adjusted by occupants to reduce glare, both daylight and the solar heat gains are varied. An integrated model is necessary to capture the interplay between all building control systems.

ENERGY BALANCE

Energy exchanges occur via several channels: internal loads, ventilation, envelope, thermal mass, and HVAC – see Figure 5. Internal loads depend primarily on the occupancy conditions in the building; it is assumed that internal loads are constant during any given hour. Ventilation and envelope loads are proportional to the indoor-outdoor temperature difference, and their magnitude can vary modestly within a single hour as the room's air temperature floats between the upper and lower thermostat bounds. Thermal mass loads are more complicated: variation depends on the instantaneous indoor temperature, the incident heat flux, and the temperature distribution within the mass itself.

One way of solving large thermal systems is to assign each surface a temperature node, generate a system of energy balance equations, and use matrix inversion to solve the system of equations. Because some of the heat transfer coefficients are non-constant, it would be necessary to frequently re-invert the large matrix, and this is impractically slow.

Instead for each room, all of the loads Q_i (in units of W) are computed independently for the various channels of energy exchange. The computations are made only as frequently as needed: once per hour for internal loads, and 5 to 10 times per hour for envelope, thermal mass, and ventilation loads. Here we outline how each of the four types of loads is computed and show how they can be used to predict HVAC loads.

Internal Loads

Internal loads Q_{int} consist of the sum of heat generated by equipment, artificial lighting, and people. These values change throughout the day based on occupancy schedules, available daylight, and lighting control strategy. Each internal load is modeled as a constant during any given hour. Occupants provide a constant source of energy; 60W of sensible heat is typical for an average person sitting in an office.

Envelope and Solar Gains

Energy exchanges through the building envelope include directly transmitted radiative gains through window elements, and convective/conductive gains through windows, walls, and other insulating members. Instead of using tabular U-Values and Solar Heat Gain Coefficients (SHGC), which are typically only appropriate for harsh design conditions, heat transfer coefficients are computed dynamically based on environmental conditions. This is important because radiation coefficients vary with material temperature and because spectral properties

of glazing elements vary with angle of incidence. Variation in radiation coefficients are computed using a linearized radiation heat transfer coefficient. Angular-spectral variation is determined via the Fresnel equations (ASHRAE 2005, Siegel).

Transmitted solar gains include the portion of sunlight reaching the room interior. TMY2 weather data files supply values for direct-normal and diffuse-horizontal radiation flux. These values are converted to incident values on a vertical surface using the solar geometry calculations outlined in ASHRAE (2005). Each hour the transmitted fraction of incident radiation is computed. Multiple reflections are considered to determine the energy absorbed, reflected, and transmitted by all elements of a multi-layered façade. Spectrally-selective materials are modeled with a tri-band radiation model: IR, visible, and solar-thermal radiation are each considered separately. The thermal-circuit method shown in Figure 6 is used for computing gains through the windows Q_{window} and walls Q_{wall} . Thermal mass effects are assumed negligible for envelope components, and a steady-state model is used.

Radiant interactions between blind, window, and room surfaces are computed using a radiosity method, and the temperature of each surface is computed at every timestep. Double skin façades and airflow windows, depicted in Figure 7, can be modeled in a similar manner, though an additional mass-flow energy balance must be computed. The air flowing through the window cavity can exchange energy by convection with the window pane and with the blinds. Since the temperature can vary significantly in the vertical direction of such windows, the cavity is discretized into 5 to 10 vertical slices. A thermal circuit, similar to the one shown in Figure 6 is solved repeatedly, beginning with the lowest slice and working upwards. Supply windows of this kind can introduce fresh air into a room via a vent at the top of the window. In such cases the temperature of the air at the cavity exhaust is computed and used in the ventilation load computation.

Thermal Mass

It is assumed that the building's thermal mass is concentrated in the floor of each room. The amount of thermal mass – low, medium, or high – is determined by the thickness (0.02, 0.10, or 0.20 m) of a slab of concrete which makes up the floor.

Solar energy transmitted through fenestration is assumed to be evenly distributed over the surface of the floor. A fraction, equal to 80% is absorbed at the floor surface, and the remainder is reflected to other surfaces in the room – walls, objects, etc. An approximation is made that room surfaces other than the floor and the exterior wall/window exist at the room's air temperature. Since the interior walls have a moderately high internal conduction resistance compared to surface convection, most of the radiation absorbed by these surfaces will ultimately reach the air by convection. Thus as a first approximation, the transmitted solar radiation that is not absorbed by the floor is added directly as a thermal load to the air.

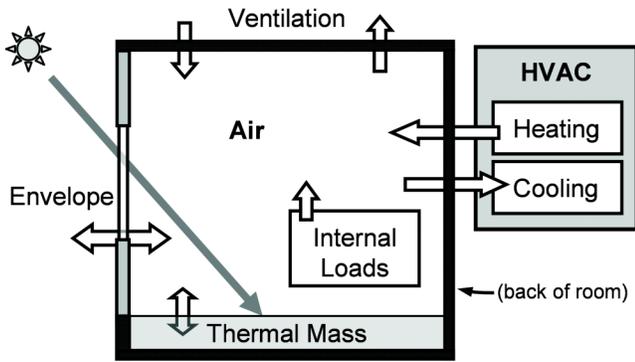


Figure 5 Heat exchange with the air in a room. Arrows indicate possible directions of heat flow.

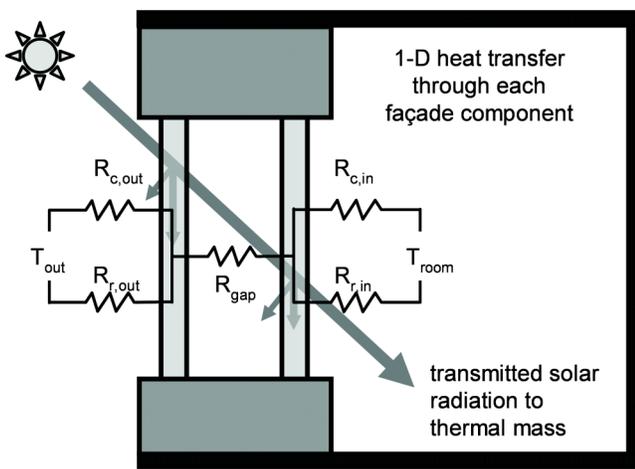


Figure 6 Thermal circuit for heat exchange through a sample window.

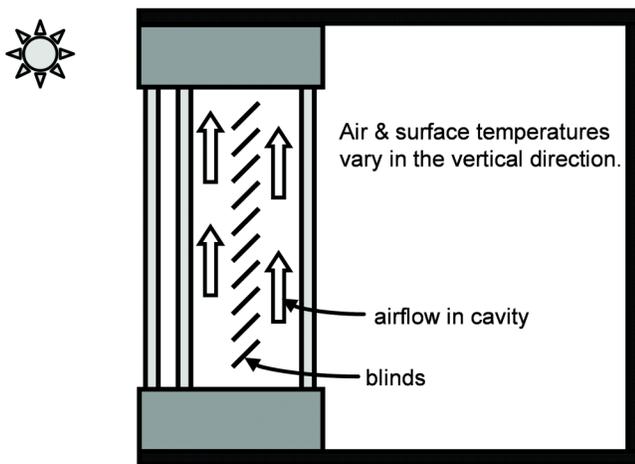


Figure 7 A sample airflow window: air enters the cavity bottom and exits at the top. Intake and exhaust vents can connect to either the room interior or the outdoors.

For very low-mass floors a lumped-capacitance approach is fast and reasonably accurate. Higher mass floors that can sustain a vertical temperature distribution require a depth-discretization to compute thermal response. A conservative horizontal slice thickness Δd can be selected by ensuring the surface node satisfies the Biot relation

$$Bi = \frac{h\Delta d_{min}}{k} \ll 1 \quad (1)$$

This minimum slice thickness d_{min} is then used as the thickness for all layers. Similarly, a maximum stable time step t_{max} is determined using the Fourier relation

$$Fo = \left(\frac{k}{\rho c_{mass}} \right) \Delta t_{max} \frac{1}{\Delta d^2} \leq 0.5 \quad (2)$$

For the depths listed earlier the minimum number of slices may be as high as 25 and the maximum time step for an explicit solution is on the order of 30 seconds to 1 minute.

Using values of t_{max} and d_{max} a convection/conduction energy balance is performed on each node of the discretized slab floor, as shown in Figure 8. Using a combined surface convection and IR-radiation heat transfer coefficient $h=8.0 \text{ W/m}^2\text{-K}$, and one-dimensional conduction through the depth of the thermal mass, a basic system of linear heat balance equations is constructed in matrix form. This matrix is inverted once and used repeatedly throughout the annual energy simulation to update the temperature distribution and to compute how much energy is exchanged with the air via convection. The energy traveling from the thermal mass surface to the air Q_{tm} is computed as the sum of convected energy and reflected solar energy.

Since constant coefficients are used, the matrix is inverted only once and it is computationally inexpensive to frequently compute the temperature distribution in the thermal mass. When using an extremely conservative t of one minute over a yearly simulation, calculation time for thermal mass response is less than 5 seconds on a modern desktop computer.

Ventilation and HVAC Loads

Ventilation exchanges consist of mass exchange with the outside environment. Fresh air is introduced to the room at the outdoor temperature and mixed with the indoor air, while indoor air is exhausted to the outside environment at the same rate.

In mechanically ventilated systems the flow rate is linked to the occupancy to establish safe levels of fresh air. Typical ventilation rates range from about 2.5 to 10 L/s-person for non-smoking and about 40 L/s-person for smoking areas (ASHRAE 62.1-2004). As the ventilation energy is linked to the time-varying room air temperature, it must be re-computed several times per hour.

When natural ventilation is permitted, a crossflow model is used to compute the air change rate based on the aspect ratio of the room, dimensions of the window orifice, surrounding building height, and wind direction and velocity taken from

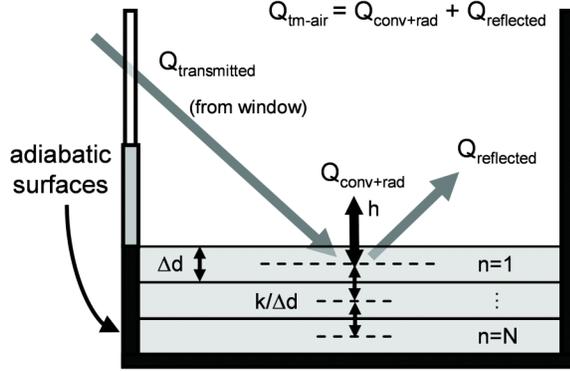


Figure 8 Thermal mass floor schematic.

the weather data. Windows are opened or closed in a logical manner based on the outdoor and indoor temperature to help improve occupant comfort and reduce HVAC loads.

Assuming air is well-mixed within a zone, an energy balance on the air within a room can be written as

$$mc_{air} \frac{\partial T}{\partial t} = Q_{window} + Q_{wall} + Q_{int} + Q_{tm} + \dot{m}c_{air}(T_{ext} - T) \quad (3)$$

where

- c_{air} = the heat capacity of air
- \dot{m} = the mass flow rate due to ventilation
- m = the mass of one roomful of air
- T = instantaneous room temperature
- T_{ext} = outdoor temperature

Discretizing Equation (3) in time with an implicit formulation (using $T = T_{t+\Delta t}$ in the RHS) and solving for room temperature at the next timestep yields the following:

$$T_{t+\Delta t} = \frac{mc_{air}T_t + \Delta t[Q_{window} + Q_{wall} + Q_{int} + Q_{tm} + T_{ext}(\dot{m}c_{air})]}{mc_{air} + \Delta t(\dot{m}c_{air})} \quad (4)$$

where Q_{int} is computed once at the start of each hour and remains constant during that time period. The values of Q_{window} , Q_{wall} , and Q_{tm} are computed at the start of each timestep explicitly using T_t as a room temperature. These loads are assumed constant over the duration of t . For this assumption to hold, the timestep t must be small enough such that the air temperature does not vary substantially from one step to the next. A conservative 5 minute time step is currently employed with good result. At each timestep Equation (4) is solved to predict the room temperature at the next time step.

If a temperature bound is exceeded, heating or cooling HVAC loads are applied to return the zone-air to the upper bound temperature when the air becomes too hot, or the lower

bound temperature when the air becomes too cool. The magnitude of the heating/cooling load is simply as follows:

$$Q_{HVAC} = mc_{air}(T_{bound} - T_{t+\Delta t}) \quad (5)$$

where the room temperature at $t + \Delta t$ then takes the value of the boundary (max or min) that it crossed. If natural ventilation is permitted, the windows are adjusted (opened or closed) to assist with heating or cooling. This will adjust the mass flow rate of air from the mechanical rate to that which arises from environmental conditions. Heating and cooling loads are tallied and monthly and annual loads are reported.

Optimizer

A building design optimizer has been developed (Lehar 2005). The user selects a given scenario that has been investigated and indicates which of the major design parameters are allowed to vary or be held fixed among: window typology, glazing type and area, room dimensions, insulation type and building orientation. Maximum and minimum thresholds for some parameters can be specified, such as window area and room dimensions. The program then searches through a large array of previous solutions to determine the parameter set that yields a minimum total yearly energy. A branching fuzzy-logic classifier has been implemented to interpolate within the multi-parameter space of known solutions. This is then combined with a simulated annealing technique to locate the optimization region. In keeping with the goal of the program for a rapid response, the optimizer is designed to run within one to two minutes. The object is to aid the designer by suggesting designs that approach best energy efficiency. Without this module the designer might be exploring a series of designs that are all relatively inefficient.

DOCUMENTATION AND VALIDATION

Care has been taken to validate the program's elements against industry-accepted standards, accredited simulation software, and analytic models. Detailed comparisons and documentation are published on the program's website. Validation results are presented for steady-state and transient window solvers, the thermal mass model, and a full-scale calibrated software comparison.

Window Solver Validation

Steady-state heat flow calculations were used to validate the window solver program. Center of glass U-Values and Solar Heat Gain Coefficients (SGHC) for normal-incidence were computed for a variety of window configurations. The Lawrence Berkeley National Labs (LBL) software WINDOW5 was used for making comparisons. Optical and thermal properties were matched in both programs for four types of glass: clear, blue, low-emissivity (Low-e1) and very low-emissivity (Low-e2). Cavity depth of multi-layered glazings was set at 12.7 mm. Interior and exterior convection coefficients were set at constant values of 4 and 26 W/m²-K,

according to the specifications of the NFRC-100 and ISO-15099 standards. Radiation coefficients were computed dynamically by both programs.

Results of the comparisons are shown in Figure 9. Most cases agree to better than one percent. The few cases which differ by 5 to 10% are multi-layered glazings with at least one low-emissivity pane. Because radiation is reduced in these cases, the fill gas thermal resistance is a dominant factor in the overall heat transfer through the window. The error is likely due to the simplifying assumption that pure conduction occurs in the fill gas. In reality small amounts of convection can take place within the gap, assisting heat transfer. Such errors are acceptable as the intent of the program is simply to show differences between general types of window configurations.

Thermal Mass Validation

We have compared our thermal mass model with the analytical solution for a semi-infinite solid. Figure 10 shows results for a 0.20m-thick slab of concrete with an adiabatic bottom surface. From top to bottom, the curves indicate the temperature of the surface-node, the central-node, and the deepest-(semi-adiabatic)-node of the thermal mass as a function of time. Figure 10a shows results for a constant heat flux of 400 W/m^2 incident on the slab surface with no convection. Figure 10b illustrates the convection-only case, where the slab is exposed to a constant environmental $T=320\text{K}$ with a convection coefficient of $8.0 \text{ W/m}^2\text{-K}$. Both cases start with a uniform initial slab temperature of 300K and the simulation runs for a period of one hour. By computing an average final temperature through the slab depth, the net-energy gain is found for each case. Agreement is better than 0.1% for the constant heat flux case and 2.1% for the convection case.

Daylighting Verification

Close agreement between the MIT Design Advisor and the daylighting software Radiance has been demonstrated. A comparison of daylight distribution over each of the room surfaces can be found in the reference work (Lehar 2004).

Energy Plus Comparison

A series of calibrated comparisons have been made against the Energy Plus software with good agreement. All parameters have been matched where possible. The climate data for each simulation is that of Boston, MA taken from the METEONORM library and used in both programs. As the MIT software has yet to implement a humidity model, all humidity has been completely removed from the weather data files for the comparisons. The cases are each built from an identical base simulation, with one or more parameters varied, and are described in Table 2.

Case 1 represents an internal load inside an adiabatic box, and the required sensible cooling load has been computed to maintain a maximum zone temperature of 26°C . The cooling load in Case 1 should be – and is for both models – exactly equal to the internal loads. All other cases (2-7) have been run

to compute heating loads only, based on a minimum zone temperature of 20°C . Room temperatures were allowed to float freely above 20°C . The high and low thermal mass cases correspond to floor thicknesses of 0.20 and 0.02 m, respectively.

Results of the comparison are shown in Figures 11-12 and agreement is reasonably good in most cases. The greatest differences occur in cases with large glazing areas and with high thermal mass. Differences associated with glazing area appear to stem from differences in the U-Values. By applying similar conditions to windows in Energy Plus, U-Values were found to be at times 10% higher predicted by the MIT Design Advisor. Such variation is likely due to the way in which convection is modeled inside window cavities. Differences associated with thermal mass size are likely due to the simulation techniques employed. As an example, due to stability constraints in the Energy Plus methodology, the minimum timestep allowed is 1/6 hour.

CONCLUSION

Simulation tools, when used in early-stage design, can help produce buildings with improved energy efficiency. In practice, simulation is used only after building designs are completed and when it is too late to implement design revisions. The large time investment associated with preparing simulations and interpreting their results prohibits their use at the early stage. Complex user input options further prohibits non-technical users, including architects and building designers, from even attempting to analyze their designs without special training.

The MIT Design Advisor has been presented as one simplified tool for quickly exploring the energy requirements of competing design concepts. A restricted input space has been described to minimize setup time. A rapid thermal model has been described for computing and graphically displaying monthly and annual energy loads. Comparisons with industry-accepted software tools and analytic models have been made with good result.

Preliminary trials with students and architects have shown encouraging results. Simplified approaches to simulation can be useful for both educational and practical purposes.

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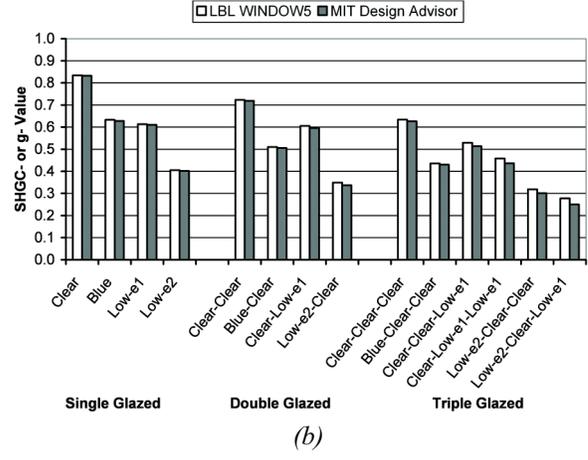
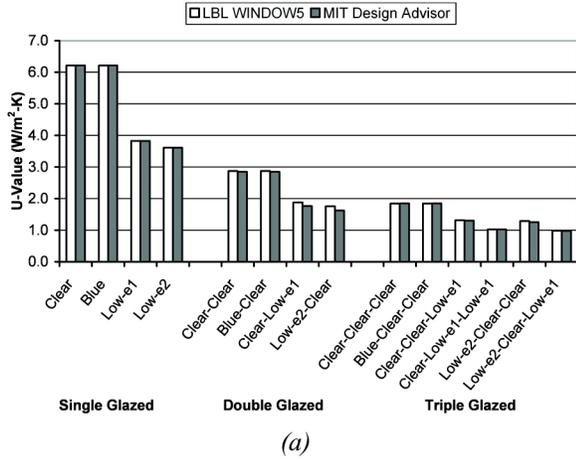


Figure 9 Steady-state comparisons of (a) U-value and (b) SHGC.

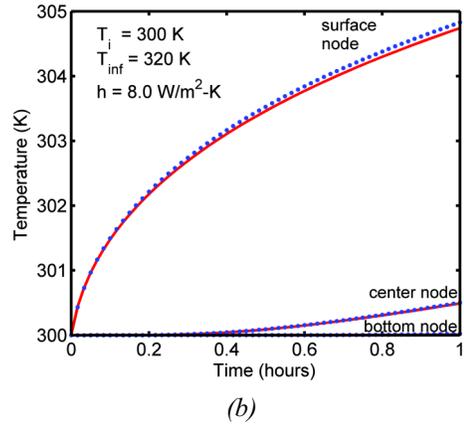
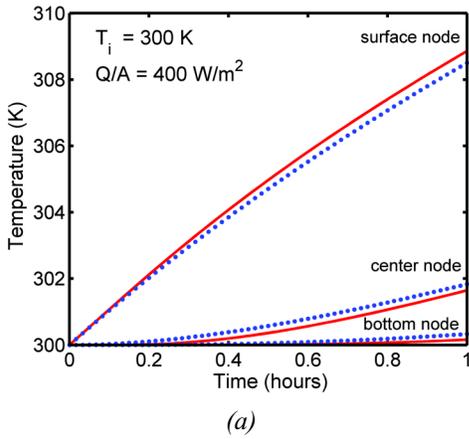


Figure 10 Thermal mass comparison, temperature distribution in a concrete slab: design advisor (dots) versus closed-form, semi-infinite slab solution (solid curve) for (a) constant heat flux and (b) convection.

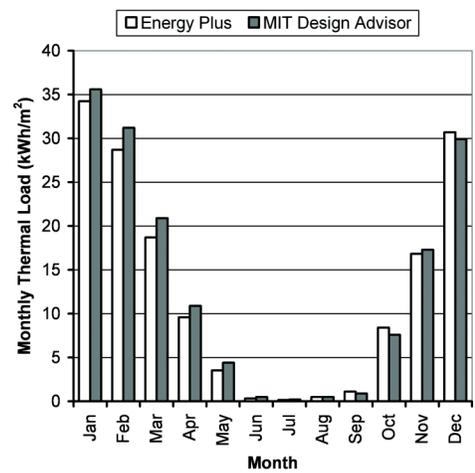
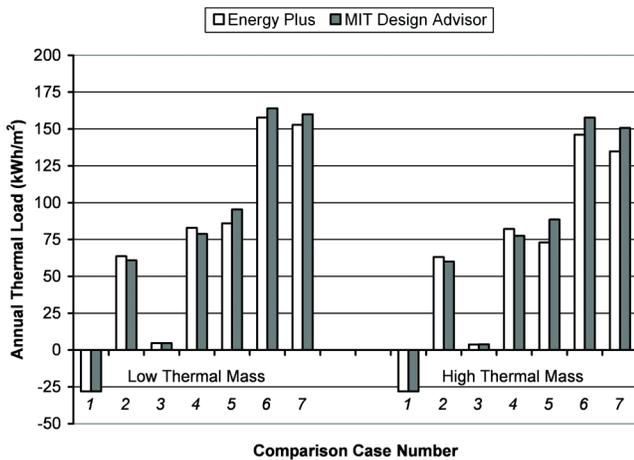


Figure 11 Annual thermal load comparisons.

Figure 12 A monthly comparison: Case 7 with low mass.

Table 2. Energy Plus Comparisons

Case Number	Description
Base Case (Features in Common Unless Otherwise Noted)	Location: Boston, MA, no humidity Primary façade orientation: E Room dimensions: 5 × 5 × 3 m (width, depth, height) Mechanically ventilated building Adiabatic walls (×4) Adiabatic ceiling (×1) Thermal mass floor (×1) with adiabatic lower surface Zero % windows Internal load: zero Ventilation rate: zero
Case 1	Base case + 6 W/m ² internal load from 7a.m. to 8p.m.
Case 2	Case 1 + 1.8 ach from 7a.m. to 8p.m.
Case 3	Case 1 + east facing wall has R-value of 4.6 m ² ·K/W
Case 4	Case 3 + 1.8 ach from 7a.m. to 8p.m.
Case 5	Case 3 + triple-glazed clear-pane window on east wall comprising 84% of wall area; remainder of wall is adiabatic
Case 6	Case 5 + 3.6 ach from 7a.m. to 8p.m.
Case 7	Case 5 + internal loads and ventilation ON 24 hours per day

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