SimBuild 2006

Second National IBPSA-USA Conference
Cambridge, MA
August 2-4, 2006

THE MIT DESIGN ADVISOR – A FAST, SIMPLE TOOL FOR ENERGY EFFICIENT BUILDING DESIGN

Bryan Urban and Leon Glicksman
Massachusetts Institute of Technology, Cambridge, MA

ABSTRACT

We present a simplified software tool for architects to assist with early-stage design of energy efficient buildings. Energy consumption in the buildings sector accounts for 25 to 30 percent of global carbon dioxide emissions.

Due to inherent complexity, building modeling tools are often deferred to the later stages of design. In later stages many decisions are already finalized and the opportunities for design improvement are limited, expensive, and harder to implement. By helping designers address efficiency and comfort in the first hours of the design process, significant energy savings can be realized more easily and at reduced cost.

We provide an overview of the Design Advisor tool (http://designadvisor.mit.edu) including the input parameters, results, and some important modeling information.

INTRODUCTION

The daily operation of commercial and residential buildings comprises roughly one-third of the world's primary energy consumption; heating, cooling, and artificial lighting systems account for the largest portion. Because buildings are typically operated for many years, there is great potential for reducing global energy needs through improved building design.

Many existing energy simulation tools for buildings are very sophisticated and promise a high level of accuracy. Popular tools such as Energy Plus and DOE-2 are quite effective at simulating final building designs and are typically used for demonstrating compliance with performance standards such as LEED.

The tool we present is different in that we target the early-stages of the design process: a time when design details are often sparse and uncertain, simulation time is limited, and major decisions are not yet finalized. Most tools are overly complicated for this task and do not provide an easy way to compare the tradeoffs between design options. The aim of our project is to provide a fast, simple tool for architects and building designers to assist in the decision making process during the first hours of design.

In this paper we outline the capabilities and limitations of the Design Advisor tool. First we discuss the input parameters and compare our interface with those of popular industry-standard programs. Next we present some example software outputs and show their utility for building design. Finally we summarize the major assumptions inherent in the model and present a basic overview of how the predictions are made.

SIMULATION – USER INTERFACE

If a design tool is to be useful to most architects, it must not require an extensive technical background or lengthy amounts of training. Existing software tools have largely been designed for engineers, resulting in simulation packages that require detailed floor-plan inputs, promise excessively high accuracy, and produce results in a non-graphical manner. Setup time for these programs can take hours or days. At the early stage such extreme accuracy and detail is unnecessary and in fact unrealistic.

Instead we take a simpler approach: by restricting the input space to the most critical design parameters we can rapidly predict a design's performance. Our primary objective is not an exact performance prediction of the final building design. What is important is that the user is able to identify which design factors have the highest impact on energy use and thermal comfort relative to the others.

Although we restrict the detail in the inputs, the computational model is still quite sophisticated. Discussions of simulation technique will follow.

Input Space

Described below are the basic input options available to the user for describing a building configuration:

1. Simulation type: 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 adjacent to each façade;
2. Window description: type of window (single-, double-, triple-glazed, or double-skin façade), special coatings on window surface (clear, low-e, blue, etc.); presence or absence of blinds; and window area as a percentage of wall area;
3. Wall description: insulation material and thickness;
4. Building description: location (city), and rectangular building dimensions (NS and EW);
5. Occupancy conditions: people per square meter, lighting requirements in lux, equipment load in watts per square meter, and hours of operation. Alternatively, the user can select an occupancy type (residential, office building, factory, etc.) and typical values for the above options are populated automatically;
6. Room description: orientation of the building or façade (North, South, East, or West); room depth, width, and height;
7. Ventilation strategy: mechanical system, natural ventilation, or a hybrid combination of the two;
8. Thermal mass: low or high thermal mass; and
9. Window overhang: depth of an overhang to provide shading from solar gains.

Most of these parameters can be selected from pre-defined options such that the user requires no prior technical knowledge to complete the setup. Beyond these basic required parameters, the following advanced options are available for more detailed simulation.

- Blind settings: blind width, color, angle when closed, daytime and nighttime blind schedules (always opened, always closed, responding to temperature, or responding to solar intensity)
- Double skinned façade settings: cavity depth, air flow rates through the façade, vent supply/exhaust locations (interior or exterior)
- Air changes: liters per second per person
- Lighting control system: lights always on, or lights dimmed to supplement sunlight (single dimmer for entire room, or individual dimmers for each fixture)
- Thermostat: set upper and lower bounds on the room temperature

Figure 1 illustrates logic of the software (Lehar 2003). After the basic parameters are defined by the user, weather data is loaded for the selected city and both are passed into the simulation software. An energy model predicts required heating, cooling, and lighting loads and thermal comfort conditions for the occupants. The daylighting model can compute the distribution of sunlight entering the room for any time of year.

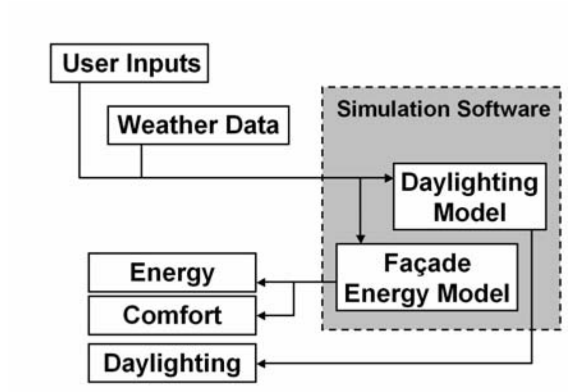


Figure 1.Block diagram of software logic.

Setup information for up to 4 building scenarios can be saved simultaneously for fast and easy design revision and iteration. The entire setup process can be completed in under 5 minutes by an untrained user, and simulation time is typically less than 30 seconds.

Users often asked which factors are most critical for reducing building energy consumption. The answer depends greatly on the climate of the building's location – though factors like air change rate and window options (especially percent glazing and blind settings) often show dominating effects.

It is critical that heating, lighting, and cooling energy be considered together. Changing a building parameter to improve one of these factors will often affect the others. Adding blinds can reduce solar thermal loads, but when blinds are closed, more electric lighting is needed, which adds heat to the room. The precise outcomes of these feedbacks are not always intuitive.

SIMULATION – GRAPHICAL RESULTS

Equally important to a simple user interface is a simple way of viewing and comparing results. As soon as the simulation is completed, graphical results are available indicating energy consumption, lifecycle costs, thermal comfort, daylighting illustrations, and building code compliance. What follows is a brief description and example of each of these.

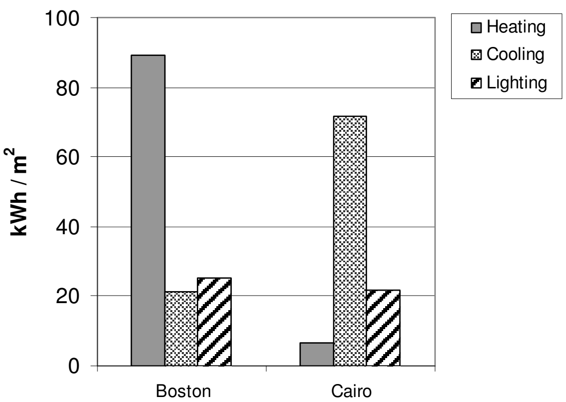


Figure 2. Sample prediction of primary energy usage for two identical buildings in very different climates.

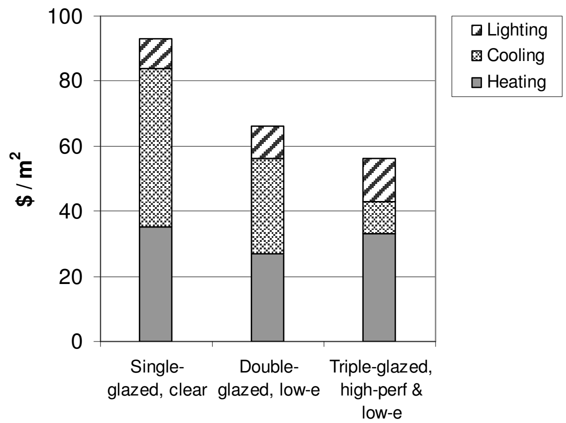


Figure 3. Net-present cost of energy for 3 building designs: windows more efficient from left to right.

Energy

The façade energy model rapidly computes the amount of primary energy needed for heating, cooling, and lighting in the building. Monthly and annual energy requirements are returned and results of up to four simulations can be viewed simultaneously for quick design comparisons. Figure 2 illustrates the primary energy consumption of two identical buildings in different locations. Dominance of heating and cooling energies are reversed from the Boston case (left) to the Cairo case (right) due to the differences in climate.

A more detailed description of the computation process and modeling assumptions is available in the ENERGY MODEL subsection below.

Lifecycle

Weighing the merits of reduced energy consumption against the sometimes-higher initial cost of more efficient building components is an important design step. Advantage can come in the form of lower energy costs or lower emissions due to less fuel consumption.

The user can specify the cost of heating energy ($ / therm), the cost of electricity ($ / kwh), the discount rate of capital (percent / year), and the expected lifetime of building operation (years). Results are adjusted and displayed graphically as in Figure 3. Typical values for these parameters are provided as defaults. The user can compare the net-present cost of energy, annual energy costs, and annual CO_2 emissions of competing designs.

For example an building designer may wish to decide if investing in high-performance windows is a good idea. After simulating three buildings which differ only by window type, the graphs in Figure 3 show the net-present cost of energy for the lifetime of each building. Switching from single-pane clear glass to double-pane low-e coated glass results in savings of roughly $27/m^2$. Comparing this amount with the net-present cost of various window systems allows the architect to decide if this savings will warrant the upgrade to a more efficient window.

We have elected not to include the capital cost of building materials in the software as these figures tend to vary by location and project. The building designer should have access to equipment pricing, and cost-benefit comparisons can be made accordingly.

Thermal comfort

Thermal comfort is illustrated in two ways depending on the ventilation strategy selected by the user – one for naturally ventilated buildings and one for mechanically and hybrid ventilated buildings.

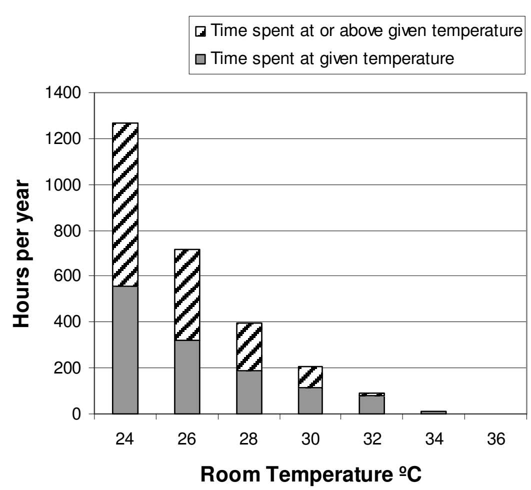


Figure 4. Thermal comfort for a naturally ventilated building in Boston.

Using natural ventilation exclusively for cooling can result in an uncomfortably-hot building during the hot season. For naturally-ventilated buildings the energy simulation predicts room temperature for every hour of the year and a diagram is generated illustrating the number of hours per year a given temperature is met or exceeded. This is useful for understanding whether or not natural ventilation is appropriate for a given project. Figure 4 illustrates a representative natural ventilation thermal comfort graph for a building in Boston, MA. Shaded bars represent the number of hours per year spent at a given room temperature, and striped bars illustrate the hours per year a given room temperature is exceeded.

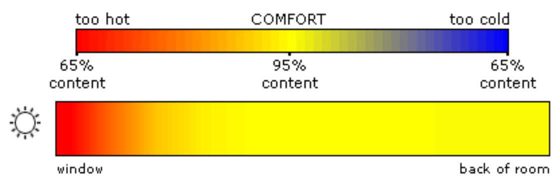


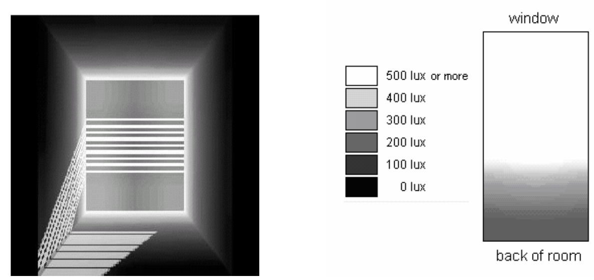
Figure 5. Thermal comfort during summer. Most occupants feel too hot near the single-glazed window.

When a building is mechanically ventilated, it is still possible for occupants to be thermally uncomfortable in the room. For these cases, our simulation adjusts room temperature such that an occupant in the center of the room is comfortable. Occupants near the window or the back of the room may feel too hot or cold, and we provide a graphical tool for understanding how comfort varies as a function of distance from the window, season of the year, and time of day. A scale of Predicted Mean Vote or PMV is used for this purpose and a sample output is shown in Figure 5.

Daylighting simulation

Studies indicate that productivity of workers and occupant happiness can be improved by increasing exposure to sunlight. Most buildings can meet at least some of their lighting requirements from natural light. A rapid daylight simulation module has been incorporated to allow visualization of light entering the room. Two simulations have been included: the first (Figure 6a) is a 3-D view of a room looking at the window, and the second (Figure 6b) is a 2-D plan view of the daylight reaching the workplane – an imaginary surface 0.5 meters above the floor.

Calibrated comparisons between the Design Advisor model and the software package RADIANCE have shown very close agreement (Lehar, 2004).



(a) **(b)**

Figure 6. (a) 3-D daylight simulation of a room with blinds. (b) 2-D daylight simulation of the workplane.

Building codes

Building codes have been developed for many climates and locations and can be used to assess building performance. The Design Advisor can compare building designs against the ASHRAE 90.1-2001 standard and the UK Standard Part L.

The ASHRAE standard lists maximum allowable requirements based on the climate of the building location. Limits on window and wall U-Values, the Solar Heat Gain Coefficient, and maximum allowable glazing percentage are clearly established in tables. If the described building meets all of these requirements, it is said to meet the prescriptive code requirements and our program will indicate (non)compliance with above items. In cases where the building does not meet the prescriptive requirements, the user will be shown which elements have caused the building to fail. Requirements relating to the roof, doors, and ground are not evaluated in the Design Advisor software at this time, however these losses will likely be introduced in future versions of the software.

When one or more of the prescriptive requirements is not satisfied, a building is still capable of meeting the code requirements. First, a notional building that shares features of the building in question (and that is modified to meet the minimum requirements of the prescriptive method listed above) is generated by the Design Advisor. The energy performance of this notional building is then simulated, and if the proposed design consumes less primary energy (or in the case of the UK code, produces less CO_2 from energy) than the notional building in question, it will satisfy the code.

ENERGY MODEL

Here we note the basic modeling techniques and assumptions that are used, and to illustrate which types of buildings are best and least suited to be modeled by this tool.

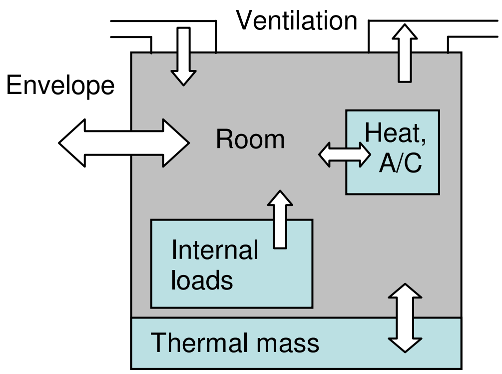


Figure 7. Heat transfer with the air in a room.

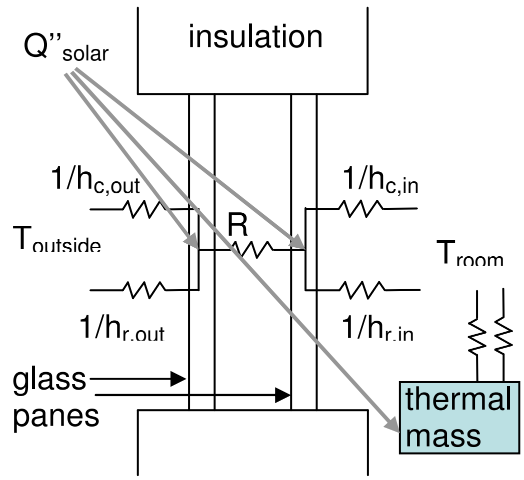


Figure 8. Cross section of building envelope, and thermal circuit for finding heat flow through a double-pane window.

Climate data for a typical meteorological year (Meteonorm, 2000) are used for the selected world city to calculate losses and gains of heat through the building envelope. In addition to outdoor temperature, the hourly climate data include both direct and diffuse solar-thermal and visible light intensities.

Each hour of the year, a thermal balance with the room is computed. The cartoon in Figure 7 depicts the potential flows of heat. Double-headed arrows indicate that heat can transfer in either direction (into OR out of the room), while single-headed arrows indicate heat flowing in one direction only.

The net heat exchange with the room, Q_{net}, is computed each hour as the sum of individual heat exchanges:

(1) $$Q_{net} = Q_{loads} + Q_{envelope} + Q_{thermal\ mass} + Q_{ventilation} + Q_{heat,\ a/c}$$

Internal loads

The heat gain due to internal loads is computed as the sum of: equipment loads, occupant loads (assuming 60 W/person), and lighting loads. Internal loads can vary depending on the time of day and occupancy schedule, which defaults to an 11-hour day beginning at 7am and ending at 6pm for 7 days/week. At the start of each hour the daylight module determines how much electrical lighting is required to supplement the incoming daylight. See the paper by Lehar 2004, for details and validation regarding the daylighting procedure.

Envelope

The room exchanges heat through the windows, window frame, and insulation in the wall. Heat transfer through the window units is computed by solving a 1-D network of thermal resistors. A heat balance is solved for each node to determine the nodal temperatures and the total heat flowing into or out of the room.

When blinds are included a radiosity method is used to compute the net radiation exchange between the blinds and adjacent window panes. The software can also model double-skin façade systems with air circulation between glazing layers.

An example steady-state heat balance equation for the first pane of glass on the double pane-window in Figure 8 is given as

(2) $$Q''_{solar}(\alpha_1 + \tau_1\rho_3\alpha_2) = \frac{T_1 - T_2}{R} + (T_1 - T_{out})(h_{c,out} + h_{r,out})$$

where α, τ, and ρ are the absorptivity, transmissivity, and reflectivity, and subscripts represent glass surfaces numbered from outside to inside. T_1 and T_2 are the temperatures of panes 1 and 2 respectively. Q''_{solar} is the component of incoming solar-thermal energy incident on the glass surface in W/m^2. Heat balance equations for the other nodes take a similar form.

The spectral properties vary with angle of incidence and Fresnel relations are used to account for this variation. Visible light and solar-thermal radiation are treated independently allowing the simulation of spectrally selective glass products. Properties for α, τ, ρ, and emissivities of the various glass coatings were obtained from the ASHRAE Fundamentals 2001.

A linearized model for generating a radiation heat transfer coefficient between bodies is used:

(3) $$h_r = 4\varepsilon\sigma\left(\frac{T_{body1} + T_{body2}}{2}\right)^3$$

where ε is the effective emissivity. Values for h_r are recomputed hourly to reflect variations with temperature. Internal and external convection heat transfer coefficients are assumed to be 4 and 14 W/m^2-K, respectively, reflecting an average between winter and summer conditions. The "R-" value represents the thermal resistance of the window pane, and is computed with a 1-D transfer model according to the surface emissivities, gap and pane thicknesses, and conductivities of glass and air.

Once the temperature of the inner-most surface is determined, we compute the heat flowing from that surface into the room as:

$$\text{(4)} \qquad \frac{Q_{window}}{A_{window}} = (T_2 - T_{room})(h_{r,in} + h_{c,in})$$

Losses or gains through the window frame and insulation are computed in the same manner, with window frame U-Values assumed to be 4.2 W/m^2-K. An area-weighting is used to determine energy flow into the room:

$$\text{(5)} \qquad A_{envelope} Q_{envelope} = A_{window} Q_{wndow} + A_{frame} Q_{frame} + A_{ins} Q_{ins}$$

Thermal mass

The thermal mass is structured as a block of concrete that covers the entire floor area of the room. Solar thermal energy that is transmitted directly through the window unit is assumed to be absorbed entirely by the surface layer. In the double-pane case this amounts to:

$$\text{(6)} \qquad Q_{thermal\ mass,in} = A_{window} Q''_{solar} (\tau_1 \tau_2)$$

Temperature variation in the vertical direction of the thermal mass is considered by slicing the mass into many horizontal layers. Heat conduction through the concrete is balanced with radiation and convection at the surface, and the temperature of each layer is computed every hour in the same manner as the window exchange described above.

Ventilation

Ventilation is required to maintain safe levels of fresh air for the building occupants. Mass flows of air continuously move heat into and out of the room. When outside air is at a different temperature from the room, heat is lost or gained by ventilation. The energy exchange due to ventilation is computed simply as:

$$\text{(7)} \qquad Q_{ventilation} = \dot{m} C_p (T_{in} - T_{out})$$

with m-dot as the mass flow rate of air and C_p the specific heat of air. Air in the room is assumed to be well-mixed and at uniform temperature.

Heating and Cooling

Once all the heating loads are computed the software will calculate the expected end-of-hour room temperature by finding the net heat into or out of the room and adjusting the average room temperature accordingly:

$$\text{(8)} \qquad T_{room,new} - T_{room,old} = \frac{Q_{net}}{\dot{m} C_p}$$

The room temperature is then updated and the calculation repeated for the next hour. Upper and lower bounds on indoor air temperature are specified by the user. If $T_{room,new} > T_{max}$ (or $< T_{min}$), then some $Q_{heat,a/c}$ must be applied to keep the air temperature within the bounds. Finding the exact amount of heating and/or cooling energy requires a second iteration. The time during the hour at which the temperature reaches a threshold is determined, and the air temperature is then fixed at the threshold for the remainder of the hour, as $Q_{heat,a/c}$ is applied to maintain a steady energy balance.

Natural Ventilation

Air change rates for natural ventilation are predicted with a separate module that considers the size and geometry of the window openings and typical values of pressure coefficients for office buildings. Windows are opened and closed intelligently each hour based on the temperature of the outside air and the internal room temperature to achieve the most comfortable climate possible without mechanical assistance.

In the hybrid ventilated case, natural ventilation is supplemented with a mechanical system such that when the room gets too cold or too hot and the outdoor conditions are not helpful, the windows will shut and the mechanical system will use energy to make up the difference.

The energy displayed on the graphs in Figure 2 does not represent the heating, cooling, and lighting loads. Instead, it represents the amount of primary energy, or chemical fuel, required to meet these loads. For cooling energy, we assume a chiller COP of 3.0 operated electrically, and we include the conversion efficiency of chemical energy at the power plant to electrical energy at the building (assumed typical value of 0.30). Thus, if the cooling load were 1 unit, the energy required and displayed in the graph is 1/(3.0x0.30) or 1.11 units. For heating energy, we assume a perfect conversion of chemical energy into heat energy in the boiler plant – so the ratio in this case is 1:1. Lighting loads are converted into energy by the same power plant efficiency of 0.30, and fixtures are assumed to be fluorescent bulbs with a conversion efficiency of 0.135 W/Lumen.

Limitations of the model

Heat transfer between floors is neglected, and losses to the ground or the roof are not considered. This approximation is adequate for large, multi-storied buildings where the roof and ground perimeter make up a relatively small portion of the building surface area. For smaller buildings such as single story homes, this approximation may grossly under-predict heating or cooling loads. Future versions of the software will include roof and perimeters losses at the ground level.

We do not consider the energy required for dehumidification of the air in humid climates. This can add a substantial amount of energy (on the order of 40%) to the cooling energy required. Fan energy is also not yet considered.

Further documentation and extensive help-files are available online.

FUTURE WORK

We plan to add support for more detailed HVAC simulation, inclusion of ground and roof losses to the heat balance, and prediction of dehumidification energy in the future versions of this software.

We are now involved in model validation and will use calibrated simulations from industry accepted tools (DOE-2, Energy Plus, CAPSOL) to measure and compare results. Preliminary benchmarks using our window-solver have shown good agreement with ASHRAE values of U-Values and Solar Heat Gain Coefficients. Results of the validation will be made available on the web.

CONCLUSION

Buildings are responsible for a tremendous amount of energy consumption due in part to their long lifetimes and continuous operation. Efficient design is critical, especially at the early stages – as poor decisions made early become difficult or impossible to correct.

Existing energy simulation tools fail to meet the needs of architects and building designers at the early stages of design due to the excessive complexity of the tools and requisite technical knowledge.

The MIT Design Advisor seeks to meet this need by providing a fast, simple design tool to assist with the selection of appropriate building components and systems. Paramount to the success of this project are the simplicity of the user interface and the ease of comparing results, streamlining the process of rapid interaction toward improved design.

ACKNOWLEDGMENTS

Project support has been given by the Permasteelisa Group and by the Cambridge-MIT Institute. We would like to acknowledge the many helpful conversations with James Gouldstone and Matt Lehar, and the development of the natural ventilation flowrate model by Jinchau Yuan.

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