A SIMULATION TOOL FOR THE OPTIMIZATION OF ADVANCED FACADES

M.A. Lehar and L.R. Glicksman
Building Technology Laboratory, MIT, Cambridge, MA

ABSTRACT

We present a multi-purpose simulation tool designed to evaluate the energy performance of double-skinned façade systems in comparison with conventional windows. The method used for estimating energy consumption consists of two separate simulations, a heating/cooling energy model and an electric lighting energy model. The heating/cooling model is explained in this paper. The simulation program in which the model is embedded is designed to return results in real time, and contains engineering assumptions intended to make the interface simple for lay users to master quickly. Previous simulations of double-skin facades have generally focused on the local properties of the window, such as its U-Value and solar transmission, without accounting for the impact on the ventilation strategy of the building as a whole. This tool simulates the performance of DSFs in the context of a whole-building analysis.

INTRODUCTION

A need has been identified in the architecture and building industries for energy simulation tools that contribute effectively to the design process. The increasing number of building designs hailed as being "green," or "low-energy" are, in the vast majority of cases, never subjected to a rigorous analysis until they are already built or in the process of construction. It is very unusual for an architect to conduct predictive energy simulations during the preliminary, or "brainstorming" phase of a project. This is often due to the time and effort involved in running a simulation, including the construction of detailed mock-ups, the construction of finite-element computer models, and the hiring of legions of staff to conduct and oversee these operations. The commitment of resources is often so great that it cannot be justified except to demonstrate the merits of the final working design. The architect chooses among his early design ideas according to his intuition or his knowledge of precedents, and energy simulations that might support innovative approaches are left out until the design plan has become fixed.

The dependence of the building industry on precedent, as opposed to new research, as the deciding factor in the design of building systems is illustrated by the relative scarcity of double-skinned façade systems in North America. Double-skinned facades, or "DSFs," are widespread in Europe, but have yet to gain acceptance in the North American building industry, mainly due to the absence of precedents in the region. Though aware of the success of DSFs in Europe, American builders remain skeptical because of the belief that DSFs would not perform as well in an American climate. Computer models can provide convincing predictions of DSF performance in any climate, but are difficult to include in the design process of any given building because many parameters critical to the model may not have been fully agreed-upon during the initial design stages.

In recent years, the government has sponsored the development of computer programs, such as EnergyPlus, that provide customizable building energy models to assist designers. This software is capable of modeling energy consumption in buildings with high detail, accuracy, and flexibility. However, such tools are invariably complicated to learn and implement, require detailed information about building geometry and materials, and can consume hours of computation time before delivering results. As a consequence, designers tend to refer to such tools only at an advanced stage of design, by which point most of the decisions affecting a building's energy performance have already been made. To compound these problems, the details of a ventilated window technology, such as a DSF, would be particularly difficult to model realistically in most building energy software models.

To address the shortcomings of more cumbersome simulations, we have designed a suite of building energy simulators that model explicitly the individual components of a DSF. The simulations restrict flexibility in order to offer users greater ease-of-use and speed. A design tool that can be quickly mastered by non-technical designers, and that runs fast enough to allow them the scope to experiment with many different versions of a design during a single sitting, could prove useful at an early stage in the design process. By including a range of DSFs in the list of available façade simulations, we intend to provide evidence of the benefits of DSFs in the context of the user's particular building project.

SIMULATION METHODOLOGY

Input procedure

The layout of the web interface for the tool, called "MIT Design Advisor," is intended to be simple enough that a new user would not need to consult documentation in order to use it. Help files are nevertheless provided, and are accessible through information buttons located next to each of the input controls. The interface that confronts the user as the page opens contains the most rudimentary input controls. Users who wish to manipulate the simulations' more detailed settings may call up additional command windows as required. A user must specify, using input parameters, a room that is representative of his proposed building. However, in the program's simplest mode of operation, a user may select an "existing scenario" from a list of well-known energy-efficient buildings around the world, and all inputs will be set automatically to be consistent with the chosen scenario. The user can then change the building location to any city and study the performance of the façade in any orientation. This feature provides both an illustration of the program operation and a benchmark against which users may compare their own buildings.

Module design

The Design Advisor web tool is divided into three main modules: "Energy," "Comfort," and "Daylighting." Fig. 1 shows the flow of data as user inputs are entered into the web page, relayed to the simulation software, and finally output to these three modules, accessible through the web interface. The "Energy" module simulates exchanges of heat through the outer skin of the building, and shows yearly estimates for the required heating and cooling energy. "Comfort" is an addendum to the Energy simulation that presents information about the intensity of infra-red radiation that can be felt by an observer at various distances inside the room. "Daylighting" predicts the distribution of sunlight in the room, according to time of day and location, and calculates a year-long average of the amount of daylight projected onto work surfaces in the room. "Daylighting" then offers an estimate of the amount of electrical lighting energy required to make up for the lack of natural daylight in certain areas of the room. Since the software retains weather data for every hour of the year, in each of the cities where a user may situate his building, the modules are run on an hourly basis.

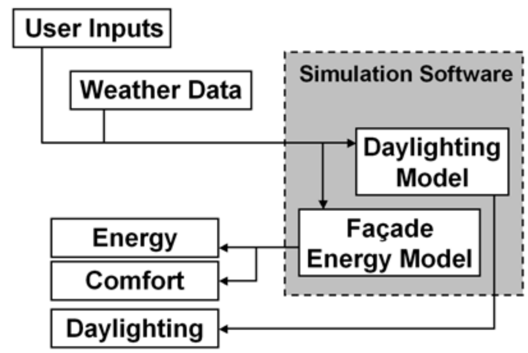


Figure 1. Organization of the web tool

This paper will discuss the general methodology for the "Energy" component of the web tool. A detailed explanation of the calculations used in the Energy module is presented in Arons. An overview is presented here, along with a discussion of the preliminary results from the simulation.

Façade Energy Simulation

To predict the amounts of heating and cooling energy that a building design will require, the simulation receives basic information from the designer, detailing room dimensions, orientation, location, internal loads, air-change rate, and façade typology. The web interface allows the user to choose from a selection of facade typologies, including both conventional and advanced window systems. The output that the user sees is in the form of monthly and yearly heating and cooling loads. Behind the interface, the loads are calculated using hourly weather data for the entire year. We simulate the conventional typologies (single-, double-, and triple-glazed) by representing the façade as a conduction resistance, or "U-value," in a thermal circuit. A solar heat-gain coefficient is used to model the attenuation of sunlight through a conventional window. Advanced double-skin facades, which incorporate a channel of moving air within the window, require a more complex model, accounting for both the movement of air within the façade and the thermal obstruction created by the blinds. In neither case does the simulation consider the heat capacity of the building fabric, so that there are no transient thermal effects: the simulation results for each single hour are completely independent of the results for any other hour.

The inside-ventilated DSF typology (Fig. 2) one of the façade types used in the simulation, is composed of a double-glazed unit on the outside, a single glazing on the inside-facing surface, a set of blinds in the narrow cavity between, and air circulating at a fixed flowrate through the cavity. The inlet and outlet for the cavity are not necessarily open to the interior space, as shown in Fig. 2, but may be connected by a duct to a central air supply. The components of the DSF are treated as separate objects by the program code, and may be easily rearranged to create other DSF typologies, like the examples in Fig. 6. DSF designs have either fans control airflow, or rely on natural convection. The present model is for the latter case.

In the inside-ventilated typology, the transfer of heat from the outside air (left side of Fig. 2) to the interior of the space is calculated by iteratively solving energy balances at 7 stations (nodes) for each of 20 different vertical positions ranging up and down the façade profile. The nodes correspond to the outer

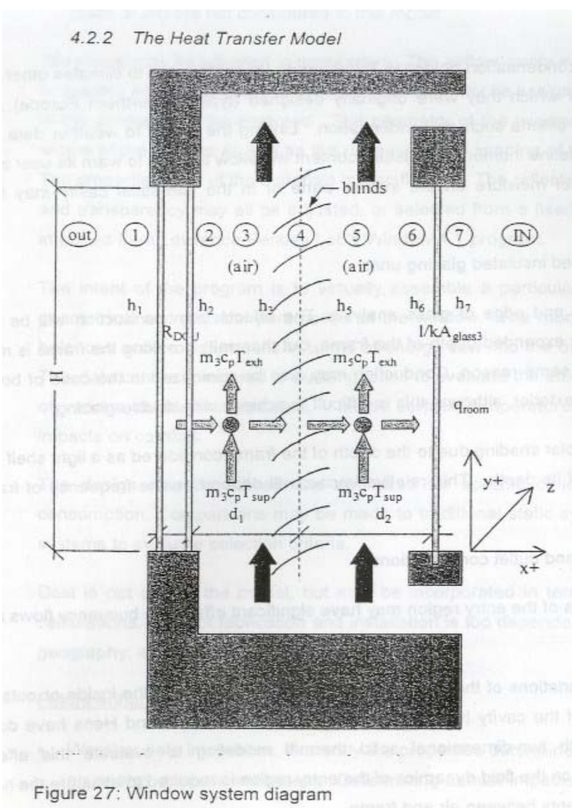


Figure 2. The inside-ventilated DSF system (illus. Dan Arons)

and inner surfaces of the double-glazed unit, the midstream position in the part of the cavity outside the blind-curtain, the blind centerline, the part of the cavity inside the blind- curtain, and finally, the outer and inner surfaces of the single glazing. Convective, conductive, and radiative transfers are taken into account. Infrared radiation exchanges are possible within the double-glazed unit, between the glass walls of the air cavity, and between each of the glass cavity walls and the blinds.

For radiation exchanges between the layers of the DSF, view factors are calculated between the participating surfaces. In the case of the air cavity, an exchange of radiation between the two glass surfaces of the cavity must account for the blinds positioned between them. To facilitate the calculation of the radiation exchange, the blinds and glass surfaces are assumed to be gray, diffuse emitters and reflectors with uniform radiosity over each of the surfaces. The upper and lower blind surfaces have the same temperature but unique values of the radiosity. In the most complicated case, in which the blinds are open, the heat transfer is developed from a model that considers a four-way radiation exchange among the two glass panes and both the lower surface of the blind above and the upper surface of the blind below each horizontal slice of the window where an energy balance is performed. Fig. 3 shows a resistive analogy for the 4-surface radiation exchange. "2" represents the outer surface of the air cavity, "6" represents the inner surface, and "4" is the blind layer, whose temperature is taken to be uniform for all blind slats. Radiosities r_{4_u} and r_{4_l} refer to the upper surface of the blind below and the lower surface of the blind above, respectively.

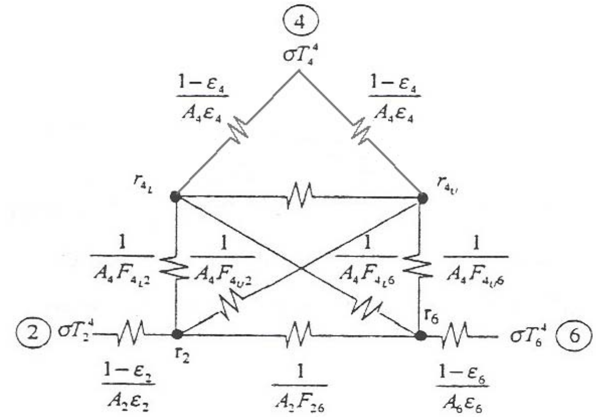


Figure 3. Resistive analogy for the 4-surface radiation problem (Illus. Dan Arons)

The view factors between the glass surfaces and the blinds were calculated for each blind angle by using the crossed-strings method. This assumes that the distance between successive blinds is small compared to the width of the DSF.

The infrared radiation within the DSF is obtained from the solution of four simultaneous equations for the radiosity of glass surfaces2, 6 and the upper and lower surface of the blinds, surface 4 in figure 2.

Each equation for the radiosity can be written:

$$(1)\ r_i = \varepsilon_i \sigma T_i^4 + (1-\varepsilon_i)\sum_{j=1}^{N} F_{ij} r_j$$

where N is the number of surfaces in the DSF. The equations can be linearized by linearizing the expression for T_i^4 around the mean temperature of the DSF. Define ΔT so that $T_i = T_m + \Delta T$. Then expand T_i^4:

$$(2)\ T_i^4 = T_m^4 + 4T_m^3\Delta T + 6T_m^2\Delta T^2 + 4T_m\Delta T^3 + \Delta T^4$$

When $\dfrac{\Delta T}{T_m}$ is much less than 1, this can be simplified using the definition of ΔT to

$$(3)\ T_i^4 \approx T_m^4 + 4T_m^3(T_i - T_m)$$

Rearranging,

$$(4)\ T_i^4 \approx 4T_m^3 T_i - 3T_m^4$$

Once the radiosities are found, the net radiative heat flux can be calculated as

$$(5)\ Q_i = \frac{\sigma(4T_m^3 T_i - 3T_m^4) - r_i}{(1-\varepsilon_i)/A_i\varepsilon_i}$$

Both temperatures and the radiosities at each of the nodes, including those within the air cavity, is then found by solving a matrix equation corresponding to the linear system of equations representing the energy balance at each slice of the window profile.

This re-phrasing of the radiative transfer expression makes it possible to include the node temperatures in a system of linear equations representing the energy balances for both conductive and radiative exchanges. For each node, the short wave solar radiation absorbed by that element is included as a heat source.

Because the air in the cavity enters at room temperature – different in most cases from the average temperature of both the blinds and the inside surface of the double-glazed unit, cavity air temperatures will vary continuously between the base and the top of the façade. To account for this variation, we carry out the heat transfer analysis described above at 20 separate elevations in each of the two air passages alongside the blinds. At each level, we calculate the amount of heat transferred to each air passage using the following formula:

$$(6)\ \Delta \dot{Q} = \Delta A_{slice}(h_{glass}\Delta T_{glass} + h_{blind}\Delta T_{blind}),$$

where ΔA_{slice} is the frontal area of the section ("slice") of the façade, equal to 1/20 times the total area; h_{glass} and h_{blind} are the convection coefficients with the outer and inner walls of the cavity, respectively; and ΔT_{glass} and ΔT_{blind} are the differences in temperature between the cavity wall and the previous cavity air temperature. To estimate h_{blind} when the blinds are open, correlations for air flow over a bank of cylinders are used.

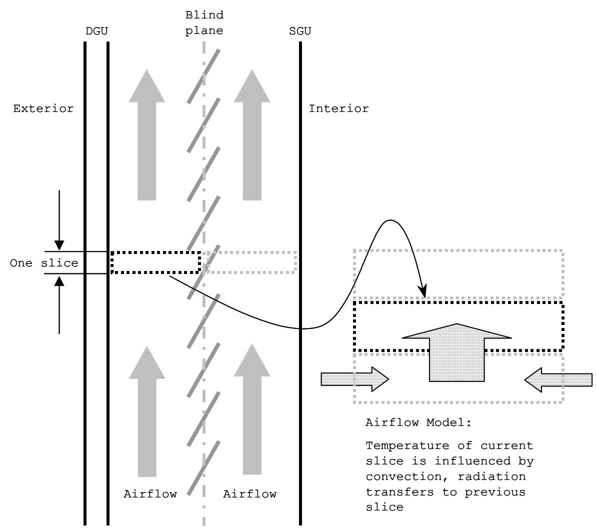


Figure 4. Iterative cavity air temperature calculation

The differential rate-of transfer, $\Delta \dot{Q}$, can be used to compute the differential change in cavity air temperature in the vertical (flow) direction:

$$(7)\ \Delta T = \Delta \dot{Q} / (\dot{m}_{air}\, C_{p,air}).$$

ΔT is now added to the previous cavity air temperature (the temperature of the air at the elevation of the slice beneath) to give the air temperature in the present slice. The procedure is shown schematically in Fig. 4.

Using this approach, we find the temperature of the air in the cavity as a function of preexisting temperatures, beginning with the temperature of the air at the cavity inlet. For each "slice," the cavity air temperature is taken as the air temperater entering the slice from below. The cavity temperature is not included in the set of unknowns that are solved for in the matrix equation. Instead, in the construction of the matrix equation $Ax = B$, in which x represents the vector of node temperatures and node radiosities of the façade components, the heat from the cavity air is included in the B vector, while the coefficients of temperatures of the other nodes reside in the A matrix. A determination of the cavity temperature at the present slice occurs immediately before each solution of the matrix equation.

An hourly history of the heat flow through the façade can be deduced from a complete knowledge of the temperature data at two neighboring stations within the facade. The total amount of heat lost or gained by the interior space is tallied, hour-by-hour, and the monthly and yearly totals are returned to the user. The lean calculation strategy allows users of the website to receive results within seconds of submitting inputs.

RESULTS

Results from the Façade Energy simulation were obtained using data available on the Design Advisor website. We examined five different window typologies: the four shown in Fig. 5, as well as a conventional double-glazed case with interior blinds but no air cavity, used as a control. The outside-ventilated window (Fig. 5c & d) is composed of a double-glazed unit on the inside, a single pane on the outside, and an air cavity between which contains the blinds. This is the reverse of the order of components in an inside-ventilated window, in which the single pane is on the inside (Fig. 5a & b). The building in our experiment has been modeled as a complete enclosure in which the only possible transfers of heat to the interior are (a.) through the facade and (b.) by the displacement of ventilation air. The building has a square plan and measures 12m on each side. It is composed of rooms measuring 2.8m along the façade and 6m deep, with a total room height of 2.7m (the number of rooms in a building need not be an integer in our model). There is no mixing of air between rooms. The depth of the air space in all ventilated windows is 145mm, and the flow rate of air through the cavity is maintained at 50 m^3/hr per meter around the perimeter. The glazing is clear glass, extending around the entire perimeter and from floor to ceiling, with no opaque section remaining. All windows are equipped with blinds, having an absorptivity of 0.3, which are set to close automatically when the interior temperature rises above 25°C, and which also remain closed during the night. Between the hours of 8 a.m. and 7 p.m., the building is occupied to a density of 0.10 persons/m^2, each assumed to generate heat at an average rate of 117 W, and heating from electrical equipment amounts to 3 W/m^2. Incandescent overhead lights are continuously adjusted to the minimum level required to maintain a light intensity of 500 lux in all parts of the building during business hours. An air change rate of 2.0 changes per hour has been assumed, and 2 cm-thick concrete slab floors serve as the building's only thermal mass. Latent heat is not considered in the analysis.

The performance of various window systems when used in the test building is shown in Fig. 6 for sites in London, Montreal, and Cairo. Previous experiments (Lehar and Glicksman, 2002) have indicated that building performance is relatively insensitive to changes in certain design parameters. Heating and cooling loads in double-skin windows typically depend weakly on the depth of the window cavity, provided that there is no reverse-flow through the inlet. The window type labeled as “DGU” (a double-glazed unit with blinds) is the control window in each of the three cities studied. The two separate inside-ventilated and two outside-ventilated types have been distinguished by the designations “in-out,” “out-out,” and so forth. The first word in the pair indicates whether the source of the cavity airstream is inside or outside the building envelope, and the second refers to the location of the cavity outlet (see profiles in Fig. 5).

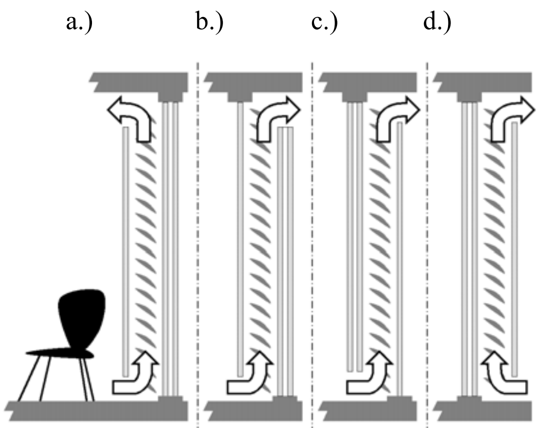


Figure 5. Four window typologies:
a.) Inside Ventilated (in-in)
b.) Inside Ventilated (in-out)
c.) Outside Ventilated (in-out)
d.) Outside Ventilated (out-out)

Cooling and heating loads are sometimes represented in terms of an enthalpy change in the room air. It will be noted that this is not strictly an equal basis for comparing real heating and cooling costs, since the required energy must be delivered to a heating unit in a different form from that used by a chiller. We have therefore calculated the loads in terms of the total quantity of fossil fuel that must be consumed for the heating or cooling operation. Heating represents a one-to-one conversion of chemical energy to a change in room air enthalpy by combustion in the plant furnace. Cooling requires a conversion from chemical to electrical energy (where we have assumed an efficiency of 0.3), then from electrical to a resulting change in room air enthalpy (with a COP of 3 for a typical chiller unit). The cooling load represented in Fig. 6 is actually greater than the attendant change in enthalpy by a factor of 1/(0.3x3), or 1.1.

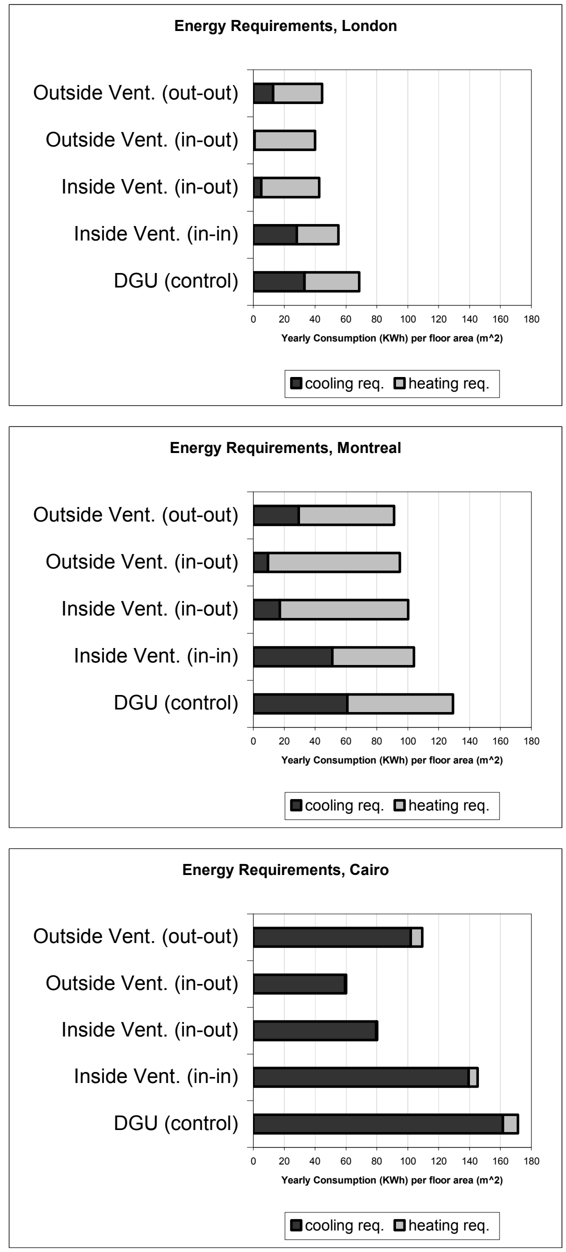


Figure 6. Heating and cooling loads for identical buildings situated in London, Montreal, and Cairo

Two of the window typologies considered are designated “in-out,” meaning that the cavity air originates inside the room and is exhausted to the outside, the only difference being that one of these is outside-ventilated, with the air cavity on the outside, and the other, inside-ventilated. An “in-out” design requires that the cavity airflow rate be matched or exceeded by the rate at which exhaust air would otherwise be removed from the room. If this is not the case, the energy cost increases due to the need to bring in and condition air from the outside to meet the higher air-change requirement. All such "enthalpy" loads are accounted for in our model. This consideration also applies to the "in-in" typology, in which the room air experiences a change of enthalpy as it is cycled through the façade and returned to the room.

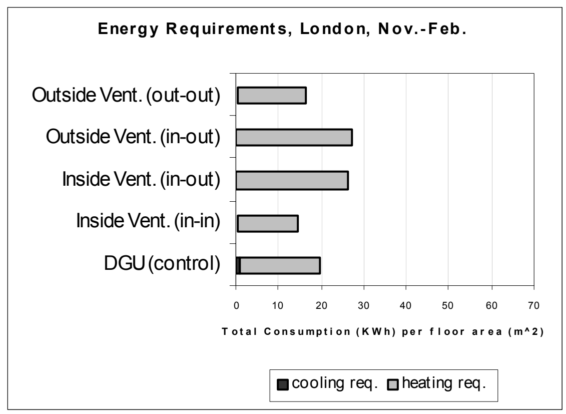
DISCUSSION OF RESULTS

Cross-ventilated typologies, in which the cavity air originates within the building and vents to the outside, generally outperform the sealed enclosures. This is quite understandable during the cooling season, when the outside temperature is high and the blind temperature within the cavity still higher because of solar heating. In this scenario, chilled exhaust air from the room will lower the cavity temperature more effectively than the warm outdoor air, making an "in-out" ventilation path preferable to an "out-out" one. During the shoulder seasons, when outdoor temperature is lower than indoor, most of the cooling load can be attributed to solar heating of the blind surfaces. In this case, however, cavity air from outside the building will lower the blind temperature more than exhaust air at room temperature, and an "out-out" typology is preferred. During the heating season, the advantage of an "out-out" typology is even more pronounced. Fig. 7 shows heating and cooling loads for all typologies, during the winter months from November through February only. The significant gains in heating efficiency from using an "out-out" venting strategy are mainly due to the additional air-change load that the "in-out" strategy imposes on the building. The rate of intake of air required for 2 air changes per hour is 1555 m^3/hr. for our building. The rate required to supply air to the "in-out" windows is 2400 m^3/hr., leaving a deficit of 845 m^3/hr. In our model, the air change rate is automatically changed to make up the difference, so that the original rate of 2 air changes per hour is increased to 3. The higher heating load for the "in-out" windows in Fig. 7 is due to the greater volume of cool air from outside that must be heated as it is brought into the building.

When the performance over the entire year is considered, the outside-ventilated façade type, in which the window blinds and air cavity are positioned outside the insulating double-glazed unit, shows the best overall performance in our tests (Fig. 6). The best choice of outside-ventilated strategy, whether "in-out" (cross-flow) or "out-out" (single-flow), depended on the time of year. Specifically, a large difference in temperature between the outside air and the room air tended to compromise the efficiency of a cross-flow strategy. Ideally, the window would be able to function in either state, cross-flow or single-flow, depending on the seasonal requirement. To switch from one state to the other, the outlet air could be diverted by an operable flap. If we assume that such a system is used, and allow the state of the window to change from one month to the next, we achieve the optimal efficiency shown in Fig. 8, and labeled "Outside Vent. (out-out winter, in-out summer)." As shown, we found that the year-averaged efficiency of the window could be improved by an additional 25% by allowing the flexibility to switch from one mode of ventilation to the other.

CONCLUSIONS

Existing energy prediction software is not sufficiently detailed or accessible enough to architects to provide useful advice on the potential benefits of double-skin façade systems. The MIT Design Advisor web tool aims to address this shortcoming by offering a rapid simulation of façade performance that is tailored to the individual circumstances of each building to be tested.



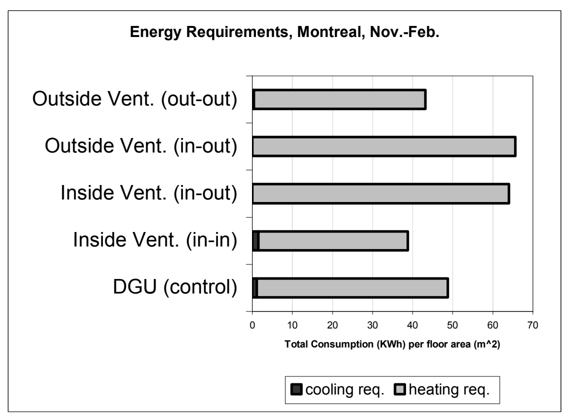
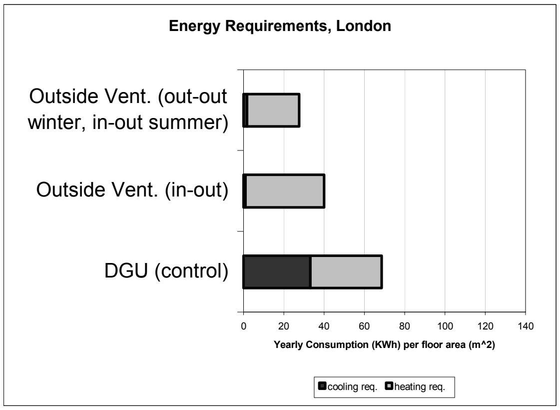


Figure 7. Heating and cooling loads for November through February only



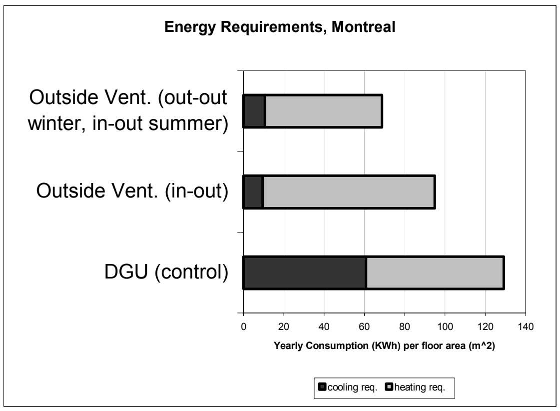


Figure 8. The outside-ventilated (in-out) typology gives the best overall result, but could be improved by adding the facility to switch the direction of the exhaust air, effectively turning the "in-out" window into an "out-out" window during certain months of the year

The outcomes of preliminary tests using the Design Advisor indicate that double-skin windows can significantly improve the energy performance of buildings when under the strict control of automatic systems. To allow DSFs to achieve their optimum efficiency, building managers must allow window blinds to be closed partially or completely during business hours, and room air change rates to be set according to the demands of the façade system. Double-skin facades can be made more effective at reducing cooling loads than heating loads in most locations.

REFERENCES

Arons, D. "Properties and Applications of Double-Skin Building Facades" MIT Department of Architecture, 2000.

EnergyPlus. Created and distributed by the U.S. Department of Energy. http://www.eren.doe.gov/buildings/energy_tools /energyplus/

Lehar, M.A. and Glicksman, L.R. "A Simulation Tool for Predicting the Energy Implications of Advanced Facades" MIT Building Technology Division, 2002. In *Research in Building Physics*. Jan Carmeliet, Hugo Hens, and Gerrit Vermeir, Ed. A.A. Balkema. Lisse: 2003.

MIT Design Advisor. http://designadvisor.mit.edu/