Physical Model and Control Application to a Smart Façade Demo Unit (SFDU)

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INTRODUCTION

Smart façade components with embedded adaptive control systems based on real-time optimization offer the potential to save energy. These control systems enable the building to dynamically react to real-time environmental input data. They can also take optimal control actions, given a set of occupant *preferences*, which are, at this point, limited to physical indoor environment variables such as thermal comfort, lighting and views through the transparent parts of the building envelope. Since the building envelope plays such an important role in the lighting and thermal regulation of the interior spaces, it is obviously the most suitable choice for the location of active control systems. There have been a number of studies that dealt with the potential energy savings of smart façade components (Ripatti 1984), (Barakat 1987), (Haddad et al. 1998, 1999), (Jones and Messadi 2000) and (Saelens and Hens 2001.) However, none of these studies addressed the application of optimal control to increase their performance. The falling costs and the higher stability of control technologies (sensors, actuators, active controllers) have rekindled interest in their incorporation in building enclosures.

Especially in Europe, experimental façade component technologies have received considerable attention as of late, both in new constructions as well as in refurbishment of buildings. The introduction in the US has not taken off, but research efforts are ongoing to study and optimize different variants. Slow introduction might be the result of a conservative industry waiting for proof that these systems perform in actual settings. That is why this research concentrates on deployment and prototyping in an actual setting, thus giving owners the chance to monitor and interact with the system in real life settings.

Past research (Lee et al. 1998) has also shown that an important aspect of any control strategy should be to allow the occupant to override the automated operation of the façade component at any time. In normal operation, the user is not attentive to the environmental variations and leaves operation to the automated system. At other instances, the occupant might want to override the system because of special preferences or in case indoor conditions are not to the user's satisfaction despite the fact that the system tries to reach an optimum comfort state (light and heat) at all times.

VENTILATED DOUBLE PANED FAÇADES WITH CONTROLLABLE LOUVERS

In the following sections, we lay out the progress made in the all-glass double façade systems, and highlight the attempts made in previous studies to model their inherent thermal dynamics which are considered essential in the formulation of a control strategy.

The application of glass in building envelopes procures the benefits of daylight penetration and the psychological connection to the outside but also exaggerates the heat loss and gain. In particular, the sash window type further aggravates the sick building syndrome. In the face of these challenges, major research was undertaken to develop energy efficient glazing and to promote efficient ventilation systems through the building enclosure.

The recent efforts have led to the development of a more sophisticated façade system that combines both mechanical features and architectural systems to reduce the energy consumption by means of its active operation. In fact, the all glass double façade system is the birth child of an earlier system known as the *airflow window* which consists of a ventilated cavity held within two glass panes to address the old problem of minimizing the energy load. Such windows originated in Scandinavia, where a related patent was filed in 1956. The first-large scale installation dates back to 1967 when the city of Helsinki used *airflow windows* designed by the EKONO Company, in its Building Department Offices (Brandle 1982.) With the energy crisis of 1973, the savings potential of these systems has resulted in many applications: mostly in office buildings. The first *airflow windows* in the U.S. were installed in 1980 in an office building in Portland, Oregon (Ripatti 1984.)

The recent increase in the number of buildings designed with the double skin façade system is quite evident in Europe. The 'Commerzbank Headquarter', Frankfurt by Sir Norman Foster, La Cité Internationale de Lyons, Lyons, France, the Ludwig Erhard Haus in Berlin, Germany, by Nicholas Grimshaw and Partners, and the RWE AG, Essen, Germany represent few of the well known buildings.

The existing typologies of double-skin enclosures are quite extensive (Compagno 1995), (Wigginton et al. 2001), ranging from the famous Trombe Wall to the latest smart façades. However, the summary of previous research relevant to our investigation is limited to the double paned glass systems with ventilated cavity such as the *ventilated double glass façade* and the *double glass airflow window.*

Airflow Windows

In the existing literature, distinction is generally made between the natural and forced ventilation façades (Saelens and Hens 2001.) However, it is conceivable to accommodate, in many *airflow windows* operation, both natural and forced ventilation. For the sake of clarity, in natural ventilation, the air motion is induced by thermal buoyancy and air pressure difference while in forced ventilation, the mass flow is assisted via a cavity located fan or the HVAC systems blower. Furthermore, the forced ventilation may not necessarily be achieved through physical connectivity to the HVAC system, as that shown in Figure 1.c, but could well be through separate systems that are controlled in an integrated fashion through pressure variation. Although the façade is not physically interacting with the air flow of the HVAC system (these air flows will be very moderate in comparison to forced mass flows), the control of the smart façade will be dependent on the control state of the HVAC system at any particular time. Some findings from previous studies on the performance of three types of windows with forced air flow regime in the cavity are discussed below (Figure 1.)

The '*exhaust airflow window system*' (Figure 1.a) allows the indoor air to flow through the cavity and into outside. In the cooling season, the air flow helps reduce the cooling load when the heat picked up in the cavity is discharged outside. In the heating season, the exhaust air flow helps reduce the transmission loss through the fenestration. In addition, the exhaust air flow helps maintain interior glazing temperature close to the room temperature, resulting in better comfort (Haddad et al. 1998.) Mueller (1984) tested in the laboratory ten different types of *exhaust airflow windows* by changing height of window, pane distance, external glazing and shading device (vertically laminated louvers and roller blinds), etc. He found that the interior glazing temperature does not differ more than *5°C (9°F)* from room temperature during extremely chilly winter days. According to his research, the solar heat gain coefficient of this type of *'exhaust airflow window'* is extremely low, between *0.1* and *0.2*, which can be achieved with conventional windows only by means of external solar control devices.

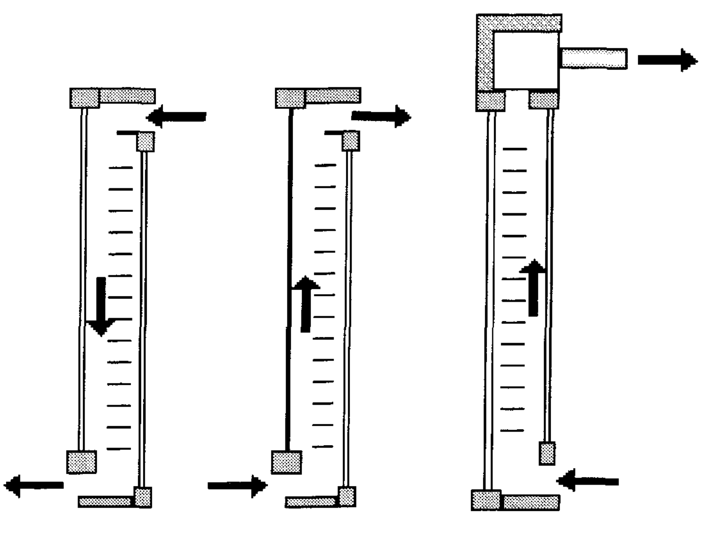


Fig. 1. Three Types of Airflow Window Systems Tested by Barakat (1987)

The *'supply airflow window system'* (Figure 1.b) allows outdoor air to flow through the cavity and into the room. This system helps reduce the heating load when heat picked up in the cavity flows into the room. In addition, the outdoor air satisfies the fresh air requirement of the space. Haddad et al (1998) developed a computer program to simulate the performance of a conventional triple-glazed window and the *'supply airflow window'* in the cold climate of Ottawa, Canada. They found that in the cooling season, the supply air window may increase the cooling load when the heat picked up in the cavity is delivered to the space. But, the *'supply airflow window'* led to higher monthly net heat gains, especially during the winter when it is the most beneficial. This increase is due mainly to a reduction in the conductive heat loss rather than an increase in the solar heat gain. Their results also support the fact that the *'supply airflow window'* can be employed continuously to satisfy the ventilation requirement of the space with a small penalty for cooling during the summer.

Barakat (1987) performed an experimental study to assess the performance of the *'supply air window'* during the heating season in Ottawa, Ontario, Canada, by comparing it to conventional double and triple-glazed window. Barakat found that the *'supply air window'* recovered 50% of the energy required to heat the ventilation air. Overall reduction in purchased energy compared to a double glazed or triple glazed window was 25% and 20%, respectively.

The third type is the *'return airflow window system'* (Figure 1.c) which allows indoor air to flow upward through the cavity and then return via a duct system to the central HVAC equipment. Ripatti (1984) used the TRNSYS-E program to evaluate the performance of the *'return airflow window system'* at three different locations in the United States (Fort Worth, TX, Columbia, MO, and Madison, WI. Each location represents a particular climate) and simulation results have shown that the thermal performance of *'return airflow window systems'* is superior to that of a double insulated window.

All-Glass Double Façades

The thermal behavior and expected energy savings from the all-glass double façade systems depend on many variables. The properties of the glass, the shading element and their geometric relationship with the sun are very influential. Furthermore, the size, location and setting of vents relative to the neutral pressure level, climatic conditions, wind speed and direction are also aspects to take into consideration. The interactions among these variables induce a great deal of uncertainty for the behavior and performance of these systems.

In naturally ventilated double skins, models to determine the expected thermal buoyancy and wind pressure throughout the cavity are very complex for both downward and upward flow. In addition, the specific application of operable horizontal louvers inside the cavity further complicates the proper modeling of the air flow rate and heat exchange within the cavity. There are few serious studies that have attempted to model the overall amplitude and direction of the air flow in a naturally ventilated envelope (Faist 1998), (Jones et al. 2000), (van Paassen et al. 2000), (Todorovic et al. 2000) and (Saelens et al. 2001.)

The findings from these studies are generally experimentally derived using procedures for thermal buoyancy (Andersen 1995) and (Li et al. 2001). Wind pressure differences are usually calculated from pressure coefficients (C_p values). Only Zhang et al. (1989) and Li et al. (2001) developed CFD-models to determine the mutual effect of wind and thermal buoyancy.

The numerical study by Todorovic et al. (2000) shows that during the cloudy condition of winter months the cavity temperature in their double skin façade gets 6-8 °C (10.8-14.4 °F) higher than the outdoor temperature when the vents are closed. The temperature of the cavity can be 10-12 °C (18-21.6 °F) higher during the clear sky condition. Furthermore, they conclude that the double skin façade can reduce by more than 50% the heat losses during winter months because the un-vented cavity acts as a buffer that can reduce the temperature difference between the inside and outside, and thus reduce the heat transfer. They also found that in midseason and if un-vented, the cavity temperature can be higher than that of the inside due to the solar radiation heat build-up. In summer, however, the cavity temperature can be higher than that of the inside due to the solar radiation heat build-up. They, thus, conclude that though, in the summer, the clear glass installed in the double skin façade allows a lot of solar gain passing through, the heat on the glass can be removed via the convective heat exchange caused by the stack effect within the cavity. However, in winter season when heat is needed, the heat build-up in the cavity due to the solar radiation can be circulated into the occupied space to reduce the need for electric heating.

Air Cavity Proportions

With respect to the proportion of the air cavity in the double façade, simulation studies conducted on a proposed retrofit, with such a system, for the four-story ZTL Engineering School Building in Luzern, Switzerland, produced some interesting results. In reviewing the output from the COMIS-TRNSYS simulation software (2001), the authors conclude that the stack ventilation of the double skin façade may not always be thermally beneficial. Particularly, if there is some leakage of the built-up hot air into the occupied space at the uppermost floor, overheating and low air quality may result. Hence, this study suggests that such problems might be avoided by raising the neutral pressure plane that can be accommodated by increasing the height of the outlet shaft above the roof level. In addition, they recommend a maximum cavity height of three to four stories.

Louver System Modeling

In a number of studies, the analytical modeling of the louver systems has been successful for a cavity-installed blind (fixed and operable) as it is impacted by the solar radiation and interreflections. These studies were concentrated on modeling the solar radiation transport through the slat-type blinds and the interaction between the diffuse or purely specular blind and the glass (Bilgen 1984), (Rheault et al.1987), (Talmatamar et al.1995), and (Cho et al. 1995.) From recent studies, the combined effects of the reflection from real surfaces that contain the mix of specular and diffuse reflection were adequately developed (Pfrommer et al. 1996).

DESCRIPTION OF THE SMART FAÇADE DEMO UNIT (SFDU)

In this work, we begin with the investigation of a naturally ventilated active envelope, which is developed to allow air flow through cavity by thermal buoyancy and wind pressure difference. This natural flow implies that air can circulate according to the dampers setting, i.e., closed or open, all depending on the weather conditions and the fresh air intake option. While we also recognize that natural flow may not always be as effective as forced ventilation because of changing weather conditions and wind patterns, the installed inlet/outlet *airflow dampers* will help control the venting of the cavity. Obviously, later research is planned for the integration of the SFDU with the HVAC systems, but for now the interest is focused on understanding the basic science of the airflow within the cavity.

The Smart Façade Demo Unit or SFDU, as it will be referred to, represents the adopted prototype that we consider in this two-track research. For the first track, the emphasis is put on the thermal behavior of the double skin glass façade under natural conditions. In the concurrent second track, the optimized control and operation of the unit is undertaken, as explained below. Forced air through the cavity is not being considered at this time, the natural flow of air is controlled via the active operation of the dampers, and the sun mediation by adjustable louvers.

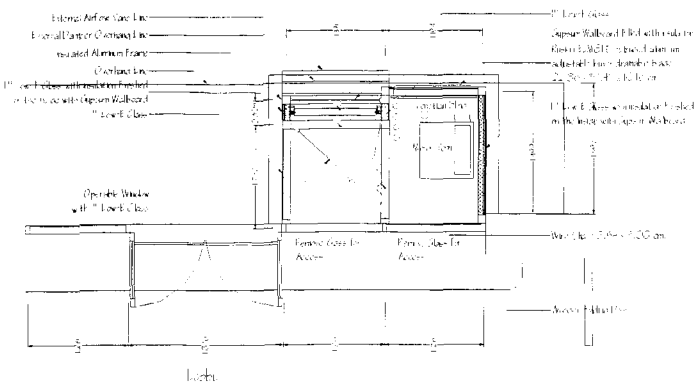
The unit, conceived for these purposes and shown in Figure 2, measures *3.05 m (10'-0")* high, *1.19 m (46.85")* wide and *0.20 m (8")* deep. The aluminum-built SFDU is currently under construction, and soon to be attached to the south wall of a building in a university campus.

This demo unit consists of a glazed, double-envelope system with both outer and inner layers made entirely of *25.4 mm (1")* thick low-e glass panes, each held within an aluminum sash. Electronically controlled ventilation grilles are incorporated at the top and bottom of each glass layer for ventilation purposes (Figure 2.) A *90 mm (3.5")* wide airfoil louver system is installed within a *0.2 m (8")* deep cavity, and at *38 mm (1.5")* away from the inner glass layer.

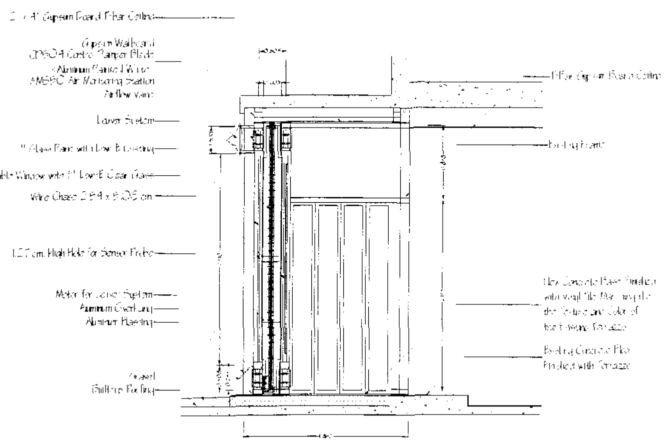
The four *airflow dampers* contain blades of an airfoil profile that is more aerodynamically efficient than the traditional flat ones. In fact, the airfoil blade has 1/4 to 1/10 less pressure drop across, compared with the traditional damper design (Kitchen, et al. 1978). Moreover, the inner glass window is operable, which also allows easy access for cleaning or hardware maintenance.

A wind scoop is placed on the outside at the exit of the upper damper. It functions as a vane that protects from the rain and the wind pressurization. The wind scoop blocks out the wind and prevent the equal pressurization by the wind that enters from the top and bottom dampers. Furthermore, the wind scoop helps create the negative pressure that attracts the air flow from the cavity by changing the direction of the wind or establishing positive pressure. In addition to the wind scoop, at the exit of the lower outside damper, an overhang is installed above the lower damper to prevent the water penetration.

The SFDU is fitted with wire channels for data acquisition and controls. The unit's sensors and motorized actuators are directly linked to a data collection and control system as will be explained in the next section. Although most ventilated cavities use roller blinds to minimize internal air flow turbulence (Mueller 1984), the decision to install horizontally laminated louvers was driven by the necessity to maintain visual comfort, i.e., connection to the outside.



a) Layout of SFDU Set-Up



b) Section Through SFDU (Drawings by Mate Thitissawat, Ph.D. Student)

Fig. 2. ACAD Drawings of the SFDU Currently under Construction

STATE MONITORING AND CONTROL ARCHITECTURE OF THE SFDU

In order to apply the SFDU in any local setting, a flexible architecture of the monitoring and control system is important. Therefore, special attentions have been given to the way the sensors and actuators can be pre-wired in the factory, in order to enable a plug and play type of installation on site. An important requirement was that the system should provide the opportunity to be monitored and controlled remotely, i.e., 'anywhere, any time'. The last requirement is met by equipping the system with a local computer station that is connected to the Internet. The computer runs as a server that can be accessed from anywhere using only a standard web browser. The total architecture is explained in detail in Figure 3.

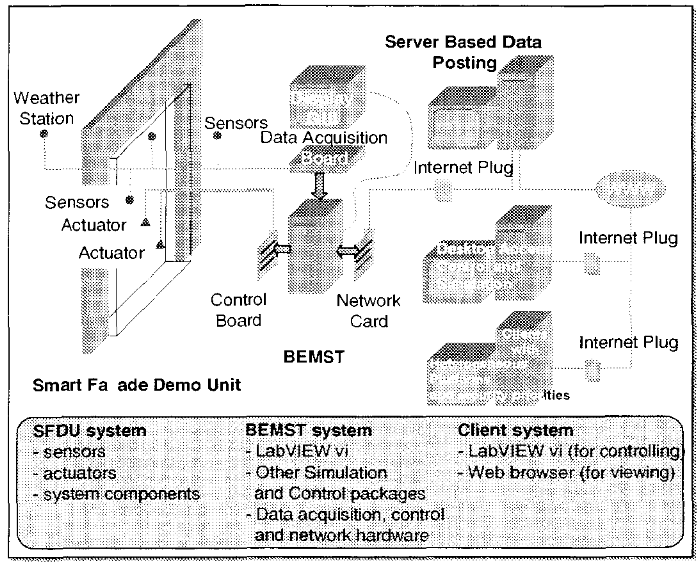


Fig. 3. Architecture of the Complete System

The physical state of the unit is monitored by a set of factory installed sensors that measure radiances, mass flows, temperatures, etc. The data is automatically sampled by a local monitoring unit and logged on the local data logging station, the Building Environmental Monitoring STation (BEMST). An important function of the BEMST (Figure 4) is to operate as a gateway between the data collection and a web hosted server of the data. In the current prototype these functions are actually combined into one computer which comes as an integral part of the BEMST.

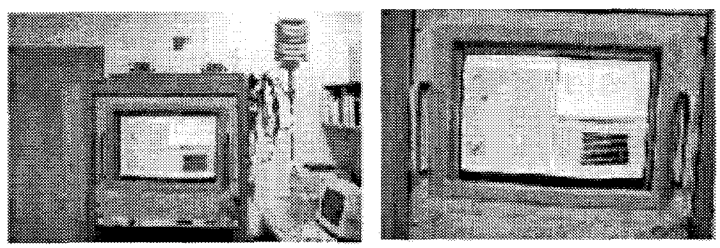


Fig. 4. Front View of the BEMST Showing Direct Data Output

The BEMST is a unit that can be brought on site and connected to the Smart Façade Demo Unit. With an Internet connection, the data recorded by the BEMST are sent to the server.

The BEMST is equipped with a number of sensors hooked up to the outside weather station. The connection boards for the sensors in the SFDU are pre-installed and calibrated and need only to be connected to the unit after installation. The various sensors include those of solar radiation, light levels, humidity, temperature and air velocity/direction. The BEMST is also featured with a data acquisition system comprised of a

CPU, two input/output cards, and the data sampling software. In addition, it contains a variety of probes capable of monitoring, in a time series, the various environmental parameters.

The controllable parts of the SFDU are operated by a set of controllers that actuate the state of the smart devices; each actuator transmits its state to the web server and accepts commands from a local control algorithm. Users with appropriate user privileges can override the local algorithm and manually control the device from anywhere in the building through a standard browser.

A vital part of the data architecture is the web-enabled access to the façade-unit. This permits any local or remote user with the correct permissions to monitor sensor readings and control actuator values. A server collects the sensor data from the BEMST and serves this data real time on a web page. The same logic is accomplished for the control of the unit, by giving a user access (through a browser client) to the current actuators values and allowing their remote control through a web interface supported on the server. Obviously, the unit must allow user intervention, and should thus have an embedded control component that continuously monitors the unit and adjusts the control parameters unless a user takes over and issues an adjustment that overrides the suggestion by the embedded control unit.

The active connection between the unit sensors and actuators is accomplished through the data channeling software running on the BEMST. In the present prototype set-up, the monitoring station is a prominent stand-alone component, which in future applications would obviously be minimized and integrated in the building energy management system.

BENCHMARK OBJECTIVES AND STRATEGY

The target of benchmarking the SFDU is to create awareness of smart technologies, improve and fine tune the technology based on deployment in real life circumstances and with real occupants. At the same time, it allows a continuous improvement of the underlying simulation models that are being developed and refined through an extensive calibration based on the observation of gathered data. Ultimately, the improved model will increase the confidence in the simulation of design improvements, and especially in the control strategies that we optimize using these simulation models.

Another major benefit of the benchmark is the verification of the 'objective function' (usually called 'cost function' in the mathematical formulation) that is used as the target for the optimal control algorithm. The objective function is a weighted mix of different targets, i.e., maximum reduction of heating and cooling demands, optimal natural lighting conditions, maximum reduction of electrical lighting hours, maximum thermal comfort and maximum view performance to the outside. All of these different targets need a careful inspection and definition. The control algorithm will then use a strategy to issue a control action that maximizes the weighed sum of all of these targets at any time. There is hardly any research available relating different occupant preferences for these multiple (and usually conflicting) targets to occupant tasks, gender, etc. In the benchmarks, occupants are given two modes of access to influence the control actions, i.e., 1) manual overriding, as explained above, 2) through the specification of occupant particular preference profiles. All user actions in both categories will be monitored during the benchmark leading to new data on the type of interaction that occupants prefer, depending on the kind and duration of task performed in the internal space. This will lead to a better understanding of individual preferences and how often they are changed as more experience is gathered with the operation of the smart façade. These occupant centric issues will be the target of the next stage of the research.

In summary, the benchmark serves the following purposes:

- study the performance of the system under a range of weather conditions, and refine the simulation to accurately predict its behavior
- detect flaws in design and operation of system
- design an optimal control strategy, that can respond to user defined preferences between multiple, and possibly conflicting system and occupant objectives
- simulate local occupant intervention and study ways in which user and control system interact
- evaluate user satisfaction with the system through post occupancy evaluation (POE)
- showcase the remote access to the unit operation and state inspection; and involve the building services engineers in fine-tuning the unit control and operation through this novel interface

CONTROL AND SIMULATION ASPECTS

The behavior of a building envelope results from a complex interaction of its passive and active systems, exposed to changing external and internal boundary conditions and subjected to control actions, generated by the autonomous goal searching algorithm of the control system or by non deterministic user interactions with the system. The complexity is further increased by the fact that the control algorithm has to respond to changing occupant preferences and also has to be able to recover after a manual intervention by the occupant. We are thus confronted with a complex physical system (nonlinear and time variant) with a super imposed control 'agent' that has to perform multi aspect optimization in order to determine the next control action.

This study is carried out using a simulation approach that is adequate to describe complex interrelations and control aspects of interacting building systems. The basic simulation engine of the toolbox is based on a semi discrete finite element space discretization of the mathematical physical description for each component resulting in a set of differential/algebraic equations (DAE). The size of the resulting system of equations is dependent on the granularity of the discretization. For this reason different models with different granularity have been developed and compared. It was found that the lumped model depicted in Figure 5 performed adequately in most circumstances, provided the set of lumped parameters are calibrated from experiments on site, i.e., in the actual local conditions. The lumped system contains 5 nodes as shown in the figure.

This work which includes the formulation of the mathematical model and a novel self- calibration procedure will be addressed in another publication.

However, based on the global system of equations, the following studies were performed:

1. Identification of the (minimal) set of suitable control parameters and the way the user should be given access to them, i.e., based on what subset of the observable state vector and based on what feedback to the user. This set consists of the two main control variables: ventilation regime *(u1)* and slat angle *(u2)*, depicted in Figure 6.

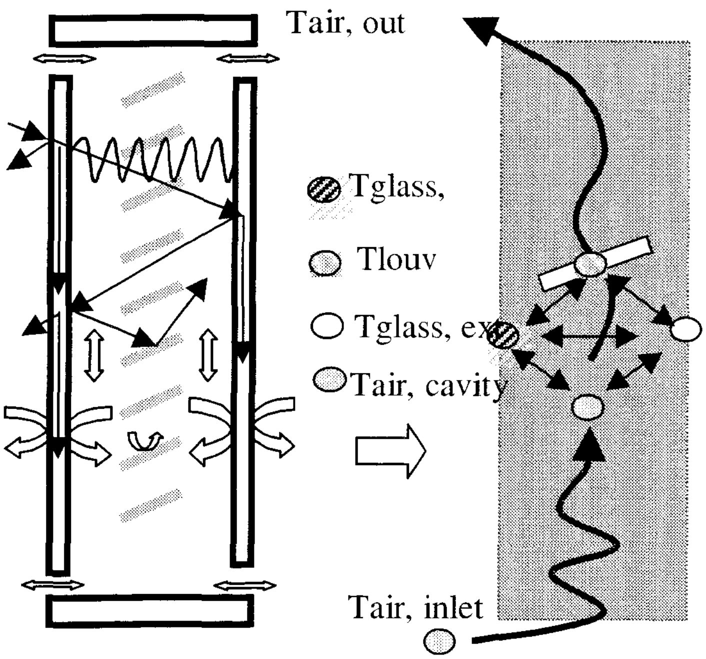


Fig. 5. Lowest Order Lumped Simulation Modelof Ventilated Double Façade

2. Stability and sensitivity tests of the system aimed at studying the response of the system to user interactions. This has led to a number of restrictions of the allowed user interactions and the frequency with which they may occur. This study is being continued for the current onsite deployment of the unit.

3. Assessment of overall energy efficiency of the system under different control strategies. A recent study by our research team shows that gains, as a result from optimal control versus an uncontrolled system for a standard winter and summer day, can be substantial. Overall efficiency increases from 0.5 to 0.7 in winter and an increase from 0.64 to 0.82 in spring/fall in the average Atlanta climate (Park 2001).

One of the priorities of the ongoing research is to verify that the predicted energy efficiencies can indeed be obtained in real situations, to identify the negative impact that occupant interactions may have, and to verify user satisfaction. Therefore, it is not sufficient to predefine control strategies. Rather, the system model needs to be part of a web based 'control center' so that, based on predictive state simulations, advice can be given to the user, informing whether the system is in near optimal state or needs adjustments. The next section provides an overview of these ongoing developments. The following section concentrates on the implementation of these interactions.

MODEL BASED CONTROL AND INSPECTION

As indicated above, the control unit is an important component of the system. Smart systems save energy by imposing a control strategy that is devised to be the most optimal under given conditions. Such a strategy could either be predefined in a set of fixed rules or could be determined at every time. The latter typically involves performing simulations on an embedded model of the unit leading to a choice of the next action based on the model predictions. This type of control is called model based adaptive control.

In the current phase of the research, different control strategies have been designed for testing in the onsite deployment. In the current set-up of the system architecture, the controller function is performed on the server by a software component. This component can either be a representation of a rule-based controller or a full-blown decision component driven by simulation predictions. Preliminary studies on predictive control have shown that the derivation of simple control rules is promising, but more tests and on site verification need to take place.

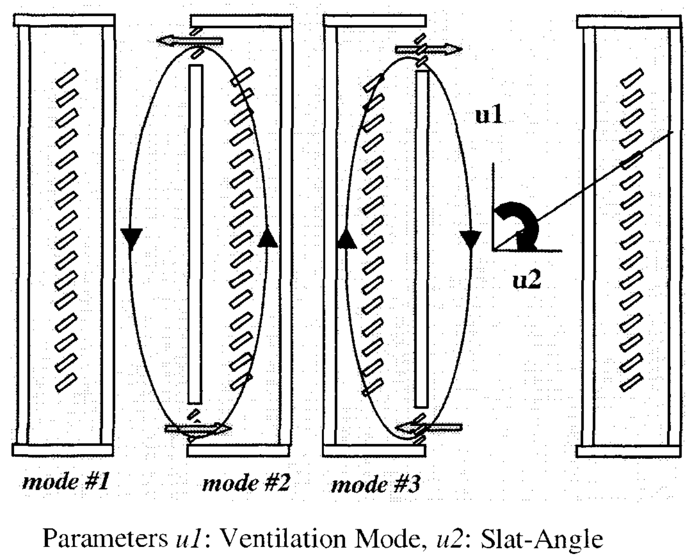


Fig. 6. Control Parameters: Ventilation Regime and Slat Angle

During the in-situ benchmarks, access to the state of the system and control parameters is accomplished in a straightforward manner. The BEMST data-logging component stores the data in a database that is accessible through a web interface. The screen output can be either tabulated or shown as a graph as in Figure 8. Moreover, both measured as well as simulated data can be shown in the same graph. This is very useful in the calibration stages when the comparison of actual and calculated data is to verify the correctness of the model in relation to the current external conditions. In the benchmark stages, it will also be helpful to have direct access to the model representation in order to track the way that the different components behave and the way that certain control rules are invoked. Figure 7 shows a particular implementation of a web based model inspection. It shows a MATLAB/SIMULINK representation of the lumped model that was developed, whereas Figure 8 shows an output window of a running simulation.

With appropriately chosen physical parameters, external conditions and control settings, the model simulates the state and control actions of the actual system in the measured external conditions. In the early stages of the benchmark, the model serves as an easy way for the developers to (remotely) detect anomalies in the system behavior and communicate these with the benchmark service engineers on site.

The purpose of the model is thus threefold:

1. to underpin model studies and test feasibility of smart components in some climate zones

2. to design a base control mode to operate the unit

3. to serve as back end simulation engine to determine control actions during operation

CONCLUSION AND FUTURE WORK

The main conclusion of the project is that the calibration and testing of a smart façade component can be performed on-site through rapid deployment of a configurable test unit which is built from a kit of parts and pre-wired with sensors and actuators. The unit is delivered 'Internet ready' which allows immediate testing to be controlled remotely. This approach enables a unique opportunity for manufacturers to undertake design refinements in parallel with actual onsite testing, circumventing expensive climate chamber experimentation. This is believed to be a big plus for the rapid introduction of experimental façade technologies on the American market.

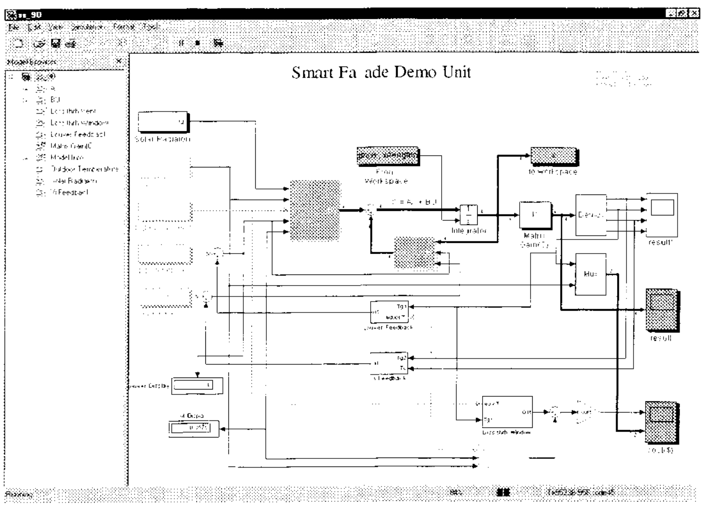


Fig. 7. Simulink Model Architecture

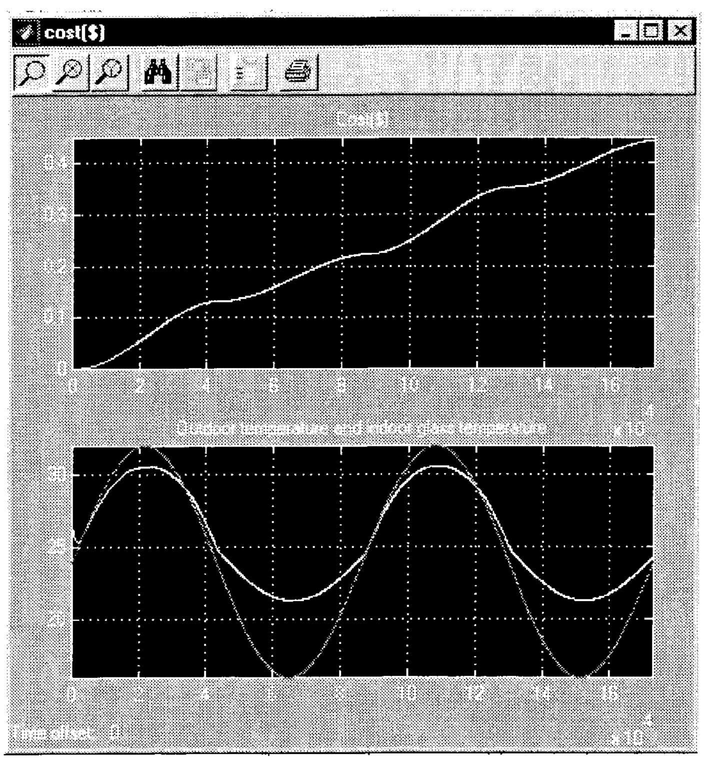


Fig. 8. Typical Simulink Output

The introduced prototype unit is currently being tested in in-situ experiments. The experimental data is used to calibrate the model and determine the physical parameters, using robust parameter estimation techniques. In a future extension, a procedure will be developed to enable self calibration. In a typical installation, the calibrated model will subsequently be used to design adequate control strategies and deploy the system in the architecture of Figure 3.

The immediate next step in the research project is the deployment of the unit in an actual project where the technology is considered as part of the refurbishment.

Future research will address the scalability of the technology, dealing with such issues as:

1. the miniaturization of the BEMST and web server and their integration in ordinary online building management systems

2. integration into the hierarchical nature of the control systems, and determination of optimal controls on whole building scale together with the reduction of the complexity of control strategies such that they can be programmed in a simple PLC

3. the group dynamics of user interaction with smart façade systems in typical office settings; this deals with group dynamics and occupant specific preference profiles

The impact of controllability of the local indoor environment in relation to worker satisfaction, retention and health issues is another long-term research issue.

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