ANALYSIS PROCESS FOR DESIGNING DOUBLE SKIN FACADES AND ASSOCIATED CASE STUDY

Ian Doebber and Maurya McClintock
Arup, San Francisco, CA

ABSTRACT

Double Skin Façade systems, adopted prevalently across Europe for a number of years, are becoming increasingly popular in the United States. However, the design community lacks validated modelling programs and the knowledge base (established on real performance data) necessary to understand the complex thermal behaviour of Double Skin Façade systems. The following paper summarizes how naturally ventilated Double Skin Facades systems are analyzed and designed despite limitations. Specifically, the paper highlights how currently published information and a suite of modelling programs are used to determine:

- the critical design criteria affecting thermal performance,
- the optimal solution to those criteria, and
- the anticipated performance of the final design.

The intention is to provide insight for research initiatives to make real performance data publicly available, establish analysis methods, and to develop validated modelling programs.

INTRODUCTION

Since the late 1970's, Double Skin Facades (DSFs) have experienced accelerated growth as the architectural community realizes that DSFs provide the ability to incorporate full height glazing for improved aesthetics and daylight penetration without compromising the façade system thermal performance. With deeper daylight penetration and greater control of façade heat loads, DSFs are considered a 'green' technology by the general public and provide a very visual sustainable image for the building.

Traditional advanced façade systems (high performance glazing with fixed shading devices) are capable of meeting the thermal comfort requirements of expansive glazing for all orientations in the heating season and north/south orientations in the cooling season. However, meeting the solar control requirements for the low solar angles of easterly and westerly orientations during the cooling season demands a façade system that incorporates operable shading.

Although different definitions of DSFs exist, the basic concept is a façade system that comprises an external and internal glazing system separated by a ventilated cavity housing an operable blind or shade. The main advantage of DSFs is the greater control they provide over the thermal/fluid exchange between the perimeter zone and the outside environment. For example, in the summer, outdoor air or return air can be brought into the cavity via natural or mechanical ventilation to expel the radiant heat absorbed by the cavity shading device and glazing to the ambient environment. In the winter, DSFs can act as a passive solar heater by sealing the cavity and using the absorbed radiation to minimize the façade heat loss.

With greater controllability and flexibility, DSFs have a more complex thermal/fluid behavior than other advanced façade systems. Better knowledge/experience, available performance data, and modeling capabilities are necessary to maximize the potential of DSFs. Unfortunately, most of these resources are currently unavailable leaving engineers hard pressed to make design recommendations.

The gap between the demand of DSFs and the limited building physics support is evident from the inconsistent performance record of existing DSFs. A well cited German article written by Dr. Karl Gertis, director of the Faunhofer Institute of Building Physics in Stuttgart, Germany and renown expert in façade systems, cites a study that measured the performance of different buildings with DSFs (Gertis 1999). The data showed that some buildings with DSFs were 'energy guzzlers' while others were exceptionally energy efficient.

There are two reasonable explanations for the wide range of DSF performance. First, certain DSFs are being applied in climates where they are not well suited. Dr. Gertis as well as other critics believe that DSFs are mistakes in the German climate where most architectural competitions for high rise buildings in Germany currently include DSFs. Second, DSFs are not being properly designed. Dr. Gertis blames the lack of performance measurements on existing DSFs and lack of proper modeling tools.

Working for an engineering firm that has designed a wide assortment of DSFs, the authors are very aware of the lack of resources for designing DSFs. The following paper illustrates the process the authors use to analyze DSFs to indicate to the building research community what additional information and modeling tool capabilities would improve the design process. Although DSFs affect other performance aspects of the façade system (i.e. acoustics, daylight penetration, condensation) the paper focuses only on the thermal comfort and energy performance of DSFs.

ANALYSIS PROCESS

The following section summarizes the available methods and modeling programs to analyze DSFs, how the authors use these resources in the analysis process, and what information / guidelines / modeling capabilities are necessary to improve the design and analysis of DSFs.

Guidelines and Performance Parameters

As far as the authors are concerned, there are currently no standard guidelines on how to design or analyze DSFs. Nor are there standardized and regulated parameters by engineering / manufacturer agencies which specifically characterize the performance of DSFs. Instead, DSF thermal performance is defined using the same parameters as standard façade systems (Solar Heat Gain Coefficient (SHGC), U-Value, and internal glazing temperature) plus a couple parameters to define the thermal / fluid behavior in the DSF cavity (cavity airflow and temperature).

The National Fenestration Rating Council (NFRC) has created a standard for calculating / measuring the SHGC and U-Value of a façade system. Unfortunately, these typical façade parameters are not ideal for defining the performance of DSFs. Over the same range of environmental conditions, the SHGC and U-Value for a DSF will have a much greater variability than with a typical façade system. In addition, the SHGC and U-Value for a DSF will vary by the floor due to the considerable temperature difference across the height of the air cavity. Currently, the NFRC does not provide a standard SHGC and U-Value calculation procedure for characterizing the thermal performance of DSFs.

The internal glazing temperature is another typical façade performance parameter because it has a large effect on the thermal comfort of the occupants in the perimeter zone. According to ASHRAE 55, the surface temperatures surrounding an individual in a sedentary environment should be within 5-10°F of one another. Any surface that exceeds this range causes asymmetric radiative discomfort. A recent analytical study by the UC Berkeley Center for the Built Environment (CBE) funded by the NFRC further bounds the acceptable limits of the internal glazing temperature based upon the proximity of the occupant to the glazing surface (Center for the Built Environment 2006).

The additional parameters used to define the performance of a DSF include the cavity airflow and temperature. These parameters show how well a DSF expels absorbed solar radiation during the cooling season and its capability for providing natural ventilation between the air cavity and adjacent spaces. Similar to the SHGC and U-Value, there is no standard procedure to calculate the cavity airflow and temperature in a DSF.

Modeling Tools

The following section gives a brief description of the modeling programs the authors use in the analysis of DSFs.

Window 5.2 is a publicly available program that analyzes the thermal performance of various glazing and framing configurations (Lawrence Berkeley National Laboratory Windows and Daylighting Group 2006). Unfortunately, the Window 5.2 program is not capable of modeling shading devices nor ventilated airflow through glazing cavities. Therefore, the Window 5.2 program is used to vet different glazing systems when determining the different inner and outer skins to include in a DSF system.

Advanced Window Information System (*WIS*) includes all the features of Window 5.2 and routines for simulating solar shading and ventilation in glazing cavities (WinDAT Thematic Network 2004). The main advantages of using WIS are its:

- flexibility to model intricate façade configurations,
- extreme level of detail for defining the thermal characteristics of the façade components,

- detailed output, and
- having an open use policy for continual improvement / validation for well over a decade.

The main disadvantage of WIS is that it is a steady state simulation tool and can not model the thermal performance of a façade system across a design day without individually inputting and simulating the environmental conditions and façade operation for each time step.

NATFAC is a DSF modeling tool that simulates the basic thermal performance of mechanically driven and naturally ventilated facades (Holmes 2003). NATFAC is geared toward the preliminary design stages with basic input to analyze high level design concepts quickly. NATFAC simulates the performance of the DSF model over user defined design days. The approach negates thermal mass effects which is a reasonable assumption considering the time constant for glazing is relatively short. The output focuses on the key thermal performance criteria necessary to influence the design.

Of critical importance is understanding how NATFAC simulates the airflow through the cavity. For both ventilation modes, the program models the airflow as a one-dimensional vertical flow between two parallel plates. Any horizontal component of the airflow is ignored. For the mechanical ventilation mode, the user specifies the flow rate through the cavity and source of the incoming air (interior / exterior). For the natural ventilation mode, an iterative method is used where the airflow through the cavity is calculated based upon the temperature driven buoyancy force. Then the pressure loss is calculated based upon a user specified airflow resistance in the form of a pressure loss coefficient. A simple stepping algorithm is used to adjust the airflow until convergence is achieved. NATFCA does not model ventilation between the air cavity and adjacent spaces nor wind effects.

NATFAC was validated against measured data from a constructed DSF for a research project under the EEC Solar House Program (Ove Arup 1993). For several different glazing and shading device combinations and operations, performance criteria were measured and compared versus that modeled by NATFAC. The glazing, shading, and air cavity temperatures compared well except at extremely low airflow. The overall heat gain (direct radiation plus convection and thermal radiation from the inner surface) and solar efficiency (percentage of the incident solar radiation extracted by the ventilated air) compared well between the measured and predicted values. The obvious drawback of NATFAC is that it is mainly focused on the initial design phase and an in-depth analysis of a DSF is limited.

ROOM is an energy simulation program that models the transient air and heat flows through a single zone over a year or design days (Ove Arup & Partners Oasys Limited 2006). ROOM is capable of modeling a high level of detail, particularly the performance / operation of advanced façade systems and their impact on the thermal comfort and conditioning load of a perimeter space. ROOM can simulate any layered assembly of glazing, air / gas cavity, and operable shading devices (roller shade or blind) as well as a variety of exterior shading devices (overhang, fins, slatted louvers etc). Unfortunately, ROOM can only model mechanically driving ventilation through a cavity in the façade system.

The postprocessor of ROOM is extremely visual and can show the effectiveness of different shading configurations at limiting transmitted solar radiation into the perimeter zone. Also, for a given set of thermal comfort parameters (metabolic rate, air speed etc), ROOM will calculate the People Percentage Dissatisfied[1] (PPD) across a discretized grid of the perimeter zone based on the air temperature, surrounding surface temperatures, and incident solar radiation. Although the ROOM program can not be used to model DSFs, it is helpful for determining the optimal shading system and using the NATFAC results to calculate the thermal comfort across the perimeter zone.

EnergyPlus is a whole building energy simulation program that is capable of modeling DSFs (Department of Energy Building Technologies Program 2006). For mechanical ventilation, a window simulation feature allows the user to specify the airflow through a glazing cavity as well as the source and exhaust of that airflow. For natural ventilation, the ventilated cavity must be created as a separate zone and a standalone multizone airflow program that is linked with EnergyPlus is used to calculate the buoyancy driven airflow through the cavity. The advantage of simulating a DSF in EnergyPlus is the high level of detail that can be applied to the model and the DSF can be modeled in conjunction with the rest of the building to understand the DSF influence on the mechanical system. The main disadvantages of EnergyPlus is the amount of effort necessary to build the DSF model and that modeling a DSF using EnergyPlus has not been validated.

[1] PPD is the percentage of occupants in a space that are thermally uncomfortable based upon the Fanger Predicted Mean Vote comfort index

The use of *Computational Fluid Dynamic* (*CFD*) programs such as StarCD and Fluent are rapidly increasing in the building industry. CFD programs provide the highest level of detail aside from real data for analyzing thermal / fluid behavior. Consequently, they are ideal for analyzing DSFs. Unfortunately, the complexity of the modeling process demands a high level of understanding by the user which results in a longer analysis time and substantially increased cost.

Analysis Process

Figure 1 gives a comprehensive interpretation of the analysis process by which the authors optimize the DSF configuration and components for a particular project. The end goal is to design a façade system that meets the thermal comfort and energy performance required by the design team and the building code. The authors seek to achieve these goals by translating the high level requirements into performance constraints at the façade system level and then at the façade component level. The design engineer uses conceptual knowledge of the thermal / fluid behavior in DSFs and design experience to make these translations. Then the analysis process reverses direction. Manufacturers performance data for the façade components and the DSF configuration are input into a model and simulated to determine the system and building level performances.

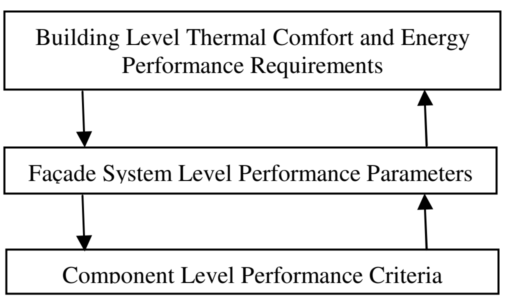

Figure 1 Flow chart of the general process the authors follow for designing and analyzing a DSF system

The following section summarizes the main analysis process the authors use to optimize the DSF system after the completion of the design development phase where the DSF configuration, orientation, and height have been specified.

Pre Modeling Process: The whole building thermal comfort and energy performance requirements are translated into performance requirements at the DSF system level and component level. The thermal comfort requirements are typically based on a maximum PPD across the perimeter space. The energy performance requirements are typically based on a maximum allowable heating / cooling load across the perimeter space.

The design engineer coordinates with the design team to create a baseline DSF system with which all modifications will be compared. Then the design team specifies a list of modifications to the baseline design to determine different ways to optimize the DSF. These modifications normally include different types of glazing and shading devices. The Window 5.2 and WIS programs are extremely helpful at this stage for providing quick performance information on various façade assemblies. The thermal / optical properties of the glazing and shading devices as well as other relevant performance information for the other façade components (i.e. louver-damper free area) are obtained from manufacturers' data.

The modeling process is based on design days rather then annual simulations. Normally, the DSF models are simulated for three design days which are created from banded weather data to represent the winter, summer, and mid-season.

Modeling Process: The initial phase of the modeling process is conducting a cavity airflow sensitivity analysis to account for the lack of knowledge and measured data to properly model the thermal / fluid behavior in the cavity. The NATFAC program quantifies the airflow resistance using a pressure loss coefficient based upon experimental data on pressure loss in ducted systems. To account for the inherent uncertainty of using duct pressure data to simulate the airflow of such a complex system, the baseline DSF configuration is modeled for a range of pressure loss coefficients. Based on experience of knowing what a reasonable airflow would be and the sensitivity of the DSF performance parameters (SHGC, U-Value etc), the design engineer chooses a conservative pressure loss coefficient for the rest of the modeling process. Note that for some projects, instead of specifying a single pressure loss coefficient, the airflow sensitivity analysis is done for all the DSF configurations. The effect of wind on the cavity airflow is not analyzed.

Using a single or range of pressure loss coefficients, the baseline DSF model is validated against the likely performance of the system. These performance expectations are based on experience from previously designed DSFs and simulation results from other programs. For example, NATFAC results are typically compared against results using WIS. Although comparing the results from two simulation programs is not as ideal as comparing against measured data from a similar DSF, it does provide insight to whether the baseline DSF is correctly being modeled.

Once the design engineer feels confident in the baseline model, the remaining DSF modifications are modeled. First, the simulation results are used to calculate the performance parameters of each DSF system. Then, these results are input into ROOM to calculate how the various modifications affect the PPD and conditioning loads of the perimeter space. Additional modifications are modeled until the design team is satisfied that all reasonable design alternatives have been considered.

Post Modeling Process: The design engineer interprets how the different DSF configurations will affect the thermal comfort and energy performance of the perimeter space and makes recommendations accordingly for the final DSF design. These recommendations focus both on the general configuration of the DSF, performance criteria for the individual components, and the control strategy for each of the seasons. The extent of these recommendations depends on the scope of the design engineer.

CASE STUDY

Building Description: The Seattle Justice Center is a 300,000 ft2, 11 story facility in downtown Seattle. The building plan is constrained on two sides by high rise buildings and opens up to daylight and views on the southeast and southwest orientations. As the southwest façade overlooked what was to be the central court of the new Justice Center Complex and views of Elliot Bay, the design team proposed to maximize transparency and design full height glazing on this orientation. Since the City of Seattle has mandated that all new buildings meet a 'LEED Silver' rating or better, the design team needed to balance the full height glazing with a high level of thermal comfort and achieve an overall building energy use target of 20% less than the ASHRAE 90.1 energy efficiency requirements. To meet these constraints, the design team realized early in the design process to look into a DSF system for the southwest façade.

Scope: The engineering firm associated with the authors was brought onto the design team to provide preliminary guidance on the critical design issues related to the DSF system and to conduct a solar / thermal analysis at the 100% design development phase to determine ways to maximize the thermal performance of the DSF.

Performance Goals: The thermal comfort requirement was to maintain a maximum of 10% PPD within 4' of the internal glazing surface. Although a whole building energy savings was specified, the design team did not set a minimum energy performance for the perimeter zone. Still, the perimeter zone heating / cooling load associated with each DSF configuration played an integral role in finalizing the design.

Façade Configurations: The *baseline façade* configuration was a "traditional" double glazed, low-e single skin façade. The *basic DSF* configuration consisted of:

- A 9 story naturally ventilated cavity with operable louvers at the top / bottom,
- Sealed outer skin comprised of a single pane of clear glazing,
- Sealed inner skin comprised of clear, double paned low-e glazing,
- An operable shade in the cavity capable of lowering to 8' off the finished floor surface, and
- Fixed, horizontal shading / catwalk located at the light shelve on each floor.

Three seperate modifications to the basic DSF were:
DSF Modification 1 - Replacing the operable shading device with fritted glazing in the clerestory section of the inner skin
DSF Modification 2 - Relocating the horizontal shading / catwalk from the light shelve level to the floor slab level and allow the operable shade to lower to 6'-6" off the finished floor surface
DSF Modification 3 - Replacing the operable shade with a horizontal shading device at each floor level and replacing the interior skin with single pane, low-e glazing

Analysis: A preliminary analysis determined the operable / fixed shading combination most effective at minimizing the transmission of solar radiation using the ROOM program. The model consisted of one structural bay with an 18' deep perimeter zone. Based on the results, the design engineers recommended the operable shade because it provided greater control over the transmission of radiation into the perimeter zone and its location in the cavity was more effective at expelling absorbed radiation to the ventilated airflow in the cavity. The design engineers also recommended locating the fixed horizontal shading / catwalk at the floor slab to allow the operable shade to be drawn to a lower level. Based on these preliminary results, the design strategy of DSF Modification 2 was incorporated into the basic DSF configuration for the remaining analysis.

The NATFAC program was used to perform a sensitivity analysis on the sizes of the cavity upper and lower level openings using the basic DSF configuration. Three different design days were simulated: a summer day, a sunny winter day, and an overcast winter day. Three different pressure loss coefficients were calculated to represent 30% free area louvers, 60% free area louvers, and 100% free area for the upper and lower cavity openings. Figure 2 shows that the larger the free area of the louver, the larger the cavity airflow for the summer design day. The design engineers recommended that the operable louvers provide a minimum of 60% free area and were robust enough to withstand 500 fpm air velocity without fluttering. In addition, the results showed the DSF effectiveness at minimizing the perimeter zone heat loss during the sunny winter design day while the cavity openings were closed.

Finally, the NATFAC model simulated the different DSF design alternatives for the summer design day. The analysis focused on the conditions at the top floor as it experienced the highest cavity air temperature. The outputs from the NATFAC model were input into the ROOM program to calculate the PPD distribution across the perimeter space. Figure 3 shows the PPD across the perimeter zone for the basic DSF system. The PPD ranges for each DSF design alternative are shown in Table 1.

Table 1 Worst case PPD range across the 11th floor perimeter zone for each façade system

	PPD Range
Baseline Facade	70-100%
DSF Modification 1	40-60%
DSF Modification 3	40-60%
Basic DSF	10-30%

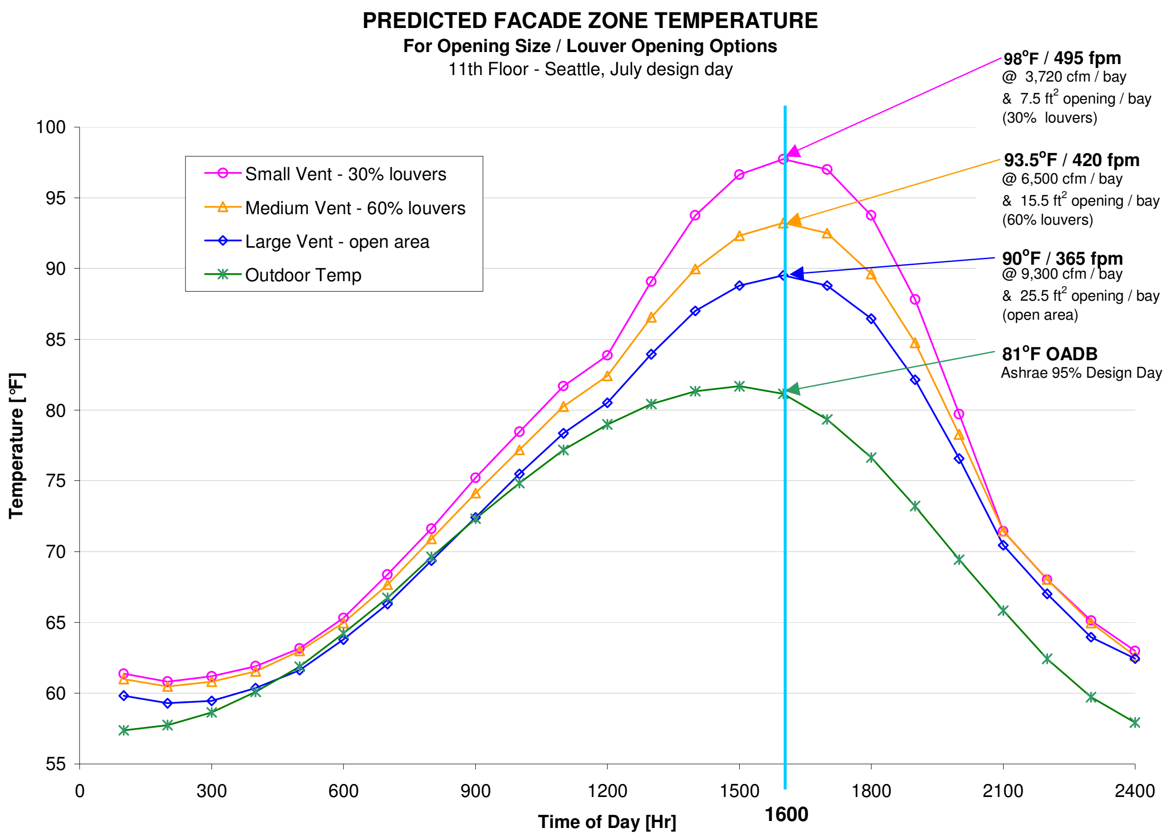

Figure 2 Cavity air temperature at the 11th floor across the summer design day for different louver free areas for the basic DSF configuration

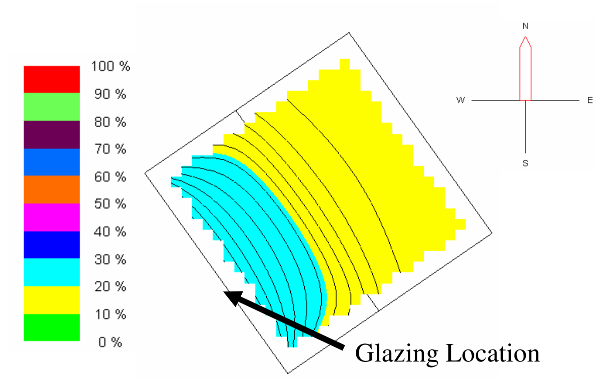

Figure 3 PPD distribution across the 11th floor perimeter zone for the basic DSF configuration

The cooling energy necessary to maintain a 74ºF temperature set point was determined directly from the NATFAC outputs. Table 2 shows the cooling airflow required for each façade configuration and the savings with respect to the baseline façade system. The energy savings of the basic DSF configuration were translated into the energy savings for the whole building. Since the perimeter zone area represented a small fraction of the overall building conditioned area, a 33% cooling airflow reduction resulted in a 2% overall building energy savings.

Table 2 Perimeter zone minimum cooling airflow for the DSF design alternatives and savings with respect to the baseline façade system

	A/C supply	**Savings**
	[cfm / perim. zone]	[per perim. zone]
Baseline Facade	750	-
DSF Modification 1	680	9%
DSF Modification 3	590	21%
Basic DSF	500	33%

Based on the results, the design engineer recommended double clear low-e interior glazing, operable shade in the cavity drawn to 6'-6" off the finished floor surface, fixed horizontal shading / catwalk at the floor slab level, and a minimum of 60% free area for the louvers at the upper and lower openings of the cavity.

ANALYSIS IMPROVEMENTS

The authors see three initiatives that would significantly improve the design and analysis of DSF systems.

The first initiative would be a database consolidating general descriptions and measured performance data on a wide variety of existing DSFs. The performance information would include any measured data by the Building Management System (BMS) concerning the operation of the DSF (cavity air temperature, cavity airflow, positions of the damper, operable shade, operable window) and adjacent perimeter space (air temperature, supplied airflow). The database would provide design teams real performance data to determine whether a DSF would be appropriate for their project / climate. Also the performance information would be used by the mechanical designer to validate the results from their analyses. The database should also include the annual energy consumption per condition floor area and peak power demand for the heating / cooling seasons to give an idea of the over performance level of the building. Any other information, particularly comparing the predicted performance from an energy model to the actual performance of the DSF would be extremely beneficial.

The second initiative would be developing a method to model the thermal / fluid behavior in the DSF cavity based upon measured data and analytical / numerical analyses. Simulating the cavity airflow and convection at the glazing / shading surfaces is often the most tedious and circumspect aspect of modeling a DSF. Yet accurately characterizing the thermal / fluid behavior in the cavity is extremely important as it makes a significant impact on the overall performance of the DSF. To illustrate the importance of the cavity airflow, an example west facing 10 story DSF was modeled in NATFAC with and without natural ventilation in the cavity. At the 10th story with no cavity ventilation, 700 cfm of 55ºF supply air was required to maintain the 74ºF setpoint in the perimeter space. Yet with natural ventilation in the cavity, only 430 cfm was required, a 40% reduction.

The airflow sensitivity analysis should be replaced with a method of calculating the cavity airflow resistance based upon the geometry of the cavity, configuration of the openings, performance of the louver / damper and operable windows, and obstructions in the cavity. This method should also include a way to characterize the airflow through openings in the inner and / or outer skins. Then a method should be determined to define the convective heat transfer coefficients at each glazing / shading surface exposed in the cavity based on the airflow behavior (i.e. velocity and turbulence). Ideally, the NFRC should standardize and regulate these methods so that the design community can make apple to apple comparisons between performance data published by manufacturers and research journals.

The third initiative would be the development of a robust DSF modeling program that combines all the capabilities of the currently available programs (Window 5.2, WIS, NATFAC etc) plus a few additional features. Ideally, its capabilities would include the ability to model:

- the thermal / optical interaction of glazing and shading systems,
- static (steady state), design day, and annual simulations,
- natural or mechanical ventilation in the cavity and the associated airflow through the dampers and operable windows,
- the adjacent perimeter space conditions (temperature, conditioning loads, thermal comfort),
- any configuration of operable shades (roller and blind) and fixed shading,
- daylight penetration and associated reduced electric lighting,
- schedules or control algorithms to control the cavity dampers, operable shading, and operable windows, and
- the thermal bridging effect of the framing system.

Two optimal ways to model the cavity airflow would be a bulk airflow method similar to the COMIS program or a simplified CFD method. Although CFD would provide greater accuracy and flexibility, it would increase the runtime substantially and increase the potential for incorrect input with users who are not familiar with CFD. A bulk airflow method would be better suited by providing the necessary accuracy without making the input too complicated for the users nor significantly slowing down the simulation time.

The program could be standalone or integrated into an existing whole building simulation program like DOE2 or EnergyPlus. A standalone program would not be limited by a host programs structure and could output performance results for use in seperate whole building simulation programs (similar to how Windows 5 can be used with DOE2 or EnergyPlus). An integrated program could coincidently model the DSF along with the rest of the building to simulate the performance effects on the mechanical system. The program output would calculate the SHGC and U-Value of the DSF system for each timestep to enable users to quickly compare the performance of various façade system configurations. The program would be built both for quick simulations with defaulted physical parameters but also provide advanced users the flexibility to enter in their own parameters values or equations.

CONCLUSION

Double Skin Facades can allow full height glazing while meeting the thermal comfort and energy performance requirements of most perimeter zones. For optimal performance, DSFs need to be matched to the correct climates and properly designed. The building research and design community has an obligation to improve the currently available information and modeling tools so that design engineers can supply the increasing market demand with DSFs that meet all the performance expectations of the design team.

REFERENCES

Center for the Built Environment (CBE). 2006. Window Performance for Human Thermal Comfort, Final Report to the National Fenestration Rating Council.

Department of Energy Building Technologies Program. 2006. EnergyPlus Energy Simulation Software,[Online] Available: http://www.eere.energy.gov/buildings/energyplus/ [25 April 2006]

Gertis, K. 1999. Sindneuere Fassadenentwicklungen bauphysikalisch sinnvoll? Teil 2: Slad-Doppelfassaden (GDF), Ernst & Sohn Bauphysik 21, Heft.

Holmes, M., Pilgrim, M. 2003. NATFAC: A Simple Tool for the Comparison of Options for a Double Skin Façade, The proceedings of the International Conference Façade Design and Procurement, Bath, UK.

Lawrence Berkeley National Laboratory Windows and Daylighting Group. 2006. Window 5, [Online], Available: http://windows.lbl.gov/software/window/window.html [25 April 2006]

Ove Arup & Partners. 1993. CEC DGX11, Joule 11 Programme. The Solar House. Thermal analysis of ventilated glazing. UK.

Ove Arup & Partners Oasys Limited. 2006. E+TA suite, [Online], Available: http://www.oasys-software.com/ [25 April 2006]

WinDAT Thematic Network. 2004, Advanced Window Information System (WIS), [Online], Available: http://windat.ucd.ie/wis/html/index.html [25 April 2006]