II

RESEARCH ARTICLES

PERFORMANCE EVALUATION OF THREE DIFFERENT FAÇADE MODELS FOR SUSTAINABLE OFFICE BUILDINGS

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ABSTRACT

Sustainable development issues are currently the driving forces of many building projects. The building façade is critical for the architectural expression and has a large affect upon large parts of the building's environmental performance. This study investigates the advantages of using multidimensional computer aided modeling and simulation to produce a sustainable façade design. A first step towards green building design is to establish a list of parameters which can then be used as design criteria, e.g. environmental performance, thermal visual and acoustic comfort, etc. Computer simulation and an analysis of recent projects in Hong Kong can help to determine the performance according to these design parameters whilst environmental impacts due to energy consumption are considered to be an important design parameter, it is also important for comfort criteria to be considered.

1. INTRODUCTION

While some countries have developed their specific visions of how to incorporate sustainable development, particularly to the built environment, other countries like Hong Kong have just begun to formulate the problem. Thus, an opportunity exists to reevaluate current design practice in order to find a sustainable building solution. This could be achieved by optimizing the building envelope in order to enhance, not only its energy efficiency, but also to provide improved comfort for the occupants.

Computer simulations are typically carried out in order predict the performance of a building during the design stage. Since there are a number of design criteria, normally it is necessary to run different simulations with different software tools in order to fully assess the building design.

Computational power has rapidly increased which now gives designers the opportunity to run a number of simulations with a number of design options. Building simulation software tools have become very sophisticated in simulating energy flow in buildings (Clarke 2001). In Hong Kong, the building envelope turned out to account for more than 55% of the cooling load of a building (Lam 2000). Especially advanced ventilated façades are difficult to assess due to the airflow through the façade (Saelens 2002). In order to develop useful façade design criteria it is helpful to give a short description of what sustainable buildings are.

1.1. Sustainable Buildings

The OECD project on sustainable buildings for the future identified five objectives for sustainable buildings (John 2005):

- Resource efficiency;
- Energy efficiency (including greenhouse gas emissions reduction);
- Pollution prevention (including indoor air quality and noise abatement);
- Harmonization with environment;
- Integrated and systemic approaches.

In Hong Kong, the Chief Executive made clear in his 1999 Policy Address that Hong Kong follows the framework for sustainable development (HKSusDev 2004). The Sustainable Development Department in Hong Kong is working on formulating a Hong Kong specific strategy. The warm and humid climate in Hong Kong demands a specific focus on the appropriate façade design. At the moment, existing regulations give maximum values for thermal heat transfer

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through the building envelope (EMSD 2006). Comfort criteria are not taken into consideration.

1.2. Sustainable Building Envelope

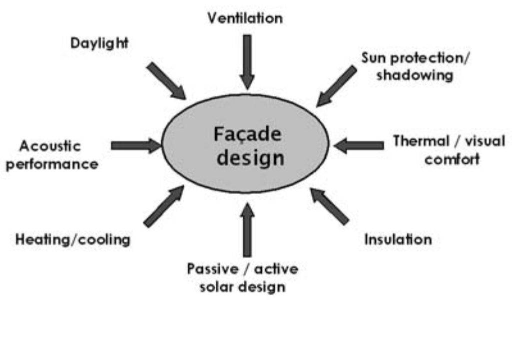
The U.S. Department of Energy has a clear "Roadmap" to the Building Envelope design within the next 15 years that is closely linked to other "Roadmaps" that incorporate visions for 2020 on lighting and HVAC systems. The building envelope ought to be (DOE 2004):

- Affordable
- Durable
- Energy-positive
- Environmental
- Healthy and Comfortable
- Intelligent

The building envelope includes all the building components that separate the indoors from the outdoors. The envelope of the building consists of the exterior walls, the roof, floors, windows, and doors. In addition to giving the wall the desired appearance, the envelope must withstand the stresses to which it is exposed and must protect the enclosed space against the local climate, ideally moderating the outdoor climate (Annex44 2006a). Designs for exterior walls for buildings have seldom been developed in a systematic and rational way (John 2005).

An intelligent façade (IF) is defined as "a composition of construction elements confined to the outer, weather-protecting zone of a building, which performs functions that can be individually or cumulatively adjusted to respond predictably to environment variations, to maintain comfort with the least use of energy" (Wigginton and Harris 2002). This has also be termed a 'climate responsive façade' (Annex44 2006b).

FIGURE 1. Integrated façade concept.



A number of strategies may be used to achieve energy-saving goals such as natural ventilation, night-time cooling, maximizing the use of natural light, solar assisted air-conditioning. The implementation and optimization of these strategies produce a complex interaction between façade and building. Advanced Integrated Façades (AIF) gather all the concepts and establish a tight connection with building energy and control systems.

Summarizing, an AIF is, from architectural and technical points of view, in tune with the physical and climatic conditions of a particular location. It is a building envelope that exhibits adaptive characteristics, it has a dynamic behavior providing the basic functions of weather proofing, security and privacy, of conditioning energy flows in their various forms, in order to minimize energy consumption. Being tightly connected to the building energy and control systems, an AIF has to contribute to environmental sustainability and make the building a structure with climatic sensitivity. Figure 1 illustrates a possible concept of integrated façade design where several building elements and systems are integrated into the façade design.

One promising development of advanced façade systems is the double-skin façade (DSF). Conduction through the window system can be significantly reduced by making use of the air gap. The complexity of the new concept and technology requires careful and responsible planning. Heat transfer due to convection is the most complex one depending on the temperature distribution in the gap, the air velocity, and pressure field. To predict the performance of a DSF is thus not trivial. The temperatures and airflows result from many simultaneous thermal, optical, and fluid flow processes that interact and are highly dynamic (Chen and Van Der Kooi 1990; Garde-Bentaleb et al. 2002; Prianto and Depecker 2002; Qingyan and Weiran 1998; Xu and Chen 2001; Zhang and Chen 2000). These processes depend on geometric, thermophysical, optical, and aerodynamic properties of the various components of the double-skin façade structure and of the building itself (Hensen 2002). The temperature inside the offices, the ambient temperature, wind speed, wind direction, transmitted and absorbed solar radiation, and angles

FIGURE 2. Airflow concepts of DSFs.

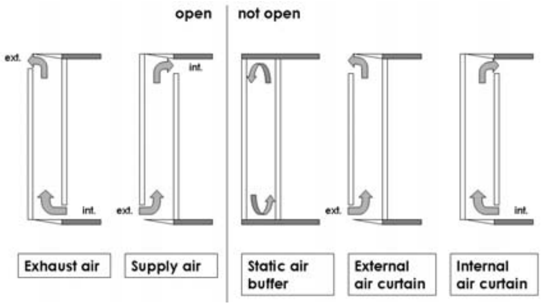
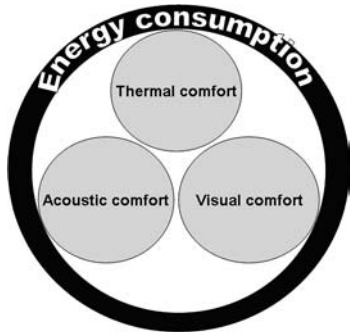


FIGURE 3. Façade modeling objectives.



of incidence govern the main driving forces (Manz 2003; Reichrath and Davies 2002; Zhai et al. 2002).

When looking at the various airflow concepts, it is important to note that all main types of DSFs can be combined with both types of ventilation and all types of airflow concepts. This results in a great variety of DSFs. Figure 2 shows the different airflow concepts that can be applied to DSFs (Oesterle et al. 2001). More recently, DSFs have been developed that act as climate responsive elements with hybrid ventilation (natural and mechanical) concepts with a possibility to change the airflow concept due to different weather conditions in different seasons (Heiselberg et al. 2001).

There are opportunities and barriers of design and implementation of integrated building concepts across all disciplines. This is often due to a lack of connection between integrated building concepts, processes and tools, and related experiences with designing and implementing responsive building elements often strongly related to issues and questions from different projects and experience thus rendering the concepts to not be easily adopted. For example, U-values and g-factors are powerful means to describe the heat transfer through envelope parts. However, in the case of multiple-skin façade, due to the airflow through the cavity, the shading device and the many possible typologies, they become hard-to-use, typology dependent, and multi-dimensional functions of system and material properties (Saelens 2002).

2. OBJECTIVES

This paper tries to establish a list of performance criteria that can help to design sustainable façades. It investigates the advantages and procedures of multidimensional computer aided modeling and simulation for a sustainable façade design approach. In order to meet the requirements for future façades it has to minimize the energy consumption of its building. At the same time comfort criteria have to be addressed. Here, thermal, visual, and acoustic comfort have been identified as most important criteria. The concept is illustrated in Figure 3.

The design of a double-skin façade system was used exemplify the different dimensions of modeling involved. Detailed results of the three comfort studies illustrate the difficulty in evaluating advanced intelligent façades.

3. METHODOLOGY

A first step towards sustainable façade design is to establish a list of parameters that are used as design criteria. Focusing on the façade design of a building as the architectural and aesthetically most sensitive area of a building, a list of parameters is proposed that help to evaluate the sustainable value (Table 1).

TABLE 1. Parameters for integrated lewis arrow font design. In brackets not considered.

Parameters	Calculation	Outcome
Energy performance	annual energy consumption	kWh/m^2
Thermal comfort	Ta, Tr, RH, v, MET, clo	PMV, PPD
Visual comfort	daylight factor, daylight coefficient, daylight autonomy	DF, DA, DC
	[glare	Gl]
[Acoustic comfort	intrusive noise reduction, reverberation time	R, trb]

A simple office room was chosen to run a series of simulations (Figure 4). Three cases have been analyzed, namely the annual cooling load, thermal, and visual comfort. Then, different window systems were analyzed and the results were compared.

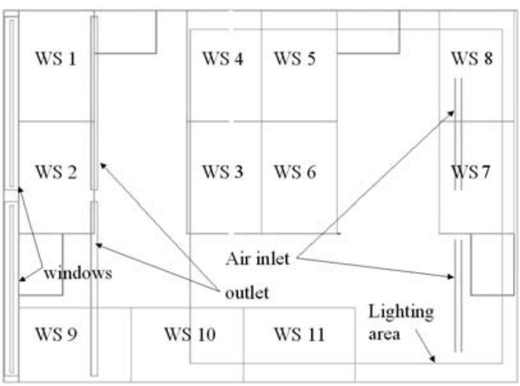
The first case was using dynamic building simulation (TRNSYS 2004) to determine the annual energy performance of the room. Instead of U-value and g-value for the description of the performance of DSF, an office room was attached to the façade and the cooling load was calculated. The calculations are based on hourly weather data provided by Meteonorm (Hui and Tsang 2005).

The second case was used to establish thermal comfort in the different zones. It is defined in the ISO 7730 standard as "that condition of mind which expresses satisfaction with the thermal environment" (ISO_7730 and EN_ISO_7730 1991).

The third case was used for visual comfort simulation. There are at least two issues that have to be considered; daylight and glare. The use of daylight can be expressed as daylight factor, which is the fraction of outside illuminance to indoor illuminance. The Glare Index (GI) as well as Guth's visual comfort probability (VCP) of the façade system are other indicators that have not been used here (Osterhaus 2005).

The final case is acoustic simulations in order to establish the acoustic performance of the façade of the room and has not been considered in this example.

FIGURE 4. Model office room plan with work spaces 1 to 11 (WS1 to WS11).



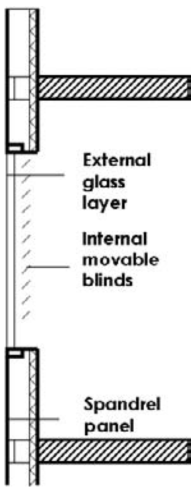
3.1. Energy Performance Analysis

Three façade models were used to compare their performance. The first model is a curtain wall system which acts as a base case for comparison. The second model is a natural ventilated external air curtain. An internal shading device was positioned in the 600mm deep cavity. The third model is a mechanical ventilated internal air curtain with a cavity depth of 240mm. The model room was simulated with 6.6m width and 8m depth as described in Figure 4. The façade was facing south, and a schedule was used to simulate the office use (working hours from 8:00 a.m. to 5:00 p.m. on weekdays).

Base Case Curtain Wall. The model consists of a single glazed curtain wall (CW) system. The glass layer consists of a 10mm clear glass with internal shading device. The window-to-wall ratio is 44%. A comparison of the performance of different other glass types has been reported (Haase and Amato 2006b). Figure 5a gives façade details and an example of a building in Hong Kong.

External Air Curtain. The design proposal includes a DSF with 600mm cavity with one-storey double-skin façade. Both glass layers were selected as single

FIGURE 5A. Façade detail of base case curtain wall window (BC) and example of a building in Hong Kong (IFC2, HK Central district, built in 2003, architects: Rocco Design Limited, Cesar Pelli & Associates Architects).



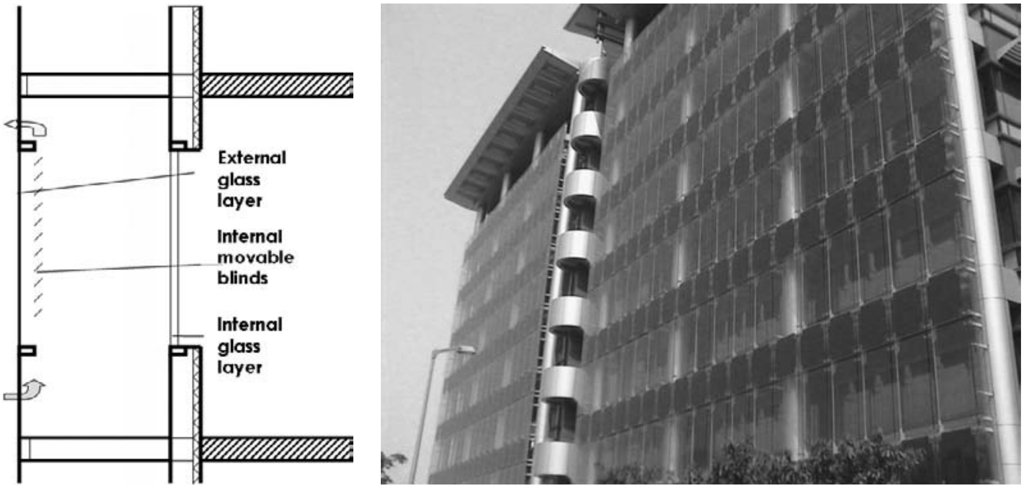


FIGURE 5B. Façade detail of double-skin façade (DSF) and example of a building in HK (Building 5, HK Science & Technology Park (Phase 2), built in 2002, architect: Simon Kwan & Associates Ltd.) (Haase and Amato 2006a).

clear glass (10mm).The DSF is open on bottom and top to the outside allowing a naturally ventilated cavity. A shading device is positioned in the cavity and solar controlled (DSF1). A regulator indicates the times of the year when the enthalpy of the air in the window gap is exceeding the enthalpy of the outside air (DSF2). The regulator will then exhaust the air which is expected to result in energy savings. Figure 5b gives façade details and an example of a building in Hong Kong.

Internal Air Curtain. The windows are connected to an additional second layer of glazing placed on the inside of the window to create a DSF. The mullion's depth of around 240mm is needed for structural purposes and leaves space for the shading device that can be opened and closed automatically. At the same time the mullion can be used to introduce a second glass layer on the inside. It is open to the room at the bottom and has a ventilation slot on the top of the window. Air is vented through the airflow window from the room back to the HVAC system (AFW1). A control opens the cavity of the double-skin to the exterior, allowing used air from the room to be exhausted. The purpose of this design is to improve the thermal performance of the airflow window (AFW2). Figure 5c gives façade details and an example of a building in Hong Kong.

3.2. Thermal Comfort Analysis

Here, the office room with different south facing façades (BC and AFW) was chosen to run a series of simulations. The room was divided into 11 different work spaces. A plan of the office room is shown in Figure 4. Please note the lighting zone with a heat load as specified in Table 2. Each work space consisted of a

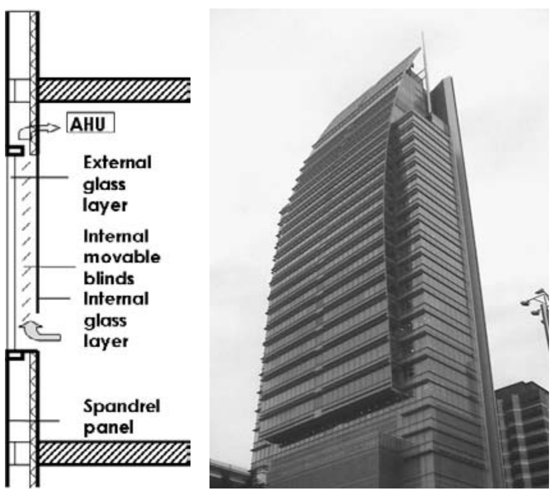


FIGURE 5C. Façade detail of airflow window (AFW) and example of a building in HK (1 Peking Road, Kowloon district, built in 2003, architect: Rocco Design Limited) (Haase and Amato 2006a).

TABLE 2. Heat loads of office room.

Power source	Heat transfer/ item	Spec. heat load (W/m²)	Total heat load (W)
Lights power	Radiative	12	318
	Convective	8	216
Work space	Desktop		—
	Drawer		—
	Computer		35
	Monitor		135
	Worker		80

desktop, a drawer, a computer with monitor, and a worker with heat loads as specified in Table 2.

Temperature and Airflow Distribution. CFD simulation of a model of an office room was done in order to establish temperature and air velocity in the different zones. The second model was using the same room with a ventilated double-skin façade system integrated into the HVAC system (Haase and Amato 2005b). For both models thermal comfort was calculated for the different work spaces and the results have been compared by using the percentage of people dissatisfied (PPD) difference between the base case and the double-skin façade system.

Thermal Comfort. Especially in ventilated or air-conditioned spaces, not only is the set-point temperature an important design criterion, but other environmental factors play an important role. Fanger (1970) related thermal comfort conditions to the following four environmental factors (Fanger 1970) and two added physiological factors that affect an individual's thermal comfort:

- Dry bulb temperature (Ta)
- Mean radiant temperature (Tr)
- Relative humidity (RH) / partial water vapor pressure in Pa (pa)
- Air movement (v)
- Metabolic rate (MET)
- Clothing level (clo)

A metabolic rate of MET=1.2 (70 W/m^2) was chosen. This is the rate for an office worker in sedentary activity (Givoni 1992). A clothing level of clo=1.0 (0.16 m^{2}K/W) was chosen. The clo=1.0 is the level of a person wearing pants, shirt, T-shirt, sweater, briefs, shoes (Howell 1998).

A comfort analysis was done with data of 21 March, 21 June, 21 September, and 21 December, at 9:00 a.m., 12:00 a.m., and 3:00 p.m. In order to monitor the influence of different airflow rates on thermal comfort at 12:00 a.m., airflow rates of 300, 600, and 900 l/s were simulated. Thermal comfort was calculated for the different work spaces, using Predicted Mean Vote (PMV) referring to a thermal scale that runs from Cold (–3) to Hot (+3) and the resulting figures for the percentage of people dissatisfied (PPD) were compared. A detailed report of the thermal comfort calculation has been reported (Haase and Amato 2005a).

$$PMV = (0.303\exp(-0.036MET) + 0.028 \times \left\{ \begin{array}{l} MET - 3.05\times10^{-3}[5733 - 6.99MET - p_a] \\ -0.42[MET - 58.15] - 1.7\times10^{-5} MET(5867 - p_a) \\ -0.0014MET(34 - T_a) \\ -3.96\times10^{-8} f_{cl}[(T_{cl}+273)^4 - (T_r+273)^4] + f_{cl}h_c(T_{cl} - T_a) \end{array} \right\} \tag{1}$$

where

p_a = partial water vapor pressure in Pa

T_a = dry bulb temperature

f_{cl} = ratio of clothed surface to nude surface area

T_r = mean radiant temperature

T_{cl} = clothing surface temperature

$$\begin{aligned} T_{cl} &= 35.7 - 0.028\times MET \\ &-I_{cl}\{3.96\times10^{-8}\times f_{cl}[(T_{cl}+273)^4 - (T_r+273)^4] + f_{cl}h_c(T_{cl} - T_a) \end{aligned} \tag{2}$$

where

I_{cl} = thermal resistance of clothing (m^{2}K/W)

h_c = heat transfer coefficient

$$h_c = \max\left\{2.38(T_{cl} - T_a)^{0.25}, 12.1\sqrt{v}\right\} \tag{3}$$

where

v = air velocity relative to the body

$$\begin{aligned} I_{cl} &\le 0.078 m^2K/W \rightarrow f_{cl} = 1.00 + 1.290 I_{cl} \\ I_{cl} &> 0.078 m^2K/W \rightarrow f_{cl} = 1.05 + 0.645 I_{cl} \end{aligned} \tag{4}$$

As PMV moves away from neutral (PMV = 0) in either direction, PPD increases. The PPD is calculated using the following equation:

$$PPD = 100 - 95 \exp(-n) \qquad (5)$$

where

$$n = 0.03353PMV^4 + 0.2179PMV^2 \qquad (6)$$

The results of PPD for the two models have been compared by subtracting the airflow window system results from the base case results.

$$\mathrm{PPDI} = \mathrm{PPD_{BC}} - \mathrm{PPD_{AFW}} \qquad (7)$$

where

PPDI = Percentage People Dissatisfied Improvement

PPD_{BC} = Percentage People Dissatisfied of Base Case (BC)

PPD_{AFW} = Percentage People Dissatisfied Airflow Window (AFW)

A positive result is therefore indicating a percentage of less dissatisfied (= more satisfied) people with the airflow window system. A summary of the results has been calculated by summing the results for the 11 workspaces together.

3.3. Daylight Assessment

The third model can be used for visual comfort simulation. A detailed daylight analysis was conducted and two issues have been considered; daylight factor (DF) and daylight autonomy (DA) for different façade systems.

Daylight Factor (DF). The daylight factor (DF) is the most common parameter to characterize the daylight available in a building. It is defined as the ratio of the indoor illuminance E(x) at point x to the outdoor horizontal illuminance, Ehor outside, under an overcast CIE reference sky.

$$\mathrm{DF(x)} = \mathrm{E(x)/Ehor} \qquad (8)$$

with

E(x) = indoor illuminance at point x

Ehor outside = outdoor horizontal illuminance

The daylight factor is an intuitive quantity that can be measured or calculated either based on calculation tables or more refined computer simulations. The use of daylight factor is not suitable to evaluate the annual daylight level in a given building, since it is based on a single sky luminance distribution. The daylight factor method, rather, provides a worst-case scenario of the annual daylight availability, since direct sunlight is discarded.

Daylight Coefficient (DC). The concept of daylight coefficients proposed by Tregenza (1983) is a method to calculate indoor illuminance levels due to daylight under arbitrary sky conditions. The idea is to theoretically divide the celestial hemisphere into disjoint sky patches. Afterwards the contribution to the total illuminance at a point in a building is calculated for each sky patch individually. It is calculated with:

$$\mathrm{DC}\,\alpha\,(x) = \mathrm{E}\,\alpha\,(x)/\mathrm{L}\,\alpha\,\Delta \mathrm{S}\,\alpha \qquad (9)$$

with

x: point in a building

S α: sky segment P

ΔS α: angular size of S α

E α (x): illuminance at x due to S α

L α: luminance of S α

Once the daylight coefficients for all segments of the sky have been calculated for a reference point, the illuminance or luminance at the reference point can be calculated for any possible sky condition by combing the daylight coefficients with the luminous distribution of the sky. The luminance of individual sky patches for a given sky condition can be calculated by using the Perez sky model.

Daylight Autonomy (DA). The daylight autonomy (DA) at a point of interest in a building is defined as the fraction of the occupied times per year, when the required minimum illuminance level at the point can be maintained by daylight alone. In contrast to DF, the daylight autonomy considers all sky conditions throughout the year by using the DC. Thus, it can be reliably simulated using dynamic daylight weather data (Reinhart and Herkel 2000).

The daylight autonomy is a relatively new daylight performance indicator and no recommended performance ranges have been established yet. The daylight autonomy characterizes the *daylighting po-*

tential of a space. As it is independent of the installed electric lighting power density and lighting control, high daylight autonomy is a prerequisite but not a guarantee for lighting energy savings due to daylight (Reinhart 2005).

4. RESULTS

The various simulations show different results depending on the purpose of the optimization process. These different parameters show the strength of an integrated approach through multidimensional modeling. It could be demonstrated that an optimized window system with a ventilated double-skin façade can not only help to reduce the annual energy consumption of the building, it can also improve thermal comfort at the work space (Haase and Amato 2005a).

4.1. Energy Performance

It can be seen from Figure 6 that the DSF saves 11% annually. The enthalpy control strategy results in annual savings of 12%. The airflow window (AFW) without control strategy increases the annual cooling load by 5%. This is due to clear glass as an outside layer compared to the reflective glass layer in the base case. The heat gain in the cavity is in the building and adds to the cooling load. With the enthalpy control strategy the annual cooling load reduction is 15%.

The results indicate that the appropriate control strategy is crucial for the optimum environmental performance of the façade system.

4.2. Thermal Comfort

The CFD analysis calculated the temperature and airflow distribution in the room. Since the room is occupied with 11 work spaces, there is a large amount of heat load on the room. Figure 7 shows the temperature distribution, and Figure 8 shows the airflow distribution for the base case. The difficulties in comparing the results were solved by further thermal comfort analysis.

The simulation results are shown in the following section. Since the temperature and air velocity were calculated for the whole room, it was possible to extract them for the 11 different work spaces. Table 3 shows the different analysis steps. From the average values for temperature and velocity PMV and PPD for each workspace (WS1 to WS11) could be determined. It can be seen that for the case with 900l/s supply air at 17° C the airflow window provides lower temperatures and lower air velocities.

The results for the PMV for the different work spaces give a similar picture. Although the PMV gives values in the range between –3 and +3 with a PMV=0 as the aim of each design effort, this results in different PPD. The PPD directly indicates the percentage of dissatisfied people, and thus a decrease

FIGURE 7. Temperature distribution in the room cut as indicated.

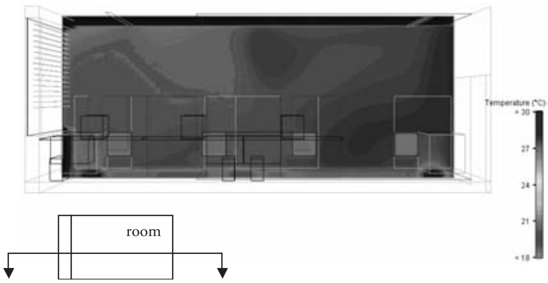


FIGURE 6. Annual cooling load savings of different façade options compared with base case.

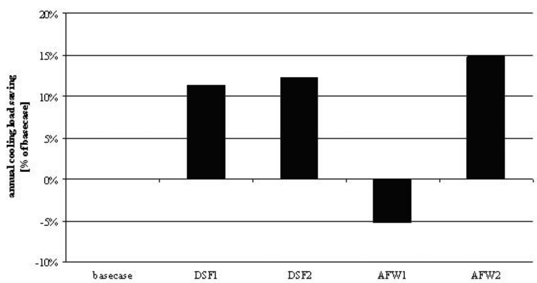


FIGURE 8. Airflow distribution in the room cut as indicated.

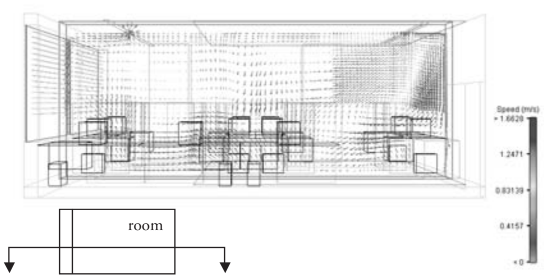


TABLE 3. Calculation results for 21 Sept.

	average temperature		average velocity		PMV		PPD	
900l/s	BC (C)	AFW (C)	BC (m/s)	AFW (m/s)	BC (–)	AFW (–)	BC (%)	AFW (%)
WS1	23.5749	21.7568	0.21708	0.17861	0.34032	0.03462	7.62946	5.14497
WS2	22.9227	21.7773	0.24572	0.16726	0.23493	0.06276	6.32719	5.44479
WS3	23.4449	21.6831	0.18144	0.12034	0.36435	0.11103	8.42825	5.46174
WS4	23.549	21.7052	0.14002	0.11836	0.4181	0.12333	8.78179	5.35953
WS5	22.7737	21.1202	0.11662	0.13003	0.28855	–0.02768	6.87888	5.34213
WS6	23.1216	21.3679	0.13515	0.13404	0.31569	–0.01004	7.18335	5.22757
WS7	22.4137	20.5361	0.21764	0.22414	0.14806	–0.25547	6.30284	7.25173
WS8	22.4265	20.9142	0.20221	0.17968	0.16311	–0.14662	6.45554	6.32713
WS9	23.3033	21.3406	0.15826	0.16602	0.35925	–0.00472	7.8312	5.32271
WS10	23.2287	21.4052	0.14444	0.16814	0.36373	0.00609	7.84321	5.14649
WS11	23.4205	21.1741	0.14833	0.15623	0.3403	–0.05429	7.50585	5.17763

of the PPD should be the aim. It can be seen from Table 4 that PMV and PPD decrease for an airflow rate of 900l/s and increase for most of the other airflow rates. The increase in PMV for an airflow rate of 900l/s ranged between 0.17 and 0.40. The PPD for 900 l/s ranged between –0.95% and 3.42%.

The decrease of PPD for airflow rates of 600l/s and 300l/s ranged between 0.87% and –1.26%. For an airflow rate of 150l/s, the increase in PPD ranged between –1.98% and –2.84%.

The decrease of PPD for airflow rates of 600l/s and 300l/s ranged between 0.87% and –1.26%. For an airflow rate of 150l/s, the increase in PPD ranged between –1.98% and –2.84% as shown in Table 4.

TABLE 4. PPD results for different airflow rates.

	PPDI (%)			
supply air	900 l/s	600 l/s	300 l/s	150 l/s
WS1	2.48449	–0.01936	–0.6863	–2.3863
WS2	0.8824	0.01678	–0.5398	–2.1351
WS3	2.96651	–1.03497	–1.2552	–2.8251
WS4	3.42226	–0.78892	–1.2604	–2.8384
WS5	1.53675	–0.02911	–0.3853	–2.4851
WS6	1.95578	–0.00191	–0.2247	–2.3941
WS7	–0.94889	0.00391	0.2027	–2.1387
WS8	0.12841	–0.02212	–0.109	–1.9862
WS9	2.50849	0.30003	0.5465	–2.0131
WS10	2.69672	–0.35926	0.6153	–2.2192
WS11	2.32822	0.128	0.8711	–2.0861

It was also interesting to investigate the different times of the day. Figures 9a to 9d show values of PPDI for different times of the day for each work space. It can be seen that for most work spaces, the PPDI were improved. Figure 9a shows the values of PPDI for March 21. PPDI is negative for almost all WS at 9:00 a.m. and positive for almost all WS at 12:00nn.

Figure 9b shows for June 21 the improvement in thermal comfort. It ranges between –1.3% (WS4 at 3:00 p.m.) and 5.4% (WS9 at 3:00 p.m.). Work spaces 1, 2, and 9, located next to the façade, all improved for 9:00 a.m., 12:00 a.m. and 3:00 p.m. on 21 September. For September 21 the improvements range between –3.8% (WS8 at 3:00 p.m.) and 18.9% (WS9 at 5:00 p.m.) as shown in Figure 9c. Finally, improvement in thermal comfort for December 21 is shown in Figure 9d. At noon, it ranges between 0.8 and 11.2% improvement while at 9:00 a.m. and 3:00 p.m. the range is between -0.8 and 1.8%.

Figure 10 gives the summarized comfort improvements (PPDI) for all work spaces for the airflow window (AFW). All analyzed dates show an improvement except for 21 March, 9:00 a.m. Most significant is the improvement for 21 December with a PPDI = 65%. Overall the analysis shows significant comfort improvement for the airflow window compared to the base case.

FIGURE 9A. Comfort improvement (PPDI) for March.

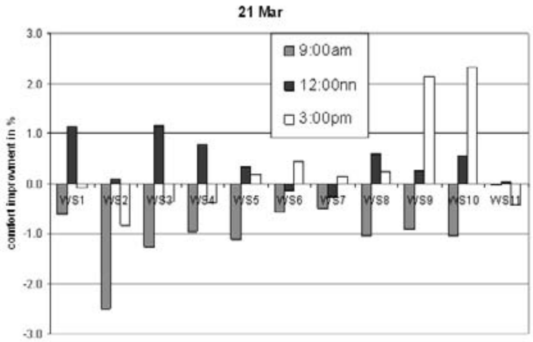


FIGURE 9B. Comfort improvement (PPDI) for June.

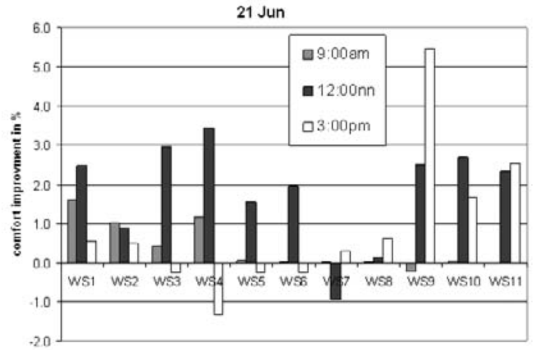


FIGURE 9C. Comfort improvement (PPDI) for September.

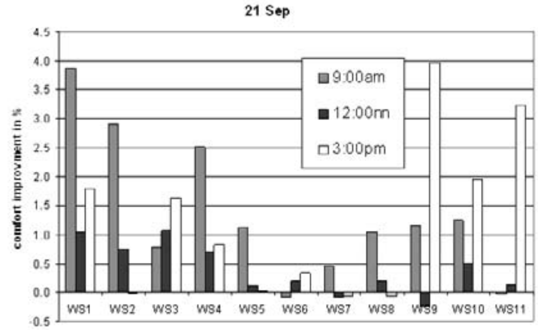
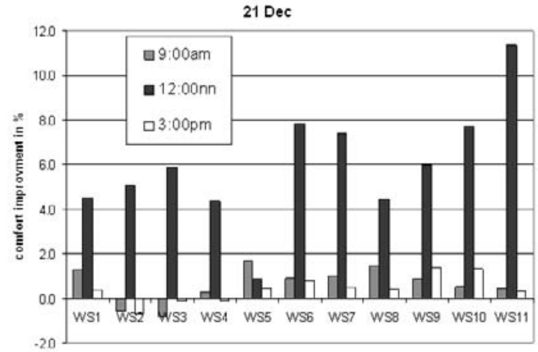


FIGURE 9D. Comfort improvement (PPDI) for December.



4.3. Daylight Analysis

The DF and DA have been calculated for different façade configurations. First, DF and DA at different positions within the room for the base case (bc1) have been calculated. Then, the same room with different façade system configurations has been compared.

FIGURE 10. Comfort improvement (PPDI) summary throughout the year.

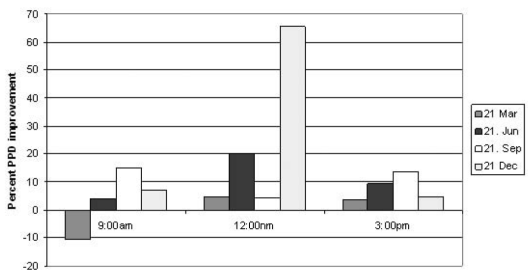


Figure 11 shows the DF and DA distribution in the room for the base case at different positions in the room. It can be seen that the DF and DA is almost the same for centre, left, and right position. The lower DF for the centre position near the façade is due to the vertical frame of the windows. Daylight Factor (DF) is for 51% of all illuminance sensors 2% or higher. From a distance of 4.2m from the façade DF fallS below 2%. DA is 85% near the façade and drops to 40% in the rear of the room with DA at the centre of the room of 62%.

For better comparison the DF and DA of different façade system configurations in the centre of the room have been extracted and summarized in Figure 12. It can be seen that the use of a DSF (dsf1) improves DF significantly. Near the façade DF reaches 12% and drops to 3.4% in the centre of the room. In

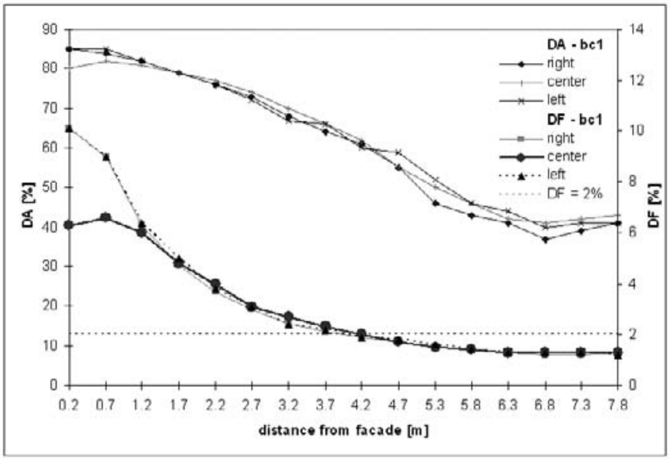


FIGURE 11. Results for daylight factor (DF) for CIE overcast sky and daylight autonomy (DA) for whole year for bc1 at different positions in the room.

further depth of the room DF drops further but not below 2%.

It could be demonstrated that the daylight performance of a DSF system is better than the base case curtain wall.

5. CONCLUSIONS

This work tried to establish a list of performance criteria that can help to design sustainable façades. In order to achieve this, the façade performance has been assessed with three different criteria; energy, thermal comfort and daylight. First, the façade related energy consumption was minimized. Here, it became obvious that a naturally ventilated façade can reduce the cooling load by up to 12%. For mechanically ventilated airflow windows the energy performance strongly depends on the control strategy of the exhaust air. Only if the air that went through the ventilated cavity is redirected with the help of a climatic regulator substantial cooling load savings are possible.

Then, comfort criteria have to be met. A climate responsive façade design can further enhance the comfort of the occupant. The results show that the thermal comfort, expressed by PPD and PMV, in the room improves if the room is equipped with a ventilated double-skin façade. Especially when the lower sun angle increases the impact of solar radiation on

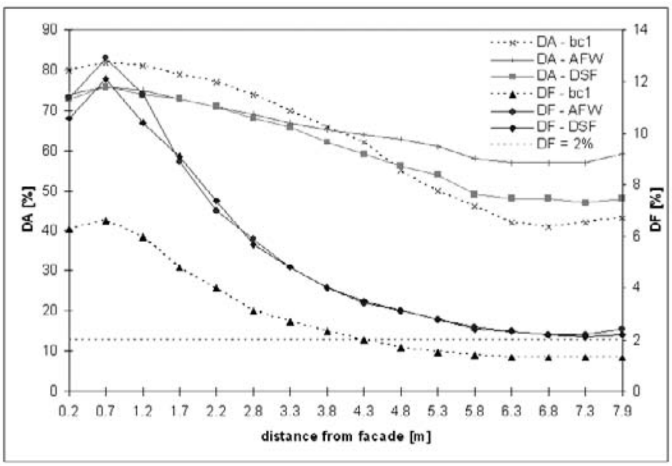


FIGURE 12. Results of comparison for DF and DA in the centre of the room.

the cooling load, the double-skin façade provides increased thermal comfort because it removes the cooling load directly from the source.

Finally, a detailed daylight assessment of the façade systems has been done. The analysis showed a performance improvement of the DSF system compared to the base case. Here, the advantage of using clear glass for both layers results in higher daylight factors. The daylight factor could be increased above 2% for the whole room depth of eight meters. Daylight autonomy can be improved especially in the depth of the room. This indicates the potential for further reduction of the use of artificial light. Therefore, a control mechanism for artificial lights should be provided to foster the potential energy savings. Further studies are needed in order to quantify possible energy savings resulting from a reduction of the use of daylight.

Sustainable building involves considering the whole life of buildings, taking environmental quality, functional quality, and future values into account. Sustainable building design is therefore the thoughtful integration of architecture with electrical, mechanical, and structural engineering resources.

Computer simulation and analysis of different building elements can help to determine the performance according to a set of design parameters. Environmental impacts due to energy consumption are an important parameter, but it is believed that comfort criteria need also to be accounted for.

Planned work for the future includes:

- Solar assisted extract air device: The opportunity for solar assisted ventilation will be examined in detail.
- LCA of different façade systems: Sustainable building involves considering the whole life of buildings, taking environmental quality, functional quality, and future values into account. Sustainable building design is therefore the thoughtful integration of architecture with electrical, mechanical, and structural engineering resources. An extended version of life cycle assessment (LCA) might help to establish objective benchmarks and design criteria for the integrated design process with a multidimensional modeling approach (Wong and Amato 2003).

NOMENCLATURE

Symbol	Description	Unit
AFW	Airflow Window	
clo	Clothing level	—
DF	daylight factor	%
DSF	Double-Skin Façade	—
E α (x)	illuminance at x due to S α	—
E(x)	illuminance at point x	lux
Ehor outs	outdoor horizontal illuminance	lux
f_{cl}	ratio of clothed surface to nude surface area	—
h_c	heat transfer coefficient	—
I_{cl}	thermal resistance of clothing	(m^2K/W)
L α	luminance of S α	—
MET	Metabolic rate	—
pa	partial water vapour pressure	Pa
PMV	Predicted Mean Vote	—
PPD	Percentage People Dissatisfied	%
PPD_{AFW}	Percentage People Dissatisfied Airflow window (AFW)	
PPD_{BC}	Percentage People Dissatisfied of basecase (BC)	
PPDI	Percentage People Dissatisfied Improvement	
RH	Relative humidity	%
S α	sky segment P	m^2
T_a	Dry bulb temperature	°C
T_{cl}	Clothing surface temperature	°C
T_r	Mean radiant temperature	°C
v	Air movement	m/s
v	air velocity relative to the body	m/s
WS	Work Space	
x	point in a building	—
ΔS α	angular size of S α	

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