THERMAL ENVIRONMENTS OF AN OFFICE BUILDING WITH DOUBLE SKIN FACADE

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ABSTRACT

As a symbol of green architecture, double skin facade (DSF) represents a design which possesses many energy saving features, but due to the complexity of the system, the real performances and benefits have been difficult to predict. The objective of this study was to inform the applicability of DSFs, and contribute to the positive impacts of DSF designs. This study compared and contrasted energy savings in a temperate climate, where heating was the dominant energy strategy, and in a subtropical climate, where cooling spaces was the dominant issue. This paper focused on a university office building with a west facing shaft box window facade. The research method was a paired analysis of simulation studies which compared the energy performance of a set of buildings in two different climates. Simulation results showed a good agreement with measurements undertaken in the exiting building during a two-week period. The results specified that DSFs are capable of almost 50% energy savings in temperate and 16% in subtropical climates. Although these indicated DSFs are more suitable for temperate climates than warmer regions, the amount of energy savings in subtropical climates were also considerable. However, due to the costs of DSFs and potential loss of leasable floor area, investigations into other feasible ventilation options are necessary before final building design decisions are made.

KEYWORDS

double skin facade, shaft box window facade, building envelope, building simulation, climate design, energy savings

1. INTRODUCTION

The building envelope separates the interior and exterior environments and protects building occupants from differing climatic conditions (Bougdah & Sharples, 2009). Consequently, the design of the building skin is a key architectural factor in determining indoor environmental quality (IEQ) (Pomponi, IP, & PIROOZFAR, 2013). Since the beginning of the last century, with advancements in structural engineering and building services, the popularity of all glass envelopes has been constantly increasing. Highly glazed facades are now very popular particularly in office buildings (Lee, Selkowitz, Bazjanac, Inkarojrit, & Kohler, 2002). However, glass

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as a building material has a low profile regarding energy saving properties, and due to low resistance to heat exchange, contributes to large heating and cooling loads (Russell, 1996). Increased energy demands mean more harmful greenhouse gas emissions and more negative impacts on the environment (Dorf, 2001). Double skin facade (DSF) is a solution for the growing trends of glass facades and green architecture (Lee et al., 2002; Saelens, Carmeliet, & Hens, 2003). However, considering the high construction and maintenance costs of DSFs, it is not an easy task to make a judgment about the financial and environmental feasibilities. Some researchers believe that DSFs are economically infeasible and long payback periods are predicted (Chan, Chow, Fong, & Lin, 2009). Research (Gertis et al., 1999; Lee et al., 2002) also indicated that not all DSF buildings meet their design objectives and hence do not contribute to lowering building energy demands and so there is great difference in the energy impacts of these types of buildings with DSF.

1.1 Theoretical background

DSFs are normally naturally ventilated and consist of an operable double-glazed window and an outer layer of safety or laminated glass separated by an air cavity of 20 cm to 2 m for easy maintenance access. The air cavity acts like an insulation and blocks the direct wind, noise and heat exchange between the interior and exterior (Oesterle, Lieb, Lutz, & Heusler, 2001). DSF systems employ passive solar principles to provide passive solutions for space heating and cooling purposes (Zöllner, Winter, & Viskanta, 2002). DSFs provide protections for shading devices in the air cavity, which also acts as a thermal buffer in all seasons (Pasquay, 2004; Zhou & Chen, 2010). Security levels are also higher for night-time ventilation and natural ventilation with fewer noise problems.

The disadvantages, however, have been debated by many researchers such as overheating in hot seasons, higher costs of construction and cleaning, higher usage of floor area, internal noise, and an increased chance of fire spreading through air cavities. As a literature review suggests, green buildings have stronger business cases in the commercial sector, such as lower operation costs and higher market values (Gou & Gou, 2016; Khoshbakht, Gou, & Dupre, 2017). Similarly, buildings with DSFs are supposed to have a higher profile in the real estate market. However, DSFs still require further investigation in order to verify feasibilities and real benefits.

1.2 Literature review

In the literature, many research studies have attempted to draw design guidelines for DSF applications and contribute to the environmental performance of these building envelope systems. In many studies, computer simulation modellings have been used for the dynamic study of DSF systems. Computer modelling of DSFs is particularly difficult due to the complexity of the dynamic design and operational system (Barták, Dunovská, & Hensen, 2001; Høseggen, Wachenfeldt, & Hanssen, 2008). DSF performance predictions by simulation methods highly depends on the accuracy of the computer model (Barták et al., 2001). Some guidelines for DSF modelling are available in a study by Dickson (2004). In a simulation study (Høseggen et al., 2008), an east facing DSF was examined and the results showed that energy demands for heating a room with a basic single skin window is 20% higher than the same building with DSF. Another study (Saelens, Roels, & Hens, 2008) disclosed that heating and cooling demands were reduced significantly by implementing heat recovery systems and controls over airflow rates. Some research in DSF has focused only on the heat transmission (heat loss and gain) through the façade (Safer, Woloszyn, Roux, & Kuznik, 2005; Zöllner et al., 2002). However, Saelens et al. (2003) indicated that instead of heat transfer in air cavities, a whole building energy analysis is imperative for reliable performance evaluations.

It was reported (Kim, Lee, Kim, & Kim, 2011) that DSFs best performed under sunny climatic conditions in terms of saving energy, and ventilation efficiency. The performance of DSFs in hot climates has been studied in a few research papers (Baldinelli, 2009; Hashemi, Fayaz, & Sarshar, 2010) and significant improvements in energy behaviour were reported compared to conventional glass walls. The effect of glazing type, window size, urban context, and orientation on the performance of DSF in the hot and humid climate of Hong Kong was also studied in a few research papers (Haase & Amato, 2006; Haase & Amato, 2009; Haase, da Silva, & Amato, 2009; Haase, Wong, & Amato, 2007). The importance of façade design and window sizing was indicated in the research. South, south west and south east facing DFSs were recommended to maximize the DSF's efficiency. The authors also suggested that it was possible to design an energy efficient DSF in this climate, however, comparative numerical values and energy savings were not mentioned. Wong et al. (2008) indicated that the type of ventilation in the air cavity and DSF type had great influence on the success and failure of the project. While, these studies have provided some guidelines, there is still a need for further examination of DSF appropriateness and potential benefits across different climatic locations. This paper aimed to investigate the applicability of shaft box window facade in temperate and subtropical climates.

2. PURPOSE OF THE STUDY

As the literature indicated, the application of DFS technology is attributed with several potential advantages. However, it was claimed that DSFs are not suitable for every climate and there is a lack of design guidelines for climatic appropriateness in climates such as subtropical. Most DSFs have been constructed in temperate climates and the literature has claimed huge energy savings for heating in these climatic regions, but there are only a few design guidelines and research performed in other climates where heating was not the most dominant issue. Currently, a considerable number of DSF buildings are appearing in other countries like Australia, where cooling loads are the main concern. This is a very common mistake that European style green architecture is built in climates such as subtropical with no supporting research of climatic suitability. On the other hand, universities are now being built not only to provide a place for study, but also to encourage and inspire innovative ideas through utilizing cutting edge technologies and creative designs (Lau, Gou, & Liu, 2014). DSFs as one of the advanced methods of ventilation systems were used in many university buildings globally and their real benefits need to be better understood.

This paper aimed to conduct a comparative study of energy loads across two different climates and to find a seasonal variation in the performance of DSF and its energy saving benefits. The simulation results were validated with measured data performed in an existing building with DSF in Sheffield, the UK (Altan, Refaee, Mohelnikova, & Kim, 2011). The measurement campaign was conducted over a period of several weeks from April to May 2010. The model validation process was an important part of the project and increased the validity of simulation results. This is a comparison study of energy loads between an optimized tripled glazed single skin facade and an optimized double skin façade in two different climates, the English temperate and the Australian subtropical.

3. METHODOLOGY

The methodology involved in this study was a paired analysis of simulation results. Two design variables, the existing building with the west facing DSF; and the paired building with super insulated triple glazed windows replaced with DSF, were analysed in two different climates.

3.1 The Base Building

The base building of this study was a university office building, the Jessop West, at the University of Sheffield in the UK. Sheffield is the capital city of South Yorkshire County and one of the major cities in England in terms of population and past industries (see Figure 1). In the Jessop West building, DSF was orientated towards the west to block the noise pollution from a busy road. However, when making this decision environmental consequences were not adequately considered.

The building is located to the east of the busy Upper Hanover Street and south of Broad Lane (see Figure 2). It is orientated north-south, but there is a passageway through the building to encourage pedestrian movement and increase the security of the building, especially on the east side. There is a setback on both the west and south sides of the building to create two plazas for community engagements.

FIGURE 1. The location of Sheffield City in the UK is marked red on the map (© Google Earth).

FIGURE 2. The Jessop West context plan and key site planning strategies (© Google Earth).

A central atrium is located at the main passage point at the apex of the three wings. Each wing is occupied by three different university departments. Shared facilities are located around the atrium and at the junctions of the wings. Figure 3 illustrates a typical plan of the floors. The ground floor is mainly for public use and student facilities with a reception. The upper floors are dedicated to department facilities and staff offices. The ground floor has a double-glazed curtain wall construction with a U-value of 1.9 W/(m^2K). Except for the west façade, all upper floor windows have triple glazing with U-values of 2.0 W/(m^2K). The entire west elevation is DSF with a U-value of 1.5 W/(m^2K). The wall construction consists of an insulated double layered concrete wall, and an enamelled glass panel on the outer skin, with a total U-value of 0.3 W/(m^2K). The floors are insulated with exposed concrete slabs with U-values of 0.22 W/(m^2K). The green roof on the building's top has a U-value of 0.2 W/(m^2K) and along with the exposed concrete regulates a large thermal mass for the structure. Table 1 summarises the thermal insulation values of different components of the studied building. As this building is a prefabricated structure, the U-values were calculated and tested during the construction in the factory, so the U-value figures in Table 1 are the manufacturer's specifications. Due to the different gap sizes between the glass layers and the insulation gas types, the U-value of the window type 1 with triple glazing is slightly higher than the window type 2 with double glazing.

Table 2 shows some basic information about the design and construction of the building. The University of Sheffield launched a competition for an eco-friendly building to accommodate the Department of History, the School of English, and the School of Modern Languages and Linguistics. The Berlin-based, Anglo-German practice, Sauerbruch Hutton won the

TABLE 1. Summary of the Main Construction Components and the U-Values.

Construction component	Location	U-value W/(m^{2}K)
Window type 1—triple glazed	Upper floors in north, east and south elevation	2.0
Window type 2—double glazed	Ground Floor	1.9
Window type 3—double skin	Upper floors in west elevation	1.5
Floor—exposed concrete	All floors	0.22
Wall—double layered back coloured enamelled glass panel	Upper floors	0.3

FIGURE 3. The Jessop West typical floor plan showing distribution of communal spaces, service rooms and cellular and open plan offices.

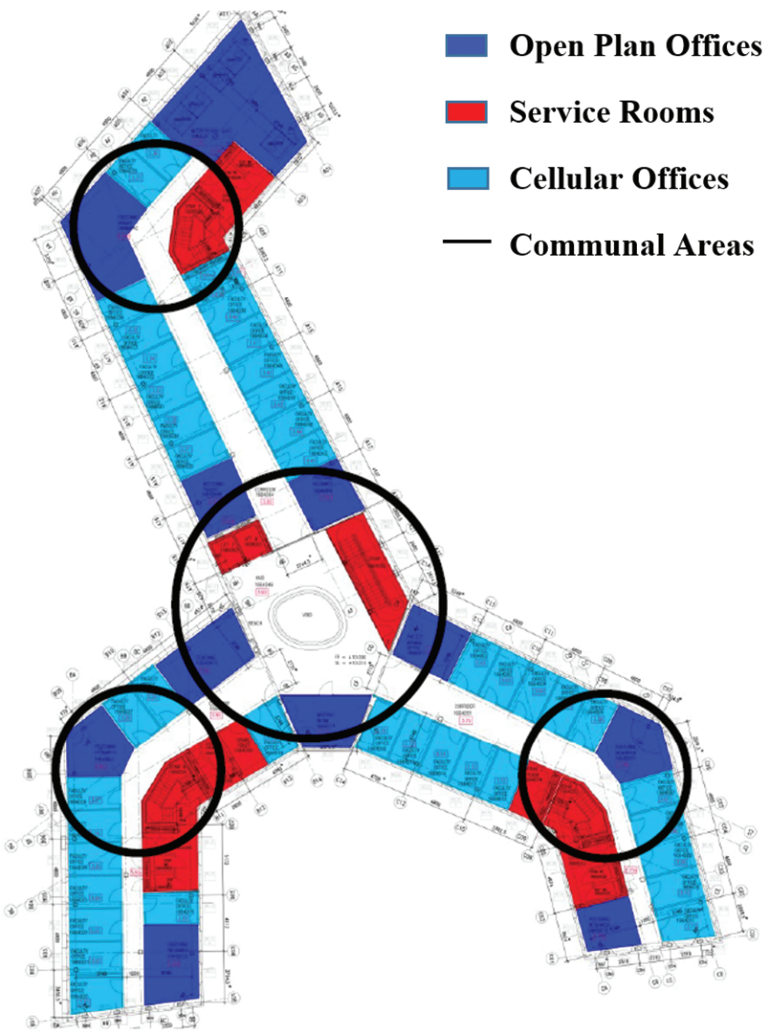


TABLE 2. Brief details of the project completed in 2009.

Project Name	Jessop West, Sheffield, UK
Construction period	2005–2009
Floor area	5,880 m^2
Project budget	£21.2 m
Location	Sheffield, UK
Climate	Temperate
Coordinates	53°22'0 N, 1°30'0 W
Context	Urban
Architect	Sauerbuch Hutton and RMJM
Structural and M&E Consultant	Arup
Building type	Education
Project Manager	Turner and Townsend
Structure	In-situ concrete structure
Style	High-Tech modern
Tenants	Arts and Humanities Department
Client	University of Sheffield
Building Height	20 m
Number of occupants	400 staff
Indoor Window Head Height	2.4 m

competition interview to design a master plan for the Jessop Hospital site in 2005. The winning design was a model of sustainability with environmentally friendly features. The project brief instructed the development of the design, up to Stage C (outline proposals) and collaboration with RMJM architects for the rest of the project. The facade was prefabricated by the subcontractor, Schneider, in Germany and brought to Sheffield.

3.2 Natural ventilation

Figure 4 illustrates the operation of the DSF on the west elevation, which is a shaft box window with a naturally ventilated air cavity. The air enters the cavity from underneath through an acoustic labyrinth. The offices have operable double-glazing windows to the ventilated cavity. The cavities have vents to solar chimneys at the top on each side. The vertical air shafts (solar chimneys on the sides of the window) have external coloured glass cladding. The stack effect in these air shafts directs the air upwards and siphons it out from the roof level. There are no air-conditioning or mechanical ventilations in this building.

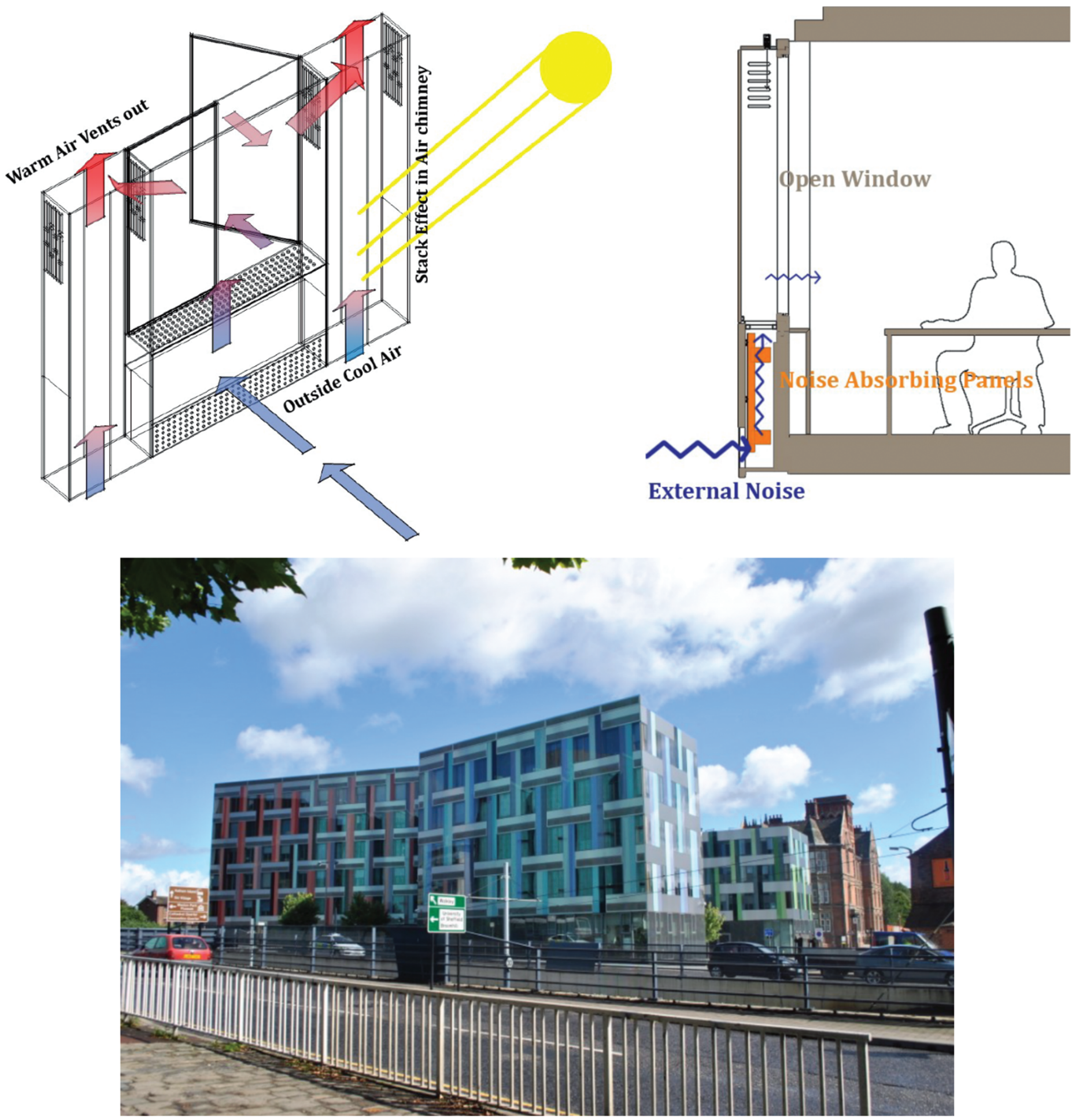


FIGURE 4. Top Left: Ventilation system of DSF of Jessop West; Top Right: Acoustic panels in DSF of Jessop West; Bottom: DSF's configuration.

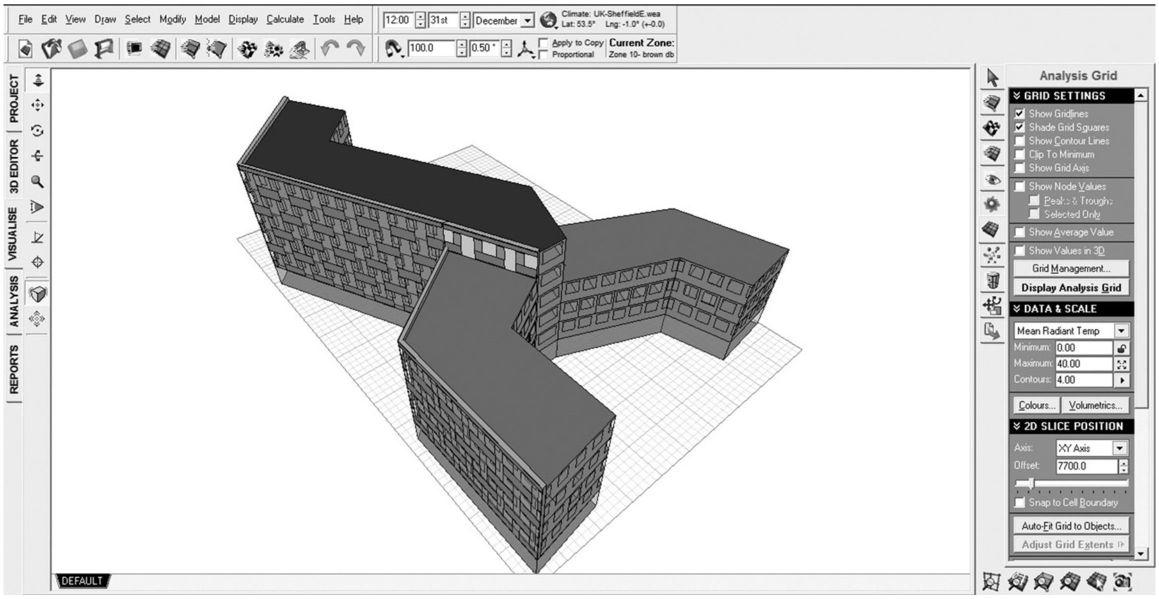
4. DSF MODELLING

4.1 Simulations

The quantitative analysis was conducted using the Ecotect software (Figure 5). Ecotect is an energy simulation tool which has a dynamic analysis engine, and has a wide range of detailed analysis tools for a building's energy performance.

The Ecotect model was drawn to have a high similarity to the existing building. The outer and inner skins were drawn as two walls separated by the air cavity, which is 500mm. The working desk area was defined as the workstation surface at 0.9m above the floor and with

FIGURE 5. Double skin facade modelled in the Ecotect.

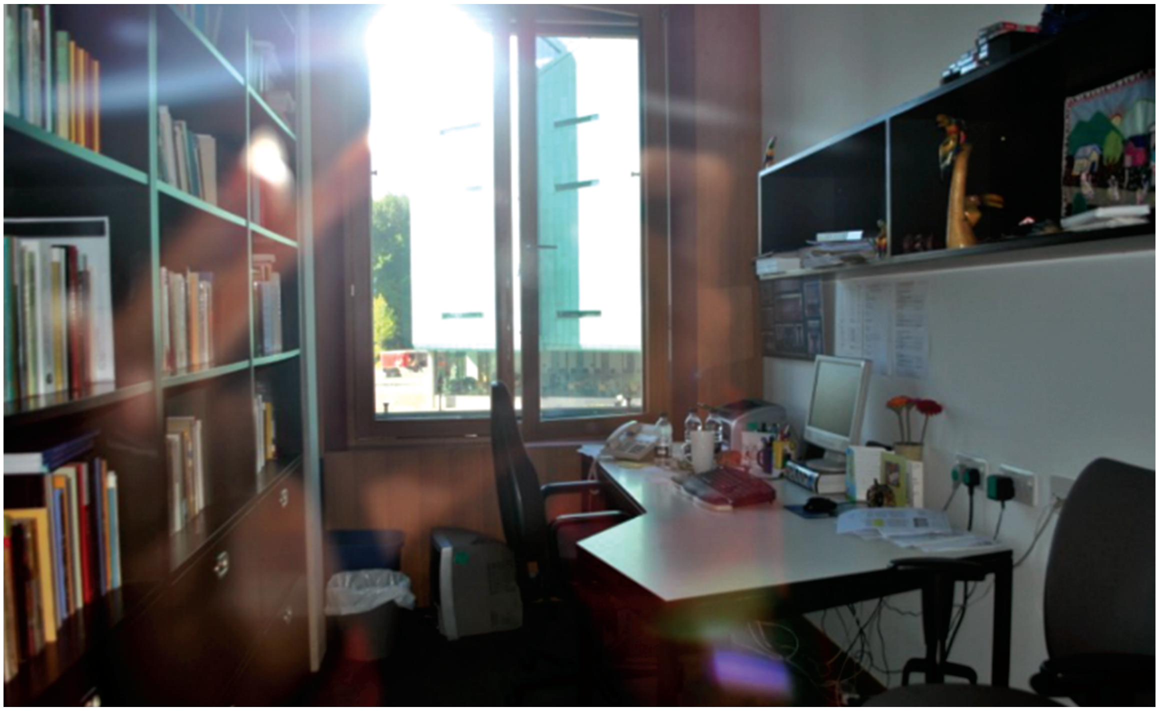


a desk width of 0.9m. In the Jessop West building, the desks in all the rooms are on the side with the person sitting behind each desk facing the side wall. Figure 6 shows the desk orientation and location in a typical cellular office. Simulation results of the existing buildings were first compared with a paired building with triple glazed windows with a U-value of 1.5 W/(m^2K). Another comparative study was conducted in the subtropical climate of Queensland in Australia, which compared the applicability of this type of DSF (shaft box window) in warmer climates, and identified energy savings, and climatic appropriateness.

The input data of simulations with ECOTECT are climatic parameters as well as equipment efficiency, occupation pattern, building material properties, infiltration, air change rate and internal heat gains from computers and occupants. The operation of windows was set from 7 a.m. to 6 p.m. during seven days a week. An air change rate of 0.50ach was set for internal windows of the offices and the inlet vents on the outer skin of the DSF were arranged to be open 24 hours during the whole year. Air speed of 0.30 m/s and wind sensitivity of 0.25 was set in the model. The internal gains from occupants and computers were also scheduled from 7 a.m. to 6 p.m. for the whole seven days. Values for both lighting and small power loads per unit per floor area were set 5 W/m^2 for sensible gain and 2 W/m^2 for latent gain on the same schedule of occupancy. Occupancy level is one person and one computer per 12 m^2. Occupant activities are defined as 70 W for clerical work based on the same schedule as above. In order to evaluate the actual building loads, no active heating or cooling systems were arranged in the simulation. The material properties and U-value calculations were based on the manufacturing specifications and parameters. Modelling of the shaft box facades, which are similar to one-storey height modules, were adapted from Dickson (2004). The modules were linked with building high vertical shafts by a bypass opening. The air enters the box windows and the stack effect in the vertical shafts sucks the air in from the sides and lets it out from the top.

Factors which were simulated in this study included discomfort degree hours, number of hours and time percentage in the comfort band, gains and losses breakdown, monthly degree

FIGURE 6. Cellular office window and working desk configuration.



days and energy savings. Heat transfer through a double skin façade is influenced by several mechanisms and factors influenced by the window physics, which impact solar radiation, conduction, and convection processes (Garde-Bentaleb, Miranville, Boyer, & Depecker, 2002; Haase & Amato, 2006; Peng, Lu, & Yang, 2013; Xu & Chen, 2001) (See Figure 7). One of the weaknesses of the simulation with this software is that it does not consider long-wave radiations of the shading devices (Kapur, 2004). As a result, the effect of roller blinds is ignored in this modelling and it is assumed that blinds are open constantly. Overall, energy demand of the building is calculated by deducting gains from the overall losses (Schlueter & Thesseling, 2009). The breakdown of gains and losses gave detailed values by different heat exchange processes through ventilation, fabric and solar radiation. The breakdown of passive gains are comprehensive statements regarding the status of heat loss and gain in buildings (Goussous, Siam, & Alzoubi, 2015).

In the model, conductive heat gains, Q_c in W, was obtained from Equation (2):

$$Q_c = U * (T_o - T_i) * A \quad \text{Eq. (2)}$$

(Hakansson, Höjer, Howlett, & Jain, 2013)

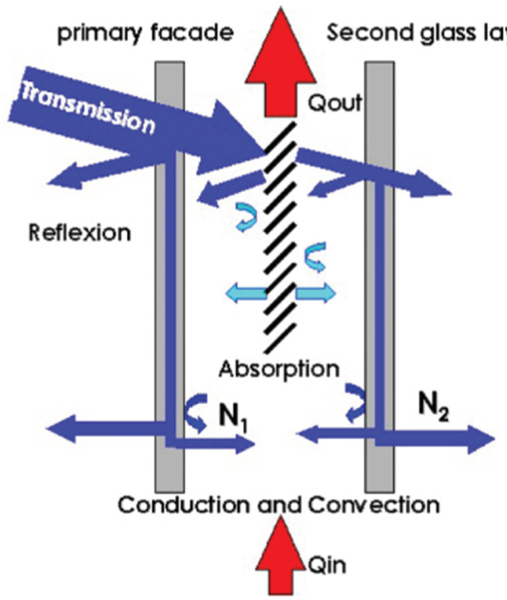
Where U was the thermal transmittance of the surface ($W/(m^2K)$, T_o was the outside temperature (°C), T_i was the temperature inside (°C), and A was the surface area (m^2).

Heat transmission through solar radiation, Q_g in W was calculated with the Equation (3):

$$Q_g = SHGC * E * A \quad \text{Eq.(3)}$$

(Hakansson et al., 2013)

FIGURE 7. Heat Transmission through DSF by conduction, convection and radiation (Haase & Amato, 2006).



Where SHGC was the solar heat gain coefficient in W, E was the total incident solar radiation on the transparency/translucent surface in W/m^2, and A was the glazing area in m^2.

Based on Stephen-Boltzman law (Harris, Miller, & Thomas, 1985), for calculation of the SHGC, the simulated direct solar gain of each glass block model ($Q_{g\text{-}glassblock}$) is divided by that of 3 mm standard glass ($Q_{g\text{-}3\ mm}$), and it is obtained from equation (4), which is based on a calculation of Losses and Gains with the admittance method:

$$SHGC_{glassblack} = (Q_{g\text{-}glassblack}/Q_{g\text{-}3mm}) * 0.87 \qquad \text{Eq. (4)}$$

(Binarti, Istiadji, Satwiko, & Iswanto, 2013)

$Q_{g\text{-}glassblack}$ is the simulated direct solar gain in W, and $Q_{g\text{-}3mm}$ is the simulated direct solar gain of 3mm standard glass.

Discomfort degree hours were the number of degrees by which the hourly indoor temperature was below or above the comfort band. Based on a full year hourly data, simulation calculates the number of hours which thermal discomfort occurred based on the adaptive thermal comfort models described by (de Dear & Brager, 2002; Nicol, 2013). The Ecotect calculations of thermal comfort is based on Equation 1.

$$T_{comfort} = 11.9 + 0.534\ T_{average} \qquad \text{Eq. (1)}$$

(Palme, Guerra, & Alfaro, 2014)

4.2 Climate

This research purposed to compare the applicability and energy savings of a shaft box window facade in two different climates, one with high heating loads and the other with high cooling demands. The base building was located in Sheffield, which represented the temperate climate of the UK. Sheffield is located at 53.3° N, 1.4° W and 131 m above average sea level and has a Temperate Oceanic Climate. The main principles of a Passivhaus design are applied in this climate to cope with the seasonal variations. Heating in winters is the dominant issue in temperate climates. High thermal insulation for building envelopes, high thermal mass and optimization of solar exposure is recommended for this climate.

Brisbane represents the subtropical climate for this study. It is located at latitude 27.4° S, 153° E, and 38 m above the average sea level. The climate of Brisbane is defined as subtropical with much smaller seasonal variations compared to Sheffield. Summers can be very hot and humid with mean temperatures of 25° C. Winters are normally very dry with mean temperature of around 15° C. There is a 10° C temperature difference between day and night in winters. Insolations are quite high and the control of solar exposure in different seasons is the major issue. The solution for moderating the temperature and humidity is in utilizing sophisticated ventilation systems.

4.3 Modelling

Two building facade treatments and two climates were modelled in this study. Table 3 presents a summary of the details of the four studied buildings. Building 1 is an existing building located in Sheffield with west facing DSF. Building 2 is in the same location with Building 1, but with a different west facade treatment. Here, triple glazed windows with a U-value of 1.5 W/(m^2K) and the same size DSF internal windows replace the west facade. Building 3, located in Brisbane, had the same DSF identical to Building 1, but located in Brisbane. Building 4 is identical to Building 2, and located in Brisbane. In all, the simulation studied the third floor was studied for simplification of the model and to reduce the simulation running time. All the internal walls on the third floor were also modelled.

The DSF air cavity was modelled as a separate zone from the floor. The whole floors were drawn as a single thermal zone. Other floors were also modelled as a single thermal zone, but with no internal partitions. One simplification in the modelling was that the adjacent structures were not modelled, so solar obstructions caused by the neighbouring buildings were ignored in the models. Another simplification in the model was that the circular atriums in the intersections of the apex were not modelled to reduce the complexity of the model.

TABLE 3. Summary of the details of the four studied buildings.

Building	Climate	Building feature	Studied floor
B 1	Temperate	Building with DSF (U-value 1.5 W/(m^2K)) in the west elevation	3rd
B 2	Temperate	Building with triple glazed windows (U-value 1.5 W/(m^2K)) in the west elevation	3rd
B 3	Subtropical	Building with DSF (U-value 1.5 W/(m^2K)) in the west elevation	3rd
B 4	Subtropical	Building with triple glazed windows (U-value 1.5 W/(m^2K)) in the west elevation	3rd

4.4 Validation of the model

The measurement campaign was conducted in the selected building spaces over a period of several weeks from April to May 2010. This measurement process was part of a larger study which focused on a post occupancy evaluation of the building. Detailed description of the measurement campaign and the post occupancy evaluation results can be found in a paper by Altan et al. (2011). Monitoring apparatus sets were HOBO U10-003 data loggers, which were placed at the height of the breathing zone of a person sitting on a chair. This is approximately 1.5m above the floor, and away from operable windows. Occupants were also requested to continue their normal routine of opening windows during the monitoring period.

For the purpose of the model validation, mean daily indoor temperatures of a single typical office (room 1.15) in the west wing were scrutinised for a period of time from 7th to 18th May. The measured outdoor temperatures were also compared to simulated values and an average temperature based on a 5-year period of historical climate. As shown in Figure 8, the simulated outdoor temperatures are slightly higher than measured values from 7th to 16th of May and slightly lower than measured values during the last three days. Following the pattern of outdoor condition variation, the simulated indoor temperatures are also slightly higher than the measured data. This means that the measured year was a slightly cooler year if compared to the 5-year average climate and simulated weather data, which explains the discrepancies between simulated data and measured data. The Ecotect similar to many other thermal simulation packages uses weather data which has been developed based on long-term weather recordings from weather stations. This means that weather conditions in a given year will not necessarily be identical with a weather data. Considering the possibility of errors in measured data and the fact that a single measured year cannot represent the typical longitudinal weather patterns, the simulated results and measured results show an acceptable agreement especially if mean temperatures over the monitored period are compared (Figure 8).

FIGURE 8. Indoor simulated and measured data of room 1.15 plus outdoor simulated, measured, a 5-year average. Mean temperatures over the studied period is also shown at the end of the line.

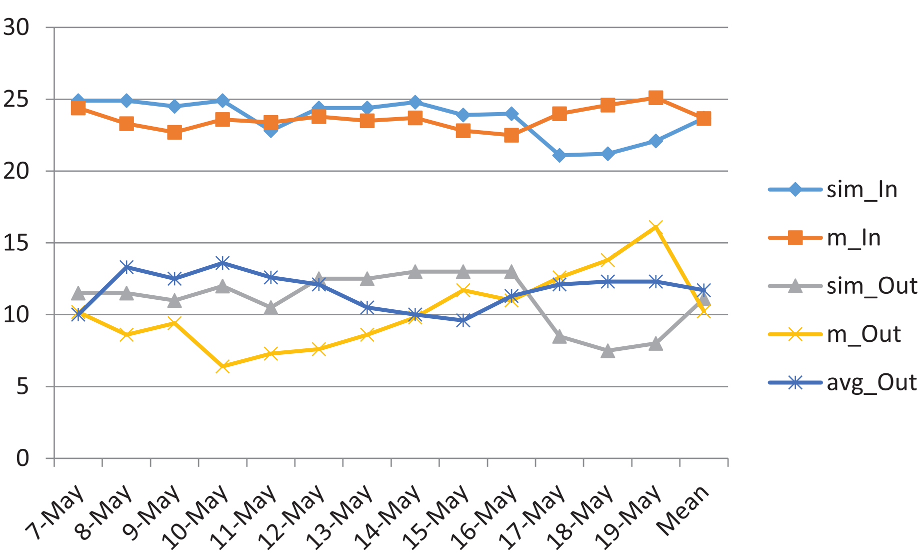
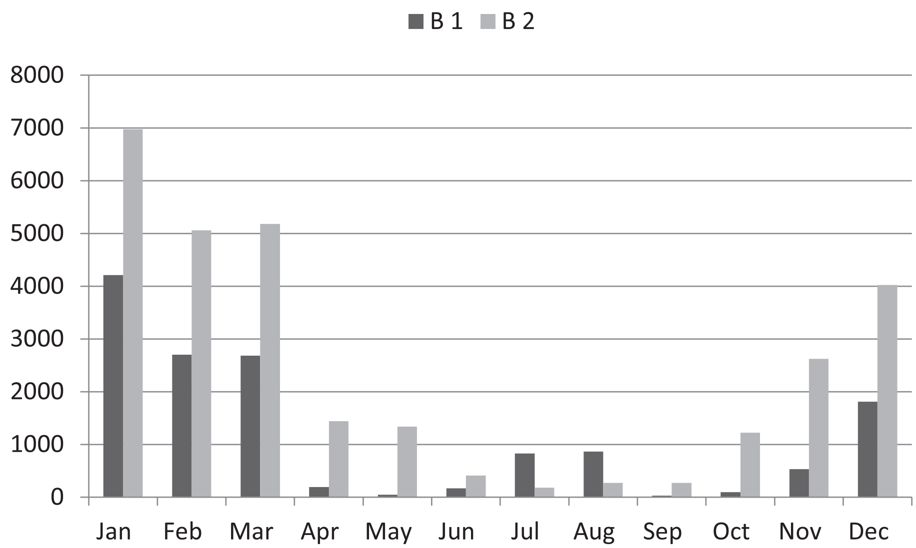


FIGURE 9. Comparison of total discomfort degree hours (DegHrs) of building 1 and 2 (Northern hemisphere).



5. RESULTS

Figure 9 shows the simulated monthly total discomfort degree hours for Buildings 1 and 2. The observations of the results showed that Building 2 had dramatically higher degree hours. However, in July and August during the cooling season, discomfort degree hours of Building 1 were higher. This indicates that the DSF decreased the total discomfort degree hours and heating demands, but caused overheating in the summer time. The breakdown of the heating and cooling degree hours as shown in Table 3 stated that the discomfort degree hours in the heating season in Building 1 with the DSF was dramatically lower than Building 2. The degree hours in the cooling season however, were higher in Building 1. The observations showed that the DSF in the temperate climate has the capability of lowering heating demands but less for the cooling demands.

Figure 10 shows the simulated monthly total degree hours for too hot and too cool for Buildings 3 and 4. In contrast to Buildings 1 and 2, in the temperate climate, building 3 with the DSF has just slightly lower degree hours in comparison to Building 4. This indicates that the DSF somewhat reduces the total degree hours for cooling demands.

TABLE 4. Annual degree hours breakdown of too hot and too cool hours.

Building	Too hot (DegHrs)	Too cool (DegHrs)	Total
B 1	1895	12271	14166
B 2	429	28980	29409
B 3	43931	0	43931
B 4	52524	0	52524

FIGURE 10. Comparison of the total discomfort degree hours (DegHrs) in building 3 and 4 (Southern hemisphere).

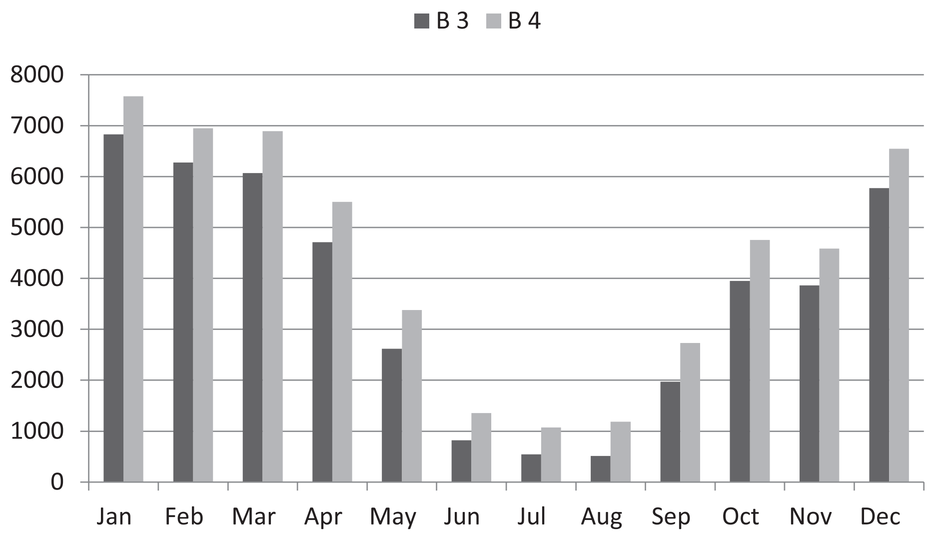


Table 5 shows the annual percentage of heat losses and gains through different means. The interesting observation here was that the ventilation losses were lower in Buildings 1 and 3, which both had DSF. This indicates that DSFs reduce heat losses through ventilation. Solar gains, on the other hand, were higher in Buildings 2 and 4. This is beneficial especially in subtropical climates, where optimizing solar gain is desirable. Fabric losses in the temperate climate were greater in Building 2. This showed that the DSF provided higher thermal insulation for the fabric and reduced heating demands. In the subtropical climate, heat loss and gain through the fabric, were lower in Building 3 with the DSF. This suggests that in subtropical climates, DSFs act as a thermal insulation for the building envelope.

TABLE 5. Simulated annual heat loss and gain breakdowns.

Building	B 1		B 2		B 3		B 4	
	Losses	Gains	Losses	Gains	Losses	Gains	Losses	Gains
Fabric	9.6%	0%	14.2%	0%	2.8%	0.3%	5.2%	0.4%
Solar air	0%	0.1%	0%	0.1%	0%	0.1%	0%	0.2%
Solar	0%	2.4%	0%	3.3%	0%	3.7%	0%	5%
Ventilation	59.5%	0%	62.1%	0%	14.6%	2%	19%	1.9%
Internal	0%	97.5%	0%	96.6%	0%	93.9%	0%	92.3%
Inter-zonal	30.9%	0%	23.7%	0%	82.5%	0%	75.7%	0.1%

FIGURE 11. Monthly energy loss (Wh) comparisons of Building 1 and 2 (Northern hemisphere).

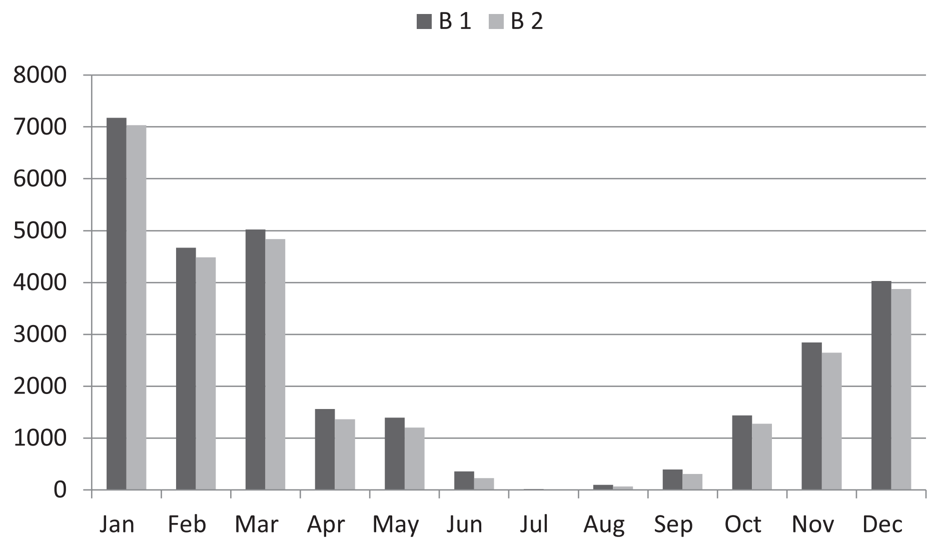


Figure 11 illustrates the monthly energy losses (Wh) of Buildings 1 and 2. The results showed that the total energy losses were only slightly different between the two buildings. However, energy gains, especially in summer time, were much lower in Building 1 with DSF compared to Building 2 (Figure 12).

FIGURE 12. Monthly energy gain (Wh) comparisons of Building 1 and 2 (Northern hemisphere).

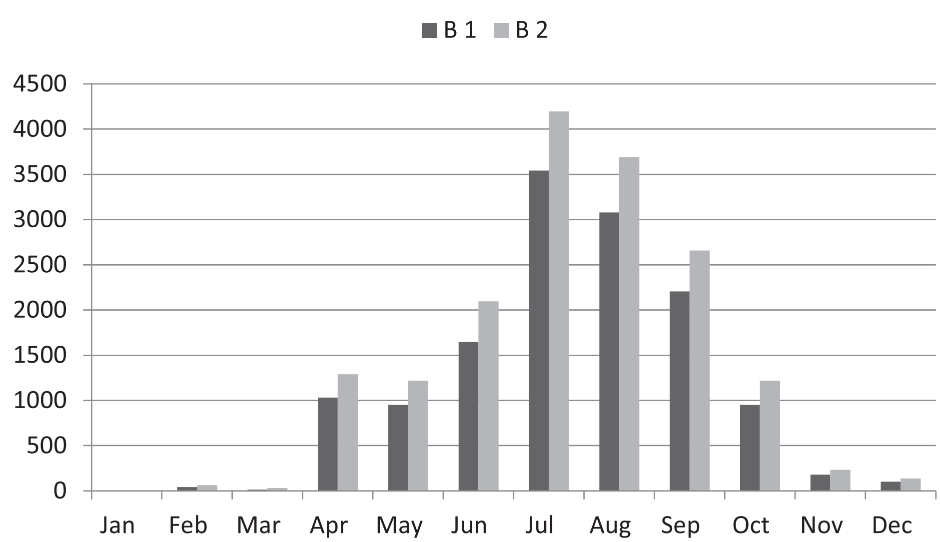
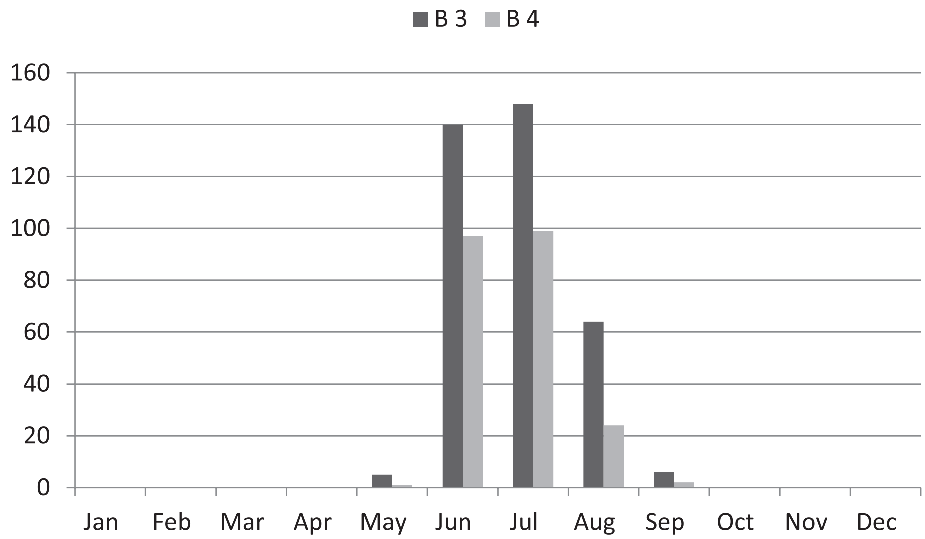


FIGURE 13. Monthly energy loss (Wh) comparisons of Building 3 and 4 (Southern hemisphere).



In the subtropical climate, the total energy losses in winter (Figure 13) were much greater in Building 3 with the DSF than Building 4. With less difference compared to heat losses, greater heat gains were observed in Building 4 (Figure 14).

Table 6 summarizes the total energy savings of the DSFs between the temperate and subtropical climates. In the temperate climate, DSF provided 51% energy savings for the building while, in the subtropical climate only 16% of energy savings were observed. This showed that, energy-wise, in the temperate climate, the DSF provided much higher savings compared to the subtropical climate.

FIGURE 14. Monthly energy gain (Wh) comparisons of Building 3 and 4 (Southern hemisphere).

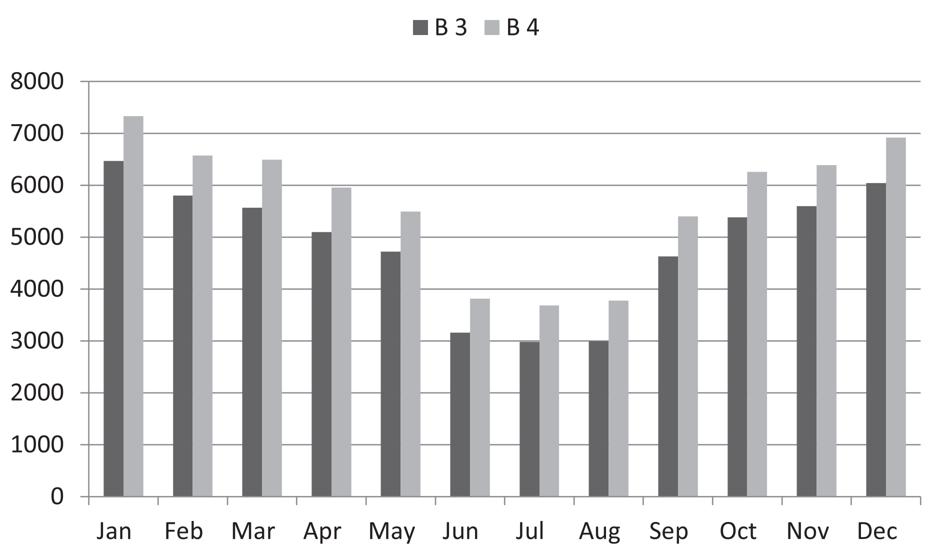


TABLE 6. Energy saving comparison between temperate and subtropical climate.

Climate	Energy Savings (%)
Temperate (B 1 and B 2)	51%
Subtropical (B 3 and B 4)	16%

6. DISCUSSION

In terms of energy, in the temperate climate the DSF outperformed the paired building with triple glazed windows by providing 51% energy savings. This building is just an example and the results of the simulation studies may be different from reality, but it can be concluded from the study that shaft box window facades have the potential to reduce energy demands by almost 50% in temperate climates. This type of DSF, however, had a lower performance profile in the warm climate in comparison with the colder region. Energy savings proved to be 16% in the subtropical region, which is still considerable in terms of energy savings. This means that DSFs in cooling dominated climates could be considered successful examples for reducing indoor temperatures and naturally ventilating buildings. Whereas, in subtropical climates, with consideration of the high costs of DSFs and only 16% energy savings, it is difficult to make a judgement whether DSFs are financially feasible. Overall, this research showed that a shaft box window facade had a higher performance profile in colder climates. However, the energy savings in warmer climates were not negligible.

In any construction projects, final decisions are based on the financial returns and payback times. Additionally, costs involved in construction projects are divided into two categories: running costs and capital costs. Energy savings contribute to lowering the running costs of buildings. However, running costs are only a small proportion in comparison to capital costs. As a result, energy saving could not be argued on its own to convince decision makers and building investors to choose a DSF option for building envelope designs. One limitation in this study was that the benefits of the DSFs were only focused on the energy savings. It is therefore recommended that in future studies other factors such as increased financial benefits due to higher productivity and occupant comfort may be analysed. In fact, other disadvantages of DSFs, such as floor area losses and maintenance expenses, should also be reviewed in addition to energy savings and increased productivity gains at decision making stages. Another limitation in this study was that the results only showed an example of a shaft box window facade's performance in two climates. Further investigation may be relevant to examine other types of DSFs in these climates and to compare energy performances. For future studies airflow through the air cavity will be simulated and will be coupled with thermal simulation analysis in order to further explore the efficiency of this type of DSF.

7. CONCLUSION

The objectives of the present work were to verify whether DSF buildings performed to their design objectives and provided considerable benefits over traditional windows. Two different climates, one heating dominated and the other cooling dominated, were chosen and climatic appropriateness explored. In the temperate climate, 51% energy savings were observed. Heating demands were especially reduced in the temperate climate, due to the fact that the DSF acted as a thermal buffer and minimized the heat losses through the fabric. Heat losses through the ventilation were also reduced slightly. Although solar gains were lower in the DSF building due to the extra outer layer, great improvement in the total energy performance of the building was observed. In the subtropical climate, much lower energy savings (16%) compared to the temperate climate were observed. In this climate, heat losses through the ventilation in the DSF were surprisingly lower compared with traditional window designs. Overall, DSFs in the subtropical climate outperformed simple window designs, but with lower success rates compared with the colder climates. In sum, it could be said that shaft box window facades are more economical in temperate climates than subtropical. However, further studies are required to generalise the idea to other types of DSF systems.

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