

Energy performance assessment of a naturally ventilated combined shaft-corridor DSF in an office building in Chicago

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ABSTRACT:

There is a great deal of interest in using double skin facade (DSF) strategies in new and retrofitted buildings, as they provide many possibilities for energy conservation, and at the same time create better thermal comfort. For hundreds of years, architects have tended to rely on intuitive guesses to design naturally ventilated buildings without detailed analyses. The lack of numerical airflow information that demonstrates the complexity and challenges in the domain of designing large naturally ventilated buildings is addressed in the literature reviews.

For these types of buildings it is important to have tools for analysis of design to evaluate a design's predicted performance in order to achieve successful natural ventilation concepts.

This study attempts to examine if the reliable simulation techniques verify the intuitive flow performance of double skin facades in a new configuration of natural ventilated building that results in reducing the energy demands yet provide both comfortable and healthy environments. The goal of this paper is to compare the base case of a typical office building in Chicago with two conventional DSF configuration and new (combined shaft-corridor) type.

CONFERENCE THEME: On Measurement

KEYWORDS: Energy performance, double skin facade, natural ventilation.

INTRODUCTION

With the emergence of energy-consumption reduction as a major national concern, the search for better approaches in improving both thermal comfort conditions and the energy efficiency of buildings is intensifying. Currently, low-energy building design features include lighting and controls, ventilation systems, and an improved building envelope. Lighting energy can be reduced through the use of natural daylighting, high efficiency fixtures and controls, such as occupancy sensors that turn lights off when there is no movement, and photosensors that reduce light output as needed to maintain a minimum level. These technologies, combined with architectural details like light shelves, high windows, external shading, and double-skin facades, increase natural daylight while reducing energy consumption associated with artificial light. Energy-consuming systems required for providing fresh air to meet indoor air quality requirements can be reduced or eliminated with the use of passive or hybrid technologies. Hybrid ventilation, or the use of natural and mechanical systems to cool and ventilate buildings, offers opportunities to take advantage of external conditions, but require a backup system to maintain the indoor environment when these conditions are not adequate. Additionally, the building facade plays an important role in achieving energy conservation. Due to technological advances, transparency and the use of glass has become an attractive envelope option in architectural design. Building glass facades can provide outdoor views and an excellent level of natural light as well as the potential for natural ventilation. However, with the use of glass, heat loss during the winter and solar gain during the summer will increase energy loads. In central Europe, which has moderate-to-cold climates, new concepts were tested that used outdoor conditions in creating climatic-responsive buildings (Givoni, 1998; Szokolay, 1980; Wigginton, 1996). Advanced facade technologies were developed for the high-end office building sector, in particular (Wigginton, 2002), and designers tried to integrate more building services into the facade system. By integrating the use of thermal mass, building-envelope systems can help temper the internal environment, and reduce the amount of supplementary heating or cooling needed to maintain occupant comfort.

This study provides a detailed description of the reference building model as designed and used

for energy analysis in EnergyPlus- DesignBuilder. The building is modelled to assess the energy performance of incorporating of three types of DSFs in comparison with the reference building. A naturally ventilated combined shaft-corridor DSF and two typical corridor and shafts are studied and compared with a single skin facade. The building is assumed to be in Chicago for simulation and weather-data purposes.

To study the facade design's impact on the space heating and cooling, a breakdown of energy components and overall energy consumption of a typical office building is presented.

First, the components of the reference building will be described. The next section discusses the influence of different types of DSFs on space heating and cooling in comparison with the base case office building. Finally, the results are compared with a traditional facade and with each other in terms of energy performance and thermal condition.

In this study, the energy performance of a high-rise office building equipped with conventional insulated glazing will be calculated by EnergyPlus and compared to a new DSF configuration. The DSF solution is innovative because it combines two common typologies: shaft and corridor type. The results proved that the new configuration had a major impact on enhancing natural ventilation and as a result, a reduction in energy usage.

I. DOUBLE SKIN FAÇADE

The concept of a DSF is not new and dates back to many years ago in central Europe when houses utilized box-type windows to increase thermal insulation (Oesterle, 2000). The DSF is an architectural phenomenon driven by the aesthetic desire for an all-glass facade and the practical desire to have natural ventilation for improved indoor air quality. Until recently the use of DSFs had become more popular in many European high-rise buildings.

A number of studies, research, and simulation programs have been done on incorporating natural ventilation in buildings and DSFs in thermal performance. Most have been carried out for solar chimneys—one way to increment natural ventilation and to improve indoor air quality—and Trombe walls prior to DSFs. Most designers found out that natural ventilation is possible in summer, even in multistory buildings (Wong, 2006). The potential of using a DSF for natural building ventilation in climates other than Europe has not, however, been fully studied.

In this study, wind-driven ventilation improved with stack effect in the novel DSF configuration and will be tested to see if it can maintain adequate comfort during summer and spring. The first step would be to study the ambience that will be used as CFD boundary conditions. Initial studies of the macroclimate were carried out through Ecotect, which allowed for efficient visualization of the local climatic conditions.

I.1. ENERGY USE IN OFFICE BUILDING

In general, energy consumption in buildings is determined by function, climate, building components, construction, control, and settings. The climate and the ambience are considered as-boundary conditions in energy simulation. Building function also has an important impact on energy use. As shown in Chapter One, significant amounts of energy (50 percent) go into the buildings and 23 percent of that goes into the office buildings. High occupancy and amounts of equipment increase the energy consumption as compared with residential buildings. Building components and construction both provide great potential for improvement of energy demand in such areas as adequate thermal insulation, a key component of energy consumption. In office buildings, a careful choice of windows and shading devices should help to avoid additional solar gains. Incorporating efficient HVAC equipment and heat recovery techniques may also reduce the energy use. Designing a high-performance facade system will make a tremendous impact in minimizing energy consumption and optimizing the thermal condition. To illustrate different energy components in offices, Figure 1 presents a breakdown of a typical Chicago office building. The results of this benchmark are presented in $\text{KW}/\text{m}^2 \text{ yr}$ and based on a survey of a large number of occupied office buildings. Typical patterns are representative for the median energy use of 2003 office buildings.

Energy End-Use Intensities for Office Buildings in Chicago

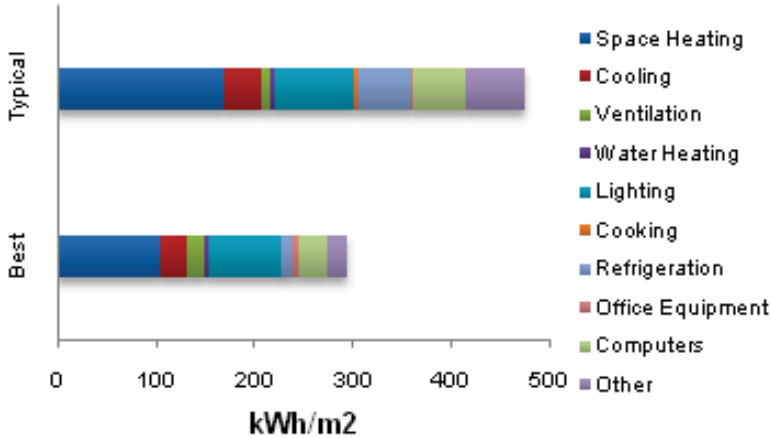


Figure 1: Energy components of typical office buildings (US Department of Energy, 2003)

2-METHODOLOGY

2.1. BASE CASE

The description concerns the real (designed) building, and the simulated model created for the energy and indoor-climate simulations.

The baseline facade configuration was a traditional, double glazed, low-E single skin facade.

Initially, the reference building was a 28-story building. It is a rectangular shape with an open plan. In terms of geometry and installations, the floors are completely identical. However, floors 1-27 are connected (floor, ceiling) with other internal building zones, while the roof on the 28th floor is connected to the outside, and the ground floor is the ground (i.e., no basement).

The height of the building is 98m, with a length of 78m, and a width of 32m. Room height is 3.5 m with a suspended ceiling. For this study, however, only part of the plan will be modelled both in energy simulation and airflow modelling analysis. It was assumed that the building divided into four blocks of 7-story high shaft modules. To simplify, the module to be studied is a rectangle 28 m by 8.5 m. The module area is 229.5 m² and includes 7 stories, making a total of 1,607m². The window area (including the frames) comprises 100 percent of the south facade. The interior design and the work places were not in the scope of the study. The four alternatives based on external skin types were compared in terms of energy use and the quality of thermal condition

2.2. INPUT

First, the site needed to be chosen as it defines the building's geographical location and weather data. Then the activity template, selected: open office space. The occupancy schedules and other data, such as metabolic rates and levels of equipment use, were set based on the office space requirements.

The occupants' schedules, activity levels, clothing and room use are tabulated in Table 1.

Zone Identification

To simplify the simulation, only one zone per story was identified. The office building faces south with 100 percent glazing.

Schedule for offices	08:00 -12:00, 13:00 – 17:00
Winter schedule	50% working during the Christmas vacations, otherwise 100% weekends closed
Summer schedule	75% working during July otherwise 100%, weekends closed
Activity level	Office Activity : 1 met = 108 W / occupant (1 met corresponds to 58.2 W / m ² body surface) Task: sitting, reading
Clothing	For winter conditions: 1 clo For summer conditions: 0.6 clo

Table 1: Occupants schedule and activity level

Zone properties description

The two main components of the energy simulation model are the building fabric and elements (walls, floors, ceilings, occupants, and equipment) and the plant components (HVAC equipment, and other environmental control systems). Ventilation, lighting and equipment, type of HVAC system, use of natural ventilation and daylighting should all be set in describing zone properties. For all of these values, office-building defaults were used, except for the HVAC system, which had a VAV system with terminal reheat that had been chosen for the base case. However, the base case was simulated with no natural ventilation. . The HVAC systems for all the cases are similar.

Then specific properties of each zone in terms of the wall properties (type, R-value, exposure, and construction), shading, window properties (type, glazing area, size and layout) needed to be set. The description of building's construction is shown in Table 2.

Building construction	Material type(from outside to inside)	Thick-ness (m)	Density (kg/m ⁻³)	U-value (W m ⁻² K ⁻¹)
External wall	Exposed concrete	0.10	1500	0.35
	Polystyrene	0.08	16	
	Concrete block	0.10	1000	
	Gypsum plastering	0.013	758	
Internal wall	Gypsum Plaster	0.025	970	1.9232
	Airgap 10mm	0.10	1.2	
	Gypsum Plaster	0.025	1090	
Floor	Cast concrete	0.10	2300	4.7
Ground floor	UF Foam	0.087	1200	0.35
	Cast concrete	0.10	2300	
	Creed	0.07	900	
	Wooden Flooring	0.03	1000	
Roof	Asphalt	0.01	930	0.25
	MW Glass wool	0.145	16	
	Airgap 25mm	0.20	2.5	
	Plasterboard	0.013	720	

Table 2: Description of building construction

The glass area in the base case is 100 percent in the south facade and double-pane low-E insulation was chosen for the glazing type. The thermal properties of materials were initially calculated by EnergyPlus- DesignBuilder. It should be noted that thermal losses due to thermal bridges were not included in these calculations. In order to be accurate, practical values should be used instead of theoretical values. The property of the reference window is as follows:

Window properties	Description	Aluminum window
	U value (W/m^2K)	4.719
Glazing properties	Description	DbI LoE($\epsilon=0.1$) Clr 6mm/13Air
	U value(W/m^2K)	2.44
	SHG	0.643
Frame properties	Description	Aluminum
	Thickness	0.02
	Surface resistance(m^2K/W)	0.040
Shading device	Description	Blinds with high reflectivity slats
	Control	Scheduled and positioned inside

Table 3: Properties of window on south façade

Other settings

Control points for the indoor environment were set at 22C minimum for winter and 24.5C for summer. The infiltration rate assumed for the reference building was 0.5 ACH (air changes per hour). There were 300 occupants in the building. The lighting was assumed to be florescent with a power of 10 W/m^2 200lux and the annual equipment energy use for the open plan was 57 kWh/m^2 . Another parameter was a control set for artificial lights, assuming that they are switched on according to occupant schedules.

2.2. OUTPUT: SIMULATION RESULTS FOR THE REFERENCE BUILDING

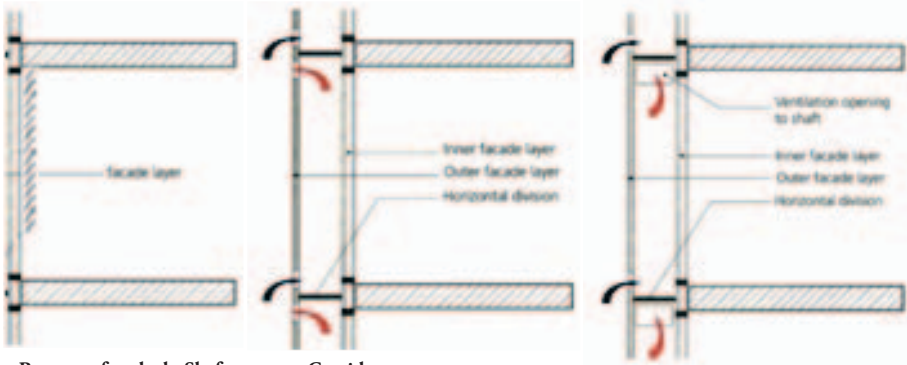
After the appropriate input to best define the typical office building was entered, the base case was simulated for the year's annual performance. EnergyPlus generates a detailed report of the heating/cooling energies, peak and annual cooling/heating loads, costs, and annual breakdown of energy consumption.

For this paper, only the most relevant output graphs were analyzed. The number of heating degree days far exceeded the number of cooling degree days and clearly showed the heating-season dominance. It was apparent that due to the cold conditions, the most significant loads and maximum energy use was for heating. In terms of breaking down annual energy consumption, the largest components were space heating, cooling, and lighting. A building cost analysis was omitted, as the major research objective was to study facades' thermal effects. The key point of adding a naturally ventilated DSF was to take some of the grid's cooling loads out. Therefore, the major focus of the analysis was on the following three output graphs:

- a) Annual Cooling and Heating Loads
- b) Breakdown of Energy Consumption

2.3. DESCRIPTION OF DOUBLE SKIN FACADE ALTERNATIVES

In this section, the energy performance of 7-story DSFs were studied and compared to the 7-story section of the reference building. The energy demands of the following facades were studied:



a: Base case facade b: Shaft type c: Corridor type

Figure 2: Diagram of the simulated double skin facades

- A seven-story naturally ventilated cavity shaft type
- A seven-story sealed outer skin-corridor type comprised of a single pane of clear glazing, wherein the facade acts as an external air curtain
- A seven-story naturally ventilated new DSF configuration combination of corridor and shaft type.

Two DSF construction types were assumed: a corridor type and a shaft type. In both cases, the cavity depth was assumed to be 1.5m and the shaft height was assumed to be 7 stories (3.5m height). The main difference of the alternative facades is that a double skin has been added to the building; with the internal skin the same as the reference building and the external skin as a single pane window (6mm). The shadings were located inside the cavity. In both DSF types, the building was mechanically ventilated, yet the cavity was naturally ventilated. The shading devices were considered to be white with a slat angle of 45°. Figure 2 shows these three alternatives for energy simulation.

The base case consists of a well insulating glazing with a U-value of 2.44 W/m² K and a solar transmittance of 0.634. The window is equipped with roller blind as shown in the Figure 2a. If we added a clear glass pane (6mm) in front of the base case with divisions along each story that allowed the exterior air to enter, the cavity a double skin facade corridor type is created (Figure 2-b). In the case of a shaft type, single glass was added to the exterior a small distance from the insulated internal glazing, while the extracted air goes to a shaft that goes through multiple stories and takes the exhaust air outside (Figure 2-c). The office was equipped with a mechanically ventilated system in case of variable weather condition and the natural airflow was not enough to provide cooling.

Almost all the literature studies noted advantages regarding the reduction of heating/cooling losses over traditional single facade systems. The lower radiant temperature increased building's thermal comfort. Also, during the winter, the cavity can act as a buffer zone and capture incident solar energy, which further improves the energy efficiency.

COMBINED SHAFT-CORRIDOR DSF

This study looks beyond typical shaft and corridor DSF solutions and provide a new type shaft-Corridor configuration. The combined shaft-corridor DSF configuration takes advantage of strategies such as ventilation driven by different combinations of wind and external stack. The most distinguishing visual feature of this configuration is it can pronounce a module by projecting or taking it back on the facade as presented in Figure 3. This configuration combined both shaft box and corridor types on the building's facade while trying to avoid their disadvantages. The cooling stacks allow for further ventilation on hot, stagnant, summer days so the building always remains within reasonable temperature levels, like that of an air-conditioned building.

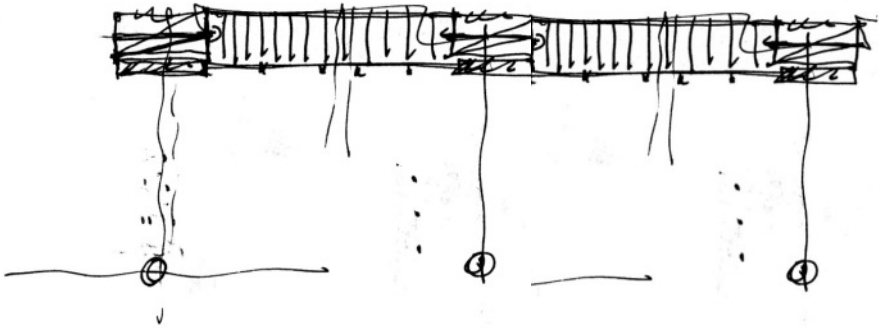


Figure 3: Sketch plan of the new configuration

One of the disadvantages of a shaft-type window is that the narrow width makes it difficult to clean and maintain. A corridor type can simply act as an internal or external air curtain. As a result, natural wind cannot be introduced to the interior space; if we open the internal screen the air inlet and exhaust air will mix. With the combined shaft-corridor DSF we tried to avoid the disadvantages mentioned above. To avoid air mixing, the inlet and exhausted air are separated through a channel. Exhausted office air will go directly into the transparent channel, which is connected to the shaft. In addition, the shaft width is increased up to 1.5m, the same as the corridor depth. Ventilation effectiveness is driven by thermal buoyancy, or stack effect, which is determined by the inlet air temperature, the height between inlet and outlet openings, and size of these openings.

Figure 4 shows how air flows through the chimney and provides ventilation inside each office module. The air gap inlet draws in fresh air at a low level and directs it into the room. The air is exhausted through the outlet at the high-level gap of the inner pane. The multi-story chimneys suck the exhausted air through a bypass opening at the top of the corridor facade. The vertical height of the glass chimney creates a stronger uplift force due to the increased stack effect.

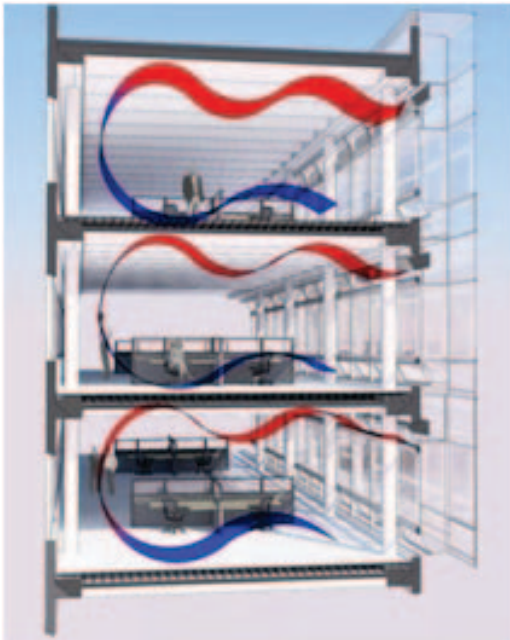


Figure 4: The combined shaft-corridor DSF configuration and show air flows within the building

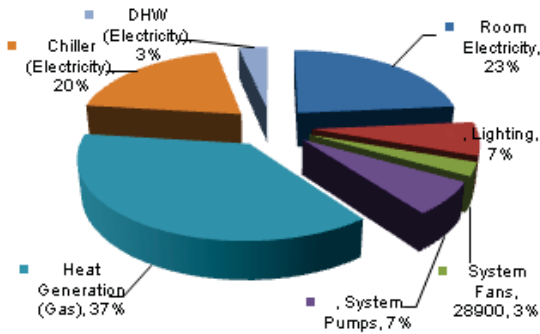


Figure 5: Energy breakdown in the combined shaft-corridor DSF configuration

3-RESLUTS: ENERGY USE SIMULATION RESULTS

An annual energy simulation on an hourly basis under Chicago climatic conditions was performed for different DSF alternatives. All inputs were the same as the reference building, with the same surface area. In the case of the corridor facade, the width of the corridor was 1.5m and the width of the shaft-type facade was 0.3m that passed through 7 stories. The energy performances of the different DSFs will be discussed in detail in this section.

The annual cooling and heating energy consumption of the combined shaft-corridor DSF is presented in Figure 5. When heating and cooling loads were compared, it is apparent that heating is the largest component of energy consumption. The heating season period is longer than the cooling season in Chicago.

The net annual gas consumption was reduced by 18 percent through the shaft, 16 percent through the corridor type, and 35 percent in the new type. As shown in Figure 6, the heating energy (gas consumption) was reduced in comparison with the two other typologies; however, in terms of cooling demand, electricity consumption decreased by five percent in the shaft type and nine percent in the corridor type. Total electricity was reduced by 15 percent in the combined shaft-corridor DSF. Cooling and heating demands will be discussed in detail for each month in the following section.

It should be emphasized that the results represent the space heating and cooling energy demands. Cooling efficiency differs from heating. The cooling demand is reduced each month in comparison with the base case, except for the month of July, when it is lower than the shaft and corridor types. However, the total annual cooling load was reduced by adding the DSF, as the exterior shading devices decreased the heating solar gain, and made it easier to lose the indirect solar gain. The results, consequences of the different climate, contradict Saalen's (2002) findings. They also indicate that the combined shaft-corridor DSF increased the natural ventilation even in hot summer months and would be a good option for the building.

Annual Energy Demand

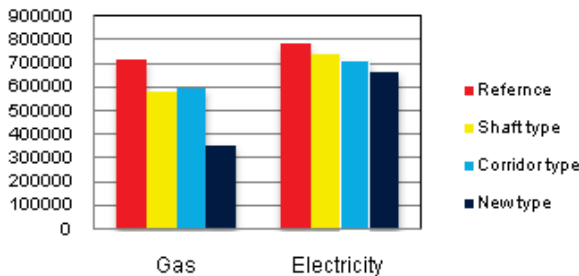


Figure 6: Annual gas and electricity demands

Cooling Energy Demand

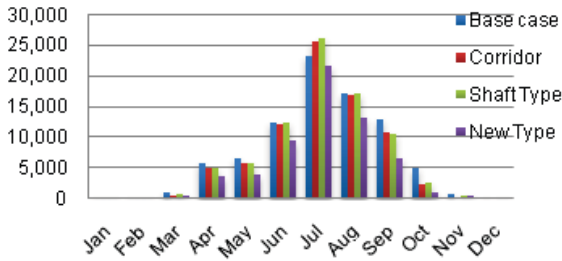


Figure 7: Annual net cooling demand for each month

The Figure 7 shows the cooling demand of each month for the four different alternatives. The total energy use for cooling has been reduced by 28 percent in the combined shaft-corridor DSF and by almost five and seven percent in the shaft and corridor types, respectively. Based on the energy simulation in Belgium by Saelens the south-oriented DSF requires 32 percent more for cooling energy than the traditional facade (Saelens, 2002), while the combined shaft-corridor DSF reduces cooling energy by 28 percent. Because of the extra pane, the DSF has a lower direct solar gain, and the shading devices situated outside while in the base case the blinds located inside which doesn't reduce the solar heat gain. In addition, with the combined shaft-corridor DSF we can take advantage of both wind and natural convection that has occurred in the stack, which improves the air velocity in eliminating the hot stuffy air from the building.

The total cooling energy is reduced by almost 28 percent, although this trend is not the same for all the types in each month, as shown in the Figure 8. The shaft and corridor types almost save the same amount, however, the total annual reduction in the corridor type is seven percent and five percent in the shaft type from the base case.

HEATING DEMAND

The energy use for heating in the combined shaft-corridor DSF configuration is several times lower than the base case demands and other DSF alternatives. In general, the results seem to be remarkably different than the cooling savings and can be explained by the following reasons: during the heating season the system would be closed thus no air is moving in the cavity. The cavity then heats up and increases the temperature of the inner pane and thereby reducing conductive, convective, and radiant losses. In addition, the whole system increases the R-value of the enclosure by providing a buffer zone in front of the inner pane. The difference between the maximum and minimum heating load is more pronounced than it was for the cooling demand. It can be concluded that in the Chicago climate, the extra pane can lower the heating load by 22 percent.

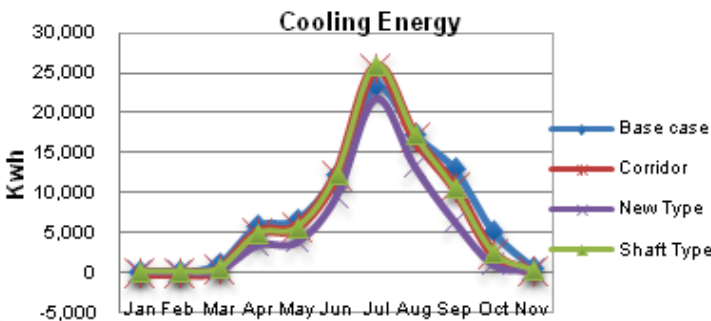


Figure 8: Cooling energy demand for four different enclosures

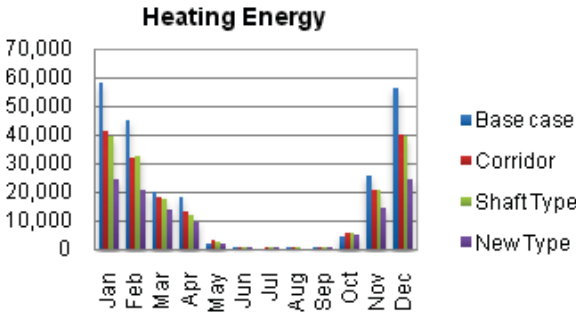


Figure 9: Heating energy demand for each month

SIMULATION RESULTS FOR THE BUILDING

In this section, the energy-use difference for heating, cooling, and lighting is compared with the three alternative facades and the base case. The energy use for heating in the reference building is 34.7KWh/m² (25%) higher than the shaft and corridor types and 72 KWh/m² (50%) higher than the combined shaft-corridor type, respectively. As expected, in all cases the energy use for heating and cooling was higher than the reference building. However, as shown in Figure 10, lighting increased in the shaft and in the combined shaft-corridor DSF in comparison with the base case by one percent. It can be concluded that 100 percent glazing provides more daylight than the combined shaft-corridor DSF and shaft types, which makes sense.

The heating energy intensity was reduced by 50 percent in the new type and 28 percent in cooling energy intensity. In total, compared with the base case, the corridor type reduced energy by 12 percent, shaft by 11 percent and the combined shaft-corridor DSF by 29 percent.

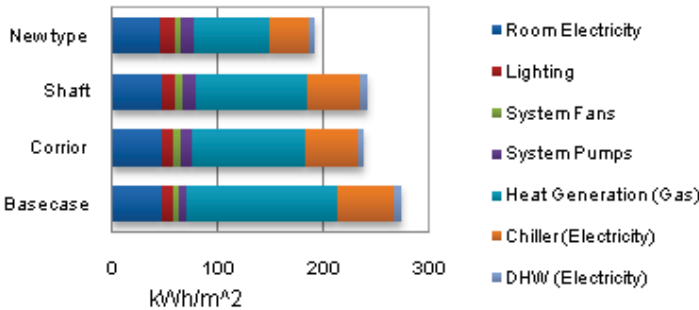


Figure 10: Impact of facade types on energy use

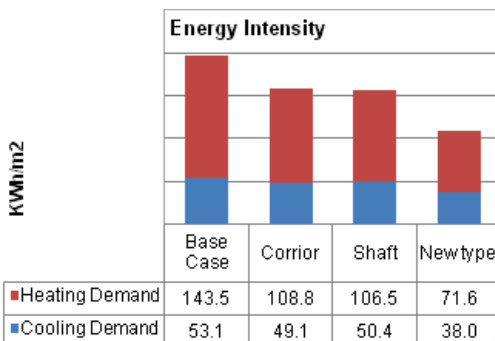


Figure 11: Energy intensity of alternatives

Case	Energy Intensity KWh/m ² yr	Percent Savings (%)
Base	274.1	
Corridor	239.3	12
Shaft	241.7	11
combined shaft-corridor	192.7	30

Table 4: Energy intensity of 4 cases and the percentage of savings

ENERGY COMPARISON

The annual energy usage per square feet area of the new DSF type, which is a combination of two typical DSF types, has been tabulated and illustrated below. The energy intensity of the new type compared with shaft and corridor types as well as an average office building in Chicago as a base case model is also shown.

It was discovered that the heating energy intensity was reduced by 50 percent in the new type from the base case, and there was a 28 percent reduction in cooling energy intensity.

In total, compared with the base case (an average office building in Chicago), the corridor type reduced energy usage by 12 percent, shaft by 11percent and the new type by 29 percent, respectively.

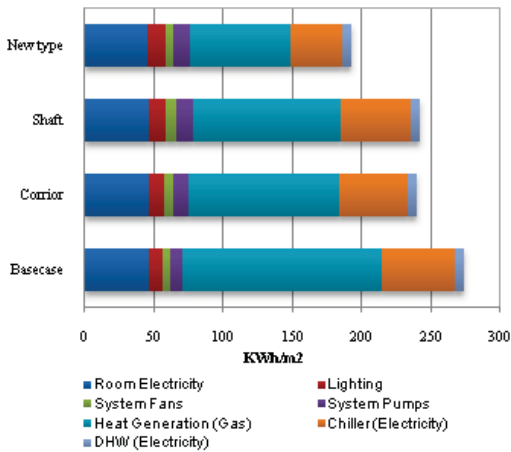


Figure 12. Simulation results for different alternatives.

CASE	Energy Intensity KBtu/SF yr	Heating Consumption Kbtu/SF yr	Heating Reduction %	Cooling Consumption Kbtu/SF yr	Cooling Reduction %
Reference building	86.87977	45.5		16.8	
Corridor type	75.86	34.5	24	15.6	7
Shaft type	76.6095	33.8	25	16.0	5
New Configuration	61.07612	22.7	50	12.0	28

Table 5: Energy usage comparisons for different alternatives

4-CONCLUSION

While there is a great deal of interest in transparent building in current architecture, larger areas of glazing area results in high building heating and cooling loads, and high levels of energy consumption. The advent of the double skin facade is a response to these problems.

In order to reduce energy use and improve indoor thermal environment, a new DSF configuration was introduced. The new DSF is a system consisting of corridor and shaft types. In this new type, chimneys are placed in such a way that air can flow through the intermediate cavity with no mixing of inlet and exhaust air. In principle, the main purpose of the DSFs (as to energy use and thermal comfort) is to allow useful solar gains into the building and to introduce natural ventilation during the shoulder season.

The energy savings achieved for this new type has been investigated to evaluate energy performance of incorporating this type in comparison with typical DSF types in high-rise office buildings in Chicago. The findings would be of utmost important in determining whether a DSF is a real possibility in incorporating natural ventilation and reducing energy usage in both heating and cooling in Chicago climate. The research found that in total, compared with the base case (an average office building in Chicago), the corridor type reduced energy usage by 12 percent, shaft by 11 percent and the new type by 29 percent, respectively.

In conclusion this new type of DSF has advantages over the typical curtain wall system in reducing the cooling load by allowing wind to be introduced as the driving force in combination with the stack effect to enhance natural ventilation.

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