sustainability

MDPI

Article

Numerical Study of Balancing between Indoor Building Energy and Outdoor Thermal Comfort with a Flexible Building Element

Choul Woong Kwon [1], Kang Jun Lee [2,*] and Soolyeon Cho [3]

1 SUSB Centre, Hanyang University, Gyeonggi-do 15588, Korea; hottrinity@gmail.com
2 School of Architecture, Hanyang University, Gyeonggi-do 15588, Korea
3 School of Architecture, College of Design, NC State University, Raleigh, NC 27695, USA; soolyeon_cho@ncsu.edu
* Correspondence: leekangjun@gmail.com; Tel.: +82-(0)10-2988-6902

Received: 22 October 2019; Accepted: 22 November 2019; Published: 25 November 2019

check for updates

Abstract: This study analyzed the environmental role of a flexible canopy as a microclimate modifier in balancing indoor energy demands and outdoor thermal comfort. Flexible building elements are often installed in traditional buildings, depending on the local climate in southern Europe. The architectural performance of a canopy was analyzed using several environmental software packages (Ecotect, Rayman, WinAir, DaySim, and EDSL TAS). Coupling methods were applied to determine the environmental influence of the attached building element, a canopy with fixed and operable panes in different orientations and locations. The results showed that the flexible canopy played a crucial role in reducing indoor energy demands (heating and electricity for lighting) and increasing outdoor thermal comfort under the canopy area. Outdoor thermally comfortable conditions ranging between 13 and 29 °C in the canopy space could be enhanced by 56.3% over the entire year by manipulating a flexible canopy, compared with a fixed canopy with 90% transparency in London. The flexible canopy with higher transparency helped increase outdoor thermal comfort in Glasgow, while one with lower transparency showed better performance during summer in London. The findings of this research will help broaden the range of architectural elements used in buildings.

Keywords: flexible canopy; outdoor thermal comfort; daylighting; heating energy demand; balancing energy; coupling method

1. Introduction

This study investigated the environmental performance of a flexible canopy as an alternative to generally used fixed ones. Flexible use of building elements could maximize their environmental potential, which influences both the energy consumption of the building and indoor environment. Flexible architectural elements such as blinds or canopies are often used in regions with Mediterranean climates [1–3]. However, there is limited research regarding the impact of flexible building elements in terms of building energy consumption. The focus is mostly on finding new engineering elements for controlling building environments with very limited information on handling or controlling common building elements.

Efforts to develop environment-friendly building designs have evolved in various ways to overcome global warming. These include using passive design approaches or considering engineering aspects (e.g., materials and renewable energy) to design environment-friendly buildings. Designers tend to apply passive design techniques in the early design stage as it is related to the building form and orientation rather than each element of the building. However, some building design elements found frequently in historic buildings work effectively to control environmental factors such as humidity and solar radiation [4–6]. In particular, flexible use of building elements (e.g., shutters and canopies) can be beneficial for controlling the building environment, in terms of both design and engineering [7,8]. However, as there is relatively little research in this regard, a combined approach comprising architecture and engineering is needed. Hence, the purpose of this study was to analyze the environmental performance of a flexible building element and determine whether it can be utilized in the current global environmental scenario.

Flexible building elements such as sunshades have been used for a long time to adapt to the external environment (seasonal, daily environment). However, the engineering approach involving the development of new building materials and equipment is mostly preferred for constructing environmentally friendly buildings. Therefore, through this research, we intend to analyze the effectiveness of flexible building elements in reducing the energy consumption of existing building elements (materials).

This research attempted to develop a flexible design strategy that can help overcome the seasonal limitations resulting from the use of a fixed canopy in school buildings with a particular transparency percentage and capacity for allowing airflow. The main idea behind proposing a flexible canopy is to overcome the limitations in its environmental performance. A flexible canopy was tested with computer simulation software using the same conditions as those for commonly used fixed canopies. The findings of this study can contribute to architectural design in terms of energy efficiency methods and design options beneficial to both designers and engineers.

2. Background Information

Changing school curriculums present challenges for everyone involved in education; hence, the role of outdoor spaces is becoming more important as an extension of indoor classrooms and as a framework for future expansion [9–11]. We analyzed the effectiveness of using a flexible canopy by examining the following performance parameters.

2.1. Thermal Comfort

Perceptions of outdoor thermal sensations are different from indoor thermal sensations, and it is even assumed that indoor thermal comfort standards are not applicable to outdoor settings. A study conducted by Hoppe in 2002 shows that outdoor thermal sensations are perceived differently from indoor thermal sensations, and indoor thermal comfort standards do not apply to outdoor settings [12,13]. Various studies have been conducted using the thermal comfort index specified for outdoor settings in urban studies. Methods for improving urban microclimates include the use of more appropriate materials, increased use of green spaces, cooling sinks for heat dissipation, and proper layout of urban canopies [14]. These methods are for outdoor spaces such as those in schools [15] to improve microclimate conditions. By changing urban structures and architectural elements, designers can create thermally comfortable outdoor spaces that are also appropriate for school environments [16]. A similar study on urban environments shows the importance of architectural and thermal diversity in urban settings. Architectural diversity comes from various spatial characteristics identified in urban space, such as geometry, orientation, urban structure, and materials [17]. Spatial diversity is also accompanied by thermal diversity, defined in terms of various microclimatic conditions related to temperature and air circulation in hot environments [18,19].

One of the main parameters influencing comfort in both outdoor and indoor spaces is solar radiation. The amount of incident solar radiation is affected by the surroundings, i.e., the presence of open or closed spaces. In winter, direct solar radiation is considered as a crucial environmental influencing thermal comfort in temperate climate zones.

2.2. Airflow

Airflow is an essential factor affecting the thermal comfort in outdoor spaces. Owing to changing global and regional conditions, it is difficult to predict and control airflow. Therefore, it is crucial to understand that there are significant differences in the wind environment from one part of the city to another, ranging from macroscale to microscale differences. Analyzing the effect of wind speed on people, the effect of building height on common flow patterns, and combining simulated wind conditions with measured thermal parameters is essential to predict outdoor thermal comfort [20,21].

The personal perception of wind speed associated with airflow was examined by Szokolay et al., (1997) [22]. However, the thermal comfort associated with airflow effects varies depending on the climate [23,24]. Winds can cause discomfort during winter cold climates; however, in humid conditions, it can be comfortable because wind promotes cooling of the human body by evaporation. For example, during periods of overheating in hot and humid areas, higher wind speeds can alleviate physiological heat stress caused by higher temperatures. In addition, the tendency of urban temperatures to exceed regional levels (e.g., heat islands) decreases as urban wind speeds increase. Installing windbreaks to avoid cold winds in cold weather will help reduce the cooling effect while it may exacerbate thermal discomfort in summer. Therefore, when designing windbreaks, it is desirable to incorporate flexibility to meet the needs during different seasons [25–27].

2.3. Applied Bioclimatic Index

The physiological equivalent temperature (PET) is a general and useful bioclimate indicator because it is expressed in °C and widely known as an indicator of heat stress. This makes it convenient for potential users unfamiliar with modern human biometeorology terms, including planners, decision makers, and the general public, to understand the concept of heat stress. For evaluating thermal conditions in a physiologically relevant manner [28], PET is defined as the temperature at which the human energy balance for an assumed indoor condition is balanced by the same skin temperature and sweating rate as in the actual complex outdoor condition being evaluated [29], which is based on the heat balance equation:

$$M + W + R + C + ED + E_{re} + E_{sw} + S = 0 \tag{1}$$

where m = metabolic rate (internal energy produced by food oxidation)

W = the physical work
R = the net radiant balance of the body
C = the convective heat flow
ED = the latent heat flow evaporate water through skin (perspiration)
E_{re} = heat flows for respiration (air heating and humidifying)
E_{sw} = heat flow for sweat evaporation
S = heat flow accumulated in body.

PET allows different users to compare their experience indoors with the essential effects of complex outdoor thermal conditions [30]. Moreover, PET can be used in different climates throughout the year [31]. Weather parameters such as temperature, humidity, wind speed, and shortwave/longwave radiation affect human energy balance. These parameters should be determined at a human biometeorological height of 0.5 m above the ground; this corresponds to the average height of the center of gravity of a standing child. Significant differences between air temperature and mean radiant temperature (Tmrt) (and PET) occur during windy winter days and under mild and sunny conditions. In these cases, extreme cold and heat stress can occur. In this study, we used solar radiation and PET to characterize thermal comfort conditions and evaluate human bioclimatological comfort employing flexible canopies with different transparency levels in locations with different climates.

As some studies [32–34] revealed, external shading devices are advantageous to prevent solar radiation from entering internal spaces in summer, while allowing low-angle sunlight to enter in winter.

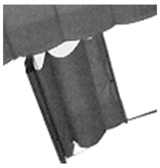
However, permanently fixed canopies cannot fully meet the requirement of outdoor thermal comfort and decreased indoor energy demand in both summer and winter. Therefore, an adjustable canopy system is recommended to address the difficulty in preventing sunlight from entering internal spaces in summer and allowing sunlight to enter in winter.

2.4. Flexible/Fixed Canopy

Providing sheltered spaces outdoors would be helpful for pupils to use outdoor spaces throughout the year regardless of weather conditions. Even though there are no specific guidelines for using outdoor spaces and regarding the duration for staying outdoors, sheltered spaces such as canopies are frequently used to enable the utilization of outdoor spaces for as much of the year as possible. Easy access to outdoor spaces enables teachers to use them as often as possible. For young pupils, free movement between indoor and outdoor spaces is essential. However, even for older pupils, direct access to outdoor spaces from their classrooms could mean frequent use of these outdoor spaces. Different types of canopies have been developed diversely and applied in schools.

There are different types of flexible canopies, namely foldable, retractable, and rotatable, which are adjustable in terms of controlling solar radiation according to sun angles, and are found in modern buildings [35,36] as seen in Table 1. These types of canopies can provide ideas for designing an optimal canopy to enhance outdoor thermal comfort in schools and reduce indoor energy consumption [37]. The main objective behind designing flexible canopies is to overcome the limitations of fixed canopies in terms of ensuring outdoor thermal comfort and reducing indoor energy consumption.

Table 1. Examples of canopies in existing buildings.

Types	Fixed Canopy	Flexible Canopy		
		Retractable	Ratable	Foldable
				
Locations	Lee-on-the-Solent Infant School, UK	Urban street, open space	Ponzano Primary and Nursery School, Empoli, Italy	Asilo Infantile Antonio Sant' Elia, Como, Italy

3. Methodology

3.1. Concept of Flexible Building Components

For explaining the concept of flexible building components, the canopy is selected, which is mostly found in school buildings in southern Europe and in the UK. The idea behind using a flexible component is that it allows for adjusting major environmental parameters (solar radiation and wind speed) according to user requirements. It can improve thermal comfort during summer and winter either through manual or automatic operation. Simulations involving flexible canopies were performed following the same methods as those used for fixed canopies, examining daylighting, outdoor thermal comfort, and energy demand.

The main factors considered for designing the canopy are as follows:

- Summer: Increase wind speed and avoid direct solar radiation.
- Winter: Decrease wind speed and allow as much direct solar radiation as possible.

3.2. Component Design

The proposed design for a flexible canopy comprises two divided panels where each panel is operable according to the season for maximizing performance, as illustrated in Figure 1. The closed canopy shown in (a) allows solar radiation to enter as the glass pane at the front is transparent while the rear glass pane has different transparencies of 0%, 50%, and 90%. The rear pane can fold toward the front pane, as illustrated in (b) according to the environmental conditions. Once the pane is folded, there are open holes to facilitate free airflow between the area under the canopy and upper open space; this would increase the wind speed under the canopy, as indicated in Figure 1c.

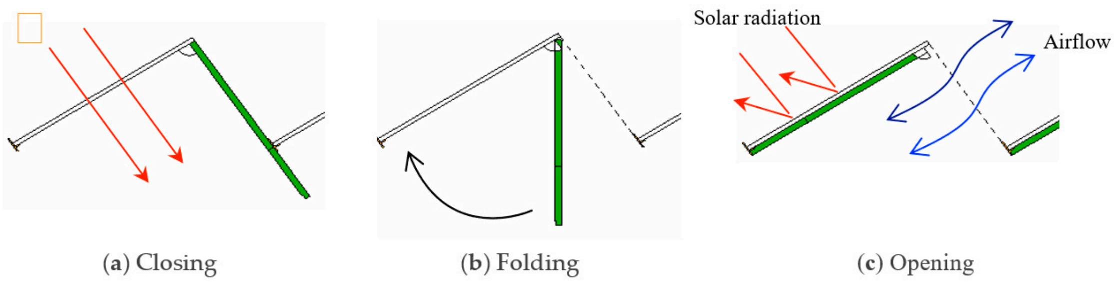


Figure 1. (**a**) Closed rear pane, (**b**) folding toward front pane, and (**c**) opening of rear pane to allow airflow.

In the prototype of the canopy unit, each jigsaw-shaped unit comprises two 1 m long and 0.4 m wide rectangular panes with the rear pane being foldable toward the front pane.

This canopy can be partially or fully folded and can be operated either manually or automatically. This flexible canopy can overcome the functional drawbacks of a fixed canopy without any influence from environmental changes. The schematic in Figure 2 shows the annual use of the flexible canopy as an open canopy in summer and closed canopy in winter. This canopy is designed for blocking solar radiation while promoting airflow to enhance thermal comfort in summer. In winter, the opposite approach is used by closing panes to reduce the wind speed under the canopy while allowing direct solar radiation to enter.

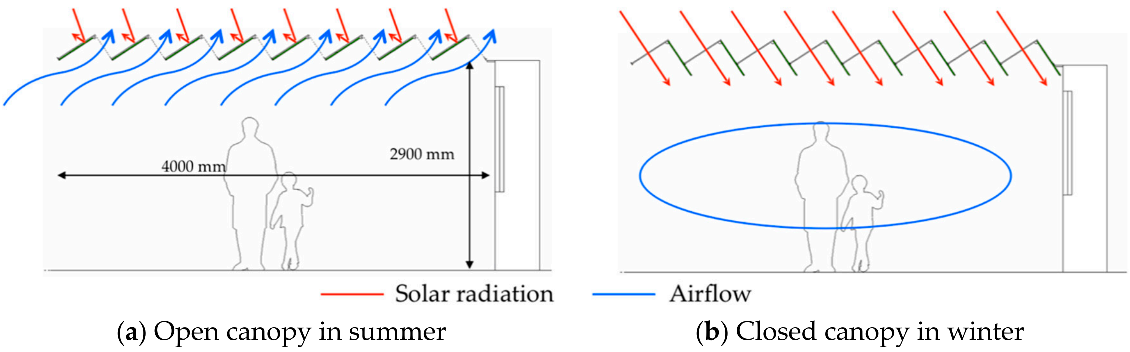


Figure 2. Schematic diagrams showing a sectional view of the flexible canopy unit in (**a**) summer (**b**) winter.

Using a fixed canopy is not beneficial considering environmental requirements in different seasons for both indoor and outdoor spaces in schools. Each flexible canopy unit can be automatically operated; manual operation is also possible whenever teachers or students want to change the canopy to suit their needs.

Modeling of the canopy for simulation studies was performed using EDSL TAS version 9.1.4, which is a dynamic thermal simulation software used to calculate the heating energy demand according to climatic conditions [38,39].

The calculated values were compared with those for fixed canopies with different transparencies, namely 0%, 50%, and 90%. The school classroom unit was set up based on typical classroom sizes in the UK, as seen in Figure 3. Diverse environmental parameters were applied considering four main orientations, thermal transmittance/*U*-values (0.25 and 0.35 W/m^{2}K for wall and roof respectively), 40%

window ratio on the front wall, and three different transparencies of the fixed canopy, as presented in Table 2.

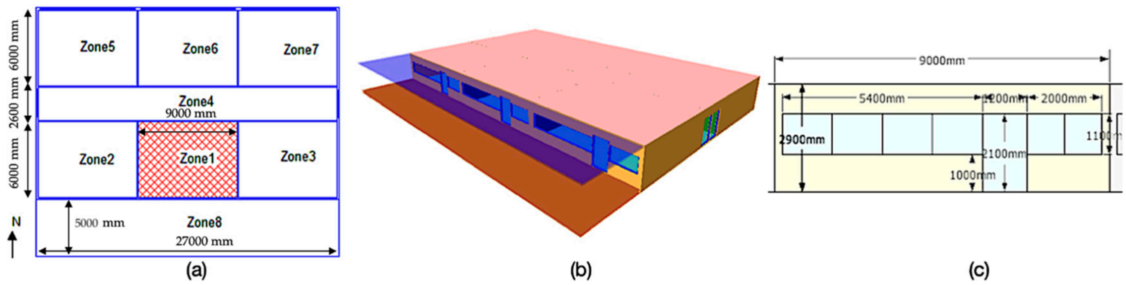


Figure 3. EDSL TAS numerical model: (**a**) Plan, (**b**) perspective, and (**c**) front façade of the classroom.

Table 2. Input parameters for modeling.

Design Variables	Classroom Built Recently	Design Variables	Classroom Built Recently
Orientation	S, N, E, W	Window U-value	U = 2.974 W/m^{2}K
Wall insulation	U = 0.25 W/m^{2}K	Room dimensions	9 (w) × 7 (d) × 2.9 m (h)
Roof	U = 0.35 W/m^{2}K	Canopy dimensions	9 (w) × 5 m (d)
Infiltration	0.5 ACH	Material of the canopy space	Glass material with 0%, 50%, and 90% transparency
Ventilation	Natural ventilation via openable window	Reflectance	Ground 0.2 Canopy 0.5
Glazing ratio	40%	Wall material	Brick

In the calculation of outdoor thermal comfort, wind speeds under the canopy are calculated with Equation (2) with WinAir4. For the wind speed input data, a prerequisite simulation for calculating the wind speed exponent (α) was performed, and the results are presented in Table 3.

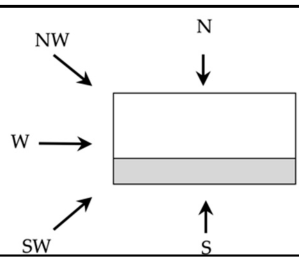
$$\frac{V_{zex}}{V_{Z10}} = \left(\frac{Z_{ex}}{Z_{10}}\right)^{\alpha} \tag{2}$$

where V_{zex}: the mean wind speed at height Z (m/s)

V_{z10}: the mean wind speed at reference height Z_{10} (m/s)
Z_{ex}: the height above ground level (m)
Z_{10}: the reference height (m)
α: the exponent characteristic of terrain roughness.

Table 3. Wind speed at height z (V_{zex}) with exponent (α) for flexible canopy (calculated by WinAir 4).

Wind Direction	Flexible canopy	
	Vzex	Exponent (α)
N	0.64	1.04
NW/NE	0.72	0.99
W	3.47	0.31
SW/SE	2.13	0.52
S	0.81	0.94



V_{10} : 7 m/s; Zex : 1 m; Z_{10} : 10 m. Wind directions (every 45°): N(337.5–22.5°), NE(22.5–67.5°), E(67.5–112.5°), SE(112.5–157.5°), S(157.5–202.5°), SW(202.5–247.5°), W(247.5–292.5°), and NW(292.5–337.5°).

In Manchester, flexible canopies facing east or west work better than those with other orientations as the funnel effect caused by the increased wind speed under east- and west-facing canopies reduces thermal comfort significantly in winter. As the transparency of the flexible canopy can be changed from 0% to 90% at any time, it can provide spaces with improved thermal comfort.

In summer, thermal comfort can be achieved by controlling solar radiation to maintain comfortable outdoor thermal conditions where the thermal index, PET, is in the range of 13%–29 °C (equivalent to slightly cold to slightly warm). Thermal comfort can vary depending on exposure to solar radiation; the extent of variation in thermal comfort deduced from the simulations was 8 °C in summer and 4 °C in winter. Other than solar radiation, controlling wind speed in winter plays an important role as there is little solar radiation during winter in the UK. Cold winds with high speeds are detrimental to outdoor thermal comfort; therefore, decreasing the wind speed is necessary to avoid the wind chill effect [40].

3.3. Thermal Comfort

The extent of thermal comfort enhancement is mainly dependent on the operation rather than the material used in fabricating the canopy. The performance would vary primarily according to the local climate and operation. In particular, if there were a high incidence of direct solar radiation, the efficiency of the flexible canopy would be higher than that in a climate with more diffused light rather than direct solar radiation. The results showed that using a flexible canopy could improve thermal comfort in flexible canopy spaces and reduce indoor overheating and daylight energy demands. The monthly thermal comfort levels plotted in Figure 4 help understand outdoor thermal performances under different canopy transparencies (0, 50, and 90) and without a canopy. The green curves indicate comfort bands; PET values in the range of 13–29 °C correspond to comfortable conditions ranging from slightly cool to slightly warm. Dark green indicates neutral conditions, i.e., neither hot nor cold, corresponding to comfortable temperatures in the range of 18–23 °C.

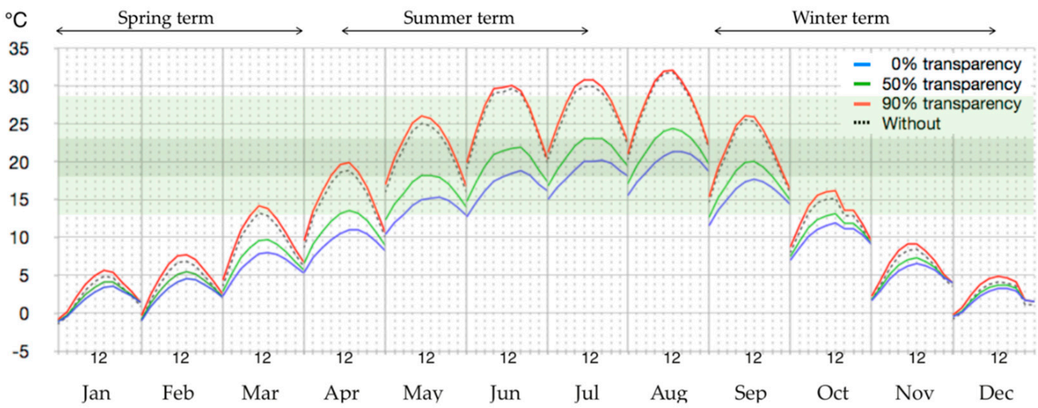


Figure 4. Monthly average physiological equivalent temperature (PET) on an hourly basis with different canopy transparencies (Comfort bands: 13–29 °C; 18–23 °C).

Figure 5 shows the outdoor comfort levels in south-facing canopy spaces. PET in the 13–29 °C range that makes occupants feel thermally comfortable is achieved to a high extent over the whole year when using flexible canopies; comfort levels of 56.3% in London, 51.2% in Manchester, and 49.2% in Glasgow were achieved. Opaque glass (0%) shows the worst performance in Manchester and Glasgow where solar radiation is relatively rare compared to London. Thermal comfort in the outdoor canopy space is enhanced by 12.6% (compared to that achieved using a canopy with 90% transparency) and by 11.7% (compared to a canopy having 0% transparency) in London, as observed in Figure 5. Yearly PETs were calculated considering a south orientation for London, Manchester, and Glasgow and are presented in Table 4. It presents the improvement observed for each orientation and in each city when using a flexible canopy over the whole year during school hours (09:00 am–4:00 pm).

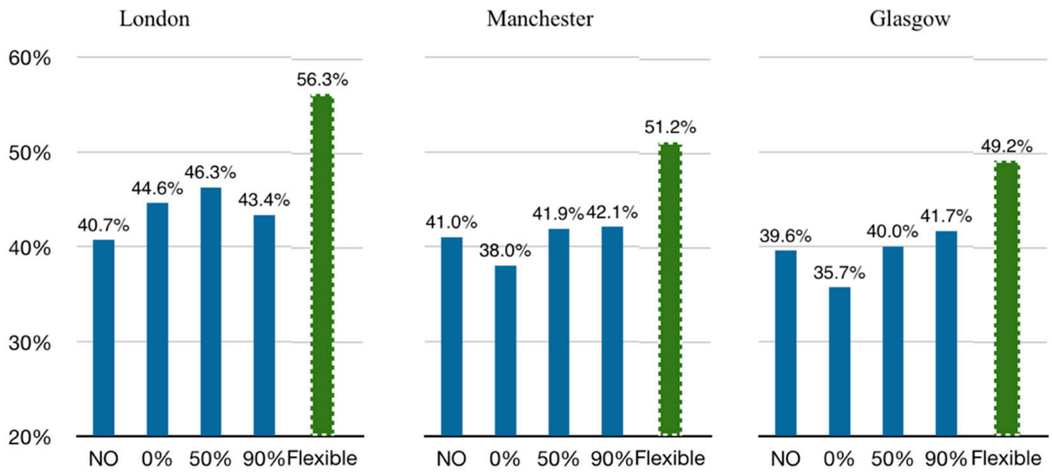


Figure 5. Outdoor thermal comfort levels throughout the year in the temperature range of 13–29 °C in outdoor south-facing canopy spaces in London, Manchester, and Glasgow.

Table 4. Outdoor thermal comfort levels in the temperature range 13–29 °C achieved using a flexible canopy with facing south orientation during the daytime (09:00 am–4:00 pm).

	London	**Manchester**	**Glasgow**
North	55.4%	50.4%	47.6%
West	54.9%	51.5%	49.6%
East	55.8%	52.4%	50.3%
South	56.3%	51.2%	49.2%

The performance efficiency of the flexible canopy was considerably more significant in London compared to Glasgow as the canopy plays a vital role in controlling solar radiation. Wind speed is also affected when the canopy is opened or closed; increased wind speeds when the canopy is open positively influenced thermal comfort in summer while having a negative influence in winter. According to the results of this simulation, it is best to keep the canopy open in warm seasons from June to September but closed in cold seasons from October to May. The improvement in thermal comfort clearly shows that the flexible canopy performs well in different cities compared to a fixed canopy by just varying the transparencies. The flexible canopy shows a substantial improvement of 16.6% in Glasgow in an east-facing canopy space compared to a canopy with 0% transparency in Glasgow. The thermal comfort improvement was in the range of 10%–12.6% when using the flexible canopy compared to the base-case simulations using canopies with 0%, 50%, and 90% transparency.

Most improvements can be achieved during the warm season as there is a profound change in thermal comfort when blocking solar radiation, as observed in the simulation involving a fixed canopy. If there is a considerable amount of solar radiation, there is also excellent potential for improving thermal comfort through manipulation when using a flexible canopy.

3.4. Daylighting

Figure 6 presents the results of daylighting simulations conducted using the flexible canopy. The primary method of reducing electric lighting is to minimize any glare problems while providing enough diffuse light in the classroom. A canopy can function as a shading device to protect an indoor area from direct radiation and maximize diffuse light, thus improving the visual conditions for the students. Blinds were included in the simulation as most schools generally use blinds operated manually by the occupants of the classroom, which block direct solar radiation entering through the classroom window. With blinds in use, 25% of the diffuse light can still enter the indoor classroom. The use of light switches was also considered in the simulations.

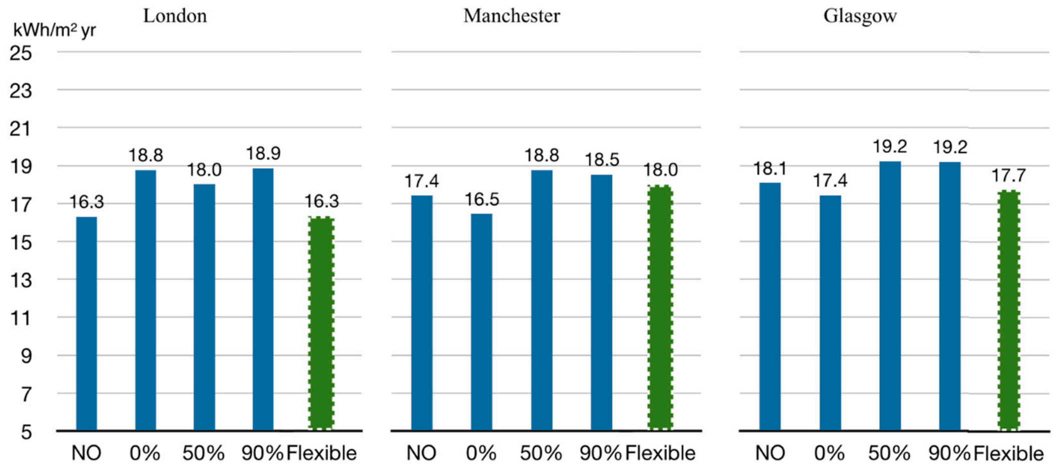


Figure 6. Annual indoor lighting energy demand for a south-facing canopy area.

The physical conditions used for the numerical model in the daylight simulations were the same as those used for the fixed canopy. The illuminance level on the working plane had to be no less than 300 lux in the teaching area [41]. The simulation period was the same as that for the fixed canopy, i.e., from Monday to Friday between 09:00 am and 4:00 pm. The measured desk height was 900 mm from the floor and reflectance values of 0.3 for the floor, 0.5 for wall, and 0.7 for the ceiling were set. At a minimum illuminance level of 300 lux, the minimum allowed level of illuminance at the desk level was used for calculating the lighting energy demand. As illustrated in Figure 6, the daylighting performance of the flexible canopy shows an improvement of approximately 20% achieved compared to that without a canopy in the case of a south-facing canopy in London. Even though there is no software yet available to calculate indoor lighting demands when using a flexible type canopy, simplified simulations were conducted. In the simulation, the method with which the blinds at the window would be operated automatically, set by the DaySim software. As direct sunlight can cause a glare problem, blinds will be drawn automatically which is considered as the same mechanical process with that of outdoor canopy system.

As shown in Figure 6, in a London classroom, the maximum potential annual saving in energy used to light the classroom when using a flexible canopy is 2.6 kWh/m^2 compared to a canopy with 90% transparency, this amounts of a saving in electric lighting energy of approximately 10%–14% per square meter.

In all cities, considerable amounts of savings in electric lighting energy can be made when using a flexible canopy rather than one with 0% transparency in which there is little available daylight. One of the advantages of using a flexible canopy is that it can minimize the use of blinds that block direct sunlight and then lead to the use of electric lights during daytime. The reduction in daylighting energy demands associated with different classroom orientations and fixed canopy transparencies were calculated through simulations using the DaySim software and are presented in Table 5. In general, there is an enhancement in the daylighting level in the classroom, thus reducing the use of electric lights. However, in the south-facing classrooms in Manchester and east-facing ones in Glasgow, more electric light is used than when using a flexible canopy. Glaring is the main reason for daytime light usage in schools. However, using a flexible canopy that can be automatically adjusted according to light conditions would potentially increase the electrical energy demand. Therefore, it is essential to consider how a flexible canopy would be operated and what its running costs would be before installation. Daylight in the classroom is influenced by the reflectance of both internal and external surfaces, size of the glazing, and architectural reflectors such as light shelves and reflectors. This simulation showed how a flexible canopy can be manipulated in the same way as an external blind, thus helping to minimize the usage of both indoor electric lighting and blinds. The simulation showed that the canopy could perform well in this respect in most orientations and cities but especially in north-facing transitional outdoor spaces.

Table 5. Annual indoor lighting energy demand (kWh/m^2 yr) when using a flexible canopy.

	London	Manchester	Glasgow
North	14.64	14.97	18.50
West	15.13	15.13	16.57
East	16.26	16.65	18.55
South	16.33	17.99	17.75

Computer simulations of internal daylighting through DaySim showed that using a flexible canopy can reduce the need for artificial lighting and allow students to benefit from daylight almost throughout the year. Even though it does not always achieve the recommended daylighting level of over 300 lux for a classroom, it can help minimize glare problems associated with direct solar radiation; moreover, illuminance levels can be increased by opening the canopy on a cloudy day. As there are several environmental factors associated with an outdoor canopy space, the solution to one problem should not compromise the environmental performance of the canopy in terms of its other functions. Therefore, the simulations involving all the other factors such as outdoor thermal and heating energy demands should be considered at the same time to optimize the canopy design.

3.5. Heating Energy Demand

The heating energy demand of the classrooms was analyzed using the same physical conditions as those when using a flexible canopy in the canopy space. Both internal and external gains influence the heating energy demand. The window size and orientation, as well as external shading devices, play essential roles in admitting sunlight into the classroom. With the same building settings as in the simulations, the heating energy demand of a classroom was determined when using a flexible canopy.

The annual heating demands of classrooms using flexible canopies are given in Figure 7 and Table 6. Using the EDSL TAS software and a design that follows current building regulations, the annual heating energy consumption was calculated to be generally low, but slightly higher than when using a canopy with 90% transparency.

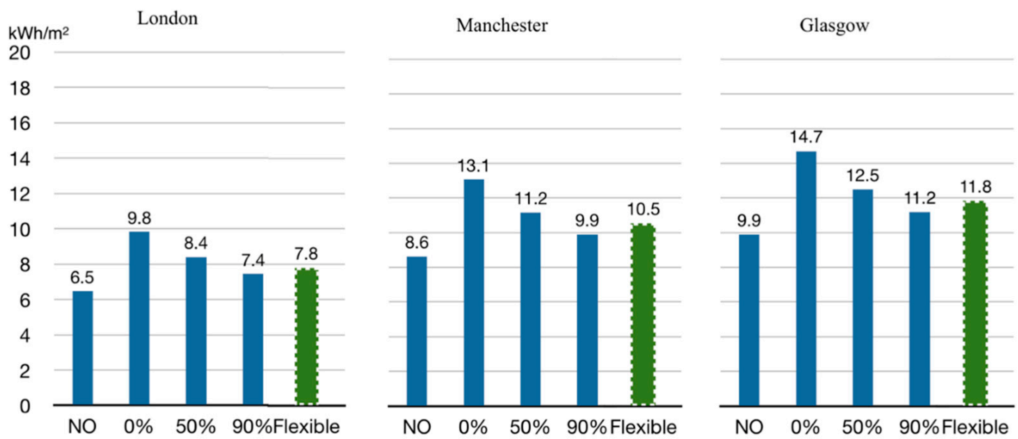


Figure 7. Annual heating energy demands (kWh/m^2 yr) of south-facing classrooms.

Table 6. Annual indoor heating energy demands (kWh/m^2 yr) when using a flexible canopy.

	London	Manchester	Glasgow
North	9.94	13.77	16.01
West	8.61	11.98	13.80
East	9.47	13.05	15.34
South	7.80	10.54	11.84

The simulation modeled seasonal operations of the canopy in which a canopy with 0% transparency was used during summer (June–July) and one with 90% transparency for the rest of the year. The canopy transparency should be selected so as to maximize the incident solar radiation in cold/cool seasons and to minimize outside heat in warm seasons. The internal heating temperature was set at 18 °C according to the recommendations of BB87. According to the simulations, Glasgow showed a higher heating energy demand than either London or Manchester, requiring a canopy transparency slightly higher than 90%, as illustrated in Figure 7.

The heating energy demand of a classroom needs to be minimized as the winter school holidays are relatively shorter than the summer holidays, meaning that students spend more time in school in winter than in summer. As contemporary buildings are built according to stringent building regulations (e.g., using high-performance building materials and airtightness standards), the mean value of the annual heating energy demand of the classroom ranged between 7.8 and 9.9 kWh per square meter in London and 11.8 and 16.0 kWh per square meter in Glasgow. Being at a higher altitude, the lower temperatures and limited solar radiation experienced by the Glasgow classroom caused an increase in heat gain. The impact of an external canopy in a transitional outdoor space on the heating energy demand of the neighboring classroom(s) must be evaluated for each school term. Using a flexible canopy can potentially reduce both the heating energy demand in winter and internal heating problem in summer (June–July) as it blocks direct sunlight by adjusting its panes to reduce overheating. Such canopy devices are popular in southern Europe. During cold periods (November–February), as much solar radiation (direct and diffuse) needs to penetrate the indoor classroom as possible to provide external heat gain. Therefore, when designing a flexible shading device, it is crucial to consider the solar altitude and azimuth angles during the hot seasons to prevent direct sunlight from passing through. The extent to which direct sunlight passes through windows depends on the orientation of the windows, the sun position at the time under consideration, and the operating mechanism of these devices, all of which need to be considered to maximize the environmental performance of the canopy.

It is useful to analyze how energy consumption and outdoor thermal comfort vary with different classroom orientations as classrooms can be allocated differently in school planning. The stacked column charts in Figure 8 present the energy consumed for lighting (colored in blue) and heating (colored in yellow) while outdoor thermal comfort is indicated using dotted gray lines. Energy consumed for lighting and heating is the highest when using a canopy with 0% transparency in most orientations, except for the east-facing classroom. The canopy with 50% transparency requires 28.9 kWh/m^2 per year owing to the glare problem during early morning hours when blinds are used to block direct sunlight. The flexible canopy shows the best performance among all the canopies. Among the fixed canopies, the one with 0% transparency should not be installed in front of classrooms while that with 90% transparency is the most suitable. In particular, energy consumption in north-facing classrooms with opaque canopies (0% transparency) increases sharply owing to the relative shortage in daylight and solar radiation.

However, it is hard for stakeholders and designers to understand energy consumption and outdoor thermal comfort with a balanced view. Therefore, it is required to use a simplified graph to select the appropriate canopy unit (based on factors such as enhancement percentage) easily; hence, it is essential to understand the simulation results in the early stages of designing. The simplified graphs developed during this study are shown in Figures 9–11. Energy and thermal comfort are combined with the enhancement percentage. Therefore, stakeholders can effectively understand the performance of each canopy considering the enhancement percentage. The average performance enhancement values considering all the cases (no canopy, transparencies of 0%, 50%, and 90% and flexible canopy) were calculated and are given in each of the figures for comparison.

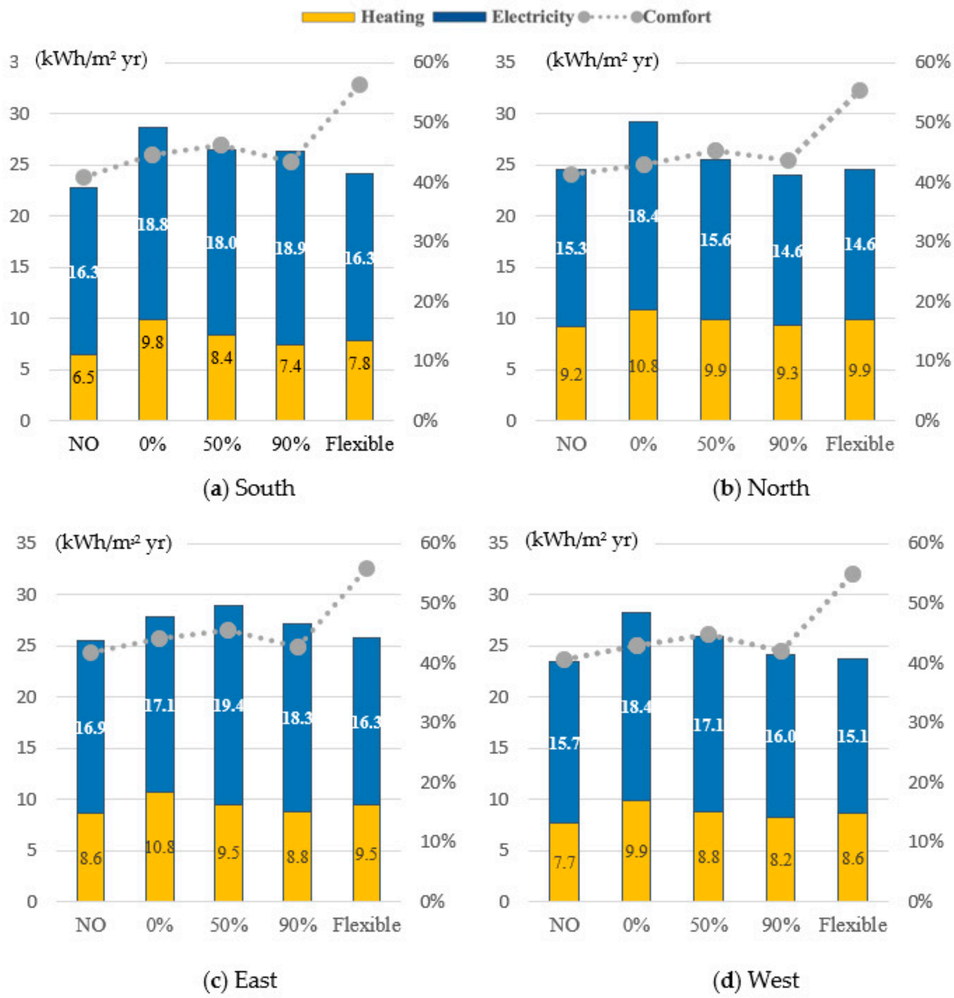


Figure 8. Energy consumption (Heating/electricity kWh/m^2 yr) and outdoor thermal comfort (%) in London.

The flexible canopy is the most effective in all the orientations, as is evident in Figure 9 and Table 7. An obvious fact is the improvement of 17% observed in the case of the south-facing classroom without a canopy. In addition, the canopy with 0% transparency shows low performance in the north- and west-facing classroom with performance decreases of 18% and 13%, respectively.

The canopy performance in Manchester is presented in Figure 10; it is slightly different as Manchester is located in the middle part of UK with relatively more cloudy days than London. The flexible canopy performed effectively in the north, east, and west orientations while the canopy with 0% transparency increases the energy consumption and discomfort in outdoor areas. East-oriented fixed canopies with different transparencies did not show satisfactory performance. A 7% improvement was observed in the west orientation with canopy, while decrements of 13, 7, and almost 0% enhancement were observed with canopies having transparencies of 0%, 50%, and 90%, respectively, as observed in Table 8. The south-oriented canopy with 50% transparency showed the worst performance. Moreover, the flexible type canopy is suitable for north, east, and west orientations.

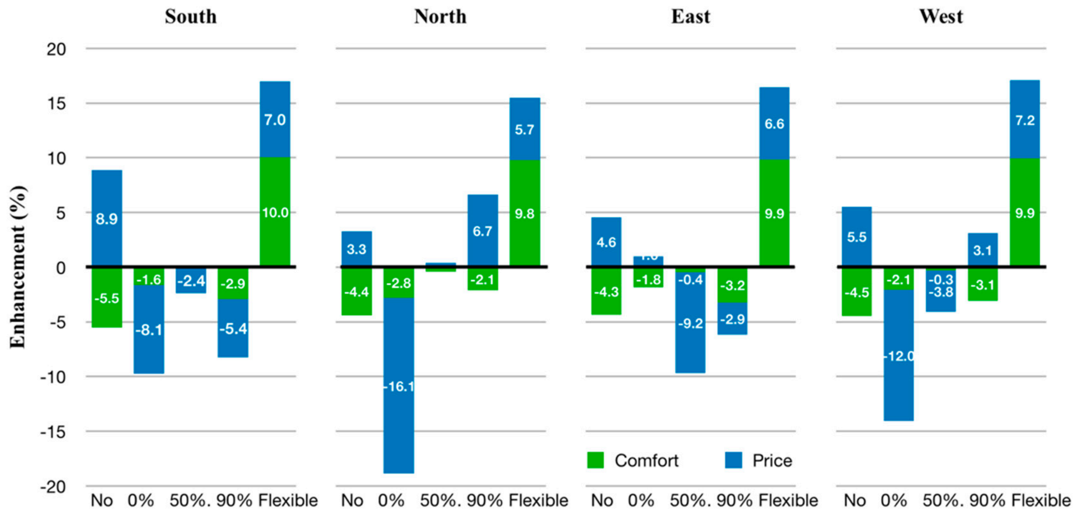


Figure 9. Enhancement (%) in thermal comfort and energy price (bill) in London.

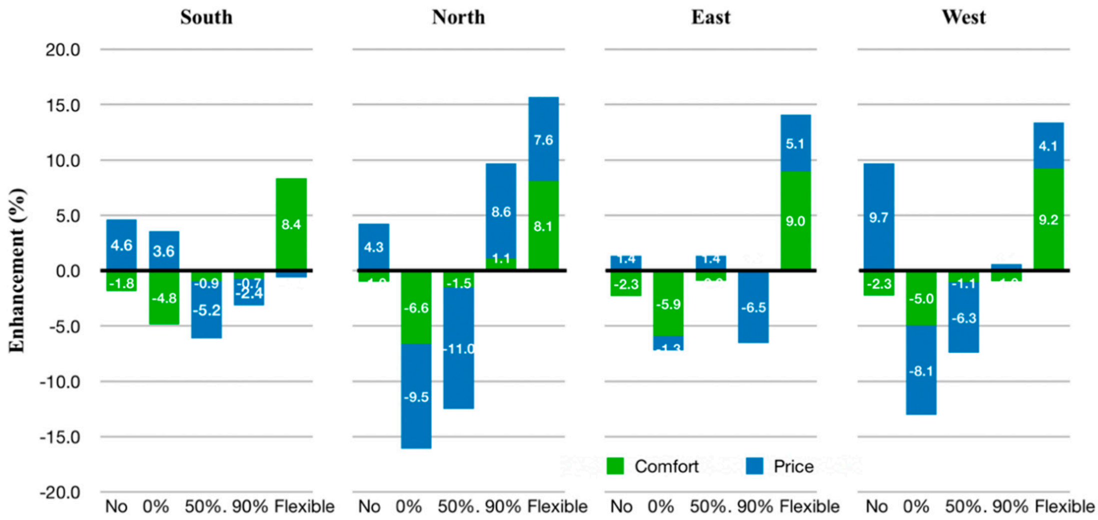


Figure 10. Enhancement (%) in thermal comfort and energy price (bill) in Manchester.

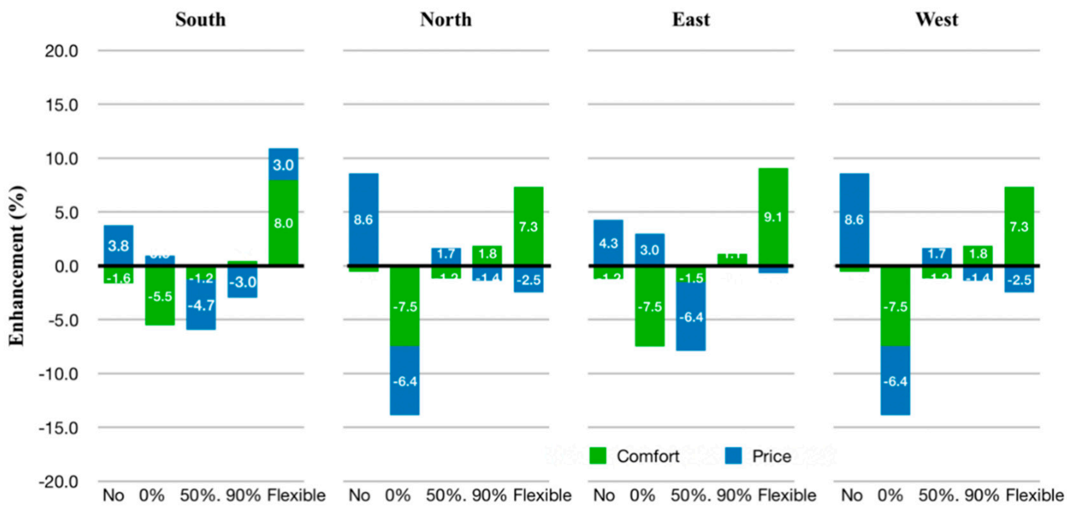


Figure 11. Enhancement (%) in thermal comfort and energy price (bill) in Glasgow.

Table 7. Enhancement (%) in thermal comfort and energy price from the average.

		NO	0%	50%	90%	Flexible
South	Comfort	−5.51	−1.64	0.00	−2.89	10.04
	Price	8.88	−8.08	−2.39	−5.37	6.96
North	Comfort	−4.42	−2.82	−0.42	−2.12	9.78
	Price	3.28	−16.05	0.40	6.66	5.72
East	Comfort	−4.34	−1.84	−0.44	−3.24	9.86
	Price	4.58	0.98	−9.23	−2.93	6.60
West	Comfort	−4.48	−2.08	−0.28	−3.08	9.92
	Price	5.50	−11.99	−3.80	3.14	7.16

Table 8. Enhancement (%) in thermal comfort and energy price from the average in Manchester.

		NO	0%	50%	90%	Flexible
South	Comfort	−1.84	4.84	−0.94	−0.74	8.36
	Price	4.60	3.57	−5.16	−2.41	−0.61
North	Comfort	−1.02	−6.62	−1.52	1.08	8.08
	Price	4.26	−9.47	−10.99	8.62	7.58
East	Comfort	−2.32	−5.92	−0.92	0.18	8.98
	Price	1.36	−1.29	1.36	−6.53	5.10
West	Comfort	−2.26	−4.96	−1.06	−0.96	9.24
	Price	9.67	−8.07	−6.34	0.60	4.14

Glasgow is infamous for its shorter summers and longer winters compared to other places in the UK. Therefore, the canopy with 0% transparency (opaque) showed the worst performance in the north and west orientations, as observed in Figure 11. There is no significant overall enhancement in canopy performance, compared to London and Manchester. Improvements of 10% and 9% improvement in the south and east orientations, respectively, were observed when using the flexible canopy tabulated, as presented in Table 9. One of the crucial functions of the canopy is to provide shelter from rain and strong winds; therefore, the appropriate type of canopy should be selected using an approach that considers both energy consumption and outdoor thermal comfort.

Table 9. Enhancement (%) in thermal comfort and energy price from the average in Glasgow.

		NO	0%	50%	90%	Flexible
South	Comfort	−1.64	−5.54	−1.24	0.46	7.96
	Price	3.77	0.94	−4.71	−2.95	2.95
North	Comfort	−0.56	−7.46	−1.16	1.84	7.34
	Price	8.59	−6.41	1.66	−1.38	−2.46
East	Comfort	−1.20	−7.50	−1.50	1.10	9.10
	Price	4.25	2.96	−6.39	−0.14	−0.69
West	Comfort	−0.56	−7.46	−1.16	1.84	7.34
	Price	8.59	−6.41	1.66	−1.38	−2.46

4. Findings and Discussion

Throughout the study, the interconnected effects of using a flexible canopy as a microclimate modifier on outdoor thermal comfort, as well as the daylight levels in indoor environments and the subsequent energy demands were revealed. The intention behind carrying out this work was to provide a better understanding of the microclimatic characteristics of outdoor canopy spaces in schools through examining common building elements and to understand the implications this would have on the comfort level of students and the energy demands of the building. The simulation results showed that using a flexible canopy can enhance the microclimate and also reduce the energy demand of the classroom by a greater degree compared to using fixed canopies with different transparencies.

The idea of utilizing a flexible canopy is based on the findings of simulations involving fixed canopies with different transparencies; a canopy with 90% transparency performs well in winter, and one with 0% transparency performs well in summer. This can save energy while maximizing outdoor comfort, leading to a potential reduction of 20% in the lighting energy demand in London and an increase of 12%–17% in outdoor comfort compared to that when using a fixed canopy (opaque).

In this research, we demonstrated that having sheltered outdoor canopy spaces in schools could be beneficial to the local microclimate of the area, thereby contributing to the creation of a comfortable outdoor environment while minimizing energy demands. A canopy used as the main architectural feature of a transitional space should serve as an extended classroom throughout the year. The simulations showed that a flexible canopy is more effective than a fixed canopy in improving outdoor thermal comfort and indoor daylighting. Most of the methods for calculating the environmental performance of a flexible canopy are similar to those used for a fixed canopy. Its flexible nature that makes this canopy adaptable for use in most areas; however, its design details and operations are extremely critical. Considerations need to be made on whether it should be controlled manually or automatically although automatic control proved effective in the simulations. Users would need to learn how to operate the canopy and understand when it may be necessary to adjust the canopy depending on the environmental conditions and purpose for using the transitional space or indoor classroom. An unsophisticated operation method may worsen the outdoor or indoor environment. The initial costs also need to be considered in terms of the value of the buildings and the length of the payback period.

The flexible configuration of a canopy can improve its adaptability to unstable environments depending on the needs of the occupant. However, the mechanical details their operation, as well as the cost and feasibility of manufacturing these canopies need to be considered. In summer, the canopy can help improve outdoor thermal comfort by preventing direct solar radiation from passing through, while at the same time increasing the wind speed either by being partly or fully open. In winter, the wind speed should be minimized and solar radiation maximized. However, as maximizing solar radiation to increase indoor daylight can cause increased glare, the operation of the canopy should be manually controllable so that it can be adjusted whenever necessary.

As a shading device, a flexible canopy can help minimize the glare problem, the main reason for the increased use of electric lights in schools. An automatically operated canopy is recommended; however, it should also be possible to operate the canopy manually should the occupants need to do so or if power supply is cut.

One vital feature of an environmentally improved transitional outdoor space is its flexibility in dealing with the changing environmental needs of the occupants. The canopy space in schools should be flexible enough to cope with the students' needs, depending on whether they are using an indoor classroom or its adjacent outdoor space. For example, if students and teachers assemble in the canopy space to listen to stories or sing songs, the canopy can be adjusted to improve the microclimate; it can either allow more solar radiation in winter block direct sunlight altogether in summer according to the environmental conditions. However, designing an operation mechanism for a flexible canopy could ultimately be difficult because of the complexities of the operating system, as it would need to be robust and secure for teachers/students to handle. Table 10 summarizes the performance of both fixed and flexible canopies according to the environmental criteria discussed in this study. This is a summary of the theoretical performance considering ideal occupant behavior and operational conditions.

Moreover, it is recommended to use flexible canopies with a combined system facilitating both manual and automatic operations so teachers can operate the canopy whenever required. Thus, it is possible to prove the hypothesis that outdoor spaces under canopies linked with indoor spaces can be environmentally enhanced in terms of daylighting levels and outdoor thermal comfort using flexible building elements.

Table 10. Comparison of the environmental performance of fixed and flexible canopies.

	Fixed Canopy	Flexible Canopy
Outdoor thermal comfort	▪ There is a limit for maximizing outdoor thermal comfort achieved mainly by protecting against solar radiation in summer and allowing it to enter in winter. ▪ Transparency of the canopy should be carefully selected.Relatively easy to install.	▪ It is the best way to provide outdoor thermal comfort by controlling the amount of direct solar radiation. ▪ More effective for south-oriented spaces than for other orientations. ▪ Automatic operation is recommended, but options for manual operation should be included.
Daylighting	▪ Transparency of the canopy does not really affect the use of electric lights in the parent building. ▪ How blinds are used in the classroom (either manual or automatic) plays an essential role in determining whether or not electric lights are used. ▪ South-facing classrooms have greater daylight autonomy than classrooms with other orientations, thus showing more potential to manipulate daylight depending on the design of the blinds provided.	▪ Theoretically, automatic control of the canopy can give the best outcome in preventing glare when operated like external blinds. ▪ Performs better in south-oriented spaces than in spaces with east or west orientations. ▪ As a shading device, a flexible canopy can minimize the use of blinds in a classroom. ▪ If an automatic blind is used in the classroom, the role of the flexible canopy in controlling daylight is lessened.
Heating energy	▪ The lower the transparency, the higher the heating energy demand in any orientation. ▪ However, heating energy demand can vary according to the size of the glazed area and materials.	▪ The operation and transparency of the canopy's front panel affect energy performance. ▪ The performance in terms of reducing heating energy is better than that of a 50% transparency canopy but worse than of a 90% transparency of fixed canopy. ▪ There is no significant improvement in performance when compared to other types canopies.

5. Conclusions

This study demonstrated flexible operation of architectural elements allowing the building to adapt in response to seasonal or daily climatic variations. A canopy was selected as the architectural element; it can help overcome any limitations resulting from building orientation and materials that can deteriorate both the indoor and outdoor environments. To analyze the performance of canopies, simulations using different transparencies and orientations were performed for flexible and fixed canopies in London, Manchester, and Glasgow, having different climates. Poor environmental performance was observed in some cases (in terms of the daylighting level, heating demand, and outdoor comfort), worse than that observed without a canopy. However, the south-facing canopy with a highly transparent pane showed better performance compared to fixed and opaque canopies in all locations. In particular, the flexible canopy significantly reduced thermal discomfort in outdoor spaces during summer by blocking direct solar radiation; moreover, it increased outdoor comfort in spring and autumn by allowing sunlight to pass through.

This study also developed a method for selecting an appropriate canopy based on the performance enhancement (%) combined with outdoor thermal comfort and indoor energy consumption including electricity used for both lighting and heating. A building element should be selected using a holistic approach than merely focusing on specific environmental factors (such as daylighting and thermal comfort). As architecture is a complex combination of design and engineering performance, building elements must be selected using combined approaches to meet the performance requirements. Moreover, the adaptability of flexible building elements can be beneficial under rapidly changing climatic conditions. Adapting to changing environmental conditions is one of the most crucial properties of building elements considering climatic changes that can occur in the future. Flexible building elements are often used in traditional architecture in different countries according to climatic conditions. Flexible elements may not be required in buildings under constant climatic conditions throughout the year as opposed to those subject to extreme conditions; still, architects and engineers need to draw from vernacular architecture for designing buildings in different regions.

Further, this study has some limitations. As there is no single software package that can simulate the effects of using canopies in both outdoor and indoor spaces at a time, coupling different software packages to observe these effects requires a skilled and experienced engineer. The methods used in this study can be changed if advanced software packages become available in the future for analyzing the environmental performance of building elements. The criteria of thermal comfort and daylighting levels can be varied using different functions depending on the types of spaces and user activities. For example, daylighting levels of 300–500 lux are needed in spaces involving visual activities such as classrooms and libraries and 200 lux for circulation areas. Perceptions of thermal comfort in different countries would vary, which can be explored in further studies. Climate data for rural and urban areas should be considered carefully as the microclimate is sometimes considerably different in different environments.

Environmental assessment (e.g., BREEAM, LEED, etc.) with flexible operation of building elements can be beneficial to prove their enhanced performance in specific cases. Therefore, the results may vary depending on the building elements and locations. Nevertheless, with these simulation techniques and methods, designers and engineers can establish more detailed metrics for using flexible building elements with the combined analysis both indoor and outdoor spaces to maximize human comfort and minimize building energy demands.

Author Contributions: Conceptualization, K.J.L. and C.W.K.; methodology, C.W.K. and S.C.; software, C.W.K.; validation, S.C. and K.J.L.; formal analysis, C.W.K.; investigation, C.W.K.; resources, S.C.; data curation, S.C.; writing—original draft preparation, C.W.K.; writing—review and editing, K.J.L.; visualization, C.W.K.; supervision, K.J.L. and S.C.; project administration, K.J.L.; funding acquisition, K.J.L.

Funding: This research was funded by the research fund of Hanyang University, South Korea (HY-2013).

Acknowledgments: This study is thankfully supported by the Industry-University Cooperation Foundation, Erica campus, Hanyang University.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Givoni, B. *Passive and Low Energy Cooling of Buildings*; Van Nostrand Reinhold: New York, NY, USA, 1994; p. vii. 263p.
2. Thomas, R. *Environmental Design: An Introduction for Architects and Engineers*, 3rd ed.; Taylor & Francis: London, UK, 2006; 272p.
3. Hootman, T. *Net Zero Energy Design: A Guide for Commercial Architecture*; John Wiley & Sons: Hoboken, NJ, USA, 2013; 441p.
4. Yannas, S. *Design of Educational Buildings; Environment & Energy Studies Programme*; Architectural Association Graduate School on behalf of the Commission of the European Communities: London, UK, 1994; Volumes 1–3, 95p.
5. Webb, A.L. Energy retrofits in historic and traditional buildings: A review of problems and methods. *Renew. Sustain. Energy Rev.* **2017**, *77*, 748–759. [CrossRef]
6. Steemers, K.; Baker, N.; Fanchiotti, A. *Daylighting in Architecture: A European Reference Book*; Published for the Commission by James & James: London, UK, 1993.
7. Loonen, R.C.G.M.; Favoino, F.; Hensen, J.L.M.; Overend, M. Review of current status, requirements and opportunities for building performance simulation of adaptive facades. *J. Build. Perform. Simul.* **2017**, *10*, 205–223. [CrossRef]
8. Grobman, Y.J.; Capeluto, I.G.; Austern, G. External shading in buildings: Comparative analysis of daylighting performance in static and kinetic operation scenarios. *Archit. Sci. Rev.* **2017**, *60*, 126–136. [CrossRef]
9. Gelfand, L.; Freed, E.C. *Sustainable School Architecture: Design for Primary and Secondary Schools*; John Wiley: Hoboken, NJ, USA; Chichester, UK, 2010.
10. Brook Lapping Productions. Learning outside the classroom primary history. In *Education in Video*; Teachers TV/UK Department of Education: London, UK, 2010.
11. Constable, K. *The Outdoor Classroom Ages 3–7: Using Ideas from Forest Schools to Enrich Learning*; Routledge: Milton Park, Abingdon, UK; New York, NY, USA, 2012.
12. Chen, L.; Ng, E. Outdoor thermal comfort and outdoor activities: A review of research in the past decade. *Cities* **2012**, *29*, 118–125. [CrossRef]
13. Aljawabra, F. Thermal Comfort in Outdoor Urban Spaces: The Hot Arid Climate. Ph.D. Thesis, University of Bath, Bath, UK, 2014.

14. Schiano-Phan, R.; Weber, F.; Santamouris, M. The Mitigative Potential of Urban Environments and Their Microclimates. *Buildings* **2015**, *5*, 783–801. [CrossRef]
15. Santamouris, M. *Energy and Climate in the Urban Built Environment*; James & James: London, UK, 2001; 402p.
16. Taleghani, M.; Kleerekoper, L.; Tenpierik, M.; van den Dobbelsteen, A. Outdoor thermal comfort within five different urban forms in The Netherlands. *Build. Environ.* **2015**, *83*, 65–78. [CrossRef]
17. Schinasi, L.H.; Benmarhnia, T.; De Roos, A.J. Modification of the association between high ambient temperature and health by urban microclimate indicators: A systematic review and meta-analysis. *Environ. Res.* **2018**, *161*, 168–180. [CrossRef]
18. Hawkes, D. *The Environmental Tradition: Studies in the Architecture of Environment*; E. & F.N. Spon: London, UK, 1996; p. 212.
19. Merlier, L.; Frayssinet, L.; Johannes, K.; Kuznik, F. On the impact of local microclimate on building performance simulation. Part II: Effect of external conditions on the dynamic thermal behavior of buildings. *Build. Simul.* **2019**, *12*, 747–757. [CrossRef]
20. Lu, S.; Xia, H.; Wei, S.; Fang, K.; Qi, Y. Analysis of the differences in thermal comfort between locals and tourists and genders in semi-open spaces under natural ventilation on a tropical island. *Energy Build.* **2016**, *129*, 264–273. [CrossRef]
21. Yang, B.; Olofsson, T.; Nair, G.; Kabanshi, A. Outdoor thermal comfort under subarctic climate of north Sweden—A pilot study in Umeå. *Sustain. Cities Soc.* **2017**, *28*, 387–397. [CrossRef]
22. Szokolay, S.V.; Auliciems, A. *PLEA Notes 3: Thermal Comfort PLEA: Passive and Low Energy Architecture International*; revised 2007; University of Queensland: Brisbane, Australia, 1997.
23. CIBSE. *Comfort*; CIBSE: London, UK, 2006.
24. Liu, J.; Niu, J.; Xia, Q. Combining measured thermal parameters and simulated wind velocity to predict outdoor thermal comfort. *Build. Environ.* **2016**, *105*, 185–197. [CrossRef]
25. He, Y.; Jones, P.J.; Rayment, M. A simple parameterisation of windbreak effects on wind speed reduction and resulting thermal benefits to sheep. *Agric. For. Meteorol.* **2017**, *239*, 96–107. [CrossRef]
26. Pomponi, F.; Barbosa, S.; Piroozfar, P.A.E. On The Intrinsic Flexibility of the Double Skin Façade: A Comparative Thermal Comfort Investigation in Tropical and Temperate Climates. *Energy Procedia* **2017**, *111*, 530–539. [CrossRef]
27. Nazarian, N.; Sin, T.; Norford, L. Numerical modeling of outdoor thermal comfort in 3D. *Urban Clim.* **2018**, *26*, 212–230. [CrossRef]
28. Gulyas, A.; Unger, J.; Matzarakis, A. Assessment of the microclimatic and human comfort conditions in a complex urban environment: Modelling and measurements. *Build. Environ.* **2006**, *41*, 1713–1722. [CrossRef]
29. Höppe, P. The physiological equivalent temperature—A universal index for the biometeorological assessment of the thermal environment. *Int. J. Biometeorol.* **1999**, *43*, 71–75. [CrossRef]
30. Spagnolo, J.; de Dear, R. A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. *Building and Environment* **2003**, *38*, 721–738. [CrossRef]
31. Hoppe, P. Different aspects of assessing indoor and outdoor thermal comfort. *Energy Build.* **2002**, *34*, 661–665. [CrossRef]
32. CIBSE. *Design for Improved Solar Shading Control*; DTI & Chartered Institution of Building Services Engineers: London, UK, 2006; 29p.
33. Littlefair, P.J. *Summertime Solar Performance of Windows with Shading Devices*; BRE Bookshop for BRE Trust: Garston, UK, 2005; 28p.
34. Van Esch, M.M.E.; Looman, R.H.J.; de Bruin-Hordijk, G.J. The effects of urban and building design parameters on solar access to the urban canyon and the potential for direct passive solar heating strategies. *Energy Build.* **2012**, *47*, 189–200. [CrossRef]
35. DfES. *Schools for the future: Designing School Grounds*; TSO (The Stationery Office): London, UK, 2006; 117p.
36. Dudek, M. *Architecture of Schools: The New Learning Environment*; Architectural Press: Boston, MA, USA, 2000.
37. Tucker, R.; Izadpanahi, P. Live green, think green: Sustainable school architecture and children's environmental attitudes and behaviors. *J. Environ. Psychol.* **2017**, *51*, 209–216. [CrossRef]
38. EDSL Tas v9.1.4 Software. Environmental Design Solutions Limited. Available online: www.edsl.net (accessed on 23 November 2019).

39. Obaidat, M.S. Simulation and Modeling Methodologies, Technologies and Applications. In Proceedings of the International Conference, SIMULTECH 2013, Reykjavík, Iceland, 29–31 July 2013. revised selected papers.
40. Kim, H.; Lee, K.; Kim, T. Investigation of Pedestrian Comfort with Wind Chill during Winter. *Sustainability* **2018**, *10*, 274. [CrossRef]
41. Great Britain. Department for Education and Employment. *BB87 Guidelines for Environmental Design in Schools: (Revision of Design Note 17)*; revised 2003; Stationery Office: London, UK, 1997.