Attaining sustainable high-rise office buildings in warm-summer-cold-winter climates: a case study on Frankfurt

Yuanda Hong[1,3,†], Wu Deng[1,*], Collins I. Ezeh[2] and Zhen Peng[1]
[1]Department of Architecture and Built Environment, University of Nottingham Ningbo, University Park, Ningbo 315100, P.R. China; [2]Department of Chemical and Environmental Engineering, University of Nottingham Ningbo, University Park, Ningbo 315100, P.R. China; [3]Research Institute Department, Shanghai Daren Construction Engineering Co. Ltd, Floor 1, Building 60, No. 1818, Lianhang Road, Minhang District, Shanghai, 201112, China

Abstract

Attaining sustainability in high-rise office buildings necessitates determining the major elements and their associating impacts on the energy performance of this building typology. This study investigates the impact of architectural and engineering features on the energy performance of high-rise office buildings within a warm-summer-cold-winter climate. A rectangular building plan form with a 1:1.44 plan ratio, vertical split core position and central atrium presented the best building performance. The plan form, core position and atrium effect accounted for 59, 30 and 11%, respectively, of an estimated 20.6% building energy savings. Furthermore, exploiting passive strategies founded on the climate and building features as defined by 'PassivHaus' standards further reduced the building energy usage.

Keywords: high-rise office; building energy saving; warm summer cold winter; Frankfurt

*Corresponding author.
wu.deng@nottingham.edu.cn
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1 INTRODUCTION

The enormous global energy consumption, with building stocks accounting for nearly 40%, was considered as the major cause for detrimental environmental impact [1, 2]. This share is predicted to increase due to the envisaged population explosion and urban development [3]. Consequently, cities are expected to expand, particularly vertically due to limited land space [4]. Accordingly, there will be an increase in building energy usage, evoking the need for urban sustainability [3].

Another contributing factor to the expected increase in building energy usage is the effect of global climate changes [1, 5]. The increase in climate variation has resulted in an increased demand for energy to improve the building comfort level. Consequently, this has a rebound effect due to the increase in greenhouse gas (GHG) emissions associated with increased energy usage [1, 6]. Several studies have focused on developing energy conservative measures (ECMs) to improve building energy performance amidst the unfavorable climatic effects. To this regard, five measures were identified [7]: building insulation [8–11], equipment system [12–15], renewable resources [16–19], conserving behaviors [20, 21] and control and management systems [15, 20, 22]. However, the location-based responses of these measures to climate variations are different. Hence, it is imperative that building design strategies for ECMs should consider design meteorological parameters according to the characteristic climate trend within that region i.

Also, the building typology and its characteristic features are also necessary parameters considered in the design of ECMs [1, 5, 23, 24]. For the futuristic purpose, a high-rise building typology is highly recommended in order to optimize land use [4, 25]. Nonetheless, the energy demand and associated emission of this building typology are high due to the increased number of materials and equipment per floor area, particularly for office buildings [3, 4, 26]. To promote cost-beneficial urban sustainability among high-rise buildings, integrated ECMs supported by passive strategies were encouraged [27, 28]. Given a particular climatic condition, several passive strategies developed by

[†]Yuanda Hong, http://orcid.org/0000-0001-7264-9034
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'Passivhaus' Institut Darmstadt in Germany were adopted toward the ecological design of buildings [29].

Passive strategies as defined by 'Passivhaus' standards involve elements that require no external energy source to be effective and include orientation effect and building plan form [30, 31], solar shading [6], core position [32–34] and atrium effect [35]. For the purpose of attaining net-to-gross area efficiencies, the square and rectangular plan forms are the most common building forms [36–38], particularly with width-to-length (W/L) ratio ranging from 1.3–1.5 for cold climates [30, 31]. Furthermore, the size, orientation and position of the core and atrium will aid in reducing heat losses by providing buffer zones and insulating internal spaces [35]. Of the four generic core positions, the split core position promoted a passive low-energy performance in high-rise buildings [32]. Other prominent passive strategies included improving thermal mass effects [28], natural ventilation, evaporative cooling (both direct and indirect) and solar heating effect [39, 40]. However, the effect of these strategies was either beneficial or detrimental to the building comfort level depending on the climate features within that geographical location.

The purpose of this study is to evaluate the impact of climate change on building ECM design, particularly for high-rise office buildings. Emphasis is on various meteorological parameters and the knowledge-driven design of characteristic building features in order to enhance building comfort levels. Considered meteorological parameters are temperature, solar radiation and wind profile, while plan form, core column position, atrium effect, air change rate (wind sensitivity) and building insulation and shading systems were the considered architectural features. This study also provides a holistic insight into the impact of several passive strategies, based on PassivHaus design standards, on the comfort level of high-rise buildings.

2 METHODOLOGY

2.1 Selection of specific city representing the climate zone

The warm-summer-cold-winter (WSCW) climate zone is considered as one of the climate zones with a wide climate variant scope. This climate zone is characterized by two extreme weather conditions throughout the year. Frankfurt (Germany) was selected as the characteristic location because of its history of iconic high-rise buildings. Accordingly, a characteristic high-rise office building was modeled based on data from Chartered Institution of Building Services Engineers (CIBSE) standards. Using the climatic features of this city, the energy performance of high-rise buildings was assessed based on different passive strategies.

2.2 Geometrical model of high-rise office building

Ecotect software was adopted as the evaluating tool to assess the annual energy consumption of the assumed office building. Various studies have validated the accuracy of this simulation tool [41, 42]. It was also approved by several architectural practices for achieving building designs aimed at reducing building energy usage [43, 44], GHG emission [45, 46] and operation costs [47].

In this study, a simplistic office building plan was used as the assumed design model to investigate the most suitable geometry for high-rise office buildings. The suitable model was defined based on the impact of building plan ratio (W/L ratio) of a rectangular building plan, core position and atrium effect on the building energy performance. The building models were designed to have the same architectural and engineering conditions for an appropriate comparison. Further description of these conditions was described elsewhere [48] and summarized below:

2.2.1 *Architecture conditions*

The designed high-rise office buildings were assumed to have the same function, total area, volume, material, typical floor area and core ratio. For this study, the architectural forms and material properties adopted for simulation are presented in Section S1 (supporting document).

2.2.2 *Engineering conditions*

The engineering assumptions for the model were based on general thermal comfort requirements defined by Fanger's model. Each building was designed with the same ventilation, air conditioning system and interior conditions. Internal thermal loads were assumed as heat gained from occupants, lighting and office equipment. Full air conditioning systems were assumed to maintain the internal building temperatures. Details of the assumptions for engineering factors are presented in Section S2 (supporting document).

Based on the assumptions, the simulation results of different architecture plan ratio, core position and atrium within the regional climates of Frankfurt (Germany) were evaluated.

2.3 Redesign model to achieve sustainable building in different climates

The obtained model with the best energy performance within this climate was redesigned using 'PassivHaus' design standards. This was aimed to investigate the impact of each passive strategy in attaining the set sustainability criteria defined by the 'PassivHaus' standard. According to the non-residential 'PassivHaus' standard and environment guide design, energy performance of a building can be improved by adopting passive strategies such as high insulation material, natural ventilation etc. These strategies are more cost-effective given their high impact per cost ratio on reducing building energy consumption and environmental pollution.

3 RESULTS AND DISCUSSION

3.1 Positive and negative passive strategies founded on climatic features

The climatic features of Frankfurt were modeled using Ecotect software. Temperature, solar radiation and wind profile were the considered design meteorological parameters (Section S3, supporting document).

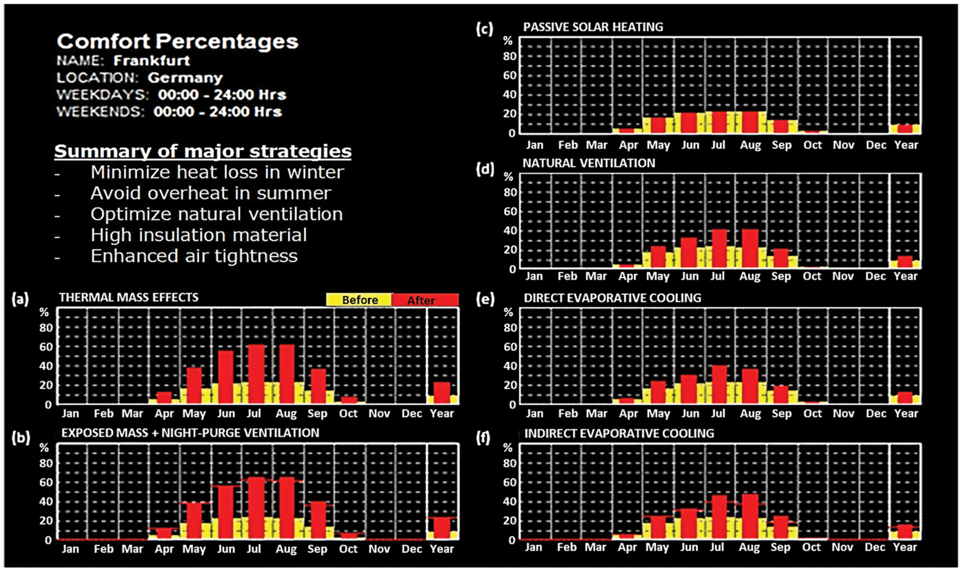


Figure 1. *Individual impact of each passive strategy on the comfort level of high-rise office buildings in Frankfurt (yellow and red bars indicate the comfort level before and after incorporating passive strategy).*

Based on the climate simulation results, the comfort level of occupants was optimized using passive measures to improve thermal comfort and internal air quality. The individual effect of each passive strategy on the building thermal comfort is shown in Figure 1. Conventionally, high-rise office buildings in Frankfurt were rated with an average annual comfort level of 9% according to CIBSE. This formed the basis for comparison for the considered passive strategies. The passive strategies independently affected the comfort level of the building either positively or negatively.

Passive strategies with a positive impact on the building comfort levels included thermal mass effects, natural ventilation and indirect evaporative cooling. The building thermal mass was observed to play a key role in sustaining the thermal comfort of the building. On an annual average, improving the thermal mass of the building was estimated to increase the building comfort level from 9 to ∼23% (Figure 1a). It was projected that a large thermal mass, subjected to insulation, was more likely to reduce the indoor temperature than a small thermal mass [49].

Similarly, natural ventilation impacted positively on the building comfort level. On average, the improvement in natural ventilation increased the annual building comfort level from 9 to ∼14.5% (Figure 1d). The intentional passive flow of ambient air into the building enabled the removal of heat or the provision of cooling [50]. In addition, this measure also promotes good internal air quality particularly when the surrounding air quality is healthy. Night-purge ventilation was observed to be a very effective ventilation measure. This measure alongside with exposed mass posited a 22% comfort level from the 9% of conventional building (Figure 1b). The positive impact of this measure was more significant from April–September and was attributed to the large diurnal swing (i.e. the difference between the daily minimum and maximum outdoor temperature) [51].

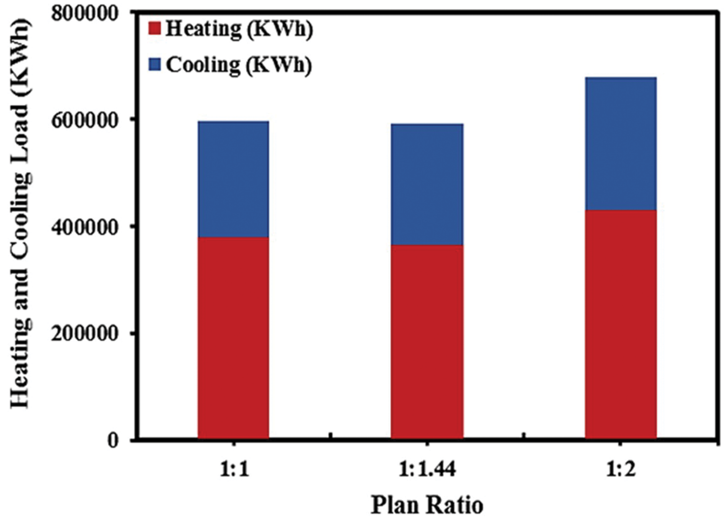
Evaporative cooling was also another passive strategy with significant benefit on thermal comfort improvement. The degree of improvement depended on the adopted approach for evaporative cooling. Independently, the direct and indirect evaporative cooling approach registered an annual average comfort level of 13 (Figure 1e) and 16% (Figure 1f), respectively. The difference in registered comfort levels can be attributed to the combined effect of regional humidity and temperature. While indirect cooling prevents direct contact between the cooled moisture air and the conditioned air, direct cooling has the potential of increasing the humidity of the ambient air. Consequently, indirect evaporative cooling sustains the relative dryness of the air, which supports inhabitants' perspiration and cooling. However, the air condition in this city is fully humid; hence, further increase in humidity will only introduce an uncomfortable living atmosphere.

Contrarily, passive solar heating was noticed to have a detrimental impact on the comfort level of high-rise office buildings (Figure 1c). A summary of the major passive strategies proposed for improving thermal comfort and air quality is described in the inset of Figure 1 below. In general, adequate exploitation of the climate features of a geographical region can aid in developing sustainable buildings, particularly high-rise buildings. However, the energy performance assessment for the assumed building is required in order to propose the most sustainable building in this city.

3.2 Energy performance evaluation

3.2.1 *Effect of building plan ratio*

In order to get the best energy performance of the simulated high-rise office building, 3 different office plans were modeled based on 900 m^2 typical floor area with core space of 9 × 9 m. The



Plan form	Width (m)	Length (m)	Plan Ratio W/L
	30	30	1:1
	25	36	1:1.44
	21.2	42.5	1:2

Figure 2. *Energy performance of different building plan forms in Frankfurt.*

three basic plan forms investigated and their respective energy performance are presented in Figure 2 (and Table S6, supporting document). The cooling and heating load of each plan form were estimated using the climate simulated results and occupant's requirement for comfort.

It was observed that the heating and cooling load of the simulated high-rise office building varied with the plan (W/L) ratio. In all considered plan forms, the heating load accounted for ~62–63% of the total annual building energy consumed. However, the rectangular plan form (W/L ratio, 1:1.44) displayed the lowest total energy consumed of ~592 MWh. The square (W/L ratio, 1:1) and rectangular (W/L ratio, 1:2) plan forms showed total energy consumed of 597 MWh and 679 MWh, respectively. This corresponds with literature [30, 31] and speculates that the 1:1.44 plan ratio to be the best architectural building plan form.

3.2.2 *Effect of core position*

Here, the impact of the core positions on the building energy performance was investigated using the 1:1.44 plan ratio. In this study, only the central core and split core [vertical (split core (1)) and horizontal (split core (2))] positions were assessed. Single-end core position was not included because of its proximity limitation [32]. Illustration of the investigated core positions, orientations and their associated energy performance are shown in Figure 3 (and Table S7 of the supporting document). Figure 3 showed that the presence of a core reduces the energy load of the building. Specifically, the central core reduced the building energy consumption by 0.05% while the split core reduced the energy consumption by 6.5–6.6% depending on the orientation of the core. This was mainly attributed to the reduction in heating load than the cooling load. There were 65% and 69% of reduction in energy consumption due to the reduction in the heating load for split core (1) and split core (2), respectively. Despite this, the split core (1) position was observed to have the lowest total building energy consumption of 553.1 MWh. Overall, a reduction of ~18.59% in the building energy usage was estimated from the additive effect of core position (vertical split core) and plan ratio (1:1.44) when compared to the maximum obtainable energy performance for the same building (plan ratio 1:2).

3.2.3 *Atrium effect*

A common benefit of an atrium is its promotive effect on natural ventilation. However, more heating/cooling will be required when the temperature is below or above human comfort range. Hence, it is important to investigate this effect on building energy performance.

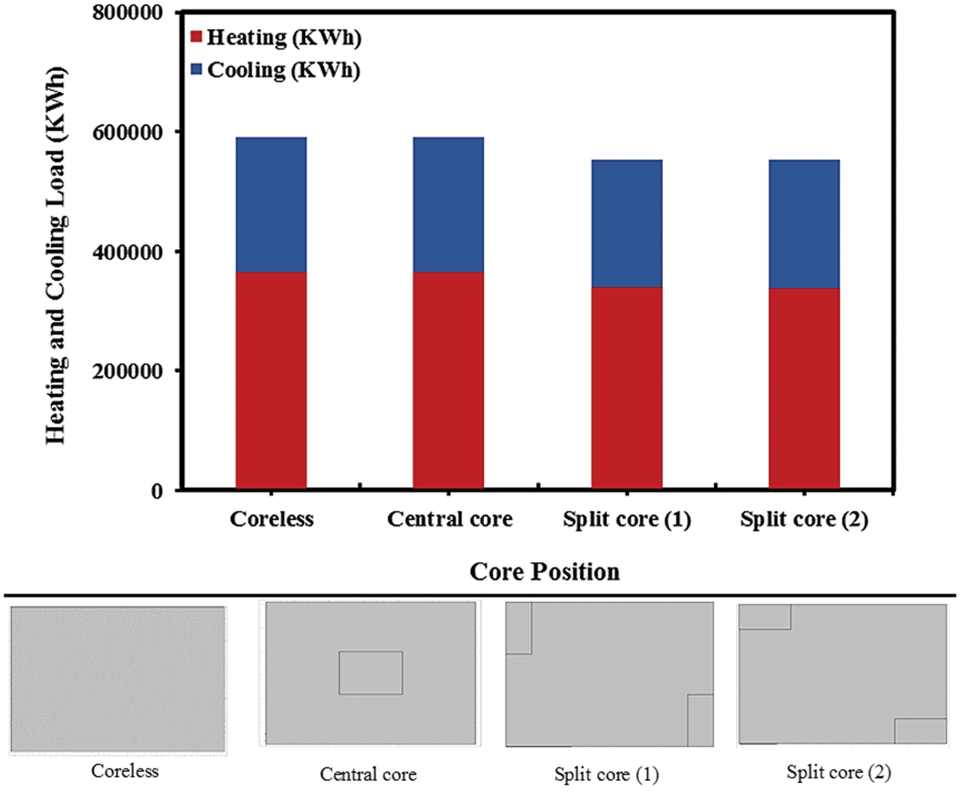


Figure 3. *Energy performance of different core positions (plan ratio, 1:1.44).*

Having considered the best suitable building plan form and core orientation, Figure 4 illustrates the atrium effect on building energy consumption. It was observed that the presence of an atrium was beneficial to a high-rise office building. The total energy consumed by the building with an atrium was 539.25 MWh, which accounted for a 2.5% reduction in total energy consumption of building without an atrium. This was attributed to the cumulative effect of heating load increase (34.1%) and cooling load decrease (60.9%). In addition, the total discomfort period hours (hot and cold periods (hours)) reduced from 3862.9–3080 hours. This demonstrates the chimney effect of an atrium. Accordingly, the building will consume less total energy for office space. Overall, a high-rise office building with 1:1.44 plan ratio, vertical split core and central atrium will hypothetically reduce the energy usage of the building by ~20.63% the building with plan ratio 1:2.

3.2.4. *Proposed best architectural building form*

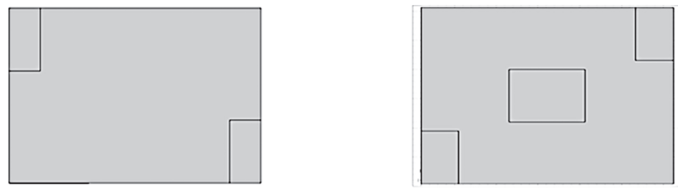
To identify the considerable key elements to achieving a sustainable high-rise office building, a cumulative impact of the passive elements on heat gain and loss in the obtained best building model was investigated for a whole year (Figure 5a).A model of this building form is shown in Figure 5b.

It was depicted that the major contributing elements to heat loss were ventilation and building fabric, which accounted for 61.2 and 38.7%, respectively. Heat loss was primarily due to the chimney/stack effect of the atrium. This was facilitated by ventilation (or air infiltration) than leakages in building fabrics. During cold periods, warm air within the building was upwardly displaced by cold air from lower floors. Consequently, the net effect increased the heat losses across all floors of the building. Moreover, the convective current and temperature gradient associated with the stack-driven air flow facilitated a heat loss distribution within each floor. Heat loss was observed to be most significant at the first and second floors with greater impact from outdoor air infiltration. Beyond these floors, heat loss was orchestrated by interzonal air infiltration. This corresponds with results from the literature [52].

On the contrary, heat was gained mostly from internal heating as a result of human activities and building equipment. This accounted for 64.4% of the heat gained in the building. The other significant factor was solar radiation, which contributed to 30.8% of the heat gain. Therefore, to improve building energy performance, necessary strategies to address heat losses by ventilation and fabric heat transfer during winter and reduction of solar irradiation in summer were considered.

3.3 Redesigned high-rise office building in different climates

To gain insight into the impact of ‘PassivHaus’ standards on the building energy performance, the best architectural building

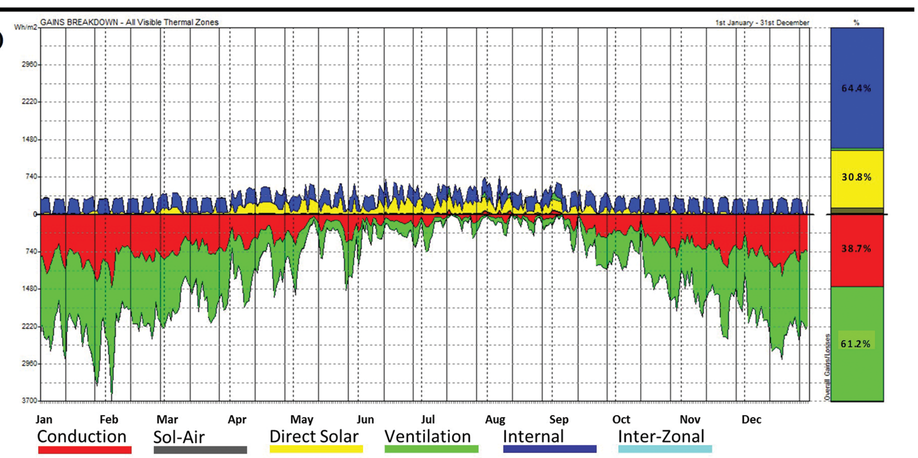


City	Design Consideration	Hot Period (hr)‡	Cold Period (hr)‡	Heating (MWh)	Cooling (MWh)	Total (MWh)
Frankfurt	Without Atrium	128.7	3734.2	340.07	213.03	553.10
	With Atrium*	107.1	2972.9	456.06	83.19	539.25

‡indicates periods when the building temperature is hotter or colder than the human comfort range
*indicates the lowest total building energy consumption

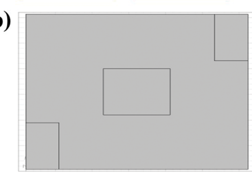
Figure 4. *Energy performance of buildings with and without atrium in high-rise office buildings (with 1:1.44 plan ratio and vertical split core position).*

(a)



CATEGORY	LOSSES	GAINS
Fabric	38.7%	0.7%
Sol-Air	0.0%	2.6%
Solar	0.0%	30.8%
Ventilation	61.2%	1.2%
Internal	0.0%	64.4%
Inter-zonal	0.1%	0.3%

(b)



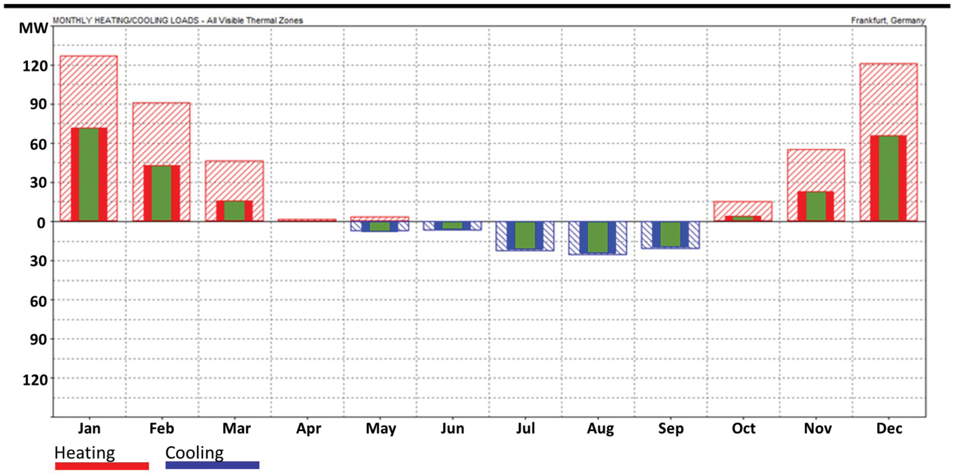
Rectangular plan form (1:1.44 plan ratio) with vertically orientated split core and

Figure 5. *Proposed best architectural building form for Frankfurt with a breakdown of contributing factors of heat gain and losses.*

form was redesigned using detailed specifications from the non-residential 'PassivHaus' standards and recommendations based on Sections 3.1 and 3.2.4. As stipulated by 'PassivHaus' standards, good performance of energy efficient building should include low *U*-value insulated materials, high air tightness, take advantage of solar radiation and promote natural ventilation. Accordingly, these elements were introduced in the redesigned high-rise office building (Table S8, supporting document).

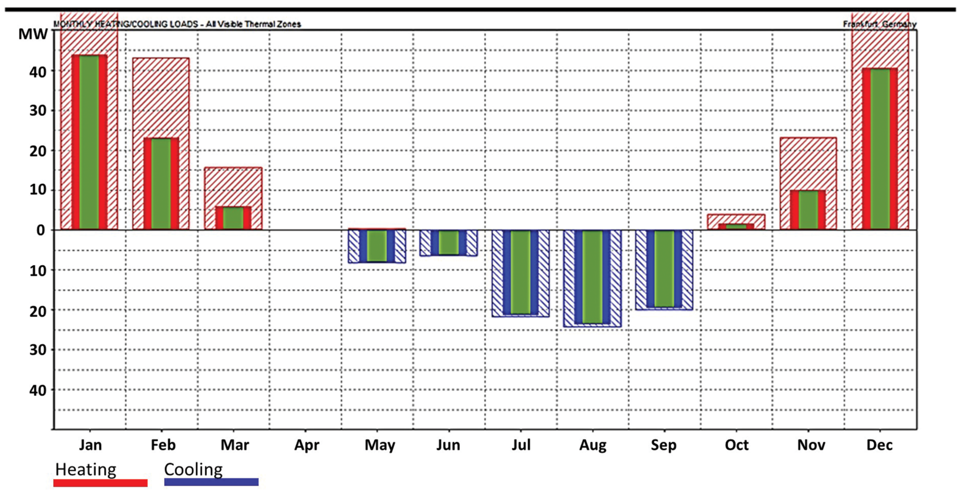
3.3.1 *Enhanced air change rate and wind sensitivity*

In this step, the airtightness of the office building was improved to reduce a large amount of heat loss from ventilation. The air change rate and wind sensitivity were set as 0.8 ach^{-1} and 0.1 ach^{-1}, respectively, indicating that the building is airtight with reduced ventilation loss. Based on the updated design settings, the energy performance of the redesigned office building was evaluated and presented in Figure 6. It was evident that the improved air tightness and wind sensitivity significantly reduced the heating load from 456.06–223.29 MWh/yr and the average space heating demand dropped to 14.90 KWh/m^{2}yr. Moreover, the cooling load also reduced from 83.19–81.56 MWh/yr with an average space cooling of 5.44 KWh/m^{2}yr. Compared with the 'PassivHaus' specification (specific space heating/cooling demand ≤15 kWh/m^{2}yr), additional measures are required to further reduce the specific space heating demand of the building.



Design Model	Heating (kWh)	Cooling (kWh)	Total (kWh)
Original	456060.54	83190.11	539250.69
Redesigned (original+ach)	223288.45	81564.62	304853.06
Redesigned (per m^2)	14.90	5.44	20.341

Figure 6. *Effect of enhanced air change rate and wind sensitivity on the energy performance of high-rise office building in Frankfurt. (Red/blue bars indicate heating/cooling loads. External and internal bars represent heating/cooling load for original and redesigned (original + ach) building model, respectively.)*



Design Model	Heating (kWh)	Cooling (kWh)	Total (kWh)
Redesigned (original+ach)	223288.45	81564.62	304853.06
Redesigned (original+ach+fabric)	125014.14	79106.69	204120.83
Redesigned (per m^2)	8.34	5.28	13.62

Figure 7. *Effect of improved fabric insulation and enhanced air change rate and wind sensitivity on the energy performance of high-rise office building in Frankfurt. (Red/blue bars indicate heating/cooling loads. External and internal bars represent heating/cooling load for redesigned (original + ach) and (original + ach + fabric) models, respectively.)*

3.3.2 *Well-insulated fabric*

According to 'PassiveHaus' and CIBSE standards, it was necessary to reduce the U-value of all components of the exterior envelope in order to restrain heat losses and gains. Using prescribed specifications as shown in Table S8, windows and external building fabric were modified accordingly. Windows were replaced with low-e triple glazing with U-value of 0.78 W/m^2/K. Other improved fabric specifications are shown in Table S9 (supporting document). Evaluated building performance is shown in Figure 7. It was apparent that improving the fabric insulation meaningfully reduced the heating load of the building. Compared with the energy performance of the redesigned air

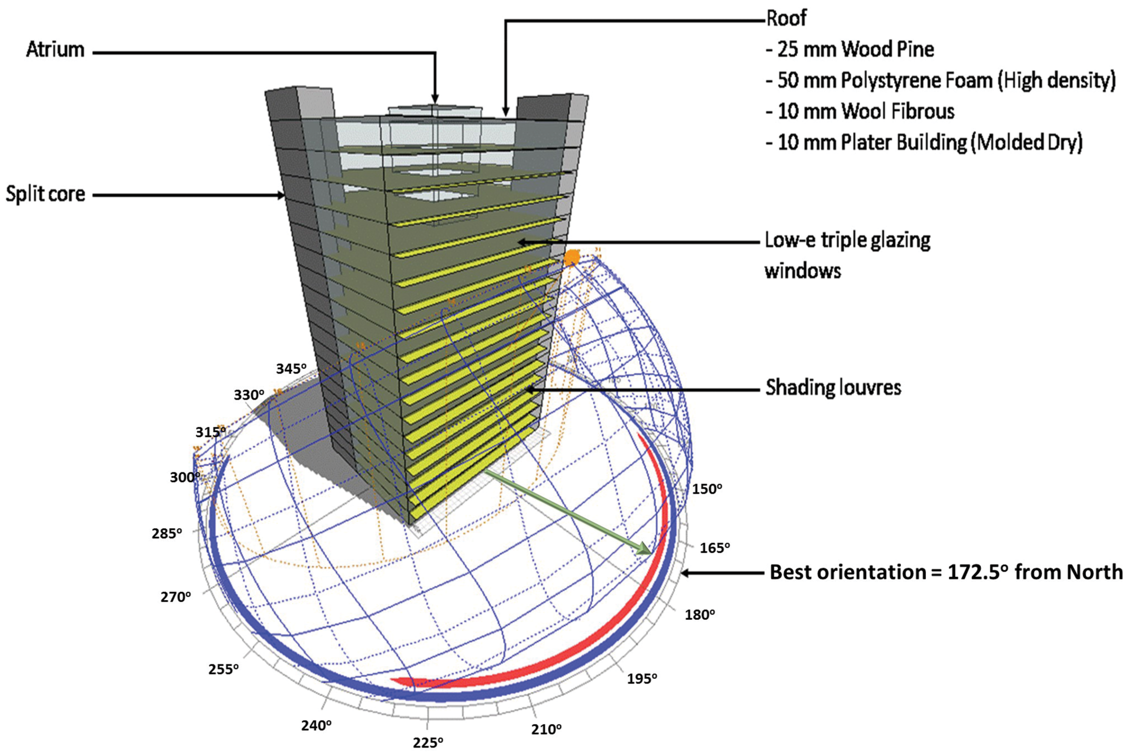


Figure 8. *Proposed model for a sustainable high-rise office building in Frankfurt, Germany. (The green arrow shows the direction of the building).*

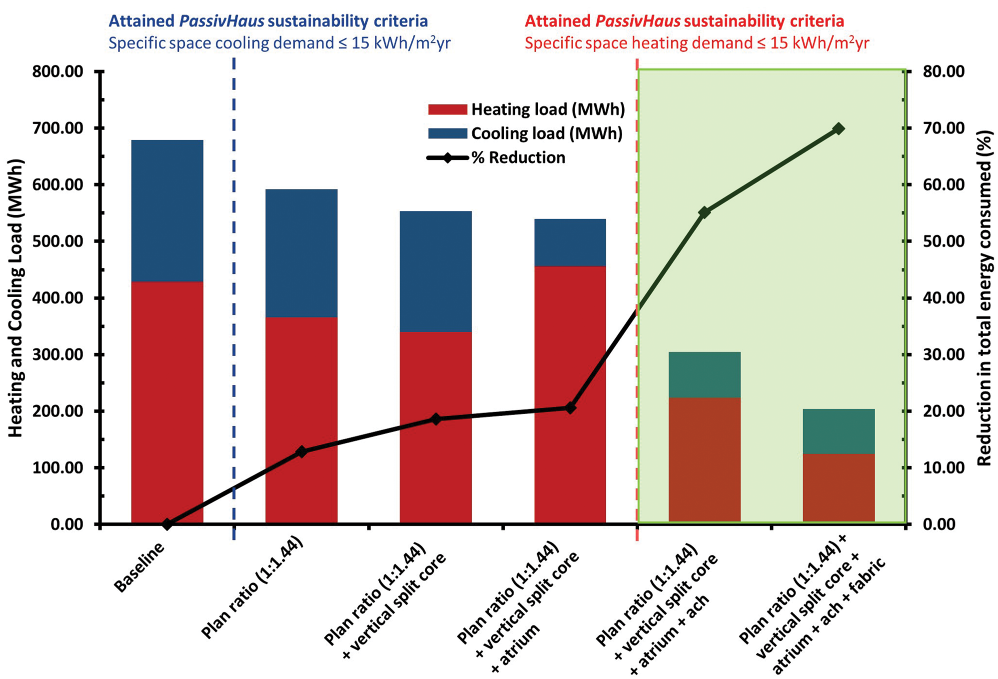


Figure 9. *Cumulative impact of building plan ratio, position and orientation of core column and atrium on the energy performance of high-rise office building in Frankfurt. (The green zone represents attained sustainability criteria defined by PassivHaus standard).*

change rate and wind sensitivity, a further 44% reduction in heating load was achieved. This significantly reduced the specific space heating demand to 8.34 from 14.90 KWh/m^{2}yr. The specific space cooling demand reduced from 5.44–5.28 KWh/m^{2}yr. In total, building energy consumption decreased from 304.85–204.12 MWh/yr.

3.3.3 *Shading device*

First, it is important to investigate the effect on the redesigned model while positioned at the best orientation as proposed in Figure S1 (supporting document). The energy evaluation for the redesigned building in the best position of 172.5° from the north showed no significant difference (Table S10, supporting document). It was observed that the heating load decreased by 0.6% while the cooling load increased by 0.9%. Hence, it was reasonable to stipulate that additional measures were required to reduce the heat gained by solar radiation even though the building has attained the required space cooling demand. This can be achieved through the use of shading devices such as shading louvers. Unfortunately, Ecotect could not investigate the effect of shading device on building energy performance. Ecotect only assumes that the presence of shading device will reduce the building energy demand. Conclusively, the proposed 3D-model of the 18-story high-rise office building that meets with 'PassivHaus' standards is shown in Figure 8.

Overall, this study provides a holistic insight into the impact of several passive strategies and architectural building features on the energy performance of high-rise office building in a WSCW climate. It demonstrates that adequate exploitation of climate features like temperature, solar radiation and wind profile can aid in developing sustainable high-rise buildings without the need for active strategies. Furthermore, adequate design of the building characteristic features can further reduce the building energy consumption. A summary of the effect study of building characteristic features is presented in Figure 9.

Overall, the total energy consumed reduced by 12.85% for changes in plan ratio from 1:2 (baseline) to 1:1.44. The introduction of a vertical split core resulted in a cumulative energy reduction of 22.83%. In both cases, the share of heating load remained at ~62%, which is slightly lower than ~63% at the baseline. Moreover, the presence of an atrium significantly increased the share of the heating load to ~85% but cumulatively reduced the total energy consumed by ~30%.

Besides, modification of the building fabric, air change rate and wind sensitivity increased the overall energy reduction to ~70%. Although specific space cooling demand criteria was attained only by changing the plan ratio to 1:1.44, however, integration of several strategies were required to attain space heating demand ≤15 kWh/m^{2}yr. This study provides a framework for designers in determining the optimum building characteristics and selecting effective passive strategies for improved energy performance of high-rise office buildings given its geographical location and climate features.

4 CONCLUSION

This research understudies the energy performance of high-rise office buildings based on climate, architecture and engineering conditions. Subsequently, it proposes the most suitable model for sustainable high-rise office building founded on performance evaluation. The results show that for the climate feature of Frankfurt, the energy performance varies with the building characteristics features such as plan ratio, core position and atrium effect. It is demonstrated that the building energy performance was most sensitive to the plan ratio. Furthermore, adopted passive strategies improved occupants comfort level and aided to attain sustainability criteria defined by 'PassivHaus' standards. Consequently, it can be speculated that adequate exploitation of the climatic and building characteristic features can provide the most appropriate retrofit strategy solutions for high-rise office buildings. Hence, it is imperative to obtain the whole relationship between climate, building characteristics and energy performance. It is worth mentioning that the understudied climate and building features do not provide a holistic assessment of their relationship. Despite this, this study provides a preliminary framework on defining the optimum building characteristics and pre-selection of effective passive retrofit elements for improving the energy performance of high-rise office buildings given its geographical location and climate features.

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