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Overheating and Daylighting; Assessment Tool in Early Design of London's High-Rise Residential Buildings

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Received: 30 June 2017; Accepted: 23 August 2017; Published: 30 August 2017

Abstract: High-rise residential buildings in dense cities, such as London, are a common response to housing shortage. The apartments in these buildings may experience different levels of thermal and visual comfort, depending on their orientation and floor level. This paper aims to develop simplified tools to predict internal temperatures and daylighting levels, and propose a tool to quickly assess overheating risk and daylight performance in London's high-rise residential buildings. Single- and double-sided apartments in a high-rise building were compared, and the impact of their floor level, glazing ratio, thermal mass, ventilation strategy and orientation was investigated. Using Integrated Environmental Solutions Virtual Environment (IES VE), temperature and daylight factor results of each design variable were used to develop early design tools to predict and assess overheating risks and daylighting levels. The results indicate that apartments that are more exposed to solar radiations, through either orientation or floor level, are more susceptible to overheat in the summer while exceeding the daylighting recommendations. Different design strategies at different levels and orientations are subsequently discussed.

Keywords: overheating; daylighting; design tool; assessment tool; London; high-rise; residential; floor-level; orientation; glazing

1. Introduction

The planet is changing. Average global temperatures are expected to increase 5 °C by 2100 [1] leading to increased frequency and intensity of summer heatwaves in urban settings. The consequences could be more devastating than the European heatwave of August 2003, which led to 70,000 deaths [2], including 2000 in the United Kingdom [3]. Due to climate change, the number of deaths from excessive heat could be three times higher by 2050 [4] as the temperatures experienced during the summer of 2003 might become the norm by the 2040s [5].

In urban environments, the heat island effect will exacerbate this phenomenon [6,7]. Cities and buildings will struggle to exhaust the heat and cool down at night. Furthermore, by 2050, 66% of the world's population is expected to live in cities [8]. In vulnerable urban environments such as London's, where a 9 °C temperature difference was observed between the inner-city and the surrounding areas during the night-time of the 2003 heatwave [9], heat risk emerges as a significant climate change issue. As a result, multiple policies aiming to reduce energy use and carbon emission emerged. For example, the UK Committee on Climate Change (CCC) implemented a 20% reduction target on the space heating demand [10], resulting in an increased level of insulation in new buildings. This led to thermal improvements in winter [11,12] and a reduction in energy consumption for new and refurbished dwellings. Policies of this type have triggered the development of several design guidelines and energy performance standards such as the ones published by the Zero Carbon Hub and the PassivHaus Trust. However, poorly implemented energy efficient design strategies have shown their limits and negative impacts [13]. For instance, an excessive internal heat due to highly insulated and airtight construction without appropriate passive cooling design strategies could compromise occupants' health and comfort in residential buildings [14]. In the UK, 20% of households may already be at risk of overheating [15], and, with the predicted climate change, this percentage will likely increase [4]. Although no universal definition of overheating exists, the phenomenon has been widely monitored [15–24], and thermally modelled [25–30] using either static or adaptive assessment criteria. Numerous studies have examined a number of dwelling types that represent broadly the housing stock in the UK. However, it is difficult to compare the results from the different studies because of a lack of standardization in their input parameters [31].

As an example of these modelling studies, series of early researches [32–34] have looked at thermal comfort of four different residential types: detached house, semi-detached house, town house and a top floor flat. The results indicated that an increase in thermal mass could significantly mitigate the overheating issue and that careful decisions should be made with regards to the design parameters that control solar heat gains. The results confirmed that top-floor apartments are the most exposed to the overheating risk in tower blocks. Furthermore, Coley and Kershaw [35] investigated a large number of buildings by testing their thermal response to 400 different variables of four build-forms (a house, a purpose-built flat, an office and a school). A linear relationship between the weather and the internal thermal conditions was found while climate change will further increase the internal mean temperatures. However, these studies were mainly based on dynamic thermal simulation methods and are exposed to a certain number of assumptions and uncertainties [30].

In another survey of dwelling types that are at a higher risk of overheating [36], 185 cases were reported in two consecutive surveys with 73% of them located in urban areas. Two thirds (73%) of observed cases were apartments of which around 37% were located on the top floors. It was reported that 48% of the overheating cases were new flats. While the proportion of new flats is small compared to the total housing stock [37], the large number of overheating cases reported in this study suggests a considerable risk of thermal discomfort in newly-built flats at higher floors; this agrees with the study carried out by Vandertorren et al. [38]. Since overheating instances were reported by residents, the difference between the measured overheating and the perceived could be significant depending on several factors such as the occupants' demographics and their level of activity. This study could be considered as "the tip of the iceberg" [36]; however, the lack of data and reporting process is a significant barrier to understanding the extent of overheating in the UK and consequently to the design of effective solutions.

Both monitoring and modelling studies have their limitations. In response, a recent study attempted to reconcile both monitoring and modelling approaches [22]. A statistical meta-model was created from over 3400 building combinations and compared with a set of data gathered from existing residential buildings through monitoring and surveys. Despite its shortcomings in model inputs and dataset, the study represents a considerable step toward the validation of modelling studies.

The various studies indicate that the most representative types of the building stock have been studied. However, none of these studies addressed in detail the high-rise residential buildings, a fast growing solution in large cities such as London [37]. The Tall Building Survey of 2017 [39] indicates that 30% of homes currently under construction in London are in high-rise buildings and that the number of tall buildings construction sites has increased by 68% since 2016, a solution to accommodate London's 10 million residents by 2030 [40].

Three main characteristics of high-rise residential buildings reinforce overheating. First, they are usually associated with lightweight construction methods with low thermal mass [16]. Second, a typical apartment in a high-rise residential building is expected to face one single direction, often preventing cross-ventilation. Third, market preferences have favoured large and convex glazing for better views and increased daylighting. From the design point of view, daylighting and overheating appear to be conflicting as stated in the UK Approved Document Part L and the Code for Sustainable Homes. Add-on, passive cooling shading devices, green roofs or shutters are considered an additional and unnecessary expenditures by developers [16].

Finally, in terms of available overheating design assessments, the Zero Carbon Home has published a detailed review of all tools and methodologies to assess overheating risk [41]. For building regulation compliance in the UK, the government's Standard Assessment Procedure (SAP), provides Appendix P that contains a procedure to verify the tolerable level of solar gains. The SAP tool considers the impact of geographical location, external temperature, thermal properties of the building tested and solar gains. However, the tool has a limited capacity to deal with complex interactions between the factors that contribute to overheating. The other category of tools used for overheating assessment is Dynamic Simulation Modelling (DSM). In comparison with the SAP's, the DSM tools can include a wider range of design parameters and can predict a large number of parameters (Internal temperatures, energy consumption, HVAC systems etc.). It is also possible to apply different overheating standards such as the CIBSE benchmarks or the adaptive thermal thresholds. They are considered as more sophisticated and requires a certain level of training.

The reviewed literature states that residential buildings are at a higher risk of overheating and indicates that top floor apartments are most vulnerable to thermal discomfort risks than lower ones. The relationship between the floor position of the apartments in the building and the overheating risk is however not clearly defined. In response, first, this study aims to clarify this relationship by assessing the overheating risk in a high-rise residential building in relation to floor position, orientation, glazing ratio and thermal mass. Second, this study investigates the relationship between daylighting and overheating risk to determine a balanced design solution. Finally, since the current overheating assessment tools in the UK have either limited abilities to predict the overheating risk at an early design stage, or are too complex to use, this study aims to develop simple design tools that rely on a rapid assessment of overheating risk and daylight performance at an early design stage in high-rise residential buildings.

2. Method

2.1. Standards and Benchmarks

Several methodologies and benchmarking thresholds are used to quantify and assess the overheating in buildings. While it is recognized that assessing overheating in existing buildings is more problematic due to monitoring limitations, overheating benchmarking at design stage is easier. In the UK, the Chartered Institution of Building Services Engineers (CIBSE) has developed weather data [42] and static overheating criteria [43] for this purpose. The criteria have evolved over time and the current CIBSE static criteria classify a building that is overheating if the internal temperature exceed 28 °C and 26 °C, in living rooms and bedrooms, respectively, for more than 1% of the occupied hours. Using the CIBSE benchmark, the UK industry assesses overheating at design stage through thermal dynamic simulation software, such as The Integrated Environmental Solution (IES) Virtual Environment (VE).

The other way of assessing the overheating is to follow the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) method [44,45]. The adaptive thermal comfort gives a temperature threshold that changes with the mean of the ambient temperature and the sensitivity of the occupants. Hence, the adaptive thermal comfort might seem more suitable to assess overheating in free running buildings. Thermal comfort is achieved via an adaptive model that relies on the interaction between the occupant and its local climate, season and weather. The downside of the adaptive thermal model is that it was based on the collection of field data from office buildings, which might make it not suitable for residential buildings.

Both static and adaptive models are arguably associated with some limitations. The CIBSE Guide TM52 (2013) explained that "all comfort standards have problems, because they try to give precise definitions when the phenomenon they are describing is inherently imprecise" [46]. Consequently, the data from the simulations are reviewed by both the CIBSE benchmarks and the adaptive method. For the bedrooms, a lower comfort temperature associated with sleeping will be used, 26 °C for the CIBSE threshold and the Cat I for the adaptive methodology. For the living room, a higher comfort temperature will be used to assess overheating, 28 °C and Cat II for both CIBSE and EN15251.

From the introduction, it is understood that daylighting design is an additional barrier when considering overheating free design. For this reason, the daylighting represents the second focus to gauge the issue and draw appropriate conclusion in parallel with the thermal comfort analysis. Looking at the current practise, the building regulation of the UK has no specific requirement for daylighting in dwellings. However, the Approved Document Part L [47] advise designers to follow closely the guidance given by the BS 8206-2 Code of practise for daylighting [48] to maintain a good level of daylighting. The BS 8206-2 set minimum average daylight factor for different spaces in dwellings. Kitchens, living rooms and bedrooms should achieve a minimum of 2%, 1.5% and 1% for the average daylight factor, respectively. Therefore, a special consideration should be given to the size of windows and glazed area to provide adequate level of daylighting while controlling solar gains to avoid overheating.

2.2. Simulation Software and Weather Files

Currently, a long list of energy and thermal dynamic simulation software exist in the market. Among the most developed and used in academia as well as industry are Energy Plus, ESP-r (Energy Simulation Software tool), and IES VE (Integrated Environmental Solutions). For this investigation, IES VE is chosen for its ability to model radiative, conductive and convective heat exchange between the external and internal environment and construction elements, and its capacity to dynamically simulate the occupancy, solar and air densities, heating elements, cooling systems and air flows. It is also one of the most used software for energy and thermal modelling in the UK industry and the academia studies [35,49].

The dynamic simulations is carried out using the "control" weather file published by the PROMETHEUS [32] project for the current climatic conditions in London Islington. The London Islington location has been selected as it represents an urban area with a low green space density and a high Land Surface Temperature (LST) [9]. In addition, for the climate change impact investigation, each simulation will be repeated with a projected Test Reference Year (TRY) for 2030, 2050 and 2080 with high emission scenario (a1fi) at 90th percentile probability. Even if the Design Summer Year (DSY) weather files have been designed especially for the overheating studies, TRY weather files represent more appropriate data for this investigation [50].

2.3. Base Model Characteristics

The study is based on a dynamic simulation of a real building in the City of London, representing a typical high-rise residential building (Central circulation core, high glazing ratio on the facades, low thermal mass, high occupancy) and incorporating best practise, which is exceeding building regulations for new residential buildings. The model is validated using the same building characteristics as the real building (Floor layout, concrete and steel structure, internal finished, mechanical ventilation, density of occupants). However, the windows and the external walls have been slightly improved to meet higher energy saving targets (see Section 2.4). Figure 1 represents the floor layout of the modelled building. The simulated apartments are modelled between two similar floors. The total floor area of the apartments varies between 60 and 70 m^2. The orientation, the glazing ratio and the shading from the adjacent buildings are considered as variables. Table 1 and Figures 2 and 3 illustrate the variation of solar radiation at different floor levels and orientation.

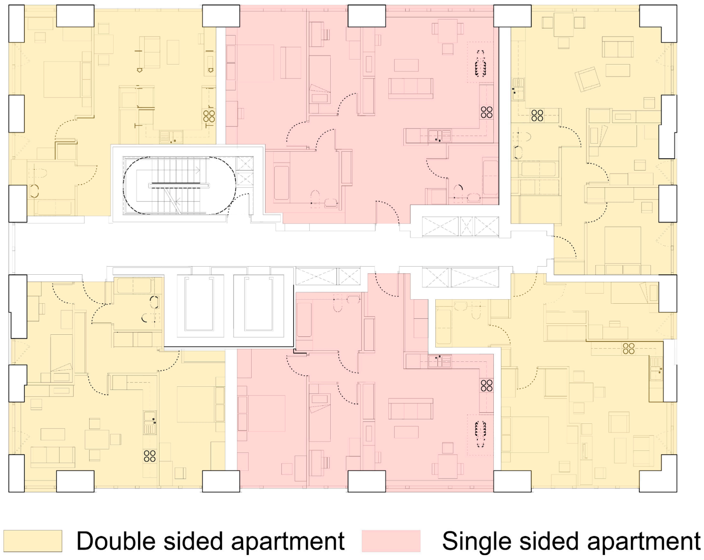


Figure 1. Floor layout of the base model.

Table 1. Solar Radiation (S.R) at 0%, 25%, 50%, and 75% Adjacent Shading Height (A.S.H).

Orientation	S.R at 0% Shaded (kWh/m^2·a) Flat Position: Top Floor	S.R at 25% Shaded (kWh/m^2·a) Flat Position: Middle Top Floor	S.R at 50% Shaded (kWh/m^2·a) Flat Position: Middle Bottom Floor	S.R at 75% Shaded (kWh/m^2·a) Flat Position: Bottom Floor
North	360	320	190	130
East	590	455	260	160
South	750	560	360	185
West	560	440	270	150
A.S.H (m)	0	12	17	33

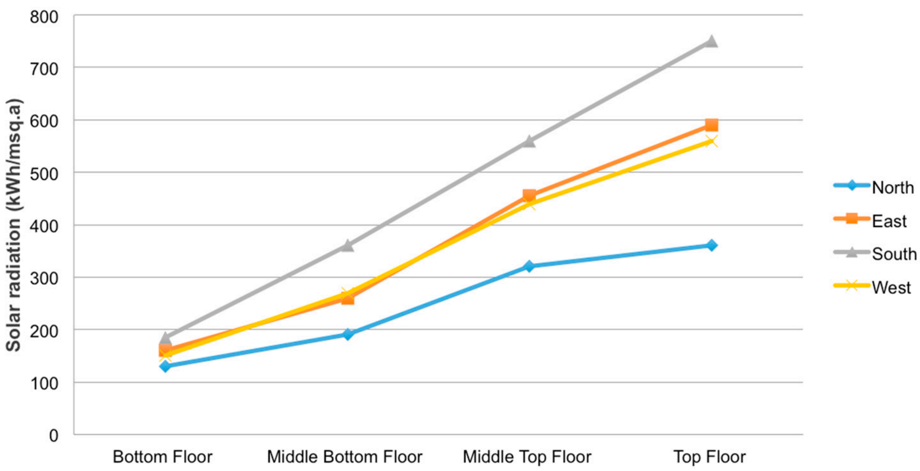


Figure 2. Solar radiation in each orientation (North, East, South, and West) and at each flat position (Bottom, Middle Bottom, Middle Top, and Top).

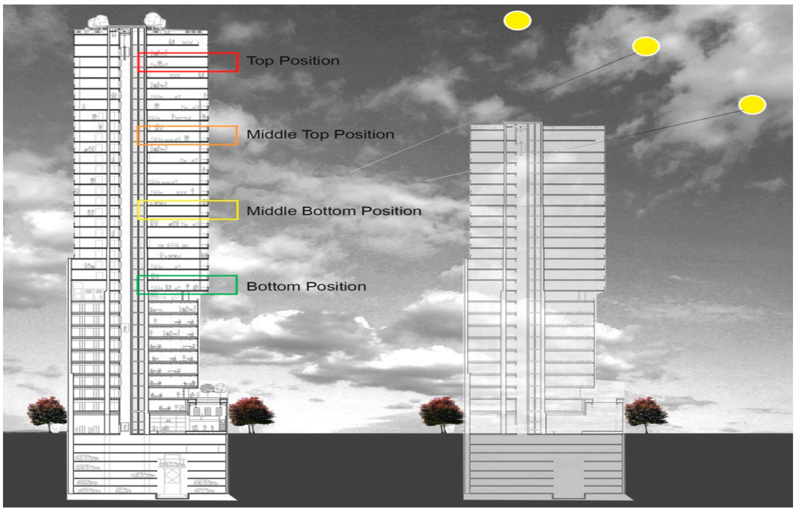


Figure 3. Apartment positions illustration.

2.4. Design Combinations and Model Characteristics

The simulation study is based on a single reference building and a set of combination of design parameters. The high-rise residential building contains single- and double-sided apartments at different orientations. All apartments were assumed to have a high level of insulation modelled with both mechanical and natural ventilation strategy. The floor location of the apartments in the building is the main variable. To support the study, variation in the orientation, the thermal mass and the glazing ratio are taken into consideration in the actual and future weather scenarios.

Table 2 summarises the design variables that are the base of 1536 cross-combinations. It should be also noted that, in a real context, the design process is more complex and might be different from the assumptions taken in this study and might consider other variables and alternative design parameters.

Table 2. Design combinations of the investigation/Design parameters of the study.

Design Variables						
Typology	Floor Position	Orientation	Thermal Mass	Glazing Ratio	Ventilation	Weather
Single-sided	Bottom Middle bottom	North East	Low	40% 60%	Mechanical	Control TRY 2030
Double-sided	Middle top Top	South West	Medium	80%	Natural	TRY 2050 TRY 2080

The building fabric and its thermal properties are primordial to the overheating investigation in dwellings. There is a considerable need to reduce the energy consumption for the space heating demand. Consequently, a super insulation strategy is used for the study. The thermal performance of the models follows PassivHaus standards, which represents an improvement of around 40% from the 2010 England and Wales Building Regulations. The thermal properties used for the models are resumed in Table 3. In addition, a lightweight (60 kJ/m^2·K) and a medium weight (140 kJ/m^2·K) thermal mass are tested. The glazing ratio is considered as another variable to gauge the thermal and daylighting performances. Glazing ratios of 40%, 60% and 80% are tested for the different models to assess the impact of the glazing on the overheating risk. For the daylighting simulation, 70% reflectance for the walls is considered, which represents an approximation for a typical light colour reflectance.

Table 3. Thermal properties of construction elements.

Construction Elements	U-Values (W/m^2·K)	g-Value	Glazing Lighting Transmittance	Window Frame Factor (%)	Window Proportion Length/Height
External walls	0.15				
Roof	0.1				
Floor	0.1				
Windows	0.85	0.6	0.7	30	0.33

The CIBSE Guide A [43] is used as a base to model the internal heat gains in the apartments. Three groups of internal heat gains, lighting, appliances and occupants (young couple with one child or an adult flatmate) are modelled (Table 4). The occupancy chosen will allow the overheating assessment of both single and double bedrooms.

Table 4. Modelled internal gains and occupancy profile.

Space	Internal Gain Category	Sensible Gain	Latent Gain	Occupancy Profile and Number of Occupant
Master Bedroom	People	50.2 W/person	23.6 W/person	10:00 p.m.–7:00 a.m. every day 2 people
	Lighting	18 W		6:00 a.m.–7:00 a.m. 9:00 p.m.–11:00 p.m. every day
	Appliances	20 W		6:00 a.m.–7:00 a.m. 10:00 p.m.–11:00 p.m. every day + 10% heat gains for background standby use 24 h/day
Bedroom	People	50.2 W/person	23.6 W/person	10:00 p.m.–7:00 a.m. every day 1 people
	Lighting	18 W		6:00 a.m.–7:00 a.m. 9:00 p.m.–11:00 p.m. every day
	Appliances	20 W		6:00 a.m.–7:00 a.m. 10:00 p.m.–11:00 p.m. every day + 10% heat gains for background standby use 24 h/day
Living room	People	75 W/person	55 W/person	6:00 a.m.–9:00 a.m. 5:00 p.m.–11:00 p.m. Every day; 2 people
	Lighting	36 W		8:00 p.m.–11:00 p.m. every day
	Appliances	120 W		6:00 a.m.–9:00 a.m. 5:00 p.m.–11:00 p.m. every day + 10% heat gains for background standby use 24 h/day
Kitchen	People	75 W/person	55 W/person	7:00 p.m.–8:00 p.m.
	Cooking appliances	1000 W		7:00 p.m.–9:00 p.m.
	Fridge/Freezer	31 W		24 h/day

For this study, the space heating system is modelled during the cold months (October–April) with a set-point temperature of 20 °C, which is the comfort temperature recommended by the Passivhaus Institute. The heating system is turned off during summer months to avoid any interference with the overheating assessment.

Mechanical ventilation is simulated first for more sensible comparisons. The dynamic simulation accounts for two types of air transfer: the mechanical air supply and the uncontrolled infiltration. The infiltration is modelled as a fixed flow rate (0.25 air changes per hour), which is best practise for a passivhaus building. Based on the concept of a balanced dwelling, the mechanical ventilation extracts and supplies air at an equal flow rate. The extract is from the wet rooms (bathrooms and kitchens) and the supply from the dry rooms (living rooms and bedrooms). In addition, the heat recovery (HR) system is modelled with a summer by-pass system.

As regulated by the Approved Document F [51], the mechanical ventilation is modelled with two ventilation rates. The first one is the background, which is maintained at a constant flow rate in relation to the occupancy of the apartments. Second, the boost feature, which is modelled to permit purge ventilation at late afternoon if there is an increase in heat gains. It is also considered in bedrooms for night purging when the internal temperature exceeds the comfort temperature and when the external temperature is below the internal one but not exceeding 10 °C difference. This will allow energy conservation during cold nights.

Natural ventilation is considered in a second set of simulations to mainly assess the difference between the potential ventilation of both typologies (single- and double-sided) and to compare the effectiveness of both natural ventilation and mechanical ventilation strategies to mitigate the overheating risk.

The bulk airflow is simulated based on the differences in pressure across the operable windows and the equivalent orifice area. The operable windows are modelled with an openable area of 20% and a maximum angle of 10°. Following the MacroFlo Calculation methods [52], it corresponds to 0.34 discharge coefficient. Consequently, the equivalent orifice area is given by the same documents as almost 11% of gross area. In addition, as the position of the flats represents the main variable for the investigation of this study, the exposure type of the openings will change depending on the position of the apartments in the building. It adjusts the wind pressure coefficient in relation to the degree of sheltering of the surrounding buildings.

It is very important to simulate the opening pattern of the operable windows in accordance with the occupancy profiles of the apartments. In brief, the windows will operate in the early morning, late afternoon and evening for the living room, and for the bedrooms the openings are used mainly for night purging. The windows of the bedrooms and the living rooms are designed to open at an internal temperature of 26 °C and 28 °C respectively only if the external temperature is lower than the internal one. The internal doors will be modelled to remain open.

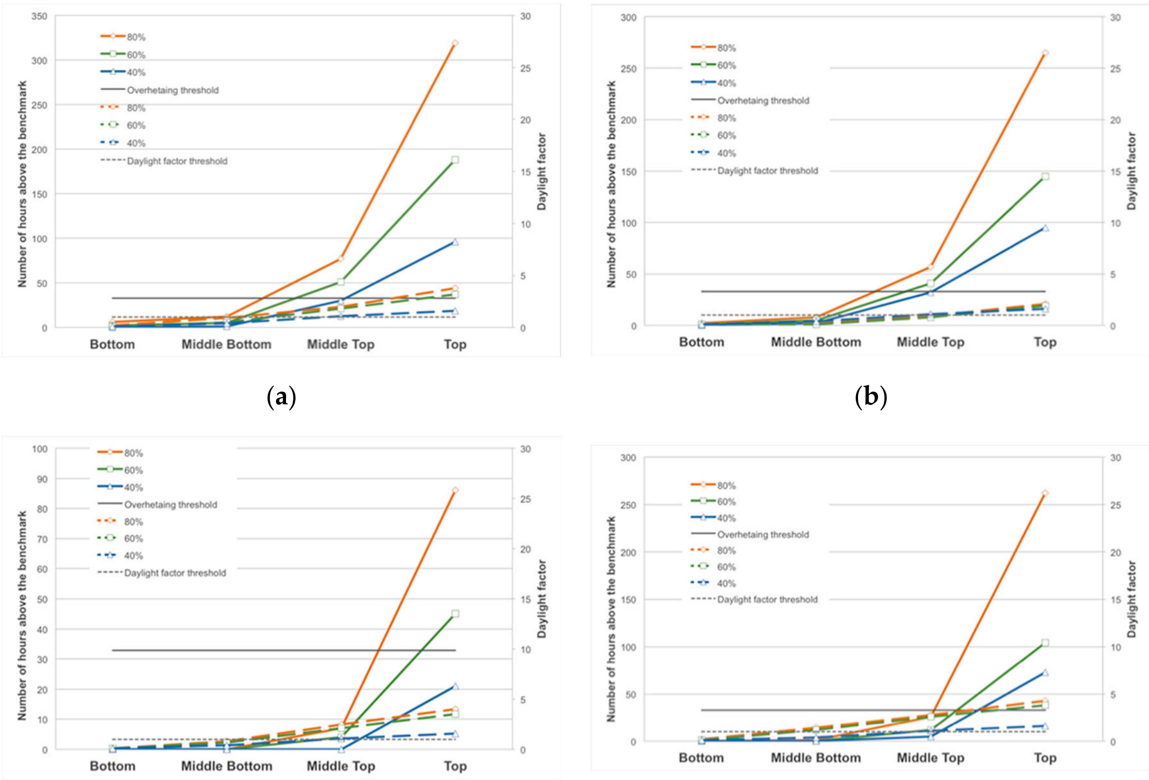
3. Results and Discussion

3.1. Overheating and Daylighting Performance in Relation to Apartment's Floor Position

Given the floor positions of the considered apartments, it is notable that both the daylight factor and the number of hours above the overheating benchmark increase from the bottom to the top floors. As an example, Figure 4a illustrates the overheating assessment and the daylight factor analysis for a south living room at different floor positions and variable glazing ratio with low thermal mass. For top-level apartments, the daylight factors for the 40%, 60% and 80% glazing ratios exceed the British Standards' recommendations. However, the hours above the benchmark are significantly higher than the CIBSE threshold. For the bottom position, it is the opposite. While the living rooms are meeting the thermal comfort benchmark, the daylight factors are at their lowest values. In addition, Figure 4a reflects the conflict between daylighting and overheating trends. Looking at different orientations several similarities can be observed. They all illustrate the same direct relationship between the floor position, the glazing ratio and the overheating risk (Figure 4a–d).

One of the main observations is that higher flat positions and glazing ratio result in a higher overheating risk, which is in line with previous studies [31–34]. Consequently, an increase in both parameters could represent a significant threat to the internal thermal comfort. In addition, for some apartments positions, it is very difficult to meet the recommended daylighting level. As can be seen in Figure 4, the bottom positions have very low daylight factors, which do not meet the British Standards' recommendations. Even if it is meeting the overheating requirement, the low daylighting factors in the bottom positions represent one of the consequences of the vertical urbanization. In terms of design optimization, finding the right solution that meets both thermal comfort and daylight is challenging.

However, this multidisciplinary study aims to optimize the design process at an early design stage. This is of particular relevance to practitioners and researchers who need simplified, quick-to-run overheating and daylighting assessment tools.



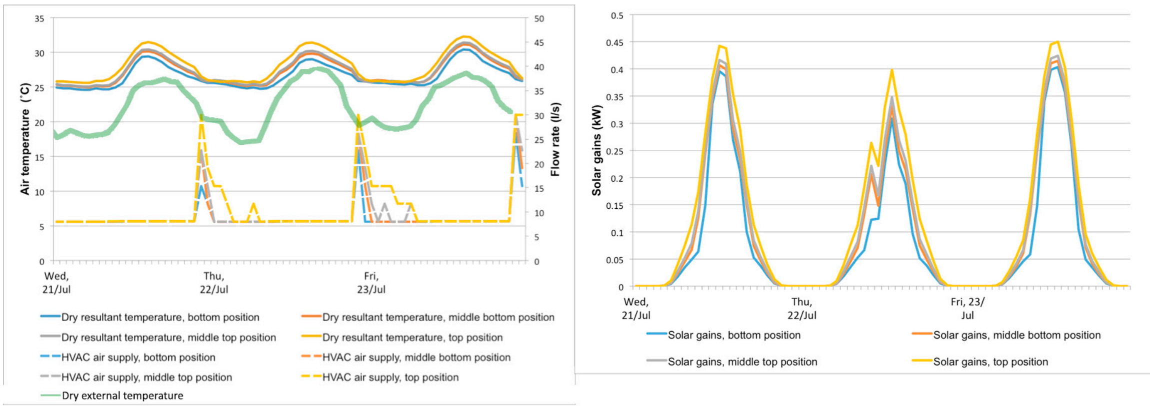
(**a**) (**b**)

(**c**) (**d**)

Figure 4. Number of hours above the benchmark and the daylight factor for the mechanically ventilated living rooms at 40%, 60% and 80% glazing ratio and at bottom, middle bottom, middle top and top position (London, Islington, and control): (**a**) south facing; (**b**) west facing; (**c**) north facing; and (**d**) east facing.

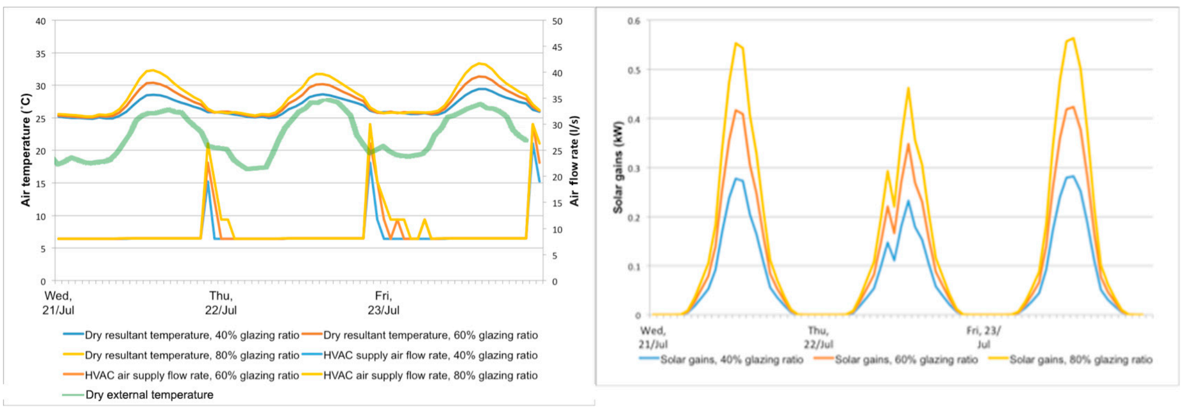
To better understand the floor position parameter and its impact on the overheating risk in high-rise residential buildings, Figure 5a shows the temperature variation of three days (21–23 July) where the flats are exceeding the overheating benchmark and the external temperature is peaking at almost 30 °C. A significant temperature difference can be observed between the same living rooms at different apartment positions. The highest living rooms are at a higher internal temperature. To explain this difference in temperature, Figure 5b illustrates the solar gains difference between the living rooms at different apartment floor position. The solar gains are much higher at top level than at bottom level because of the surrounding buildings that provide adjacent shading at lower level. That causes an increase in the total solar gains, which build up heat internally and worsen the thermal comfort. As a mitigation strategy, which is incorporated in the model, the ventilation is more frequently solicited to exhaust the heat and cool down the internal temperatures (Figure 5a).

The glazing ratio represents the second element that significantly impacts the hours above the overheating benchmark and the daylight factor. On the one hand, increasing the glazing ratio raises the overheating risk by allowing a higher conduction and solar gains (Figure 12). Looking at the ventilation at 80% glazing ratio (Figure 13), the flow rate of the mechanical system indicates that the boost feature is turned on more often and with a longer time-lapse. There is here a strong relationship between the glazing ratio, the overheating risk and the need for mitigation strategy such as the ventilation, which is in accordance with existing literature [18,53]. On the other hand, there is a direct relationship between daylighting and glazing ratio. Figures 5–9 demonstrate that the daylighting factor increases with the glazing ratio. While it seems beneficial for daylighting design to increase the glazing ratio, it can be seen as a significant threat to thermal comfort by increasing the overheating risk. As they are linked together, there is an obvious need to design for both visual and thermal comfort in the same time, and finding the optimal design solution represent the main contribution of this study.



(**a**) (**b**)

Figure 5. The influence of different flat positions in: (**a**) the air temperature, mechanical air flow rate and (**b**) solar gains of south facing living rooms at 60% glazing ratio (London, Islington, and control).



(**a**) (**b**)

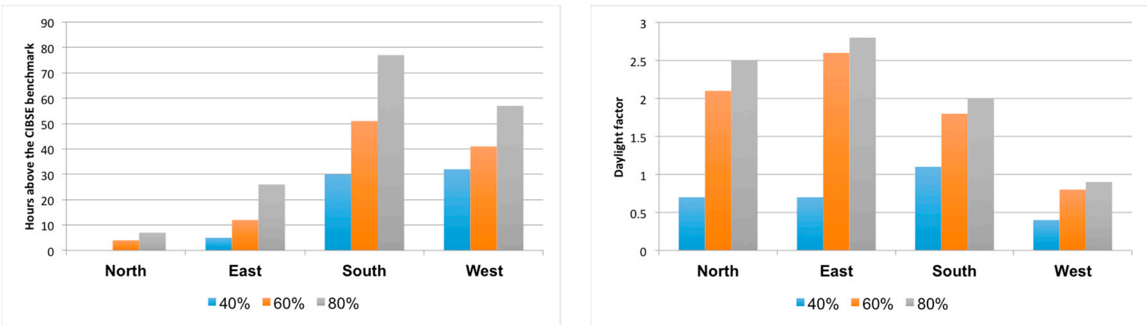
Figure 6. The influence of different glazing ratios in: (**a**) the air temperature, the mechanical air flow rate; and (**b**) the solar gains of south facing living rooms at middle top position (London, Islington, and control).

3.2. Impact of the Orientation on the Overheating and Daylighting Performances

In urban dense high-rise residential buildings, most of the apartments are expected to face one single direction. Regardless of the weather and environmental conditions, the internal environment of an apartment may react differently depending on its orientation. The results illustrate a significant difference between the number of hours above the CIBSE benchmark for north, east, south and west facing living room (Figure 7a). The north facing living rooms are at lower overheating risk than the other orientations and the South facing living rooms represent the most thermally uncomfortable spaces. In addition, the daylight factor results illustrated in Figure 7b shows that the North and East facing living rooms have a higher daylight factor than any other orientation and that the west facing living rooms have the lowest daylight factor.

An indication that daylight factor and overheating risk may be at cross-purposes has been discussed in the previous chapter. However, the orientation plays an important role in the cross-purpose relationship. For example, it can be seen that for the north orientation it is easier to meet the daylight factor while having a low number of hours above the benchmark. Conversely, for the west facing bedrooms, it is much more difficult to meet the British Standards' recommendations while avoiding overheating.

This difference in overheating risk at different orientation can be explained by looking at the solar gains (Figure 8), which are at a different intensity and occur at a different time during the day. It can be observed that the east and west facing living rooms have a peak of solar gains at almost 0.6 kW in the morning and evening respectively. While the north and south oriented bedrooms benefits from solar gains at midday with a less peaky curves. For a better understanding, the internal air temperature and people heat gains (occupancy pattern) have been included in Figure 8. It is observed that the peak in solar gains and internal air temperature for the living rooms oriented north occurs in the middle of the non-occupied period. Consequently, the living rooms overheat in the unoccupied period and lose this build up heat at late afternoon, which is significantly improving the thermal comfort for the occupant during the evening. For the south facing living rooms, the peak in solar gains is also occurring during the non-occupied period. However, the solar gains are more intense and the internal temperature increases rapidly during the beginning of the afternoon, which makes it more difficult for the ventilation to mitigate the overheating risk. Regarding the west and east orientation, the peak of solar gains is closer to the late afternoon and morning occupied hours respectively. The difference between both orientations is that the west facing living room suffers more from the heat stored during all the day, which impacts on the internal temperature during the late occupied hour. The evidence shown here explains the cause of a high number above the overheating benchmark of the south and west facing living rooms. The build-up heat during the day due to the solar and internal gains increases the internal temperature and worsens the thermal comfort, which increases the overheating risk. The orientation of the apartments can impact drastically the visual and thermal performances and finding the optimal design solution may prove to be difficult.



(a) (b)

Figure 7. The influence of the orientation in: (**a**) the hours above the CIBSE benchmark; and (**b**) the daylight factor for middle top position living rooms at 40%, 60% and 80% glazing (London, Islington, and control).

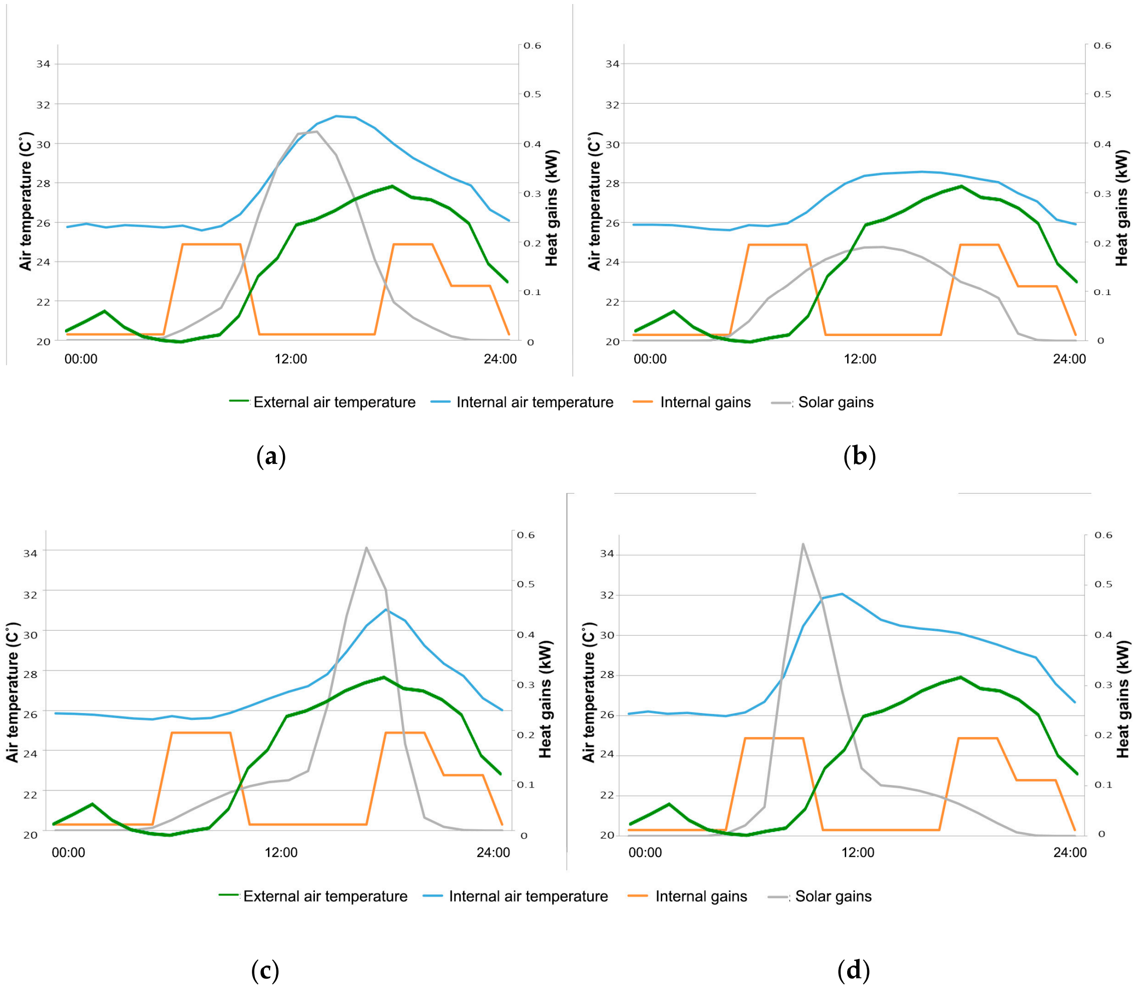
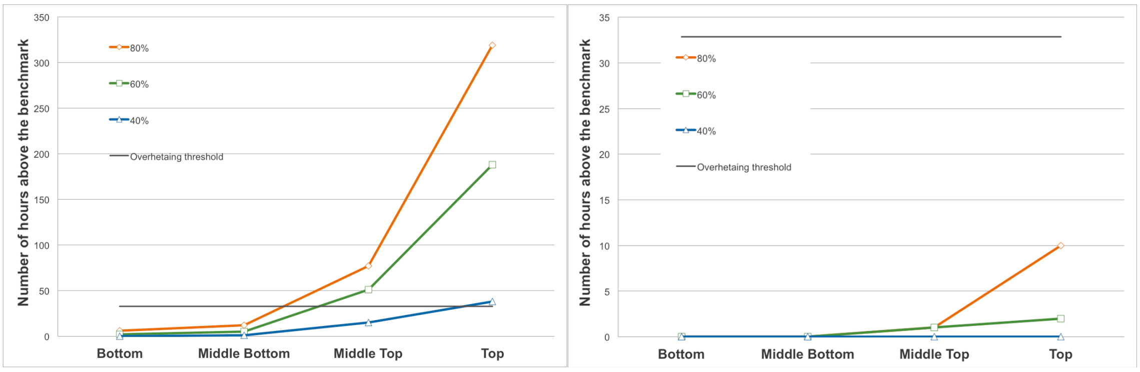


Figure 8. Internal air temperature, and solar and internal gains for the middle top living rooms at 60% glazing on 22 July (London, Islington, and control): (**a**) south facing; (**b**) north facing; (**c**) west facing; and (**d**) east facing.

3.3. Overheating, Daylighting and Ventilation Strategy

The previous simulation results were based on a mechanical ventilation strategy described in the method section, and the same models are simulated with a natural ventilation strategy. The analyses have shown that the mechanical ventilation can, in some cases, mitigate the overheating risk in the flats in an efficient way (Figures 5a and 6a). However, the mechanical ventilation strategy based on the Part F of the UK building regulation has some difficulties to purge the build up heat in higher apartment positions (top position in Figure 5a). Figure 9a illustrates the number of hours above the CIBSE benchmark for the south facing living rooms with different glazing ratios. All of the top position and most of the middle top position living rooms exceed the overheating threshold. In comparison with the living rooms, Figure 9b demonstrates that the south facing bedrooms are not at overheating risk and that the number of hours above the overheating benchmark is considerably lower. This is due to a lower exposure to internal heat gains, which can play a significant role in the effectiveness of the ventilation system. As an example, the kitchens are designed to be completely open on the living rooms. Even if both spaces are modelled independently in terms of function, they are thermally connected. The opening between the two spaces allows a complete transfer of heat and air. Figure 10 illustrates heat gains from the kitchen and the internal temperature of the living room in the south-facing apartment during 22 July, which is the middle of the overheating period (21–23 July). The first observation is that the kitchen solar gains participate in the sharp increase of the living room internal temperature during the day. Secondly, during the late afternoon, when the boost ventilation is on (Figure 11), the high cooking heat gains (Figure 10) are participating to the increase in internal temperature and the reduction of the purge ventilation's efficiency.

The earlier results, which are in agreement with previous studies [12,54], have demonstrated that there is a direct relationship between the glazing ratio, solar gains and the overheating risk. Higher glazing ratio results in a higher overheating risk. Looking at the mechanical ventilation pattern during three days in July where the south top position living rooms overheat (Figure 11a), it is noticeable throughout the increase in flow rate, that the purge ventilation feature is used during the late afternoon. It is also observed that the purge ventilation is used at a different intensity and different time duration. To mitigate the risk of overheating, the mechanical ventilation is triggered at a higher flow rate and for a longer time-lapse, which increases the energy consumption of the mechanical ventilation system. Therefore, for a reduction of both overheating risk and energy consumption, a lower glazing ratio might be considered. However, when considering daylighting, a reduction in glazing ratio seems to reduce the daylight factor, which in return might worsen the daylighting level in the apartments.



(**a**) (**b**)

Figure 9. Number of hours above the CIBSE benchmark for the mechanically ventilated south facing: (**a**) living rooms; and (**b**) bedrooms at 40%, 60% and 80% glazing ratio (London, Islington, and control).

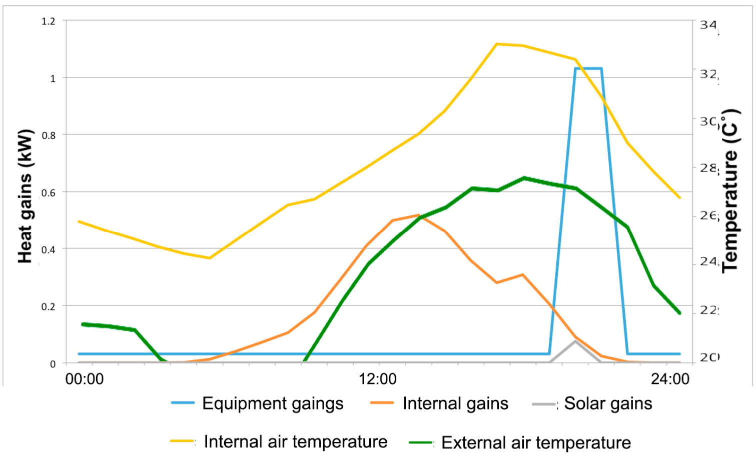
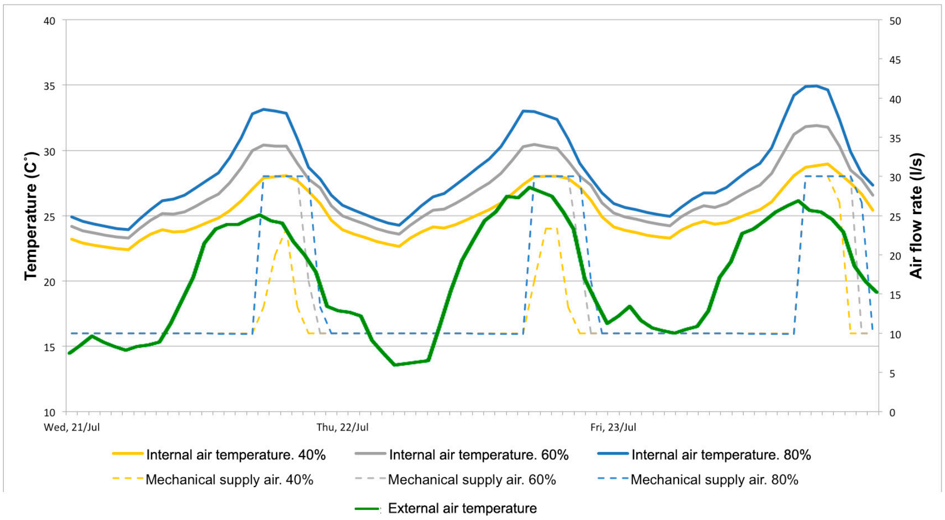
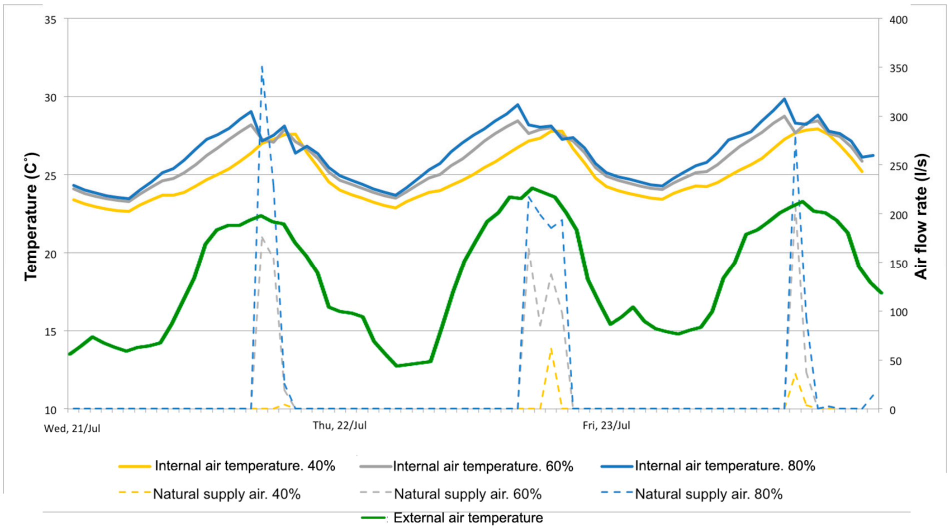


Figure 10. Internal heat gains (equipment, solar and people) and internal air temperature of the top position south facing living rooms at 80% glazing ratio on 22 July (London, Islington, and control).

Considering some issues that might occur in dense cities, such as a reduction in airflow or urban air pollution and noise level, natural ventilation strategies are being thwarted. However, when it is feasible, natural ventilation could be a very effective solution to drop the internal temperature and mitigate passively the overheating risk (Figure 11b). In most cases, the adopted natural ventilation strategy successfully mitigates the overheating risk. When comparing with the mechanical ventilation living rooms, the naturally ventilated living rooms demonstrate lower overheating exposure. Opening the windows allow a high flow rate entering the apartments, which helps reducing the overheating risk by purging the build up heat quickly.



(**a**)



(**b**)

Figure 11. The influence of: (**a**) the mechanical air flow rate; and (**b**) the natural air flow rate in the internal temperature of the south facing living rooms at top position (London, Islington, and control).

Both natural and mechanical ventilation strategies have shown their effectiveness to reduce the overheating risk. However, for the apartments that are more exposed to the solar radiation, natural ventilation seems to be more effective and helps mitigating the overheating risk. Figure 12 illustrates a comparison between the number of hours above the CIBSE benchmark for mechanically and naturally ventilated south facing living rooms with low thermal mass at 60% glazing ratio. It should be noted that 60% glazing ratio has been chosen as the middle between 40% and 80%. For the top position the hours above the benchmark for the naturally ventilated living room is nine times less then the mechanical ventilated one. A considerable reduction in the overheating risk is noticed when using natural ventilation strategy. However, as described before, some surrounding conditions and safety reasons may reduce the wind speed and prohibit the occupants to open the windows. Consequently, careful decisions must be taken when designing ventilation system.

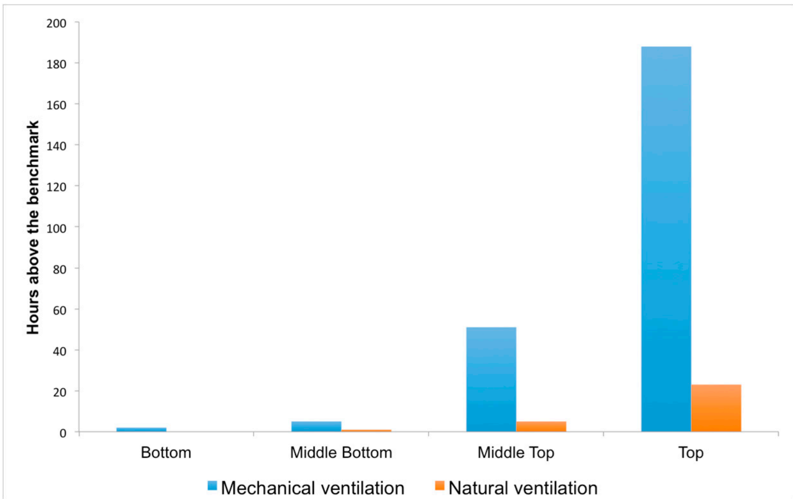


Figure 12. Number of hours above the CIBSE benchmark for both naturally and mechanically ventilated south facing living rooms at 60% glazing ratio (London, Islington, and control).

The model was designed in such a way to allow cross ventilation to occur in dual orientation apartments and hence enable airflow to cross from a space to another. This is demonstrated by the airflow rate entering the apartments and the capacity to mitigate the overheating risk. Figure 13 gives a more detailed analysis of why the dual orientation apartments perform better than the single orientation in terms of thermal comfort. Looking at one of the living rooms that are overheating the most, the west facing living rooms shows that the double-sided apartments provides a higher flow rate, which means a quicker purging capacity. It can also be seen that in late afternoon the living room in the double-sided apartments has a lower temperature. As it has been proven in previous studies, providing cross ventilation helps reducing the risk of overheating. This research highlights that a lower overheating risk give more daylighting design flexibility for dual orientation apartments, which can increase daylighting levels by increasing the glazing ratio.

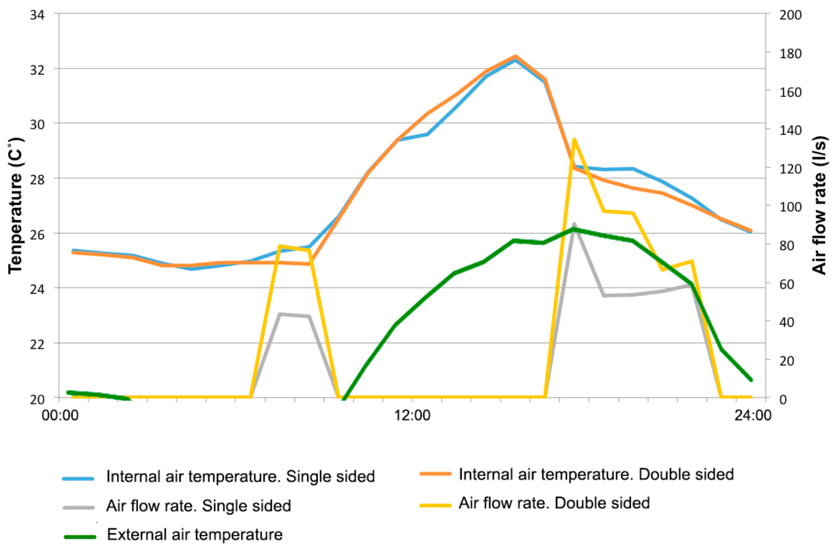
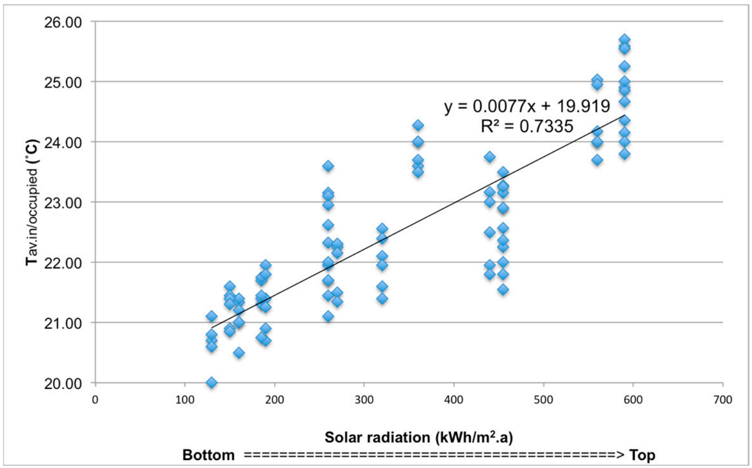


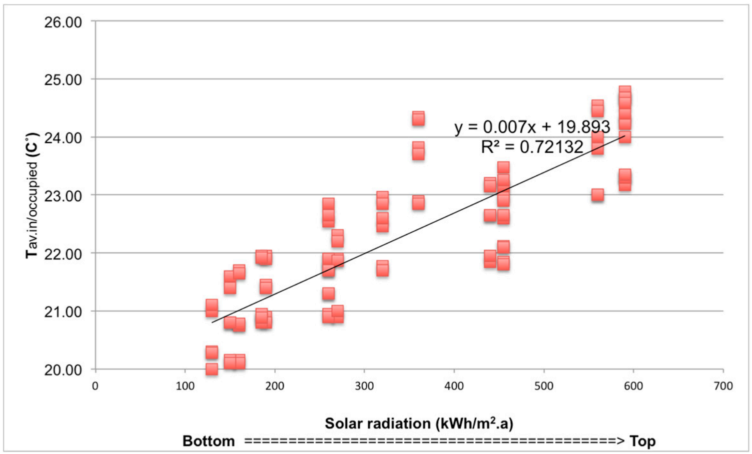
Figure 13. Internal air temperature and air flow rate for both double and single-sided apartments, west facing living rooms at 60% glazing ratio and top position on 22 July (London, Islington, and control).

3.4. Summary of Results

Based on all the results from the different design parameters' combinations, the relationship among the floor position, the overheating risk and daylighting is clear. All the temperature and daylighting data have been collected and analysed separately using a simple linear regression method in Excel to understand their relationship with the floor position. Looking at the scatter plots (Figure 14) of the results, the simple linear regression shows a coefficient of determination "R^2" of 0.7, which demonstrates a strong statistical correlation between the floor level and the predicted internal temperature. They also demonstrate that the highest apartments are more prone to overheating than the lower ones, which is in accordance with the existing literature [22,54]. The relationship between the floor level and the overheating demonstrates the need for a careful design throughout the floor levels.



(**a**)



(**b**)

Figure 14. The average internal air temperature during the occupied hours from May to September of the: (**a**) mechanically ventilated apartment; and (**b**) naturally ventilated apartment (London, Islington, and control).

Considering just the overheating issue, it seems that having the same design parameters from the bottom to the top of a high-rise residential building can be disastrous for some flats. In the other hand, the daylighting factor has a less strong correlation with the floor level of the flats (Figure 15). Although the R^2 value of the correlation between the daylighting and the floor level is almost 0.5, the daylighting scatter plot shows a similar trends that the internal temperature figures. The daylight factor increases with the height, however, in this case, it is seen as a positive outcome. Overheating risk and daylighting are at conflict and the results shown is of a particular relevance to practitioners and researchers who aim to find the optimal thermally and visually comfortable design.

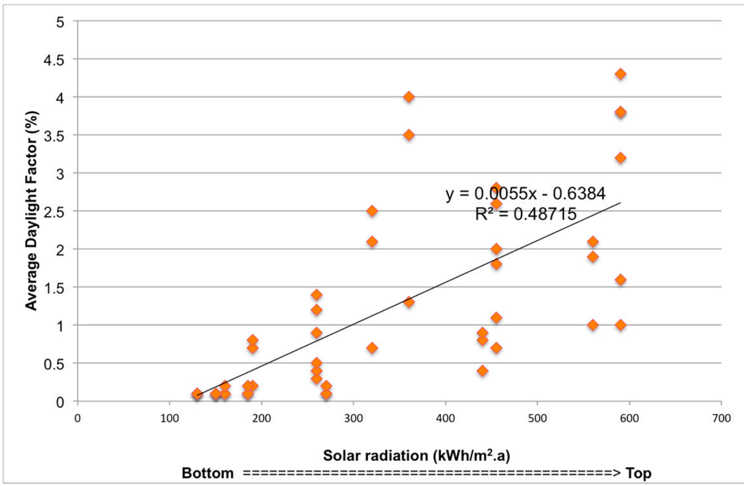


Figure 15. The Daylight Factor for both naturally and mechanically ventilated apartments (London, Islington, and control).

4. Design Assessment Tools

One of the main objectives of this study is to build simple assessment tools to help avoid overheating and meet the recommended daylighting by quickly predicting the conditions of the internal environment and rapidly assessing different design options. This section will give more details on how the tools have been created and how they can be used. The design assessment tools presented in this paper can be used only for multiple storey residential buildings in London.

The design prediction tool has been created through a multivariate linear regression method using the regression analysis tool in Excel. This method helps to build a mathematical relationship between four independents variables and one dependant variable. Three relationships are considered:

- Relationship between the design variables (orientation, floor position, glazing ratio and thermal mass) and the predicted internal temperatures of the mechanically ventilated apartments.
- Relationship between the design variables (orientation, floor position, glazing ratio and thermal mass) and the predicted internal temperatures of naturally ventilated apartments.
- Relationship between the design variables (orientation, floor position, glazing ratio and thermal mass) and the predicted daylighting factor.

Equations (1)–(3) illustrate the result of the computational process of the multivariate regression analysis. They represent a simple tool under the form of a formula that can predict the internal temperatures and the daylighting factors in relation to only four design variables. Designers and researchers can predict the internal thermal and visual conditions by inserting values for the design parameters that have the most significant impact (orientation, the floor position, the glazing ratio and the thermal mass), and the result will predict the daylighting factor and the average internal temperatures for the mechanically or naturally ventilated apartments. This can be used to quickly predict the effectiveness of a variety of design strategies and to give guidance at an early design stage.

$$T_{av.in(occup)} \approx -3.87 \times 10^{-6}\,\chi + 7.66 \times 10^{-3}\lambda + 2.55 \times \varphi - 2.63 \times 10^{-3}\upsilon + 18.65 \quad (1)$$

Equation (1). Average internal air temperature during the occupied hours of the hottest months for the mechanically-ventilated apartments.

$$T_{av.in(occup)} \approx -1.06 \times 10^{-6}\chi + 7.26 \times 10^{-3}\lambda + 3.26 \times \varphi - 6.80 \times 10^{-4}\upsilon + 18.51 \quad (2)$$

Equation (2). The average internal air temperature during the occupied hours of the hottest months for the naturally-ventilated apartments.

$$DF \approx -1.92 \times 10^{-3}\chi + 6.01 \times 10^{-3}\lambda + 2.67 \times \varphi - 1.32 \quad (3)$$

Equation (3). The Daylight Factor formula for both naturally and mechanically-ventilated apartments. where

$T_{av.in(occup)}$: Average internal air temperature during the occupied hours.
DF: Average Daylight Factor (%).
χ: Orientation, the yearly vertical solar radiation of the flat's orientation (kWh/m^2·a).
λ: Position, the yearly vertical solar radiation on the flat's facade (kWh/m^2·a).
φ: The window/wall glazing ratio of the flat (%).
υ: The thermal mass of the flat (kJ/m^2·K).

In addition, a design comparison tool was generated using the result of each single alteration made on the model. Figure 16 shows whether each design combination considered in this study meets the daylight factor threshold of the British Standards and the CIBSE overheating criteria. In addition, Figure 16 compares the same design combinations using the actual and future weather scenarios, which enables the users to assess the impact of climate change on the overheating risk.

The comparison tool can be easily used at an early design stage to assess the overheating and daylighting performance of different high-rise residential buildings. The tool considers the following variables:

- Climate data: Control, TRY 2030, TRY 2050, TRY 2080
- Ventilation strategy: mechanical, natural
- Glazing Ratio: 40%, 60%, 80%
- Thermal mass: low, medium
- Orientation: north, east, south, west
- Flat position: top, middle top, middle bottom, bottom
- Type of space: living room, bedroom

Designers and Architects can easily reduce the overheating risks and increase daylighting levels in actual and future weather scenarios by assessing their early high-rise residential design models using this simple design comparison tool, which will report to them whether each apartment is:

- Meeting both overheating criteria and daylighting levels
- Meeting overheating criteria, but not daylighting levels
- Not meeting overheating criteria, but meeting daylighting levels
- Neither meeting overheating criteria nor meeting daylighting levels

Figure 16. *Cont.*

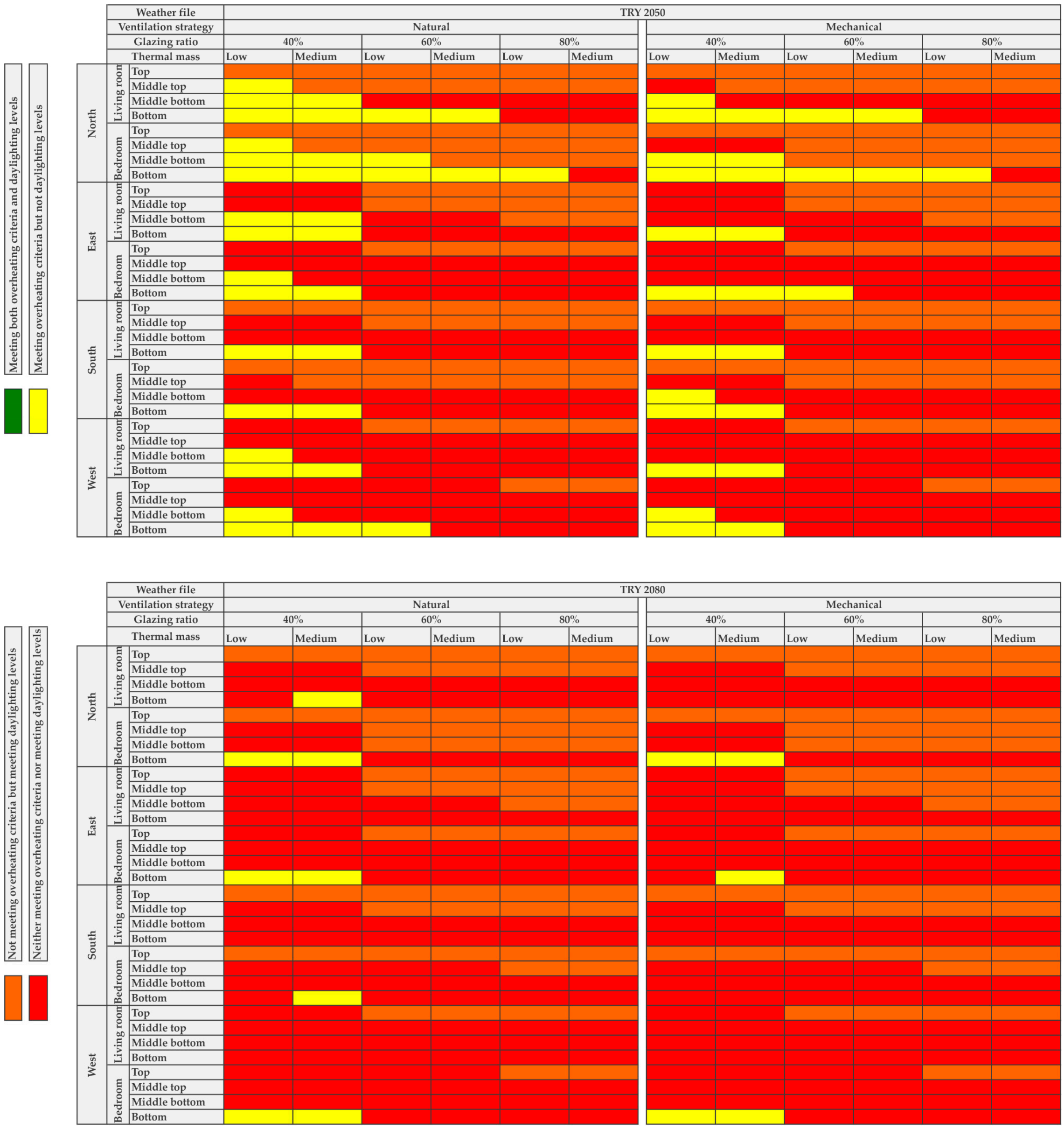


Figure 16. Overheating and daylighting comparison tool to be used at early design stage.

5. Conclusions

This paper has discussed a design optimization quest to avoid overheating and meet appropriate daylighting level in London's high-rise residential buildings. The work was based on thermal dynamic simulations to assess different design combinations while considering the typology, floor position, orientation, thermal mass, glazing ratio, ventilation strategy and the weather. The aim was to build simplified tools capable of predicting internal temperatures and daylighting levels. Furthermore, the tools give the ability to compare the overheating risk and daylight performance of different apartments in high-rise residential buildings.

The findings of the study are significant in at least two main points. First, this study has clarified that there is a strong relationship among the glazing ratio, the floor position, overheating risk and daylighting performances of apartments in London's high-rise residential buildings. When considering the same design variables, the apartments on the top floors are exposed to a higher risk of overheating and a better daylighting performance, which resulted in a major conflict between overheating and daylighting design. At lower floor positions the opposite tends to happen. The orientation adds another level of complexity. The South and West apartments were at a higher risk of overheating, while the ones on the north and east were much cooler. In terms of daylighting, the North and East apartments were preforming better than the South and West apartments. Together, the floor position, the glazing ratio and the orientation are the main parameters to consider for overheating and daylighting design optimisation.

The last key finding and the major contribution of this study is the creation of design assessment tools that help architects and researchers reduce the overheating risk and meet appropriate daylighting levels during early design stages. The prediction and comparison tools are easy and quick to run. They can provide design guidance and useful information on the thermal and visual performances of apartments in London's high residential buildings.

In terms of limitations, a validation against real monitored high-rise residential buildings can help refine the results gathered from the thermal and daylighting models. Such an exploration is beyond the scope of this study, however, further investigation could reduce the level of error and help increase the level of accuracy of the prediction and assessment tool. Another major source of uncertainty is the indoor overheating criteria. Both CIBSE fixed threshold and the adaptive thermal model are arguably associated with a certain level of limitation. On the one hand, the CIBSE fixed threshold is highly criticized for its lack of adaptation. On the other hand, the adaptive thermal comfort is purely based on data collected entirely in office buildings.

Considering the findings of this study, high-rise residential buildings are in need of different design strategies at different floor levels and orientation. The number of high-rise residential buildings is increasing significantly in London and there is an urgent need to meet the energy reduction challenges, to provide adequate indoor temperatures and to design at the recommended daylighting levels. These can be easily tackled using simple design tools at an early design stage.

Acknowledgments: The authors gratefully acknowledge the financial support in the form of fee waiver from the Special Issue Editor, Arman Hashemi and help, at early stages of this study, from Kartik Amrania, Head of Building Sustainability Department at Sweco UK.

Author Contributions: Bachir Nebia perceived the idea, carried out the simulation and co-wrote the paper. Kheira Tabet Aoul guided and participated in the writing of the paper.

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

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