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RESEARCH ARTICLE

Evaluating the impact of building envelope on energy performance: Cooling analyses

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Abstract

Buildings require a significant amount of energy for heating, cooling, and lighting. Hence, building energy performance has become one of the most important topics in the architecture, engineering, and construction (AEC) industry in the last decade. The building envelope plays a critical role in maximizing energy efficiency and decreasing energy consumption generally. The research objective of this study is to examine and compare the effects of three different building envelope types on energy performance in a high-rise residential building. A literature review and case study were performed for achieving the research objective of this study. In the literature review, records (i.e., journal articles, conference proceedings, and scientific reports) published between 2011 and 2021 were included, and Web of Science and Scopus databases were used. In the case study, passive methods including building design, orientation, insulation, and window-to-wall ratio were employed for a 10-story reinforced concrete residential building in Istanbul, Turkey. The energy performance of the different wall, insulation, and glass components utilized in the building was analyzed and compared via DesignBuilder software. Findings show that each parameter and material have a significant impact on the energy performance of a structure. This research would make a noteworthy contribution to the AEC literature and industry by analyzing the energy performance of different building envelope types and the appropriate scenarios based on the location. The results of this study can be used by policymakers and decision-makers to revise existing codes and policies for new high-rise buildings.

1. Introduction

The interest toward the building energy performance studies in the architecture, engineering, and construction (AEC) industry has been increasing in the last decades. This is because the final energy use in buildings and construction industries equates to nearly one-third of the total final energy of global energy consumption [1]. According to the key world energy statistics, residential buildings which consume 20% of the world's total energy are one of the largest energy consumers and end-users [2]. Furthermore, carbon emissions from buildings have increased by 1% per year since 2010 [2]. Hence, researchers highlight the importance of energy performance in reducing building energy consumption and carbon emissions released by buildings and construction industries [3].

Studies show that demand for high-rise buildings has surged due to rapid urban population

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expansion[4]. As the thermal resistance of the façade decreases, the energy consumption of high-rise buildings increases as a result of their high transparency ratio [5]. High-rise buildings are more affected by environmental conditions due to their larger façade area. Therefore, the envelope of high-rise buildings contributes significantly to energy sharing [5]. For this reason, high-rise buildings have both advantages and disadvantages if they are not designed properly. The amount of energy required for heating and cooling a structure is determined by the building envelope which should be optimized to reduce heating and cooling loads to a minimum level [1]. Improving building envelope performance and increasing cooling equipment efficiency cover the highest amount of buildings-related emissions among the building-specific interventions [6].

The building envelope covers several components and materials that separate the conditioned indoor environment from the outside world. The foundation, walls, windows, doors, and roof are all part of the building envelope [7]. Consequently, heat transfer and thermal conductivity of building envelope components are essential elements in the reduction of heating and cooling demand, which will result in decreasing indirect carbon emissions in buildings [7, 8]. Following the scope of the Establishment of Energy Efficiency Building Codes (EEBCs), the envelope component is addressed in every country because it has a significant impact on the energy consumption levels of buildings [9].

Previous research has shown that one of the most important factors considered in building design is the local climate. Professionals designed vernacular architecture by considering the position of the sun and available resources (e.g., orientation, window-to-wall ratio, shading, natural vents, and form of the building). Passive measures such as building orientation/geometry, shade components, and wind barriers are used for achieving this goal. Implementing passive systems could save roughly 70% of the energy required for heating and cooling. Hence, a decrease in building energy consumption requires heating and cooling indoor spaces by a significant amount [10, 11]. Building envelope could be optimized to maximize solar energy, lower greenhouse gas emissions, and reduce energy consumption [35].

Regarding International Energy Agency (IEA) report published in 2000, heating and cooling energy demand per floor area were 97.22 (KW/m^2) and 33.33 (KW/m^2), respectively [2]. Recently, considering climate change, heating demand has decreased, and cooling demand has increased as announced in the key World statistics in 2020. According to these statistics, heating energy demand per floor equates to 75 (KW/m^2), and cooling energy demand equates to 41.66 (KW/m^2) [2]. Besides, electricity demand for buildings has increased by 3.8% between 1973 and 2018. According to the statistics, heating and cooling share 10% of buildings' final energy consumption [2]. Yildiz [12] discovered that residential buildings have a significant effect on heating and cooling loads in Turkey. Although the annual energy demand of new and existing residential buildings for heating is expected to decrease by 9-29% until the 2080s, cooling demand is expected to increase by 1.7-30%- through applying passive cooling strategies.

1.1. Research background

Among the works investigated within the scope of this research, 60% of the studies (14 out of 23 studies) were related to the envelope of high-rise buildings while one was a review paper [13]. Previous research mainly focused on switchable glazing in high-rise residential building[14], the technical, economic, environmental, and comfort implications of new glazing technologies [5, 14, 15], the impact of thermal bridge of balcony slab on envelope [16], the effects of shape coefficient on envelope load and energy consumption [17], floor-to-ceiling glazed areas impact on thermal resilience [18], assessing glazing type window-to-wall ratio, sun shading, and roof strategies for envelope design [18-20], climatically responsive design and microclimate interaction with envelope structure [22], infiltration and pressurizing in higher levels of building [23], investigating heat transfer through envelope components [19, 20], examining the efficiency of light-weight and low energy dynamic insulation, air-tight cavity function, and low-E coating [24], efficient energy codes and insulation materials [25], analyzing double skin brick wall façade and thermal transmittance (U-value) [26], the impact of location and surrounding [27], improving the envelope design parameters, optimizing plan layout, and taking advantage of natural ventilation to diminish heating and cooling energy demand and carbon emissions [27, 28].

A recent study conducted by Yoon et al. [31] investigated the impact of a double skin façade on energy efficiency via EnergyPlus and Sketch-up software [30]. Besides, Mostafavi et al [13] showed that 79% of the studies (38 out of 48 studies) on energy performance were related to building envelope parameters and their impact on energy efficiency and carbon emissions. In another study, the insulation for the external wall was analyzed via Ecotect software to assess the influence of the components on building heating dominance [32]. Another previous study employed TRNSYS software for comparing the effect of wall heat transfer and glazing type [15, 30]. A recent research investigated the impact of the window-to-wall ratio on energy consumption in high-rise buildings using EnergyPlus and Octopus [33]. Similarly, Yik and Bojic [28] implemented energy simulation via EnergyPlus considering building shape and layout by switchable glazing to assess the cooling electricity demand. Moreover, Bahaj et al. [34] explored the emerging technologies for glazing intending to control energy consumption through the computer array model to simulate air-conditional load and conduct transient thermal analysis. Ge et al. [16] analyzed the impact of balcony thermal bridges on thermal performance through 2D heat transfer simulation. Besides, Raji et al. [19] intended to find an energy-saving solution by comparing the refurbished existing building via DesignBuilder. Furthermore, Kalhor and Emaminejad [25] implemented both quantitative and qualitative research on insulation thermal optimization and market by questionnaire and COMcheck tool. Abdul Nasir and Sanusi Hassan [26] performed an experimental study on the thermal performance of double brick walls (opaque and transparent) considering U-value and overall thermal transfer value. Dincer and Mihlayanlar [5] performed an analysis on the air corridor façade in the highest building in Turkey to reduce its cooling and heating demand via DesignBuilder and EnergyPlus. In a more recent study, Chen et al. [29] intended to provide a comprehensive and reliable simulation of air conditioning, lighting, and the envelope feature to develop Net Zero Energy Building through sensitivity and regression analyses.

A review of the previous research shows that some studies are addressing the impact of the building envelope on cooling demand in high-rise buildings. However, only a few studies have concentrated on the wall structure of high-rise buildings. It is crystal clear that the gap in the architecture, engineering, and construction literature is the investigation of the effects of building envelope on cooling demand in terms of building orientation, window-to-wall ratio, and wind direction. Yet, high-rise buildings have received a lot of attention in developing countries recently. Turkey has a great number of high-rise structures even though it is a developing country with a growing population and building restrictions. The global range of high-rise building energy consumption is 16%-50%, with Turkey accounting for 31% [29, 30]. For this reason, it is essential to design energy-efficient high-rise buildings with a long service life in mind. Otherwise, the building's energy consumption and carbon emissions would be staggering.

1.2. Research objectives

This study intends to find optimal building envelope components based on the relevant aspects of energy performance to design energy-efficient high-rise buildings. The research objective of this study is to examine and compare the effects of three different types of building envelopes on energy performance in a high-rise residential building. This research mainly focuses on walls (considering the building's orientation), window-to-wall ratio (WWR), and insulation.

For achieving the research objective of this study, a systematic literature review and a case study were performed. Reviewing the literature ensures the identification of similar studies on this subject domain and the research gap(s). Using the WoS and Scopus databases, the associated documents were extracted and examined manually. In the case study, DesignBuilder which uses EnergyPlus as a simulation engine was employed to design a 10-story reinforced concrete building in Istanbul, Turkey. Three variables, wall (project wall template, curtain wall template, and timber frame wall template), window-to-wall ratio (30%, 35%, and 40%), and orientation (0, 15, 30, 45, 60, 90, 120, and 135 degrees), were defined for each parameter. The envelope component and some information such as the U-value and R-value were retrieved from earlier studies to conduct cooling analyses in this research. Consequently, the following research questions were replied within the scope of this study:

- What is the relationship between the parameters of interest in this study? How do they interact with each other (e.g., wall structure, window-to-wall ratio (WWR), and orientation), and how do they affect building energy performance?
- Does the interaction of factors and the combination of parameters have a beneficial impact on energy efficiency and carbon emissions reduction?
- Does the interplay of parameters and their combination affect energy efficiency and carbon emissions reduction?

The findings revealed the best-fit components and variables for the above parameters to achieve high energy efficiency in a high-rise residential building. The results of this research would ensure a foundation for enhancing the building envelope and façade in an energy-efficient manner. Findings would provide insight into the aspects and components of the building envelope.

2. Research methodology

The research methodology of this study includes two major steps which are a literature review and a case study.

2.1. Literature review

In the first step of this research, the literature was reviewed using Scopus and Web of Science (WoS) core collection. The following keywords were used in the literary review: 'energy performance', 'energy efficiency', 'building envelope impact', 'cooling', and 'high-rise'. Studies that were published between 2011 and 2021 were analyzed within the scope of this research. Thirty publications were identified based on their time frame (2011-2021) and categories (i.e., civil engineering, architecture, and building construction technology). After selecting the publications manually, 23 articles were determined in the field of building envelope's impact on cooling demand within the categories of civil engineering, architecture, building, and construction technologies. It is worth noting that the first article on the impact of building envelopes on cooling demand was published in 2006. A review of the literature demonstrates that there are very limited studies on high-rise buildings and their envelopes.

2.2. Case study

In the second step of this research, DesignBuilder was used for designing a 10-story reinforced concrete high-rise residential building model according to ASHRAE 90.1-2016 standard. DesignBuilder was selected for modeling the case study building as this software provides modeling and various energy analyses which are performed by EnergyPlus, the graphical interface of DesignBuilder.

Climate Zone:

The case study building locates in Turkey, Istanbul at the latitude and longitude coordinate of 41.015137° North, 28.979530° East, and 37 meters above the sea. The data library and the wall elements were selected based on the most used components in Istanbul. According to the Koppen classification (Cfa), Istanbul is classified under a subtropical humid climate. Considering the climate in Turkey, winter begins in October and ends in March, while summer begins in April and finishes in September in this scenario. Throughout the year, the temperature fluctuates between 0 and 30 degrees. During the study, the course of the sun is considered for various months of the year, as illustrated in Fig. 1.

The legislative climate in Turkey's region was considered throughout the investigation. Istanbul is exposed to eight different types of winds which are Star (Yildiz), Northwind (Poyraz), Southeastward (Kesisleme), Kilba (Kible), South (Lodos), and Mistral (Karayel) (Fig. 2). Each of them has a distinct impact on the state of the surroundings. The characteristics of these winds and their direction are classified as shown in Table 1 and Fig. 2.

Case study building:

The total area of the case study building is 5400 m^2, with 540 m^2 of floor space. The width of the case study building is 27m and its height is 20m. The building measures (width and height) and form were assumed the same for all the scenarios. The stand-alone model for the case study building designed via DesignBuilder is presented in Fig. 3. Besides, the structure of the wall components (including an external wall, a below-grade wall, a semi-exposed wall, and a sub-surface wall) used in the design of the case study building is shown in Fig. 4.

Simulation criteria for cooling analyses:

After the stand-alone model for the case study building was created, the activity setup was adjusted (Table 2) and all the assumptions were developed based on ASHRAE 90.1 -2016. Additionally, the reference building design criteria are given in Table 3. The uninsulated, typical reference, obligatory energy code, and ASHRAE 90.1-2016 were used for performing the cooling analyses. In the case study, a cold winter 'best practice' was chosen as the best practice energy code. In addition, the setup for lighting, HVAC, and occupancy were adjusted concerning ASHRAE 90.1-2016 as summarized in Table 2 and Table 3.

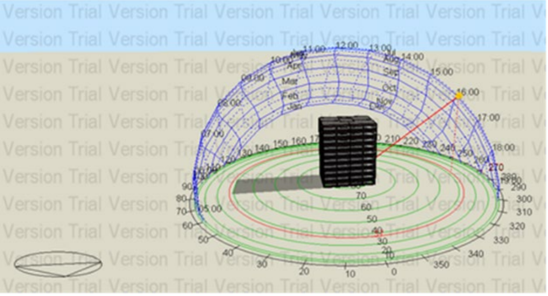

Fig. 1. The reference building designed via DesignBuilder

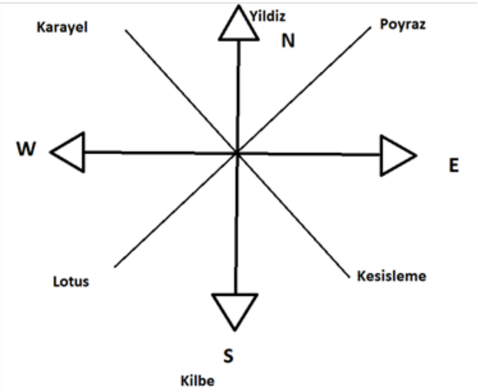

Fig. 2. Wind directions in Istanbul, Turkey

Table 1. Direction and impact of wind

Wind name	Direction	Warm/cold	Summer	Winter
Star (Yıldız)	North	Cold	Cool	Cold
North wind (Poyraz)	North East	Cold	Cool	Cold
Southeastward (Keşişleme)	South East	Warm	Provide dryness	Decrease humidity
Kilba (Kible)	South	Warm	Reason for dry bulb	Reason for dry coldness
South (Lodos)	South West	Warm	Brings rain clouds	Turns North and cold
Mistral (Karayel)	North West	Cold	Provide natural cooling	Cold

Source: these data were obtained from [36](https://www.havaforum.com/)

Fig. 3. The stand-alone model for case study building in DesignBuilder

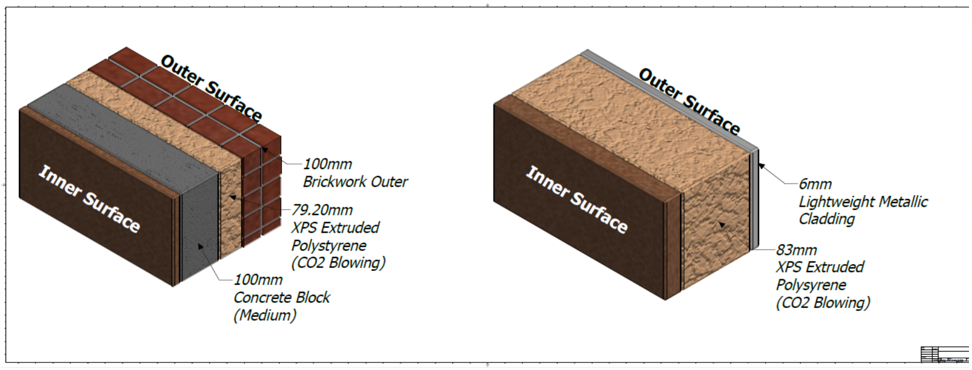

Fig. 4. Structure of wall components (left picture. curtain wall, the right picture demonstrates timber frame wall super insulated)

Table 2. Setup details for the activity tab to implement simulation

Activity template	Template	Residential –dwelling unit(with kitchen)
	Include zone in the thermal calculation	Yes
	Include zone in radiance daylighting calculation	Yes
ASHRAE 90.1 setting	ASHRAE 90.1 building type	Proposed
	Primary building condition category	Residential
	Heating source	Fossil fuel or fossil fuel /hybrid or purchased heat
	ASHRAE 90.1 lighting category	2016 space category(Dining Area-Family dining)
	ASHRAE 90.1 floor definition	User-defined
	ASHRAE 90.1 building area type	Other
Occupancy	Occupied	Yes
	Occupancy density (people/m^2)	0.0215
	Schedule	Residential occupancy
Metabolic	Activity	Cooking
	Factor (Men-1.00, Women=0.85,children=0.75)	1.00
	CO^2 generation rate(m^3/s-w)	0.0000000382
	Clothing schedule definition	Generic summer and winter clothing
	Winter clothing (clo)	1.00
	Summer clothing(clo)	0.50
	Comfort radiant tempreture	Zone averaged
	Air velocity	Default air velocity comfort calculation

Table 2. Cont'd

Holidays	Holidays per year	5 days
	Holidays Schedule	General holidays
Environmental control	Heating setpoint temperature	
	Heating (°C)	24.0
	Heating set back(°C)	18.0
	Cooling setpoint temperatures	
	Cooling (°C)	18.00
	Cooling set back (°C)	26.00
Humadity control	RH humadification setpoint(%)	10.0
	RH dehumafication setpoint(%)	90.0
Ventilation setpoint	Indoor min temperature control	Yes
	Min temperature definition	By schedule
	Min temperature schedule	Min indoor temperature for natural vent: always 7/24
	Indoor max temperature control	Yes
	Minimum fresh air (I/S-person)	2.360
	Mech vent per area(I/S-m^2)	0.305
Lighting	Target illuminance(Lux)	100
	Default display lighting density (W/m^2)	2,9063 W/m^2
	Catering	Yes

Table 3. Reference building design criteria for the cooling analysis

Floor, roof, and wall U-Values (W/m^2-K)	External Floor	0.35
	Ground Floor	0.25
	Internal Floor	1.50
	Internal partitions wall	1.00
	Roof	2.00
	Wall - Typical reference – Lightweight	0,347
Glazing	WWR	40%
	Glazing Type	reference glazing (2 layers, air)
	U-Value(W/m^2K)	1.978
	Total solar transmission (SHGC)	0.691
	Shading	No Shading Devices
Lighting	Template	Building Area Method, Multifamily – ASHRAE 90.1
	Power Density	2,9063W/m^2 at 100 lux
HVAC	Ventilation	Natural (no vents)
	Template	FCU 4-pipe, Air-cooled chiller
	Boiler Efficiency	0.85
	Chiller CoP	1.80
Occupancy	Heating Set point	18°C based on ASHRAE 90.1
	Cooling Set point	26°C based on ASHRAE 90.1
WWR	40% vertical glazing ASHRAE 90.1	40%
Site Orientation		0°C

3. Cooling analysis metrics and scenarios

Within the scope of this study, a cooling analysis was conducted for a 10-story residential building located in Istanbul, Turkey. 36 scenarios were defined to perform cooling analyses (Table 4). The orientation of either the site and the window-to-wall ratio of the reference building was assumed to be zero degrees and 40%, respectively. To conduct cooling analyses, the orientation and window-to-wall ratios (WWRs) were selected as seen in Table 4. DesignBuilder was used for analyzing 36 variations in cooling assessments. Table 3 clarifies the scenarios by the initial alphabet of the wall template, orientation, and WWR, such as C0-30, C0-35, C15-30, and C15-35. The various orientations and WWR ratios were combined into three types of construction walls (i.e., project template, curtain wall, and timber wall). Besides, it is assumed that the building in all scenarios has the same measures. Its area equates to 5400 m^2 (27m*20m).

Scenario details for the cooling analyses (Table 4), reference building design criteria (Table 3), and set up details for implementing simulation (Table 2) demonstrate the features for the cooling analyses. Terms and their definitions used in the cooling analysis are provided below:

Table 4. Scenarios details for the cooling analyses

Scenario	Features	Materials	Orientation	WWR
Reference building	Construction template	Project template	0	40%
	External wall	Reference wall lightweight		
	Below grade wall	Reference below-grade lightweight		
	Semi exposed walls	Reference Wall semi-exposed light		
	Sub-surface walls	100 mm concrete slab		
Scenario 1-18	Construction template	Curtain Wall insulated to typical reference	0,15,30,45,90,120,135	40%,35%, 30%
	External wall	Typical reference Wall medium weight		
	Below grade wall	Typical below-grade Wall medium weight		
	Semi exposed walls	Typical semi-exposed lightweight		
	Sub-surface walls	Slab energy code standard, medium weight		
Scenario 19-36	Construction template	Timber frame super insulated	0,15,30,45,90,120,135	40%, 35%, 30%
	External wall	Lightweight super insulated		
	Below grade wall	Lightweight super insulated		
	Semi exposed walls	Lightweight super insulated		
	Sub-surface walls	Super-insulated brick/block external wall		

- Design capacity refers to the total cooling load and sensible cooling multiplied by the design margin.
- Design flow rate indicates the required flow rate to deliver a sensible cooling load regarding the design supply temperature and zone air temperature of the maximum load.
- Total cooling load states the maximum sensible summation with latent loads at the time of maximum sensible cooling load.
- Sensible refers to the maximum sensible cooling load.
- Latent indicates the latent load for the zone at maximum sensible load.
- Air temperature expresses air temperature for the zone at maximum sensible load.
- Humidity states the percentage of humidity in the zone at maximum sensible load.
- Time of max cooling implies the time of occurrence of maximum sensible cooling load.
- Max operative temperature in the day is the maximum operative temperature in the zone across the design day, including periods when the zone may be unconditioned (with radiant fraction = 0.5).
- Air temperature refers to the average temperature of the day.
- Operative temperature indicates the mean of the mean internal air and means radiant temperature.
- Out-side dry-bulb temperature expresses the air temperature which shields from radiation and moisture.
- Glazing implies total heat flow to the zone from the glazing, frame, divider of exterior glazing excluding transmitted short wave solar radiation.
- Zone sensible cooling states cooling showing as negative heat gain.
- Airflow refers to the summation of outside air flowing into the zone through infiltration, natural ventilation, air distribution [37, 38].

4. Results and discussion

In this research, a cooling analyses were conducted to compare cooling design capacity and cooling demand for three different types of building envelopes. Within this scope, different combinations of wall material types, various site orientations, and different WWR were evaluated by considering the wind direction in Istanbul. Simulation results show that the cooling design capacity for the reference building concludes 429.67 kW which refers to sensible cooling and cooling load. According to the results, the cooling load and sensible cooling decrease on lower floors and increase on higher floors. Hence, it was worth noting that the last floor has a lower amount of cooling load rather than the 9th floor. Furthermore, the flow rate for the reference building is in the range of 19.76 m^3/s. Design flow rates demonstrate the flow required to provide sensible cooling. Comparing the results of design flow rate and sensible cooling per floor shows that the height of the building is not the only influential factor. The sensible cooling amount increases between the 3rd and 9th floors (9 m – 27 m) while the improvement in design flow rate occurs between the 5th and 9th floors (15 m - 27m).

4.1. Cooling analysis of reference building

The U-value for the Project template component was defined by typical reference data modified while the component was loaded. The U-value for the Project flat roof is 0.25 (W/m^2K), for the Project internal floor is 2.92 (W/m^2K), for the wall typical reference lightweight is 0.34 (W/m^2K), for the Project ground floor is 0,25 (W/m^2K), and for glazing is 1.96 (W/m^2K). Building data composes of building heating/cooling floor area (5400 m^2), building volume (18900 m^3), building external area (4370 m^2), building area-weighted average U-value (0.888 W/m^2K), and building external surface area /volume (0.231 m^{-1}). Site orientation was assumed to be zero degrees and the window-to-wall ratio was 40% (Table 4).

The results are substantial as the time of maximum cooling load was 17:30 in July. On the other hand, the minimum design capacity amount was 40.7 kW for the ground floor which was followed by the 1st floor (42.5 kW). Floors between the 2nd floor and 8th floor are in the same range approximately between 43.14 - 43.65 kW while the 9th floor is 42.17 kW which has a lower design capacity than the 2nd floor. Meanwhile, the total cooling load for the first floor is found to be 35.39 kW, which is the lowest amount followed by the 2nd floor at 36.96 kW, while for other floors it is between 37.5-37.9 kW. Notably, the 9th-floor cooling load is 36.6 kW. The total cooling load for the building is 373.63 kW. The outside dry-bulb temperature at the peak time of cooling load is 24.28 ºC and the maximum operating temperature in the day is 32.9 ºC with 48.8% humidity for the whole building. The highest heat loss for floors is -44.22 kW (negative corresponds to heat loss) followed by roofs and ceilings (-21.04 kW), walls (-9.75 kW), infiltration (-7.87 kW), and glazing (-6.8 kW). Details of the results are shown in Fig. 4 and Table 5.

According to Fig. 4, among building components, floors gain significant heat during the daytime. The maximum heat gain occurs at 6:00 am which corresponds to relative humidity at the same time. The outside dry bulb temperature impacts heat loss for the floor at 6:00 pm. Meanwhile, glazing at 6:00 pm gains more heat than other components. Notably, glazing, roof, and ground floor have a more limited temperature range of change than the other components. Accordingly, floors, ceilings, and walls have a large range of changes for heat gain/loss, respectively. As the U-value for floors is 2,929 consequently the heat gain and heat loss occur in a vast range. On the other hand, these results prove the impact of thermal conductivity and heat transfer of materials in terms of gain/loss of heat. The thermal mass of materials is one of the other important factors considering the high-temperature difference is very influential upon heat transfer.

Table 5. U-value for envelope component of the reference building

Envelope component of the reference building	U-Value (including bridging) (W/m^{2}K)
Project flat roof	0,25
Project internal floor	2,929
Wall - Typical reference – Lightweight	0,347
Project ground floor	0,25

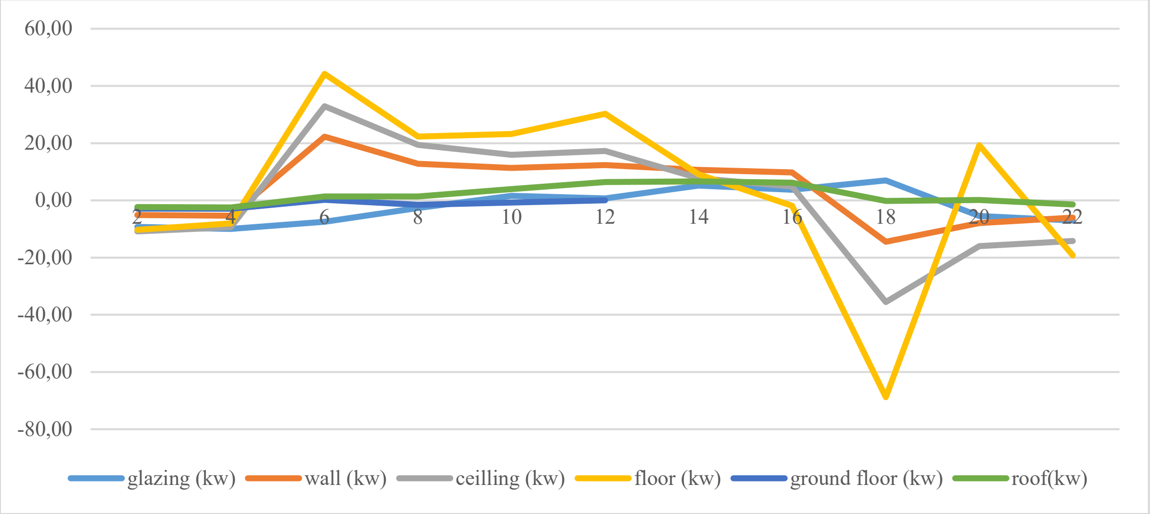

Fig. 4. Reference building cooling analysis according to components

The mean of mean radiant temperature and mean internal temperature is the operative temperature. The operative temperature and relative humidity act in opposite directions between 6:00 am and 6:00 pm, as shown in Fig. 5. Fig. 6 shows a significant increase in total cooling, sensible cooling, and zone sensible cooling. The maximum sensible cooling is reset, as is the latent load, which can be the same as the sensible cooling load if the latent is negative. As shown in Fig. 6, total cooling and sensible cooling use about 50 kW between 6:00 am and 6:00 pm, whereas before 6:00 am and after 6:00 pm, they use about the same amount. It means that latent load before 6:00 am and after 6:00 pm is negative and ignored in the analysis. Latent is the latent load for the zone at the time of maximum sensible load. The long dash in Fig. 6 indicates the linear forecast for total cooling load, which increases in the daytime. In addition, zone sensible cooling load is the sensible cooling that impacts the zone of any free air introduced internally. Moreover, the sensible cooling load and zone sensible load are interrelated. This means the design flow rate and sensible cooling are matched properly.

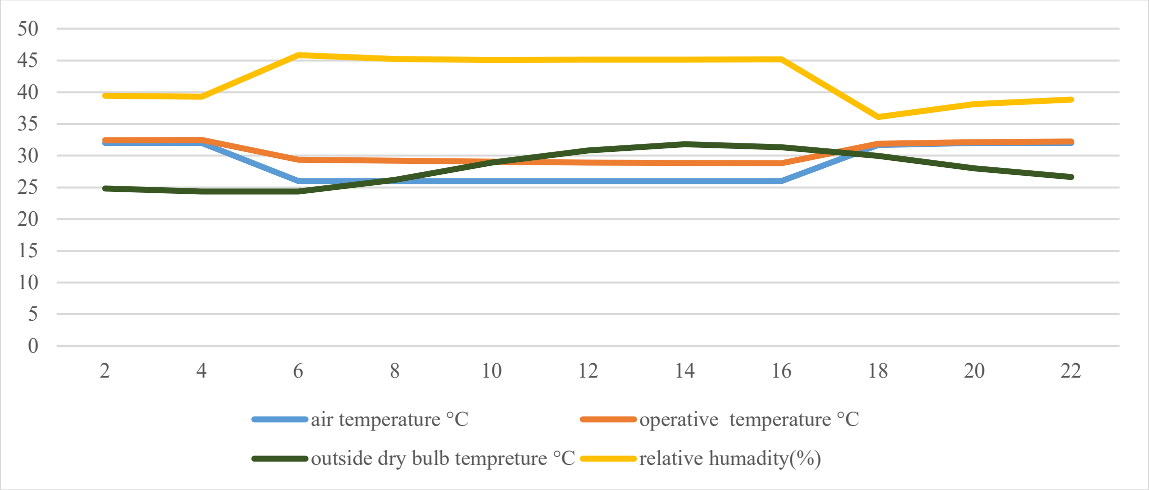

Fig. 5. Reference building temperature balance

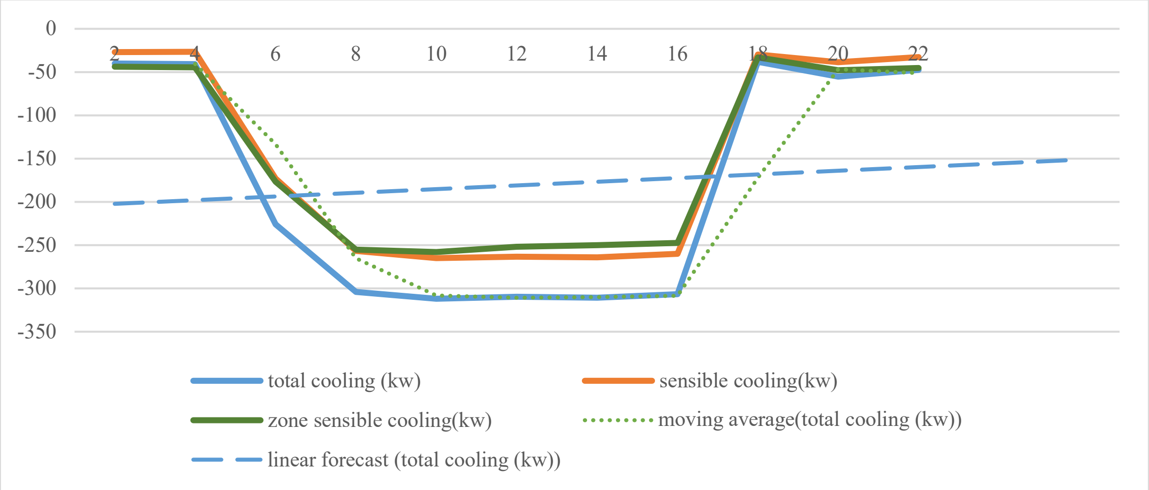

Fig. 6. Reference building cooling analysis results

4.2. Cooling analysis of curtain wall

Design capacity for scenario C-3 (curtain Wall, 30% WWR, zero site orientation) equates to 438.27 kW. The design capacity of the 1st floor is 36.65 kW, the 2nd floor is 40.69 kW, 3rd floor is 43. 07 kW, 4th floor is 43.77 kW, 5th floor is 43.95 kW, 6th floor is 44.04 kW, 7th floor is 44.09 kW, 8th floor is 44.24 kW, 9th floor is 44.34 kW, and 10th floor is 43.95 kW. The total cooling load is 372.41 kW while the lowest amount belongs to the 1st floor with 31.87 kW followed by the 2nd floor with 35.38 kW. The total cooling amount for floors between the 3rd floor and the 9th floor are intervals of 37.45-38.56 kW while the total cooling amount for the 10th floor is 37.81 kW.

Fig. 7 and Fig. 8 demonstrate the interaction between building envelope components and air temperature, relative humidity, and dry bulb temperature. The results are in the neighboring range; therefore, subsequent results of scenarios are significantly influencing cooling energy demand while providing thermal comfort. Scenario 7 (Curtain wall template, 15-degree rotation site location, and 30% WWR) has the minimum design capacity which means minor energy demand for cooling (Fig. 10).

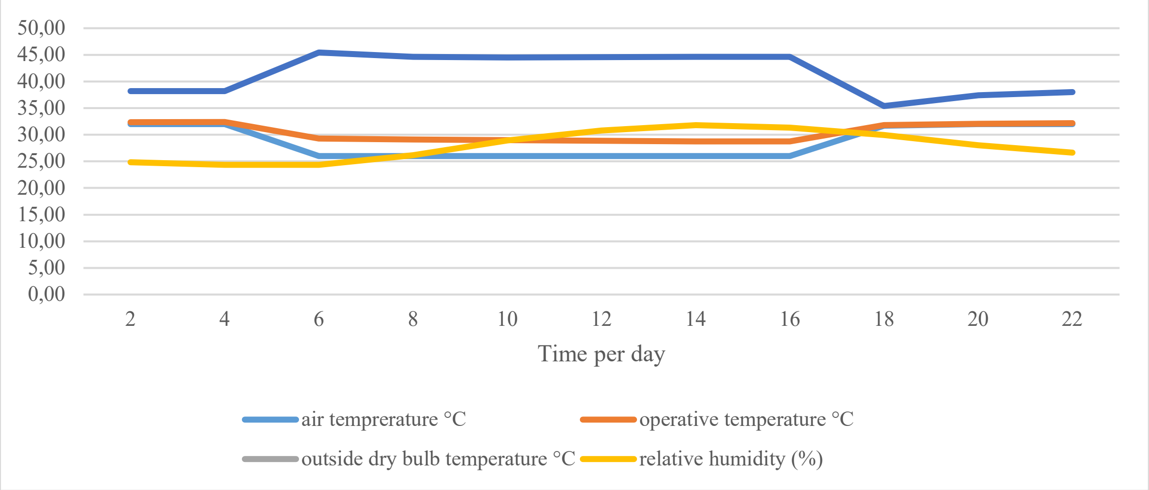

Fig. 7. Scenario C30(orientation 0 °C,30 % WWR) temperature balance

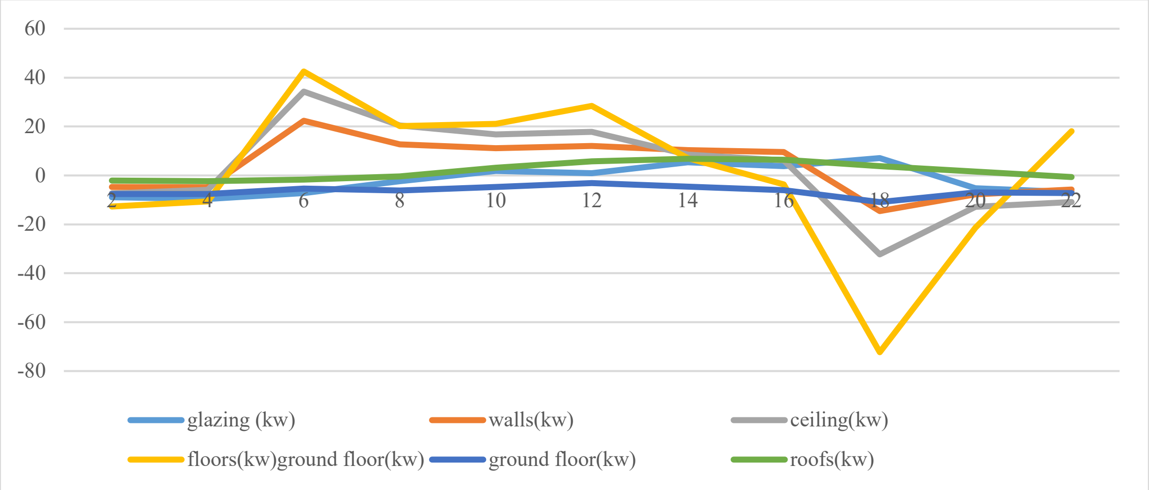

Fig. 8. Cooling analysis considering components for scenario C30(orientation 0 °C,30 % WWR)

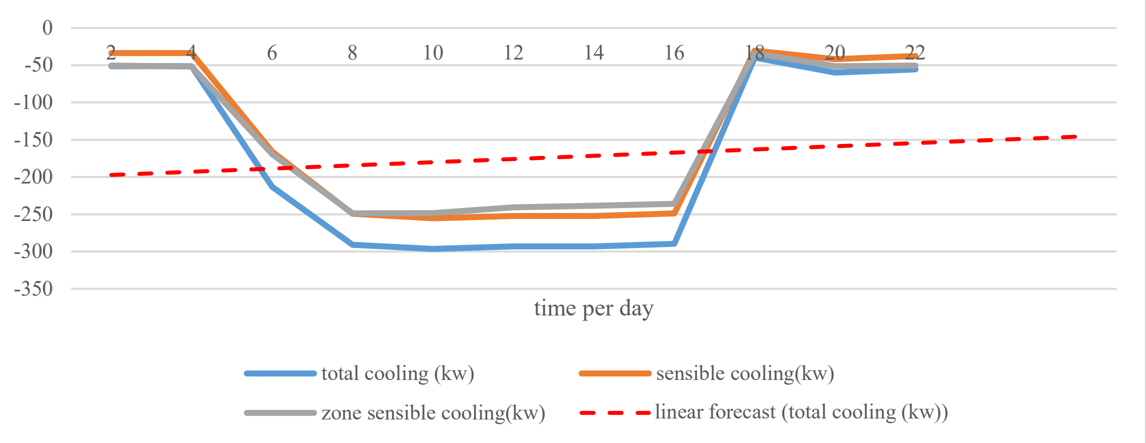

Fig. 9. Cooling analysis result of scenario C30(orientation 0° C, 30% WWR)

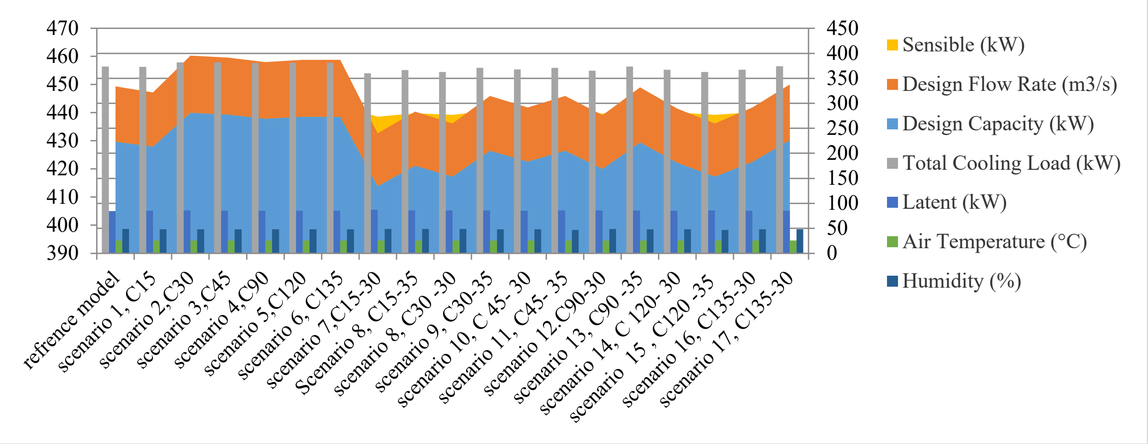

Fig. 10. Cooling analyses for scenarios 1-18 (curtain wall template)

4.3. Cooling analysis of timber wall

The third template wall structure is supposed to be a super-insulated timber frame wall. According to Fig. 11, a noteworthy difference between Fig. 9 and Fig. 6 is observed. The linear forecast line is approximately straight, and the amount of total cooling load is around 200 kW. The results of timber wall scenarios address a reduction in dry bulb temperature for each floor except for the last floor, which increases by 6 °C. Besides, the relative humidity percentage decreases for each floor by 2-3 °C. (Fig. 12), The air temperature, operative temperature, and Dry-Bulb temperature are not as high as the aforementioned templates interval 4:00-6:00 pm (Fig. 5, Fig.7, and Fig. 12) and there is an intersection at 6:00 pm. The problem here is about the last floor of the building which has remarkable heat gain due to the low air infiltration needs to the higher amount of design flow rate. The reason for the higher total cooling load is because of the last floor (Fig. 11). The maximum cooling load occurs at 2:00 pm while at the same time the amount of heat conductivity gained by the roof is higher between 10:00 am - 2:00 pm (Fig. 13). The most heat gain occurs on roofs, floors, glazing, and walls, respectively. This is because of observing higher sensible temperature in these scenarios rather than curtain wall scenarios. For example, Scenarios 24 (timber frame, 15-degree orientation, 30% WWR), 26 (timber frame, 30-degree orientation, 30% WWR), and 30 (timber frame, 90-degree orientation, 30% WWR) are the most efficient scenarios with the lowest cooling design capacity, respectively (Fig. 14).

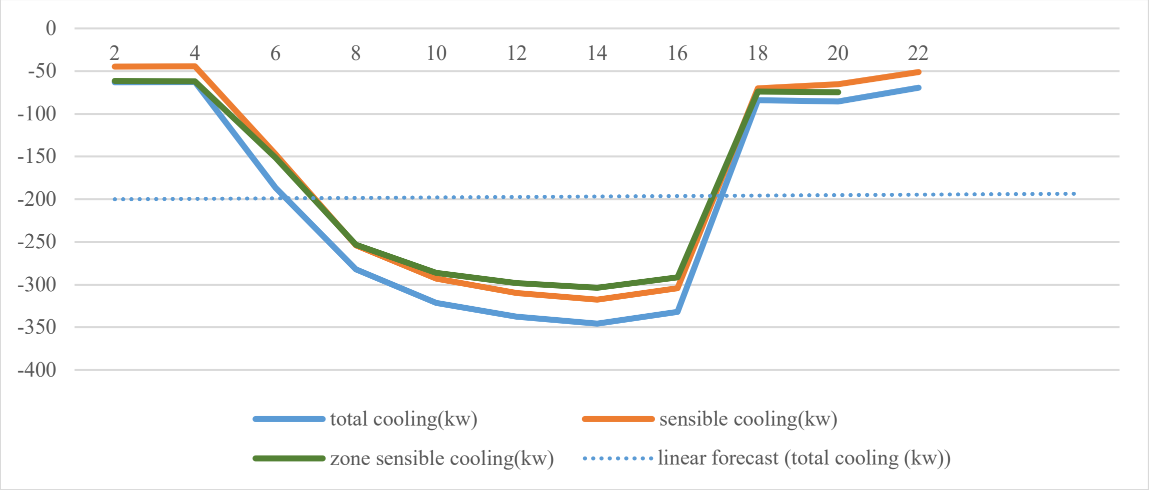

Fig. 11. Cooling analysis for scenario 19th (orientation 0 °C,30%WWR)

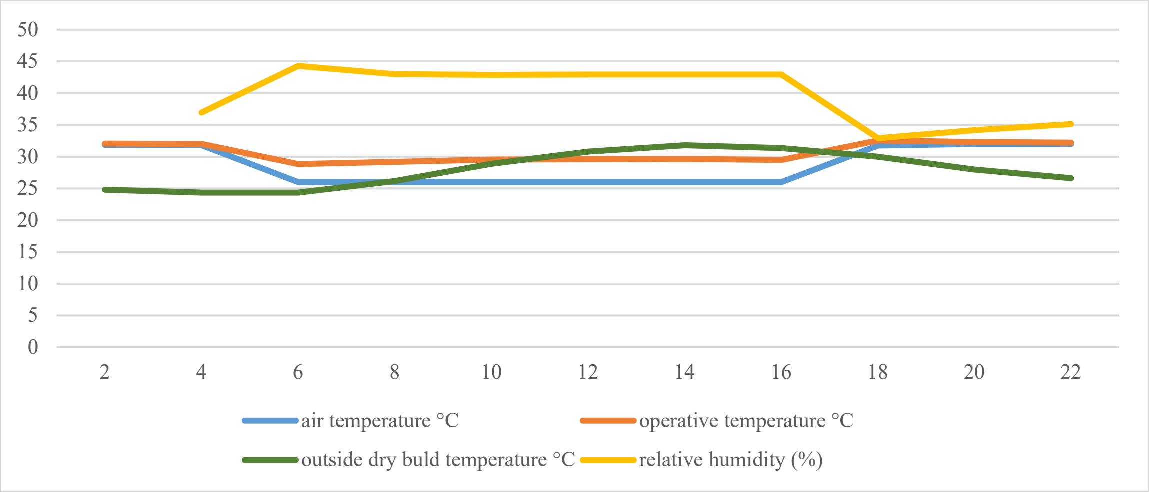

Fig. 12. Cooling analysis temperature balance for scenario 19th (orientation 0 °C,30%WWR)

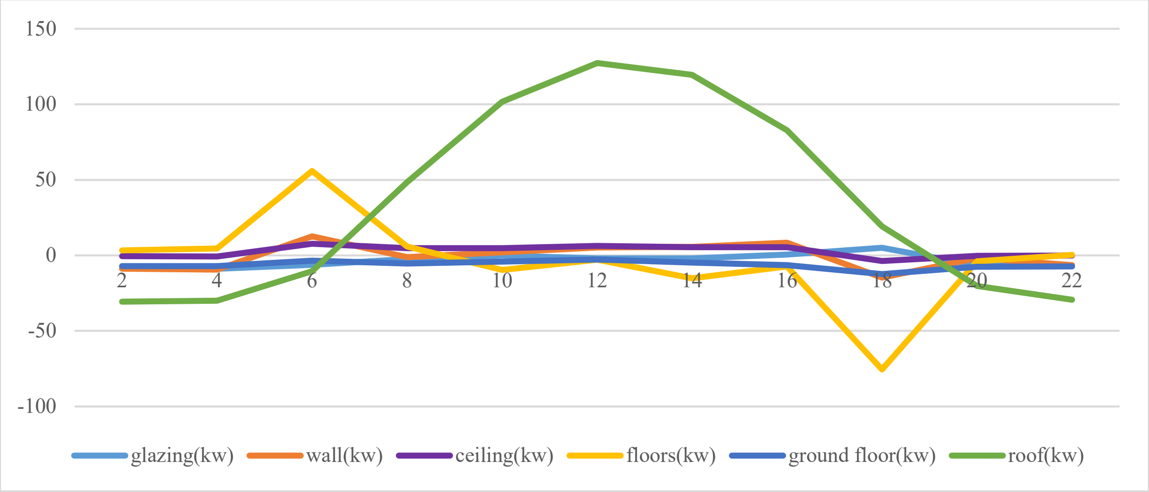

Fig. 13. Cooling analysis considering building components for scenario 19th (orientation 0 °C,30%WWR)

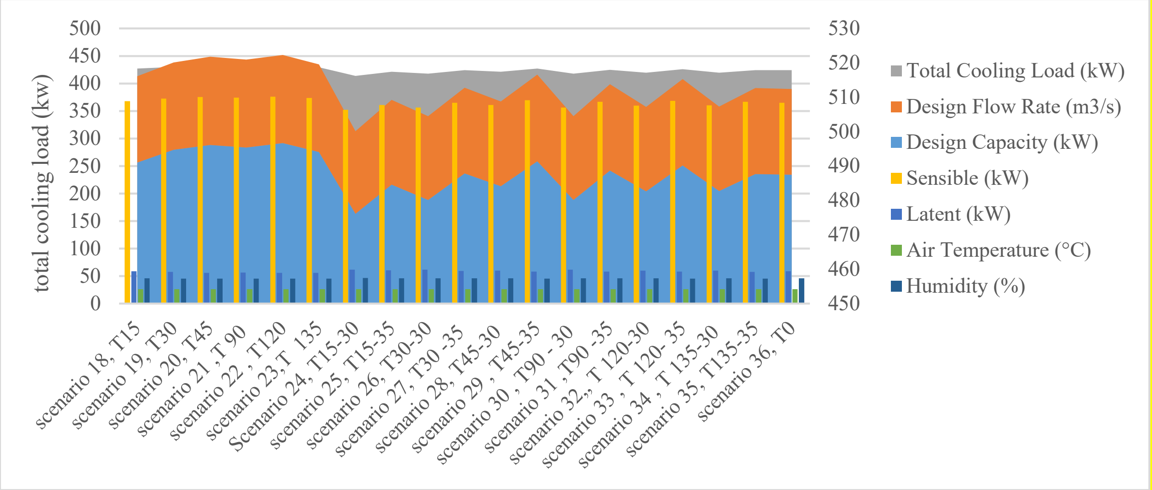

Fig. 14. Cooling analyses of third template (Timber wall) for scenarios 19-36

Fig. 13 indicates that the heat gain and loss through wall, glazing, ceiling and ground floor decrease significantly in comparison with Fig. 8 and Fig. 4. Even though, floors heat conductivity gain/loss decreases remarkably for the daytime except at 12:00 and 6:00 pm. The heat gain through the floor means the zone below is colder. As the roof gains solar radiant and longwave gains heat much more than other components. On the other hand, the air infiltration is insignificant in the super-insulation walls (i.e., timber walls) increasing the heat gains of the last floor. This means the total cooling loads for the last floor increase assertively.

5. Conclusion

This study presents the effects of different types of building envelopes on energy performance. Passive methods including building design, orientation, insulation and window-to-wall ratio were employed for a 10-story reinforced concrete residential building in Istanbul, Turkey. The energy performance of the various wall, insulation, and glass components utilized in the buildings was analyzed and compared via DesignBuilder software. This research would make a significant contribution to the AEC literature and industry by analyzing the energy performance of different building envelopes and the appropriate scenarios based on the location. The findings of this study can be used by policymakers and decision-makers to change existing codes and policies for new high-rise buildings.

Results proved that building envelope components, WWR, orientation, and wind direction interact with each other. The window-to-wall ratio in super-insulation walls acts an essential role, as it can provide natural air circulation in a suitable wind direction that is controllable by site orientation. Therefore, the cooling demand will decrease significantly. Furthermore, the findings of the analyses indicate that not every site orientation works for every wall material. For instance, 120 degrees address low cooling demand in curtain walls but not for timber walls. This means that each parameter and material has a significant impact on the building's energy efficiency and their proper combination during the design phase can increase energy efficiency and reduce carbon emissions. This study shows that the reason for differences between the results of floors in the reference building is wind exposure; as the design flow rate is the same for floors 4,5,6,7,8 (2 m^3/s) and floors 1,2,10 is the same (1.88 m^3/s). These results indicate that wind has various impacts on the building envelopes with a height under 10.5 m and middle floors of building with a height of 10.5-31.5 m (the height of each floor was assumed 3,5 m).

Scenarios in this study address two wall templates in varieties of WWR and orientation of site location. Each wall template in terms of different variables for orientation and WWR is categorized in 18 scenarios as demonstrated in Table 4. According to the findings of the second template scenario, thicker insulation could provide proper efficiency by considering the orientation of the site location. In this study, 15, 30, and 120-degree orientations were addressed to achieve a valid output as the orientation was in the North wind (Poyraz) direction which provides a balance between insulation and strain circumstances. Hence, it is important to notice the WWR which impacts heat transfer and loss remarkably. In this case, cooling energy consumption decreases by 6-7%. The outputs for the template of the third scenario demonstrate that low heating energy demand distinctly results in increasing cooling design capacity. On the other hand, the insulation layers of timber frame walls consider a significant amount of carbon emissions in the building meanwhile increasing heat loss on the last floor and cooling design capacity vastly.

A solution for decreasing the cooling demand while achieving a reduction in heating demand could be different WWR on each side of the building regarding the microclimatic station. Future research direction could be investigating roof components, roof technologies, the shape of the building precisely which would provide noteworthy results.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

References

[1] IEA. Transition to Sustainable Buildings. IEA; 2013. https://doi.org/10.1787/9789264202955-en.

[2] IEA. Key World Energy Statistics 2020, IEA, Paris.

[3] Global Alliance for Buildings and Construction: 2019 Global Status Report For Buildings And Construction: Towards a zero-emission, efficient and resilient buildings and construction sector. International Energy Agency and the United Nations Environment Programme, 2019.

[4] Maleki B, Casanovas M, De A, Antequera F. The multi-criteria assessment of sustainable residential high-rise building design. 19th European Roundtable for Sustainable Consumption and Production, 15-18 October 2019, Barcelona, Spain.

[5] Aydin D, Mihlayanlar E (2020) A case study on the impact of building envelope on energy efficiency in high-rise residential buildings. Architecture, Civil Engineering, Environment 13(1):5–18.

[6] Global Alliance for Buildings and Construction: 2017 Global Status Report For Buildings And Construction: Towards a zero-emission, efficient and resilient buildings and construction sector. International Energy Agency and the United Nations Environment Programme, 2017.

[7] Jayaweera N, Rajapaksha U, Manthilake I (2021) Enhancing the daylight and energy performance of external shading devices in high-rise residential buildings in dense urban tropics. Journal of Green Building 16(3):87–108.

[8] Data Requirements for Community Energy and Emissions Inventories in British Columbia. BC Provincial Community Energy and Emissions Inventory Working Group, 2008.

[9] Barkan, C. (2007). Energy Efficiency : Energy Efficiency : In Ashrae Standard (pp. 1–12). Retrieved from https://www.rcreee.org/sites/default/files/meetmed_ee-in-buildings_v2final_0.pdf.

[10] Kocagil IE, Oral GK (2015) The effect of building form and settlement texture on energy efficiency for hot dry climate zone in Turkey. Energy Procedia 78:1835–1840.

[11] Krayem A, Al Bitar A, Ahmad A, Faour G, Gastellu-Etchegorry JP, Lakkis I, Jocelyne G, Haitham Z, Yeretzian A, Najem S (2019) Urban energy modeling and calibration of a coastal Mediterranean city: The case of Beirut. Energy and Buildings 199:223–234.

[12] Yildiz Y (2016) Impacts of climate change on heating and cooling loads in residential buildings. Gazi University Journal of Science 29:27–34.

[13] Mostafavi F, Tahsildoost M, Zomorodian Z (2021) Energy efficiency and carbon emission in high-rise buildings: A review (2005-2020). Building and Environment 206:108329.

[14] He Q, Ng ST, Hossain MU, Skitmore M. (2019) Energy-efficient window retrofit for high-rise residential buildings in different climatic zones of

China. Sustain; 11. https://doi.org/10.3390/su11226473.

[15] Aste N, Buzzetti M, Del Pero C, Leonforte F. (2017) Glazing's techno-economic performance: A comparison of window features in office buildings in different climates. Energy Build; 159. https://doi.org/10.1016/j.enbuild.2017.10.088.

[16] Ge H, McClung VR, Zhang S (2013) Impact of balcony thermal bridges on the overall thermal performance of multi-unit residential buildings: A case study. Energy and Buildings 60:163–173.

[17] Liu L, Lin B, Peng B (2015) Correlation analysis of building plane and energy consumption of high-rise office building in cold zone of China. Building Simulation 8:487–498.

[18] O'Brien W, Bennet I. Simulation-based evaluation of high-rise residential building thermal resilience. 2016 ASHRAE Winter Conference, January 2016, Orlando, USA.

[19] Raji B, Tenpierik MJ, van den Dobbelsteen A (2016) An assessment of energy-saving solutions for the envelope design of high-rise buildings in temperate climates: A case study in the Netherlands. Energy and Buildings 124:210–221.

[20] Ha PTH (2018) Energy efficiency façade design in high-rise apartment buildings using the calculation of solar heat transfer through windows with shading devices. IOP Conf. Series: Earth and Environmental Science 143:012055.

[21] Giyasov B, Semenov V, Giyasova I. Optimization of thermal stability of structural elements of high-rise buildings to increase their energy efficiency. XXVII R-S-P Seminar, Theoretical Foundation of Civil Engineering, 17-21 September 2018, Rostov-on-Don, Russia.

[22] Saroglou T, Meir IA, Theodosiou T, Givoni B (2017) Towards energy-efficient skyscrapers. Energy and Buildings 149:437–449.

[23] Chen WJ, Claridge DE, Atif MR (2017) Using internal fan balancing system to avoid excessive pressurization on high rise buildings in hot and humid climates. Energy and Buildings 152:86–95.

[24] Han JM, Park D. Seasonal optimization of a dynamic thermo-optical ETFE facade system. 16th IBPSA Conference, 2-4 September 2019, Rome, Itlay.

[25] Kalhor K, Ememinejad N (2020) Qualitative and quantitative optimization of thermal insulation materials: Insights from the market and energy codes. Journal of Building Engineering 30:101275.

[26] Abdul Nasir MH, Hassan AS (2020) Thermal performance of double brick wall construction on the building envelope of high-rise hotel in Malaysia. Journal of Building Engineering 31:101389.

[27] Xu WJ, Jimenez-Bescos C, Calautit JK (2021) Investigating the impact of surroundings on a high-rise residential block's performance. Proceedings of the Institution of Civil Engineers- Engineering Sustainability 174(3):131–144.

[28] Yik F, Bojić M (2006) Application of switchable glazing to high-rise residential buildings in Hong Kong. Energy and Buildings 38:463–471.

[29] Chen SS, Zhao LH, Zheng LT, Bi GH (2021) A rapid evaluation method for design strategies of high-rise office buildings achieving nearly zero energy in Guangzhou. Journal of Building Engineering 44:103297.

[30] Cheung CK, Fuller RJ, Luther MB (2005) Energy-efficient envelope design for high-rise apartments. Energy and Buildings 37(1):37–48.

[31] Yoon YB, Seo B, Koh BB, Cho S (2019) Performance analysis of a double-skin façade system installed at different floor levels of high-rise apartment building. Journal of Building Engineering 26:100900.

[32] Al-Tamimi N, Fadzil SFS (2012) Energy-efficient envelope design for high-rise residential buildings in Malaysia. Architectural Science Review 55:119–127.

[33] Shadram F, Mukkavaara J (2019) Exploring the effect of several energy efficiency measures on the embodied/operational energy trade-off: A case study of Swedish residential buildings. Energy and Buildings 183:283–296.

[34] Aste N, Buzzetti M, Del Pero C, Leonforte F. Glazing's techno-economic performance: A comparison of window features in office buildings in different climates. Energy Build 2017;159. https://doi.org/10.1016/j.enbuild.2017.10.088.

[35] Hassan AS, Al-Ashwal NT (2015) Impact of building envelope modification on energy performance of high-rise apartments in Kuala Lumpur, Malaysia. International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies 6(3):91-105.

[36] havaforum. Türkiye'de Rüzgarlar 2020. https://www.havaforum.com/turkiyede-ruzgarlar/ (accessed March 15, 2022).

[37] Summary Cooling Design Table n.d. https://designbuilder.co.uk/helpv4.7/Content/Sum

mary_Cooling_Design_Table.htm#:~:text=Design Flow Rate%2C shown in,multiplied by the Design margin.&text=Air Temperature is the Air,time of maximum Sensible load. (accessed February 1, 2022).

[38] Cooling Design Detailed Results n.d. https://designbuilder.co.uk/helpv4.7/Content/Cooling_Design_Detailed_Results.htm (accessed February 1, 2022).