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Designing façade and envelope for a high-rise residential building using energy-efficient materials: A case in Istanbul, Turkey

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Abstract. The construction industry is responsible for 40% of global energy demand as buildings increase heating, cooling, and lighting demand. Therefore, building energy performance has become one of the most significant subjects for the architecture, engineering, and construction (AEC) industry in the last decade. The envelope of a building has an essential role in optimizing energy performance and consumption. The research objective of this study is to analyse and compare the impact of different envelope and façade materials on building energy performance for a high-rise residential building. The research methodology includes a literature review and a case study. The literature review analysed studies published between 2015 and 2021. In the literary review, 84 publications were extracted from Web of Science and Scopus databases, and the following sources were included: articles published in prominent journals, conference proceedings, thesis, scientific reports, and books. In the case study, passive strategies including building shape, orientation, insulation, window-wall ratio, and shelter were implemented in a 10-story residential building in Istanbul, Turkey. Design-Builder and EnergyPlus were used for analysing and comparing the energy performance of the different wall, insulation, and glass materials used in the building. Results demonstrate that each parameter and material has a considerable impact on the building energy performance. This study would contribute to the AEC literature and industry by comparing different envelope materials' energy performance and the proper scenario according to Turkey(Istanbul)'s climate. Policy-makers and decision-makers can benefit from the results of this research and amend the existing codes and policies for new high-rise buildings.

1. Introduction

In 2021, World Energy Outlook (WEO) announced that the building industry accounts for nearly one-third of total final energy consumption and 15% of end-use sector direct CO2 emissions; when indirect emissions from electricity and heat used in buildings are included, the share of emissions rises to around 30%[1,2]. Additionally, the building sector accounts for 60% of global CO2 emissions for space heating [3]. The solution to fulfil the gap between Announced Pledges Scenario and Net Zero Building is to develop energy efficiency in the building sector. WEO highlighted some key factors to close the current gap in the carbon emissions reduction aimed to be reached by 2030, which is an unwavering focus on energy efficiency and measures to reduce energy service demand through material efficiency and behavioural change[4].

Previous studies showed that local climate is the most crucial factor in building design. People built vernacular architecture by considering the sun's location and geographical resources. Locals sought to achieve this goal by implementing passive measures such as building orientation/geometry, shade components, and wind barriers. In fact, implementing passive systems could save roughly 70% of energy in the heating/cooling requirement. Substantially lowering the amount of energy require for heat and cool indoor settings[5,6]. They demonstrated that passive is not always passive. Building envelopes could be optimized to make the most of solar energy, hence reducing greenhouse gas emissions and moderating energy requirements.

Recent works focused on the impact of passive measures on building energy performance. Alternative shading mechanisms with glass insulations were proposed by Vanhoutteghem et al.[7], who demonstrated the importance of U-values and WWR in obtaining interior thermal comfort [7]. Harkouss et al. [8] looked at different climates to figure out how much energy residential structures use. Yao et al.[9], evaluated the impact of building orientation, sun-exposed areas, WWR, and shading devices on China's five passive energy reduction techniques using a region-based approach. In a more recent study, Ménard et al.[10] found that optimizing the building exterior resulted in considerable passive energy savings.

Additionally, building envelope as a factor that interacts with the outdoor and indoor environment has a crucial impact on energy efficiency in buildings[11]. Building envelope, plays an essential role in improving building energy efficiency performance due to the large surface area exposed in front of sunlight, condensation, wind, rain, and snow. Accordingly, the envelope of the building has a significant heat and cooling exchange with indoor and outdoor environments. Consequently, the building envelope is an influential element in energy demand for heating/ cooling and provides thermal comfort and proper daylight for building occupants[12].

Therefore, high-rise buildings, regarding their large surface area, have advantages and disadvantages in case they are not designed properly. According to the findings from the literature review, there are very few studies on this subject domain. Only seven publications were related to high-rise buildings. To determine the impact of building envelope factors on thermal comfort and energy consumption, Wang et al.[13] performed a sensitivity analysis. They produced moderate indoor comfort improvements while saving significant energy using the analyses' output. Figueiredo et al.[14], investigated the impacts of active and passive interventions on building energy consumption and found that integrating such measures resulted in significant energy savings for various seasonal activities. In the sensitivity analysis in the study of D'Oca et al .[15] the window-to-wall ratio (WWR) ratio appears to be an essential parameter. This work also emphasis employing a combination of passive and active strategies to improve a building's energy efficiency.

Further, building early-stage design is one of the essential steps for all types of buildings to achieve high energy efficiency. Especially in designing residential buildings due to their large scale and high energy consumption, it is necessary to consider the proper, efficient system. Additionally, high-rise building designs contain complexity and need precise design and sustainability goals to achieve high performance[16]; When building designers have options (i.e., design variables), they evaluate envelope components during the design stage. Their evaluation goes beyond the isolated performance of a single variable decision to examine the impact of one variable on another[17]. Walls, roofs, windows, doors, and foundations are part of the building envelope. Exterior cladding, exterior sheathing membrane, exterior sheathing, insulation, structural components, vapour barriers, and interior sheathings are components of a building's walls. Besides, wall assembly supports, controls, and finishes the building exterior[18].

For these reasons, construction of new buildings needs reconsidering to reduce energy consumption using renewable resources while providing occupants comfort and satisfaction. In this context, recent studies intend to focus on decreasing building energy consumption[19,20]. The variables that influence energy demand for heating, cooling, and lighting are orientation, shape, wall-window ratio, climate, and insulation. It is noticeable that a high-rise building's sustainability and energy efficiency would be neglected during design, resulting in high financial investment for renovation and retrofitting to reduce energy consumption[21]. The energy demand for lighting, heating, cooling for providing thermal comfort and occupant satisfaction would require high amounts of cost for high-rise buildings[22].

High-rise buildings get noticed recently in developing countries. As a developing country with an increasing population and limitations for constructing buildings, Turkey has many high-rise buildings.

The range of energy consumption for high-rise buildings is 16-50% worldwide, while Turkey accounts for 31%[23,24]. Consequently, designing an energy-efficient high-rise building regarding long service life is essential.

This study aims to identify appropriate envelope components according to influential variables on building energy efficiency to design an energy-efficient high-rise building. The focus of this study is on walls, and as variables, the building's orientation, wall-window ratio, insulation is considered. The literature review was conducted to distinguish related studies and the research gap. The related documents were extracted and studied using WoS and Scopus databases. A 10-story high-rise building in Istanbul, Turkey, was designed in the scope of this study via Design Builder 7.0.0.116 and EnergyPlus 9.4.0.001softwares. For each parameter, three variables were defined. In this case, the envelope component and some information, such as U-value and R-value, were retrieved from previous studies. The following research question was replied to in this research:

- What is the relation and interaction of parameters of interest in this research, and do they impact energy efficiency?
- Does the interaction among parameters and their combination positively impact energy efficiency and CO2 emission reduction?
- Does the interaction among parameters and their combined impact energy efficiency and CO2 emission reduction?

The results demonstrated the best-fitted component and variables for the above parameters to achieve high energy efficiency performance on a high-rise residential building. The study results provide a comprehensive look at elements and components of the building envelope for further researchers. Meanwhile, results establish a knowledge base for improving building envelope and façade.

2. Research methodology

The research methodology of this study consists of two significant steps: literature review and case study. First, Scopus and Web of Science were used for reviewing the literature. The keywords used in the search engine were as follows; 'energy performance', 'energy efficiency', 'building envelope', 'material', 'energy analysis', and 'Design Builder'. 648 publications were limited by duration (2015-2021) and refined categories concerning 'civil engineering', 'architecture', and 'building construction technology'. Then, 84 publications were extracted. However, there is a lack of research about high-rise buildings and building envelopes. Totally, there are 118 publications in the scope of the energy performance of high-rise residential buildings (under categories of civil engineering, architecture, building, and construction technologies); the first article was published in 2000. The publication has been forwarded by 17, 18, 11, and 10 in years 2021,2020, 2019, and 2018, respectively. These pieces of knowledge body prove insufficient consideration on high residential building energy performance. Indeed, only seven articles addressing building energy performance on high-rise buildings have been published in the last 5 years.

In the second step, a 10-story high-rise building model in Istanbul, Turkey, was designed based on ASHRAE 90.1-2016 APP G PRM using Design-Builder. The Climate classification based on the Koppen classification is the humid subtropical climate (Cfa). The sun path regarding the different months of the year is considered during analysis and shown in Figure 1. In this case, winter starts in October and ends in March, and summer starts in April and ends in September. The temperature during a year changes interval 0-30 Istanbul is placed in 40.97 Latitude and 28,82 Longitude that is elevated above sea level by 37 m. The analysis setup was arranged on normal exposure to wind, and the site orientation assumed zero degrees. Turkey's region legislative considered throughout the analysis. The energy codes and insulation standards involve uninsulated, typical reference and as mandatory energy code, ASHRAE 90.1-2016 were chosen to conduct analysis. Cold winter 'best practice' selected for the best practice energy code. This model chooses the wall element according to the commonly used component in Istanbul based on ASHRAE 90.1 and the data library. Three templates that compose external wall, below-grade wall, semi-exposed wall, sub-surface walls are demonstrated in Figure 2.

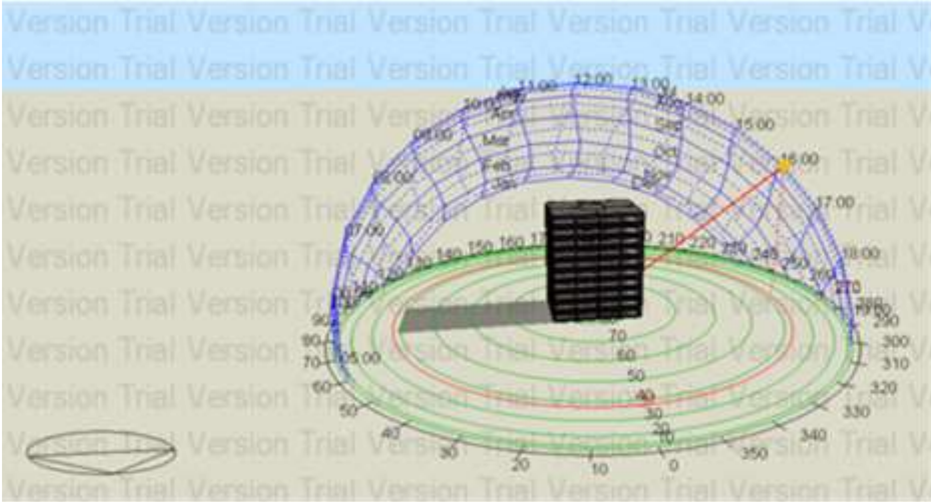

Figure 1. The reference building designed via Design Builder

The reference building is designed in 27 m width and 20 heights. The floor area is 540 m2, and the total area is 5400 m2. Basic properties for the reference building were set up and shown in Table 1.

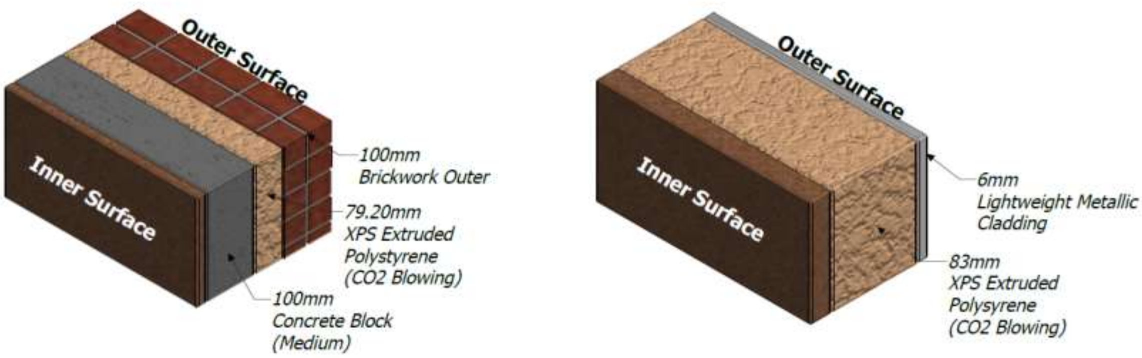

Figure 2. Structure of wall components (left picture. curtain wall, the right picture demonstrates timber frame wall super insulated)

Table 1. Energy-related properties of the reference building

Wall U-Values (W/m^2-K)	External Floor	0.35
	Ground Floor	0.25
	Internal Floor	1.50
	Internal Partitions	1.00
	Roof	2.00
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 2016
	Power Density	2,9063W/m2 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	13°C
	Cooling Set point	32°C
WWR	40% vertical glazing ASHRAE90.1	40%
Site Orientation		0 C

It was assumed that orientation for site location and window-wall-ratio of reference building were zero degrees and 40%, respectively. For the further steps, orientation (0,15,30,45,90,120,135) and WWR (30,35,40) were replaced to conduct heating analysis and cooling analysis (Table 2). Consequently, 36 statements were analysed in both heating and cooling analyses through DesignBuilder. Scenarios are named according to the first alphabet of the wall template, orientation, WWR like C0-30, C0-35, C15-30, and C15-35 Table 2.

Table 2. Scenario clarification

scenario	Features	Materials	Orientation	WWR
Reference building	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	Template	Curtain Wall insulated to typical reference	0,15,30,45,90,120,135	40%,35%, 30%,
	External Wall	Turkey Wall medium weight		
	Below grade Wall	Turkey below-grade Wall medium weight		
	Semi exposed walls	Turkey semi-exposed lightweight		
	Sub-surface walls	Slab energy code standard, medium weight		
Scenario 19-36	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		

3. Results and discussion

Within the scope of this research, heating design analysis was performed for a 10-storey residential building located in Istanbul, Turkey. The heating design analysis aims to get information about the heat gain /loss of building components/materials and the heat design capacity/total design heating capacity. The vaster surface area of the reference building was placed face to the north/south. According to Lotus and Poyraz wind direction, which are primarily from East North and West North, therefore, the north side of the building gained more interest in this study.

The variables considered for building design are as follows: total design heating capacity(kW), steady-state heat loss(kW), external infiltration (W/sqm), and sensible zone heating(W/sqm). The outputs of these variables for reference building were 279,55 (kW), 23,96(kW), 41,42 (W/sqm), and -19,62 (W/sqm). According to the results of reference building, external infiltration, external vent, glazing, and walls were the components/factors that had heat more witnessed (Figure 3).

In the first scenario, the total heating design capacity decreased to 244 and followed the other variables (Steady-state heat =21, sensible zone heat=36, external infiltration = -14) Figure 4. Significant change addressed the influence of the external wall, surface wall, and grade below walls on heat load. The results of heating analysis are shown in Figure 4. Even though results are different in a small range, it was highly notable to consider the difference in heating design capacity among floors. The third template for wall equipment is a super-insulated timber frame wall. The outputs of heating analysis for each floor heating design capacity demonstrated the wide range of differences between the two last floors and other floors. The heating design capacity for lower floors were interval 15-21 while this measure was interval 60-80 for two last floors (floor 9,10).

The four variables mentioned above (total design heating capacity(kW), steady-state heat loss(kW), external infiltration (W/m2), and sensible zone heating(W/m2)) in each analysis were approximately the same. In contrast, the external air infiltration and steady heat loss gave remarkably different results in range. For instance, external air infiltration was mostly -14 while it was -2,80 for Timber frame wall components (Figure 4).

On the other hand, heating design capacity and heat loss remarkably changed in scenario C15-30. The curtain wall structure composes 4 layers named brickwork outer, XPS extruded Polystyrene, concrete block, and Gypsum plastering. These combinations provide sufficient insulation for the envelope of the building that results in reduction of heat loss, zone sensible heat, and heating design capacity.15-30 degrees' orientation in site location provides good placement for building both for sunlight and facing wind direction. Consequently, the smaller surface of the building faces wind direction and breaks the wind speed act as a windbreaker that results in controlling thermal mass transmission in the surface of the building. Hence, the results are the same for the other orientation. Ninety degrees are the most influential as it changes the vaster surface with the smaller surface of the building, which is faced with the wind.

Moreover, WWR on the north side of the building influence the head design capacity remarkably. by implementing 35% and 30 % WWR in the reference model, the results of heating analyses are more efficient in energy consumption. The lowest heating design capacity is observed in scenarios T15-35, T30-30 which is 219 (the result for reference building is approximately 280 kW). It is crystal clear that superinsulation walls impact the results widely, but the problem is with the higher floors in the building, which gain higher heat and lose more heat than lower floors. For mentioned scenarios, the highest heat loss is for the roof's external vent, while other factors have decreased very well.

Furthermore, the CO2 embodied for three kinds of material used throughout the analysis were considered and evaluated to identify the interaction between the envelope's material and embodied CO2. Embodied CO2 were equivalent 259249 (Kg co2), 248741 (Kg co2),339924 (Kg co2) for reference template, curtain wall template, timber frame wall template, respectively. The reason for the high amount of embodied CO2 of timber frame walls is because of XPS extruded polystyrene. These results prove the crucial role of insulation and its impacts on building energy efficiency and the environment.

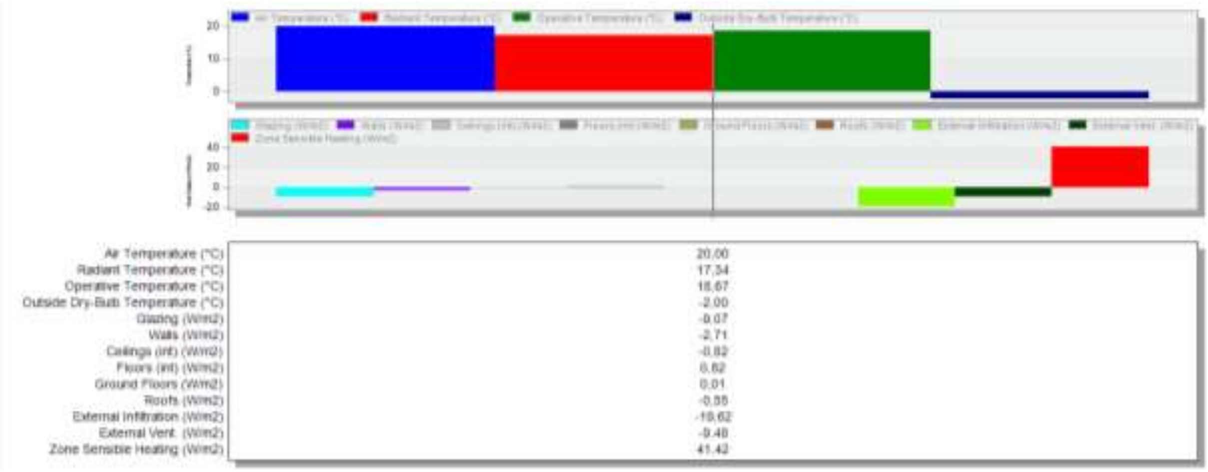

Figure 3. Heating analysis of reference building with zero degrees' site orientation and 40% WWR

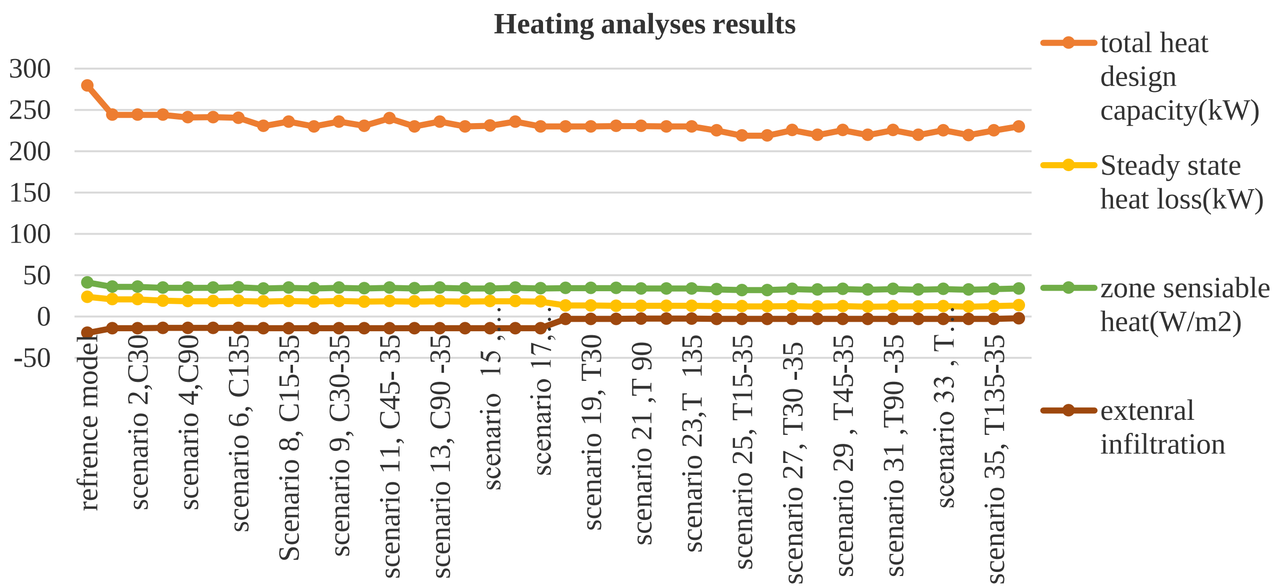

Figure 4. Heating analyses results for 36 scenarios regarding different orientations and WWR

4. Conclusion

This research presented the impacts of sustainable materials for designing façades and envelopes on building energy performance. Passive strategies, including building shape, orientation, insulation, and window-wall ratio, were implemented in a 10-story residential building in Istanbul, Turkey. Design-Builder and EnergyPlus were used for analysing and comparing the energy performance of the different wall, insulation, and glass materials used in the building. Results demonstrate that each parameter and material has a considerable impact on the building energy performance. This study would contribute to the AEC literature and industry by comparing different envelope materials' energy performance and the proper scenario according to the climate in Istanbul, Turkey Istanbul. Policymakers and decision-makers can benefit from the results of this research and amend the existing codes and policies for new high-rise buildings.

Findings show that using proper sustainable materials for building envelope and façade and arranging the building orientation and the window-to-wall ratio (WWR) provide the same situation of influential factors on heat demand. According to the outputs of analyses, curtain walls and timber walls reduce heat demand in buildings and decrease external air infiltration significantly. The only problem is that the timber wall frame, due to super insulated higher floors, receives too much heat related to the high measure for cooling demand. As a solution, the insulation for the higher floor could be different from other floors to provide thermal comfort prevent heat loss, and decrease heat design capacity. The most influential factor for the timber wall's scenario is the roof for the higher floor. The last floor's roof needs to be appropriately designed, which provides thermal comfort for both winter and summer days.

Regarding the outputs of the analyses, the shape of the building could be designed by rotating the floors 5 degrees per floor. In this case, the direction of the higher floor would be proper to cope with the wind, which acts as a windbreaker. Further, WWR facilitates in reducing heat loss caused by glazing. As a solution, the side of buildings exposed to wind needs to be designed with the WWR interval of 30-35%. Additionally, considering the results obtained, there is a complex and crucial interaction between embodied CO2 and building energy efficiency and early-stage design. However, it is essential to consider and choose proper materials for designing envelopes and facades, but simultaneously, it is essential to check out the environmental impacts. Finding sustainable replacement instead of chemical insulation would provide acquisitive efficiency for the energy of the building, occupant comfort, and environment.

One of the future works for this research could be conducting more case studies in different climate zones. Another future research direction could be comparing the outputs of heating design analysis and cooling design analysis to achieve a more comprehensive result. Another future work could be studying complex shapes for high-rise buildings considering the climate of site locations. Finally, research natural/less chemical insulation equipment and evaluate their function in the building's system.

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