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Impact of Window-to-Wall Ratio (WWR) and shading on energy demand in a residential building across five distinct climates

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ABSTRACT

This study investigates the impact of window-to-wall ratio (WWR), shading strategies, and envelope's insulation levels (U-value) on the heating and cooling demands of a block of flats across five climate zones near 40° latitude (Ankara, Beijing, New York, Rome and Wellington). The building model was developed in TRNSYS18 and simulated over a full year. Results demonstrate that shading strategy had the greatest influence on total energy demand. Among the three shading types, movable shading consistently achieved the lowest energy demand in south-facing apartments: 10 kWh/m^2·yr in Wellington, 45.5 kWh/m^2·yr in Ankara, 59.5 kWh/m^2·yr in New York, 65.5 kWh/m^2·yr in Beijing and Rome 20 kWh/m^2·yr all with 60% WWR and a U-value of 0.1 W/m^{2}K. The optimal WWR was found to be 10% for fully north-facing and 60% for fully south-facing apartments when using movable shading and high-performance insulation. Compared to unshaded configurations, movable achieved reductions up to 56% in Rome in south-facing apartments with 60% WWR and a U-value of 0.3 W/m^2·K. Moreover, a significant correlation was found between U-values and energy demand in all cities except Rome. These findings underscore the importance of integrating adaptative shading, WWR and insulation strategies into building designs, tailored to climate and orientation, to support energy efficiency and sustainable urban planning.

1. Introduction

As the global population grows rapidly, it is essential to ensure that buildings are designed and constructed to minimize their environmental impact while providing comfortable and healthy indoor spaces for occupants. The building sector accounts for a significant portion of global energy consumption and greenhouse gas emissions, representing approximately 34% of both in 2023 [1]. Despite ongoing efforts, the sector remains far from meeting the Paris Agreement target of achieving carbon neutrality in buildings by 2050. To meet this goal, it is crucial to create efficient buildings that balance thermal comfort with reduced energy consumption.

The United Nations has also set a target to enhance building efficiency and resilience against rising temperatures by 2050, with increasingly ambitious measures outlined for 2035 and beyond [2]. Reducing energy demand in residential buildings is a key strategy for lowering carbon emissions, improving energy security, and alleviating financial burdens on homeowners. The specific drivers of energy consumption vary by climate, with heating systems dominating in colder regions and air conditioning systems driving energy demand in hotter climates [3].

To achieve these goals, it is critical to assess building envelopes and their role in energy demand reduction. Factors such as the thermal efficiency of external walls, the Window-to-Wall Ratio (WWR), shading devices, and insulation all play significant roles in energy performance and emissions reduction. As urbanization and modern lifestyles drive up energy consumption, the need for energy-efficient building designs becomes more urgent, particularly in the context of rising global energy prices and the ongoing energy crisis [4].

Optimizing the building envelope is essential for improving thermal

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performance and minimizing heat loss [5]. Incorporating high-performance thermal insulation materials can significantly reduce heat loss through the building's walls and roof, thereby enhancing overall energy efficiency [6]. For example, studies have shown that optimal wall insulation can reduce energy consumption by as much as 6.77% in office buildings in China, depending on wall orientation [7]. Additionally, a study in Beijing found that accounting for U-value uncertainties based on building age increased heating demand by 26% and cooling by 13%, emphasizing the importance of accurate insulation assessments for urban energy planning [8].

Thermal inertia is another important consideration in building design. Recent research highlights its significant role in building envelopes in energy savings, particularly in cooling demand, with reductions ranging from 13% to 20%, depending on the level of external wall insulation. Thermal inertia also influences indoor comfort conditions and should thus be considered in conjunction with the U-value of the envelope. Notably, while thermal transmittance has a greater impact on heating and cooling demands, thermal inertia also plays a significant role, resulting in a variation of up to 7% in the total energy demand in some buildings [9]. Thermal mass also significantly impacts the energy demand for heating and cooling. The interaction between intermittent occupancy and thermal mass notably affects overall energy use, and neglecting this factor can lead to inaccurate assessments of building energy performance. In colder climates, for instance, high thermal mass structures may increase energy use, challenging the common assumption that greater thermal mass correlates with low energy consumption [10]. In such contexts, lightweight walls with high insulation tend to outperform massive walls. Consequently, the optimal design strategy for energy efficiency thus is climate-dependent: while high thermal mass materials are generally advantageous in hot climates, lightweight, well-insulated walls are more effective in colder regions [11].

The WWR is another critical factor in determining a building's energy efficiency and thermal comfort. While larger WWRs can increase solar heat gains, they also increase heat losses through the facade [12]. When well-designed WWR, it can significantly impact energy efficiency, thermal comfort, and occupant satisfaction. When well-designed, WWR plays a crucial role in minimizing heat losses, enhancing thermal comfort, and optimizing energy performance [13].

In addition to WWR, shading devices also play a crucial role in reducing energy consumption and enhancing thermal comfort by controlling the amount of solar radiation entering through windows [14]. Studies have explored the impact of WWR and shading devices on energy demand in various climates. For example, research has shown that smaller WWRs are recommended for hot summer and cold winter climates to achieve more stable energy performance [15]. The WWR plays a significant role in determining the energy efficiency of buildings, particularly in mixed and hot climates. According to recent studies, an optimal WWR can be achieved by balancing heating and cooling demands, ventilation rates, and daylight factors. In mixed climates, a WWR of 9-25% for south and north facades, and 6-12% for west facades, is recommended when combined with an opening ratio of 35%. This configuration supports natural ventilation, reducing the need for mechanical cooling and heating. In hot climates, a lower WWR of 6-12% is advised to minimize heat gain and maximize energy efficiency. The optimal WWR also varies depending on the orientation of the facade, with south-facing facades requiring higher WWRs than west-facing facades. Overall, careful consideration of WWR is crucial in designing energy-efficient buildings that minimize energy consumption while maintaining occupant comfort [16]. Studies in China have found optimal WWRs for residential buildings have been found to vary between 15% and 59%, depending on the orientation and design of the building, with the goal of optimizing heating, cooling, and lighting comfort [17]. Moreover, studies in Mediterranean climates, such as Rome, Lecce, and Naples, have shown that optimal WWRs can range from 23.7% to 26.1% for standard insulation, and up to 32% for spectrally selective glazing, balancing energy consumption and daylighting [18].

External shading devices further enhance energy performance by reducing overheating and controlling solar radiation. The use of fixed or movable shading devices has been shown to significantly improve energy efficiency, particularly in regions with rising temperatures due to climate change [19–21]. A considerable body of research has examined the impact of window area (WWR) and orientation on energy consumption in buildings (see Table 1). It has been demonstrated that a higher WWR can result in a reduction in energy consumption during heating yet concurrently lead to an increase in energy consumption during cooling. The studies encompass a range of climates and geographic regions, indicating that optimal strategies for energy savings can exhibit considerable variation depending on the local climate.

A number of studies have examined the impact of shading systems on reducing energy consumption, particularly in hot and sunny climates [3,16,26]. The researchers employed a range of simulation tools (e.g., EnergyPlus, OpenStudio, IES VE, etc.) to analyse the energy performance of buildings, suggesting that a singular approach to assessing energy consumption is not applicable. A multitude of factors must be taken into consideration when designing energy-efficient buildings. These include, but are not limited to, climate, orientation, glass type, and shading systems. The diversity of climates, building types, and design strategies studied has resulted in a wide variation in outcomes, suggesting that a single solution to improve efficiency is unlikely.

The U-value is a key factor in building energy performance, particularly in cold and temperate climates. Improving wall insulation (i.e., lowering U-value) has been shown significantly reduce heating demand. An analysis of the papers analysed in Table 1 reveals that eight of these studies focused on eight different countries, with the largest number of studies conducted in China. The humid subtropical climate (Köppen classification: Cfa) is represented most extensively among the selected cities. The majority of cities are located within the latitudinal range of 35° and 45°($35 \leq \varphi \leq 45$), with a smaller number of cities located at latitudes below 35° ($\varphi < 35$) and an even smaller number situated above 45° ($\varphi > 45$). With regard to the analysis of daylight, a mere five of the thirteen articles under consideration include a specific analysis of daylight or lighting conditions. The impact of lighting consumption, accounting for shading devices or WWR, has been demonstrated to range from 5% to 15% of a building's global energy demand [14,15,17]. Improving wall insulation (i.e., lowering U-value) significantly reduces heating demand, while having limited or even adverse effects on cooling in hot climates. These findings support the inclusion of U-value as a critical variable in energy simulations [23,24,28,29].

The validation of the analysis models developed in the various studies is only performed in five of the articles, suggesting that most studies do not report this information or do not focus on model validation.

The present study investigates the influence of WWR, shading devices, and U-values of external walls on heating and cooling demands in residential buildings across five climate zones near 40° latitude. The selection of this particular latitude is driven by its unique balance of annual cooling and heating demands, characterized by moderate temperatures and substantial solar radiation. The climatic characteristics of this region render it an optimal location for the study of the effectiveness of various solar shading solutions in reducing energy demands. The latitude of 40° was selected for particular consideration due to its representation of a transitional zone between temperate and subtropical climates, where the energy demands for heating and cooling are relatively balanced. This enables the evaluation of the performance of different shading strategies under conditions that are representative of a wide range of climate zones. Furthermore, the moderate temperatures and substantial solar radiation at this latitude render it an ideal location for studying the impact of solar shading on building energy consumption.

Three shading configurations are examined in this analysis: no shading, fixed shading devices, and a novel dynamic approach using

Table 1
Key points of the literature review (in chronological order).

Reference /Year	Country. Latitude (φ): φ<35; 35≤φ≤45; φ>45 Köppen-Climate	Building type	Goal:U-value	Goal: Shading	Goal: WWR	HVAC system	Specific analysis and impact	Tools
/ 2025	Country: China Latitude: 35≤φ≤45. Climate: Cwa	Room 7.5x5.5x3.5 m	3 Cases	No Shading	South (From 0 to 90%)	No needed	Cooling load and daytime temperature	Validated one office room TRNSYS
/ 2024	Country: Iraq Latitude: 35N≤φ≤45N. Climate: Bsh	Office room 5x5x2.5 m 25 m^2 One orientation	For windows	No Shading	Yes	Defined COP and EER	Reduce heating consumption for double clear glass for south-facing windows if WWR was 100 % and cooling energy consumption for north-facing windows if double theoretical-197 glass with a 25 % WWR	Open Studio (version 3.2) with Energy Plus
/ 2024	Country: Turkey Latitude: 35N≤φ≤45N. Climate: Csa Country: Pakistan Latitude: φ<35N. Climate: Bwh	Container house	Optimal for each envelope	Three shading scenarios	Optimal for each facade	Defined COP and EER	Five passive strategies: envelope layering, WWR, windows opening ratio for natural ventilation, glazing type, and shading Meeting ventilation, heating, cooling, and lighting demands Energy consumption	DesignBuilder
/ 2024	Country: Iraq Latitude: φ<35N. Climate: Bwh	Residential 5x4x3.5m	4 Cases	No Shading	North-south (20% to 35%)	Defined	Optimal WWR 25% for south orientation	TRNSYS. Validated in a previous work
/ 2024	Country: China 1 City Latitude: φ>45. Climate: Dwb 1 City Latitude: 35≤φ≤45. Climate: Dwa 3 Cities Latitude: φ<35N. Climate: Cfa Climate: Cwa Climate: Cwb	Offices building	Different insulation thicknesses	No Shading	2 Orientations (20 to 40 %)	Defined COP	Energy consumption. Optimal WWR depends on the wall insulation	TRNSYS. Validated with the energy consumption data
/ 2023	Country: Iraq Latitude: φ<35N. Climate: BWh	Room 1000 m^2	Constant with PCM	No Shading	1 window with 8 orientations WWR from 8.75% to 20%	No needed	Comfort conditions using PCM materials in facade and roof using natural night ventilation for several WWR and different orientations	Energy Plus
/ 2022	Country: China Latitude: 35N≤φ≤45N. Climate:Dwa Latitude: 35N≤φ≤45N. Climate: Bsk Latitude: φ<35N. Climate: Cfa Latitude: φ<35N. Climate: Cwa Latitude: φ<35N. Climate: Cwb	Residential 118 m^2, variable shape	Constant	No Shading	Optimal for each space and orientation (house with 3 orientations N+S+W)	No needed	Architectonical indoor spaces from design to reduce energy demand (total, cooling and heating) considering the WWR for each space. In Beijing WWR for living room and master bedroom (both with window to South) is 0.59 and 0.41 respectively	Validation method OpenStudio
/ 2020	Country: Korea Latitude: 35≤φ≤45. Climate: Cwa	Apartment 145 m^2 x 2.3m	Constant	4 types of shading systems	No variation	Undefined	Energy consumption for lighting and cooling consumption. WWR 90% facing south	Only simulation IES VE
/ 2021	Country: China Latitude: φ<35N. Climate: Cfa	Residential 10.5x12m	Constant	No Shading	North-south (0%, 20%. 40%, 60%, 80% 100%)	No needed	Energy demand for cooling Electricity demand for cooling increases by about 100 kWh for each 20% increase of WWR	ENVI-met+TRNSYS Validated

(continued on next page)

Table 1 (*continued*)

Reference /Year	Country. Latitude (φ): φ<35; 35≤φ≤45; φ>45 Köppen-Climate	Building type	Goal:U-value	Goal: Shading	Goal: WWR	HVAC system	Specific analysis and impact	Tools
/ 2019	Country: China Latitude: φ<35N. Climate: Cfa	Office room 4x4x3m	Constant	Shading external devices (1, 0.75, 0.5, 0.25 and 0)	South (25%, 50% and 90%)	No needed	Cooling, heating, lighting and total energy demand. Occupant behavior	Only simulation BCVTB for coupling with EnergyPlus
/ 2017	Country: Italy 4 Cites Latitude: 35N≤φ≤45N. Climate: Cfa 1 City Latitude: 35N≤φ≤45N. Climate: Csa 1 City Latitude: 35N≤φ≤45N. Climate: Dfa 3 Cities Latitude: φ>45N. Climate: Dfa 1 City Latitude: 35N≤φ≤45N. Climate: Cfb 2 Cities Latitude: φ>45N. Climate: Dfb	Office Building 30x16 m	3 cases	Electrochromic glazing and selective glass	South and west. From 5% to 55%	Undefined	Primary energy consumption for several configurations varying climate, envelope and lighting power. Furthermore, influence of a switchable shading device using different glazing and lighting inside the building. Considering global consumption, the optimal WWR varies from 20% to 27% depending on the U-value's envelope	Only simulation Energy Plus
/ 2016	Country: United Arab Emirates Latitude: φ<35N. Climate: BWh	Office building 4.2x8.4x4.2 m	Constant	External movable shading device: 10 states	Constant. 1 window. 4 orientations	Defined COP and EER	Primary energy performance for thermal and lighting comfort	Calculation methodology
/ 2007	Country: Belgium Latitude: φ>45. Climate: Cfb	Office building 5.4x3.6x2.7 m	Constant	With shading device. Open/ Close	Constant 40% 1 window to South	No needed	Energy demand, overheating, overcooling and visual comfort	Only simulation TRNSYS16

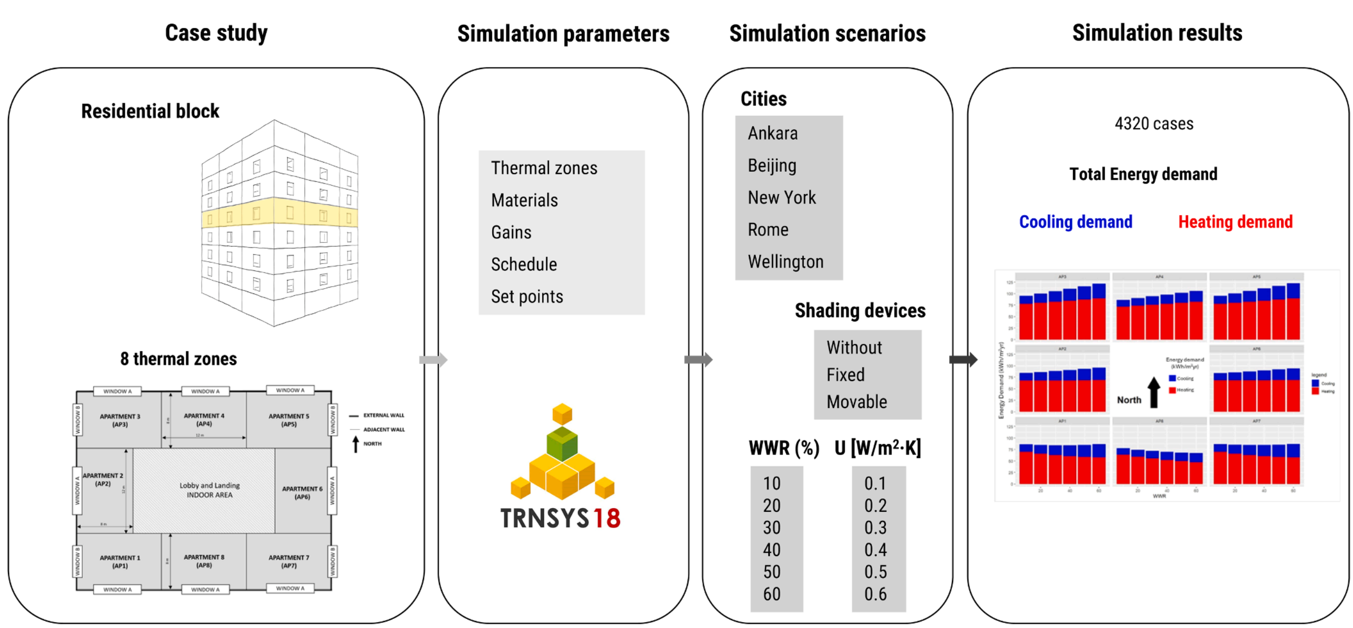


Figure 1. Methodology employed to analyse diverse factors influencing the building's energy demand under varying climatic conditions.

movable shading devices which allows adaptation to real-time environmental conditions. A consistent WWR is applied across all orientations, and a uniform shading device size is used to ensure comparability. The goal is to provide insights into the optimal design of building envelopes for energy-efficient and comfortable residential buildings. The underlying hypothesis suggests that low WWRs (e.g., 10%) combined with highly insulated envelopes (e.g., U-value of 0.1 W/m^{2}K) may lead to overheating in warmer climates due to insufficient heat dissipation through the building envelope.

2. Methodology

A model has been developed to represent a block of flats with a rectangular floor plan. Eight distinct thermal zones were defined based on orientation and the number of exterior walls with windows. Each residential unit, hereinafter referred to as an 'Apartment (AP)', was modelled as an individual thermal zone with a floor area of 96 m^2. The TRNSYS18 (Transient Systems Simulation program) was employed to assess the building's energy demand under varying climatic conditions (Figure 1). The following factors have been considered in these simulations: window-to-wall ratio (WWR), U-value of exterior walls, fixed and movable shading, and climatic characteristics of five different cities (Ankara, Beijing, New York, Rome, and Wellington). Simulations were performed over a full year to account for seasonal variations. Additionally, non-parametric statistical tests were applied to analyse the influence of the abovementioned factors on energy demand.

Although the model developed in this study has not been experimentally validated, the simulation tool used (TRNSYS) has been consistently employed in previous research by the authors across various building typologies. These include an office building [30], a typical Mediterranean house [31], a detached building in a residential area [32], and a historical building [33], all of which were validated through experimental collected data. This repeated and successful application of the tool supports the reliability of the results obtained in the present study.

2.1. Case study description

A rectangular floor plan located in a block of flats, as depicted in Figure 2, was modelled for this study. Each standard floor comprises a central communal area that provides access to eight apartments (thermal zones) per floor, where communal elements such as elevators, stairs, and corridors are located.

In this model, all apartments have identical usable floor areas but differ in facade surface area, orientation, and the number of external walls with windows, either one or two. Each apartment corresponds to a thermal zone measuring 12 meters in length, 8 meters in width, and 3 meters in height, resulting in a total floor area of 96 square meters, representing the standard size for an apartment.

Apartments AP1, AP3, AP5, and AP7 have two external walls and distinct orientations, whereas apartments AP2, AP4, AP6, and AP8 have a single 12-meter-long external wall and thus are associated with only one orientation.

Since floors and ceilings are adjacent to other building levels, these surfaces were modelled as adiabatic. Similarly, walls in contact with the central communal area were also considered adiabatic. To improve the accuracy of energy demand assessment, one window was assigned per facade orientation, requiring the specification of two distinct window dimensions. When larger windows were placed on the longer walls (12 m), they were designated as 'window A', whereas those placed on the shorter walls (8 m), were designated as 'window B'. Additionally, window dimensions varied proportionally with the Window Wall Ratio (WWR), enabling a more detailed analysis of the building's energy performance.

2.2. Transient simulation

TRNSYS18 simulation software was used in this study to obtain for cooling, heating, and total energy demand for each thermal zone (apartment) [34]. This software uses a building code validated by US Department of energy, which certifies that the model is able to simulate transient effect of thermal mass, long and short-wave radiation model, and heat transfer [35]. Initially, a 3D model of the building was developed by coupling TRNSYS with Sketchup. Subsequently, the building parameters were set using the TRNBuild interface. Type 56 was used for defining the building envelope, including thermal zones, and simulating the overall energy performance.

2.2.1. Model description

2.2.1.1. Materials. The composition of the building envelope consists of multiple layers, including cement mortar, lightweight concrete block, EPS (expanded polystyrene) insulation, and gypsum. The specific thicknesses of each layer, which determine the overall U-value of the

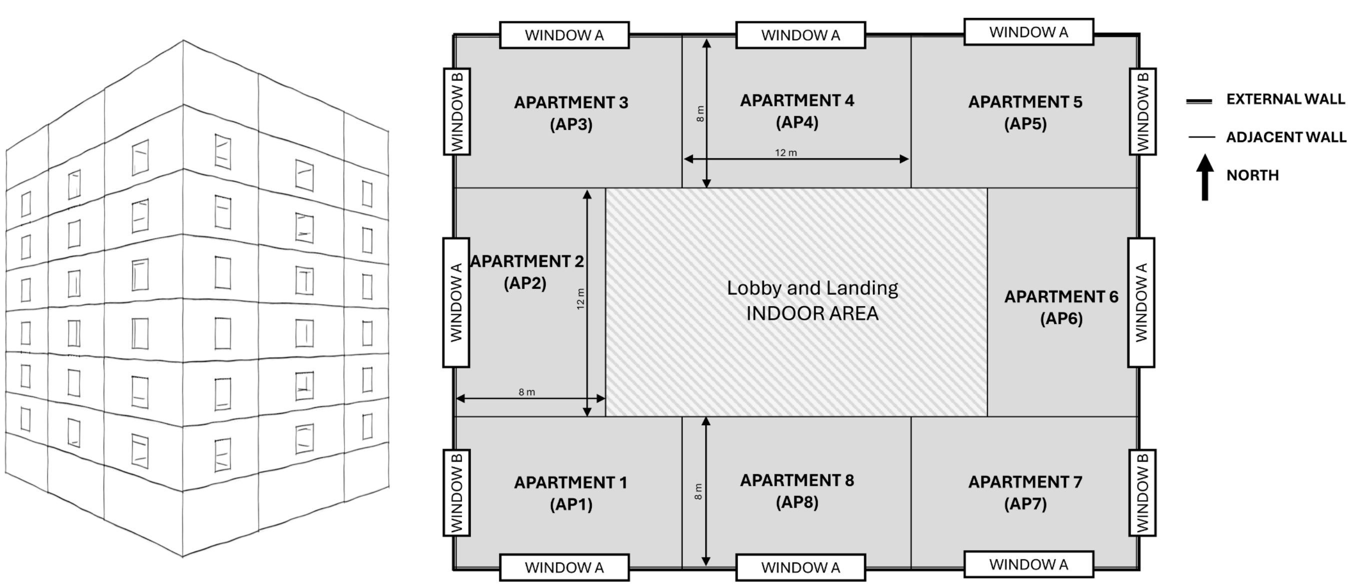


Figure 2. Eight apartments (thermal zones) and the location of corresponding windows distributed on the floor plan of a block of flats.

Table 2
Thermal properties of materials for walls and ceilings, including thickness and U-values.

Envelope element	Layer	Thickness [mm]	k [W/m·K]	ρ [kg/m^3]	c_p [J/kg·K]	U-value [W/m^2·K]
External wall	Cement mortar	20	1	1800	1350	0.1-0.6
	Concrete block	150	1.18	900	1000	
	EPS	47-337	0.035	15	1520	
	Gypsum	10	0.8	1600	1000	
Adjacent wall	Gypsum	15	0.8	1600	1000	
	Ceramic light block	150	0.45	1000	1000	2.7
	Gypsum	15	0.8	1600	1000	
Adjacent ceiling	Light concrete	100	1.35	1800	1000	0.22
	EPS	150	0.035	15	1520	
	Gypsum	15	0.8	1600	1000	

*The EPS thickness changes across the scenarios and so does the U-value with 0.6 W/m^{2}K corresponding to 47 mm thickness and 0.1 W/m^{2}K to 337 mm.

external wall, are detailed in Table 2. The adjacent walls, separating different thermal zones, are constructed using ceramic blocks and finished with gypsum layers on both sides. Likewise, adjacent ceilings and floors are composed of lightweight concrete, EPS insulation, and gypsum, with full material specifications also provided in Table 2 [36].

2.2.1.2. Windows. The windows were assigned a U-value of 1.06 W/m^{2}K, offering a balanced level of thermal insulation, making it suitable for both cool and warm climates considered in the study. This consistent U-value was selected to ensure the comparison across the different cities, allowing the analysis to remain focused on the influence of wall U-values. Additionally, a g-value of 0.586 was adopted, enabling moderate solar heat gains and enhancing year-round energy efficiency. This choice complies with ASHRAE 90.1 standards [37], ensuring adequate performance under both heating and cooling conditions.

2.2.1.3. Shading devices. Figure 3 illustrates the different scenarios used to evaluate the effect of solar gains on the building model. The baseline scenario (Figure 3a) represents a case without any solar control strategy. To optimize fixed shading (Figure 3b), a 70 cm overhang was selected for a 30% WWR, representing an average within the tested range of 10% to 60%. This length was selected as optimal after evaluating shading depths across five distinct climate zones. Results indicated that 70 cm length significantly reduced total energy consumption, while further increases yielded only marginal benefits. Moreover, its performance remained robust across all climates, eliminating the need for climate-specific adjustments. On the other hand, the movable shading system consisted in a horizontal overhang-shaped louver (Figure 3c and d) that introduces a dynamic approach by responding to real-time environmental conditions. The overhang-saped louver was set to activate (70 cm projection length) only when both the indoor temperature exceeded 24°C (aligned with thermal comfort recommendations in ASHRAE Standard 55), and incident solar radiation was above 200 W/m^2 (a commonly applied threshold in energy-efficient buildings to reduce solar heat gain and limit overheating [26,27,38]). This adaptive control enables the system to effectively minimize unwanted solar gains while preserving daylight and passive heating when beneficial. The movable and fixed shading device were assumed to be constructed from an opaque composite panel, consistent with typical architectural sun shading systems. It was modelled in TRNSYS using Type 34, and its effect was represented by a solar transmittance of 0.2, simulating an 80% reduction in incident radiation when active. Further optimization of shading material and behaviour is proposed for future work. Daylight is an important factor to take into account in living spaces because depending on the type of shading, it can have a greater or lesser effect on indoor comfort and even on electricity consumption for lighting. In this case, only a horizontal panel was introduced at the top of the window in Type 34, which, compared to previous work, has been found to guarantee minimum daylighting throughout the day and only reduces daylighting by 9% [39].

2.2.1.4. Climate characteristics. This study evaluated five cities Ankara, Beijing, New York, Rome, and Wellington, each representative of a distinct Köppen-Geiger climate classification. Ankara, located in a continental region of Turkey, is characterized by a cold semi-arid climate (BSk), marked by hot, dry summers and cold winters. Beijing, situated in northern China, experiences a hot-summer humid continental climate (Dwa), with pronounced seasonal temperature variations and a distinct monsoon influence. New York, on the east coast of the United States, falls under a humid subtropical climate (Cfa), with hot, humid summers and cold winters. Rome, in central Italy, exhibits a hot-summer Mediterranean climate (Csa), typified by dry, warm summers and mild, wet winters. Lastly, Wellington, the southernmost capital city in the world, features an oceanic climate (Cfb), with moderate temperatures and

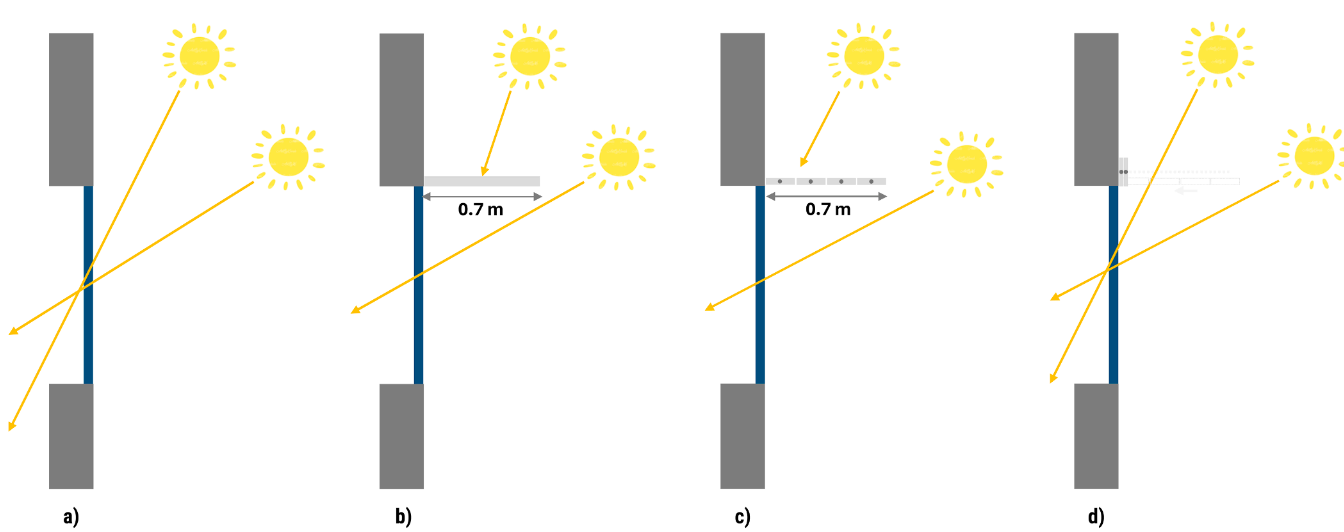


Figure 3. Shading protection defined on each model: a) no shading device, b) fixed horizontal shading device and movable shading device either c) closed or d) open.

relatively consistent rainfall throughout the year. Hourly temperature data for each city were obtained from Meteonorm, covering the period from 2000 to 2009, to ensure consistency across datasets. A summary of each city's latitude, climate type, and key climate characteristics is provided in Table 3 where ambient temperature and global radiation on each facade is described.

This selection spans multiple climate zones while maintaining a similar latitude of 40º in both the northern and southern hemispheres, thereby ensuring comparable levels of annual solar radiation and minimizing variability in solar input. This geographic consistency facilitates a more focused analysis of how regional climatic conditions influence energy demand for heating, cooling, and overall building performance.

2.2.1.5. Gains. Once the building's thermal zones were defined, internal heat gains were accounted for occupants, lighting, computers, and other typical residential sources. A four-person household was assumed, following established modelling practices that use this configuration to represent typical occupancy patterns in residential energy simulations [40]. It was assumed that the building had minimum occupancy from 08:00 to 17:00 on weekdays, with full occupancy applied outside of these hours and throughout the entire weekend. During sleeping hours, 70% of occupancy-related heat gains were applied.

According to ASHRAE (2013) [41], each seated occupant was assumed to generate 130 W of internal heat gain. The indoor air renewal rate was set at 1.1 air changes per hour.

The lighting load was set at 3.6 W/m^2 for the radiative component and 0.8 W/m^2 for the convective part, activated only when horizontal solar radiation fell below 120 W/m^2, assuming efficient lighting. Lighting was switched off during sleeping hours (23:00 to 07:00). Electrical equipment was divided into two categories based on operational patterns. Approximately 30% of the equipment load (e.g., refrigerators and standby devices) was assumed to operate continuously over 24 hours. The remaining 70%, representing occupant-driven usage (e.g., TVs, computers, kitchen appliances), was applied only during periods when occupants were both present and awake. No occupant-driven equipment gains were applied during sleeping hours. During active occupancy, the total equipment load was set at 6.4 W/m^2 for the convective component and 1.6 W/m^2 for the radiative component. The heating and cooling systems operated continuously, maintaining indoor temperatures at setpoints of 20°C for heating and 26°C for cooling.

Table 4

Table 4
Key Parameters for this simulation in TRNSYS18.

Set point temperatures	Heating	20ºC
	Cooling	26ºC
Ventilation		1.1 ACH
GainsEquipmentLighting	People	130 W/Person
		6.4+1.6 W/m^2
		3.6+0.8 W/m^2
Occupancy schedule Max. Occupancy	Min. Occupancy	from 8h to 17h
		Other time
Simulation period		Jan 1st to Dec 31st (8760 hours)

2.2.2. Scenarios evaluated

This study investigates the impact of varying WWR and U-values for external walls, in conjunction with different shading strategies, on annual heating, cooling, and overall energy demand across the eight distinct apartments.

Window dimensions for both openings A and B were adjusted according to the selected WWR values, as presented in Table 5. To maintain proportional window shapes, the height-to-width ratio was also modified as WWR increased.

By simulating various scenarios across multiple thermal zones, this study provides a comprehensive evaluation of how these factors influence the building's overall energy performance under different climatic conditions.

In this study, 4320 simulations of the case building were performed, as described in Table 6.

2.3. Statistical

The Kruskal-Wallis test was used to analyse the variation of energy demand considering the different characteristics in different cities (shading, U-value, WWR) since the assumptions required by the ANOVA test were not achieved [42]. When there are more than two groups to be compared, it is advisable to turn to other methods. This is called a one-way design, and there are both parametric and nonparametric approaches available to address the question. A more elegant approach is to apply a simultaneous multiple comparisons procedure that makes all pairwise comparisons while controlling the type I error rate (the probability of finding a difference that is not there). The Wilcoxon signed rank test provides a nonparametric alternative to the dependent sample t-test. It is appropriate in situations where the groups are paired, and the assumption of normality is unwarranted. All statistical analyses were performed using RStudio version 2024.12.0+467 (RStudio 2024.12.0+467 "Kousa Dogwood" Release), ggplot2 [43], matrixTests [44], psych [45] and Rmisc [46] packages. The adopted level of significance was α= 5%.

3. Results

A comparative analysis of the five selected cities (Ankara, Beijing, New York, Rome, and Wellington) was carried out. Principal component analysis (PCA) is a widely used statistical technique that enables the projection of observations described by multiple variables onto a reduced set of principal components. As an unsupervised method, PCA identifies the directions of maximum variance in the data without relying on any predefined structure. Among the various approaches to PCA, singular value decomposition (SVD) is one of the most employed. Climate data can therefore be summarised using two axes representing the greatest variation in the dataset. The 'prcomp' function, based on the SVD algorithm and implemented using the base SVD function, was employed.

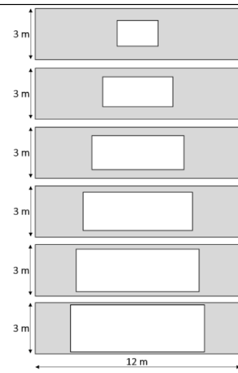
Figure 4 represents the value of the rotated data (after centering and scaling) multiplied by the rotation matrix. The climatic characteristics of the cities are thus represented in a two-dimensional space, where each city occupies a distinct point in this plane. Cities located close together

Table 3
Climate characteristics across the five selected cities along with Heating Degree Days (HDD) and Cooling Degree Days (CDD) (both obtained at 18ºC).

Location	Latitude	Climate type	Average Solar radiation [W/m^2]				Ambient temperature [ºC]			HDD	CDD
			North	East	West	South	Average	Max	Min		
Ankara	39.93° N	BSk	68.7	136.9	138.9	165.7	11.8	31.4	-5	2890	594
Beijing	39.91° N	Dwa	71.1	120.7	122.9	169.4	12.9	31.1	-8.2	3119	854
New York	40.71° N	Cfa	67.8	139.5	137.8	177.4	12.7	28.5	-3.3	2784	632
Rome	41.90° N	Csa	70.1	143.6	166.4	140.6	15.9	30.2	3.2	1572	674
Wellington	41.29° S	Cfb	154.8	117	120	56.3	13.7	20.5	6.5	1784	143

Table 5
Windows dimensions corresponding to different WWR considerations.

	Window A			Window B		
WWR (%)	Height [m]	Width [m]	Shape	Height [m]	Width [m]	Shape
10	1.5	2.4		1.5	1.6	
20	1.75	4.11		1.75	2.74	
30	2	5.4		2	3.6	
40	2.25	6.4		2.25	4.27	
50	2.5	7.2		2.5	4.8	
60	2.75	7.85		2.75	5.24	



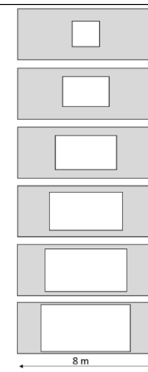


Table 6
Total cases for TRNSYS simulations performed.

Input variables	Cases evaluated	Total
Location	Ankara; Beijing; New York; Rome; Wellington	5
WWR of each facade (%)	10; 20; 30; 40; 50; 60	6
U-value (W/m^{2}K)	0.1; 0.2; 0.3; 0.4; 0.5; 0.6	6
Shading strategy	No shading; fixed shading; movable shading	3
Thermal zones	8 apartments	8
Total cases	5×6×6×3×8	4320

on the plot exhibit similar climatic patterns, as reflected by similarities in the variables from the original dataset. Notably, Ankara, Beijing, and New York form a distinct cluster, suggesting a higher degree of similarity among them. In contrast, Rome and Wellington display significantly divergent patterns, with Wellington standing out as the most distinct of the five cities. Therefore, three representative cities: Beijing, Rome, and Wellington, were selected for further analysis of the impact of U-value (section 3.2) and WWR (section 3.3) on the total mean energy demand.

Considering the 6 WWR configurations, the 6 envelope U-values and the 3 different shading strategies, a total of 108 results have been obtained for each city and apartment. The graphs in Figure 5 illustrates the

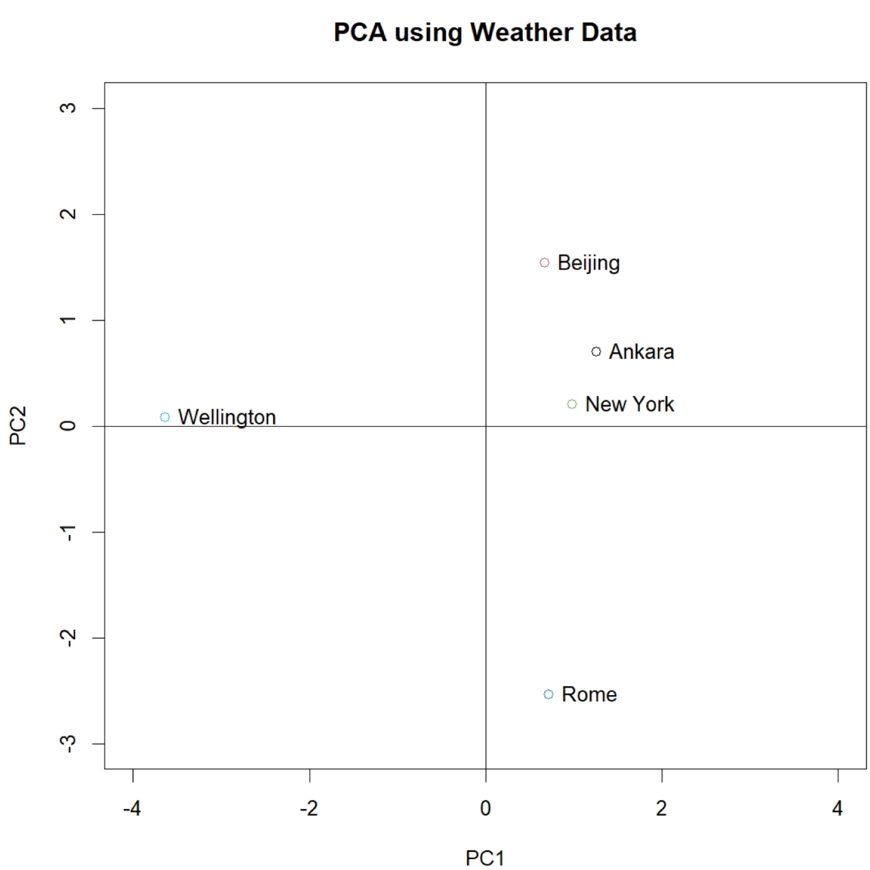


Figure 4. Principal component analysis (PCA) scores derived from weather data for the selected cities.

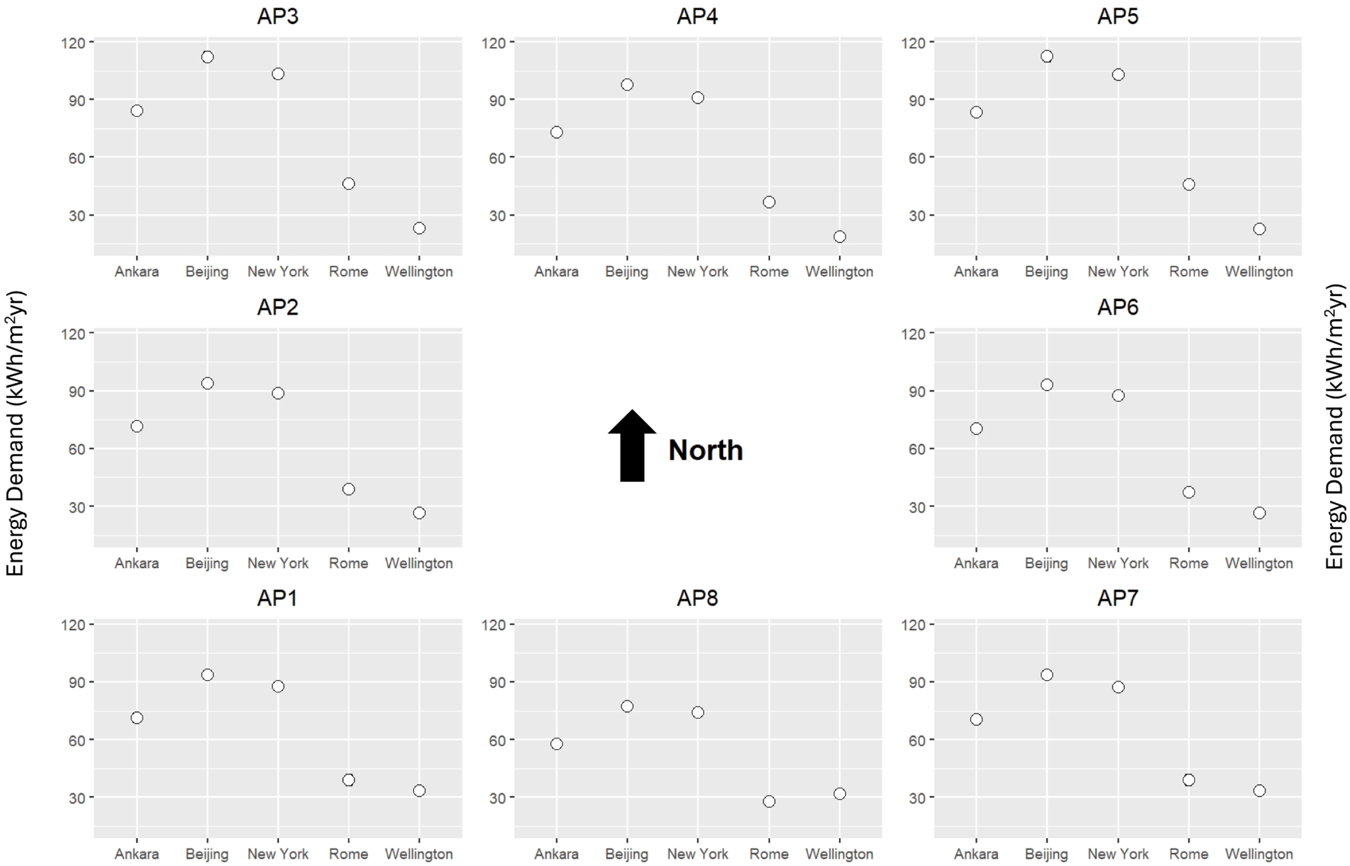


Figure 5. Total mean energy demand per unit area (kWh/m^2·year) for the eight apartments across the five cities on 108 simulation results (derived from all WWRs, U-values and shading strategies evaluated), with 95 percent confidence interval for the mean.

mean total energy demand of the 108 results for the eight apartments across the five selected cities, with 95 % confidence intervals for the mean. Ankara, Beijing and New York present similar patterns, while Rome and Wellington exhibit distinct and contrasting behaviours. In all cities, south-facing apartment (AP 8) consistently exhibits the lowest energy demand, with Rome and Wellington showing the lowest values (around 30 kWh/m^2·year). In contrast, Beijing and New York display the highest total mean energy demands across all apartments, ranging from 90 to 115 kWh/m^2·year, except for AP8, which shows a reduced value of approximately 75 kWh/m^2·year. In Ankara, total mean energy demand ranges from 75 to 85 kWh/m^2·year for most apartments, with AP8 again showing the lowest value, at 58 kWh/m^2·year.

3.1. Shading scenario

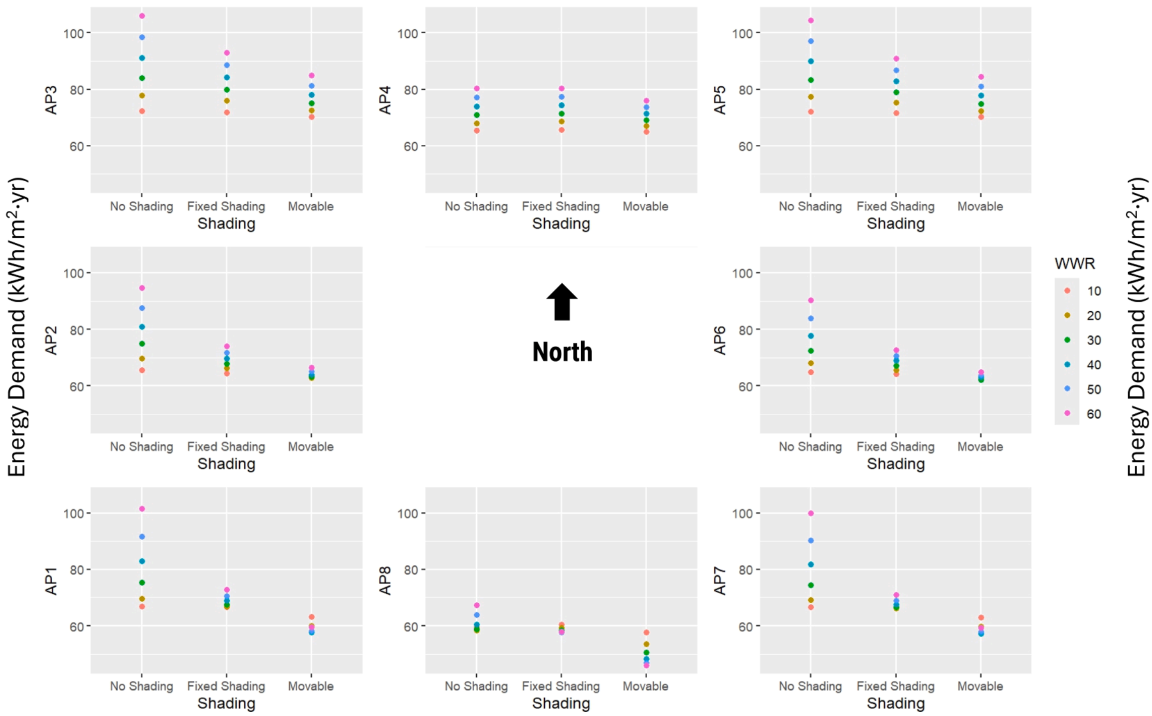
Results of the total mean energy demand (kWh/m^2·year) per apartment, with 95 % confidence interval, categorized by shading device strategy indicate that the absence of shading strategies generally leads to higher energy demand across all cities except for Wellington that exhibit distinct patterns (Figure S1.1, supplementary material). Although fixed shading provides some reduction, the use of movable shading devices generally yields the lowest total energy demand. Based on these patterns, the influence of shading strategies combined with WWR on total energy demand was conducted in the multi-orientation building configuration across the five cities, as illustrated in Figure 6. In this analysis, a U-value of 0.3 W/m^2·K was selected as the middle value.

Across all cities, energy demand generally increases with WWRs, except in Wellington. This trend is particularly pronounced in cities with significant heating or cooling requirements, such as Beijing and New York, where energy demand reaches approximately 140 kWh/m^2·yr and 125 kWh/m^2·yr, respectively, in north-facing apartments (AP3) without shading. In contrast, Wellington's mild climate results in much lower overall energy demands. Variations in WWR and shading strategies in this city have a smaller absolute impact, as baseline energy demand is low (ranging from 10 kWh/m^2·yr with movable shading in north-facing AP4 to over 38 kWh/m^2·yr without shading in south-facing AP1, both at 60% WWR).

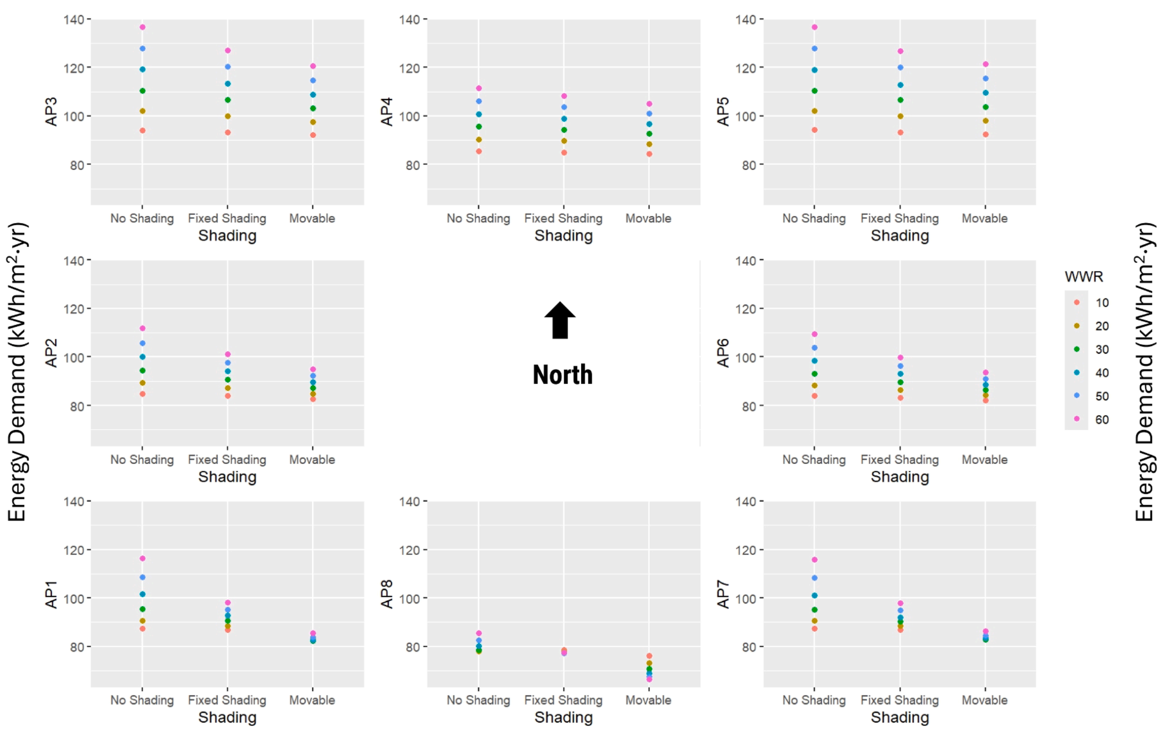
In Ankara, Beijing, and New York, the range of energy demand variation due to WWR in north-facing apartments is similar across shading strategies, though the widest variations consistently occur without shading devices. Conversely, south-facing apartments present lower energy demand when equipped with fixed or movable shading, with clear advantages over the no-shading situation.

Movable shading consistently yields the greatest reductions across most WWR levels (except for north-facing apartments at 10% WWR in all cities except Wellington). This shading strategy results in the lowest energy demand among the three strategies, especially in climates where solar control is critical. AP8 (south-facing) achieves the lowest energy demands in all cities (except Wellington) when movable shading is used. The minimum values are observed in Rome and Ankara, ranging from 20 to 25 kWh/m^2·yr and from 45 to 57 kWh/m^2·yr, respectively, across all WWR levels. Among apartments' orientations, the south-facing apartment (AP8) always shows greater energy demand reductions in all shading strategies, especially with movable and all cities except for Wellington. Specifically for 60% WWR and fixed and movable shading, Rome achieves the greatest energy reduction with 48% and 55% respectively between AP8 and AP3 and or AP5.

Kruskal-Wallis and Wilcox tests were conducted to assess differences in total energy demand across the eight apartments in Ankara, Beijing, New York, Rome, and Wellington when shading solutions were concerned (Table 7). The Kruskal-Wallis tests revealed statistically significant differences in total energy demand among shading types in most

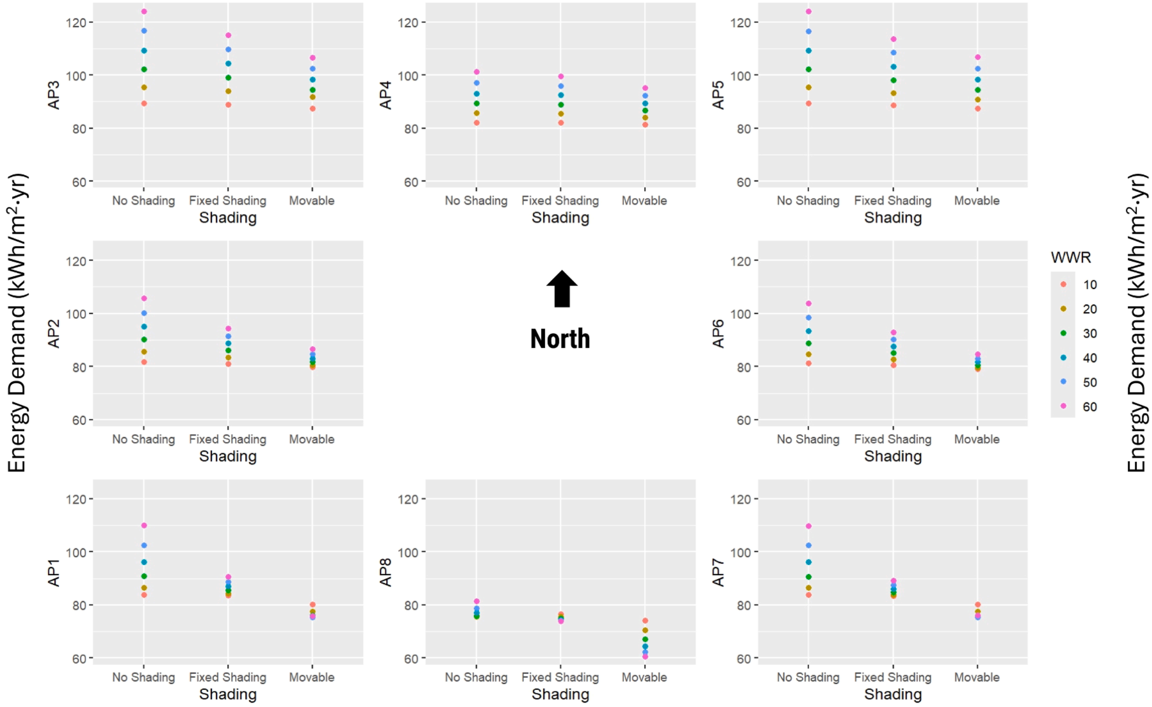


a) Ankara

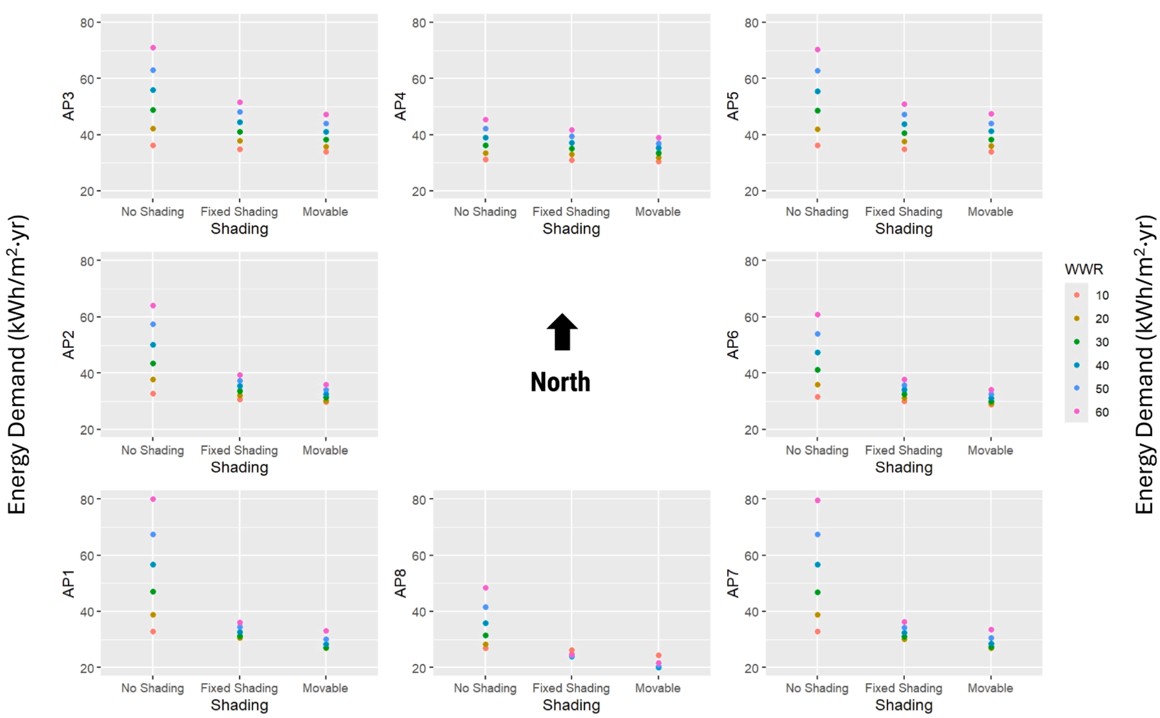


b) Beijing

Figure 6. Total mean energy demand (kWh/m^2·year) per apartment, with 95 % confidence interval, categorized by shading devices with WWR across the five cities: a) Ankara, b) Beijing, c) New York, d) Rome and e) Wellington using a U-value of 0.3 W/m^2·K.



c) New York



d) Rome

Figure 6. (*continued*).

apartments, particularly in Beijing and Ankara, with a few specific exceptions. Moreover, movable shading was found to be effective in reducing energy demand in most apartments.

The Wilcoxon test was employed to compare the total energy demand between the absence of shading and the use of movable shading devices across all cities and apartment types. The results revealed

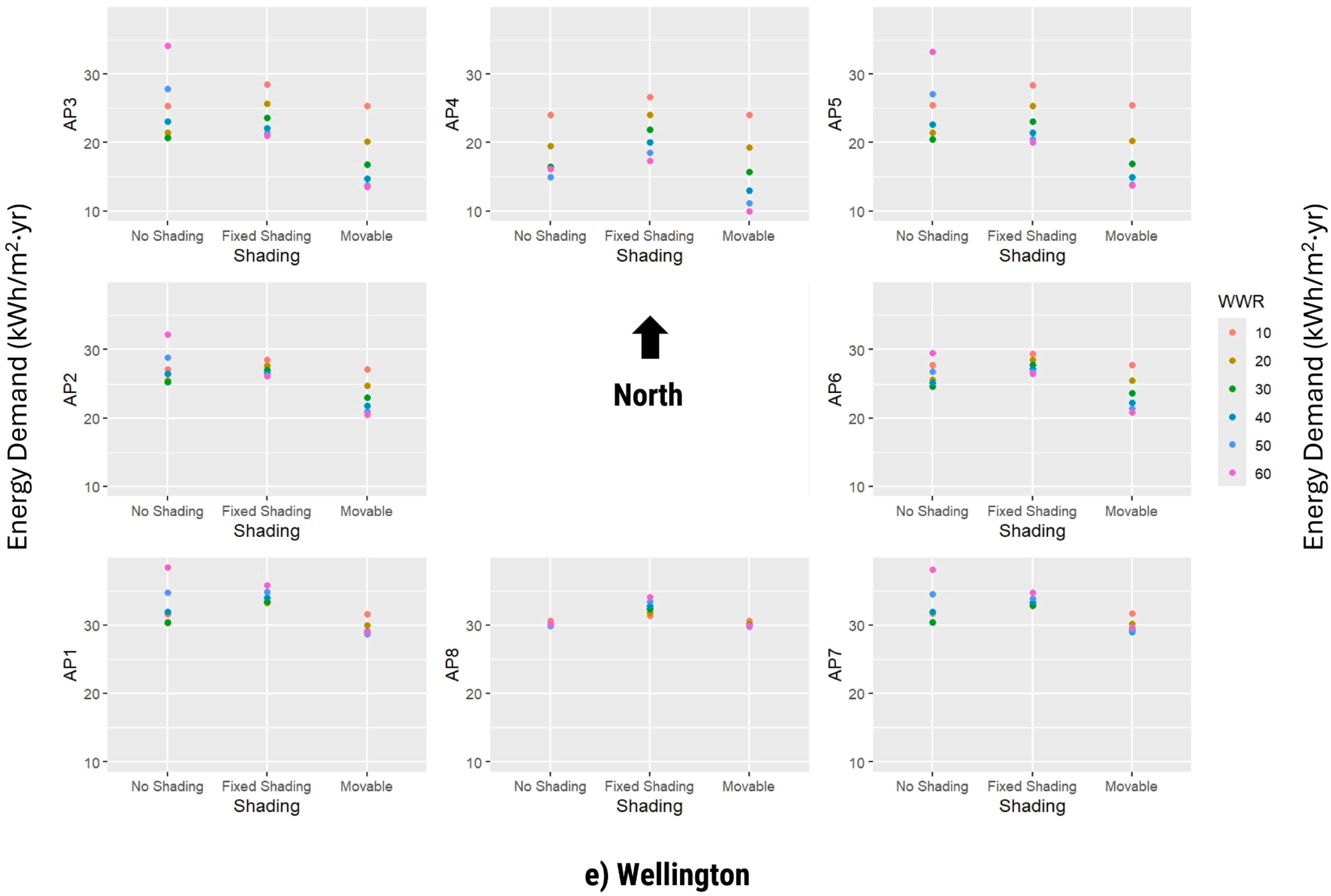


Figure 6. (*continued*).

Table 7
Kruskal-Wallis and Wilcox test results for total energy demand across the eight apartments in Ankara, Beijing, New York, Rome, and Wellington highlighting the statistical significance of shading strategies. Statistically significant results are indicated at $p < 0.001$.

	Ankara	Beijing	New York	Rome	Wellington
AP1	a,b,c	a,b,c	a,b,c	a,b,c	c
AP2	a,b,c	b,c	b,c	a,b	b,c
AP3	b	b	b	a,b	b,c
AP4	-	-	-	-	a,c
AP5	b	b	b	a,b	b,c
AP6	a,b,c	b,c	b,c	a,b,c	b,c
AP7	a,b,c	a,b,c	a,b,c	a,b,c	c
AP8	b,c	b,c	b,c	a,b,c	a,c

Comparison between groups: a: No Shading by Group Fixed Shading, b: No Shading by Group Movable, c: Fixed Shading by Group Movable.

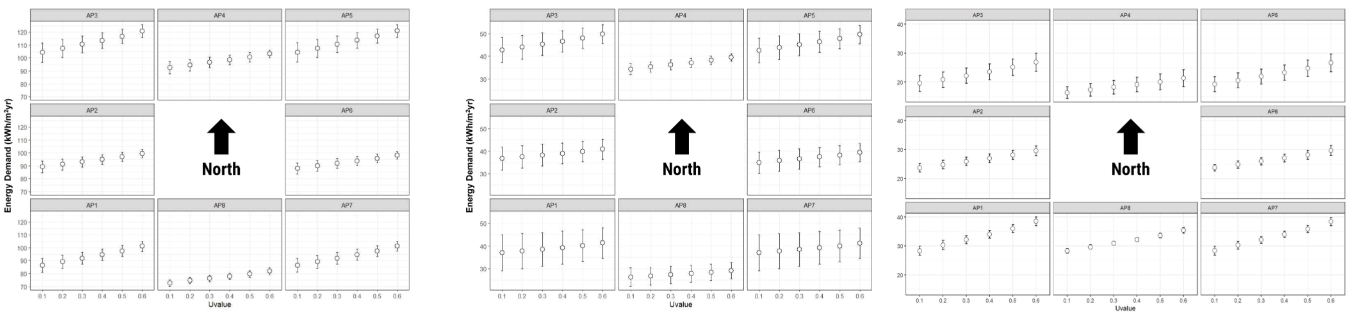
statistically significant differences in all apartments and cities. Specifically, apartments AP1 and AP7 exhibited significant differences across all shading comparisons in most cities ($p < 0.001$) with the exception of Wellington, where these differences were less pronounced. Conversely, AP4 showed a significant difference only in Wellington. Significant improvements due to movable shading were particularly evident in Rome (AP1, AP6, AP7 and AP8), as well as in Beijing and New York. Moreover, the Wilcoxon revealed significant differences between fixed and movable shading configurations across most cities in AP1, AP2, AP6, AP7, and AP8. Wellington showed statistically significant differences among all shading types for all apartments ($p < 0.001$).

3.2. U-value

In this study, the effect of the U-value on total energy demand was analysed across the eight apartments in the five cities (Figure S2.1, supplementary material). Figure 7 shows the mean total energy demand values, along with their 95% confidence intervals for each apartment, employing the U-value as the categorical variable in the three representative cities: Beijing, Rome and Wellington. The results indicated a strong correlation between energy demand and the U-value in most cities, except for the city of Rome, where no significant correlation was observed ($p > 0.001$). As in previous analysis, and expect for Wellington, the lowest energy demand is observed in south-facing apartments with the highest insulation levels, while the highest energy demand occurs in north-facing apartments with the poorest insulation.

Kruskal-Wallis and Wilcox tests were conducted to assess differences in total energy demand across the eight apartments in Ankara, Beijing, New York, and Wellington under varying U-value from 0.1 to 0.6 W/m^2·K (Table 9). The Kruskal-Wallis tests revealed significant differences in energy demand based on the U-value in several apartments in Ankara, Beijing, New York, and Wellington, although some exceptions were observed. Additionally, improvements in the U-value were found to effectively reduce energy demand in most apartments, emphasizing the crucial role of building envelope performance in enhancing energy efficiency and managing energy demand in urban settings.

The Wilcoxon test revealed statistically significant differences in most apartments in Ankara, New York, and Wellington. In particular, apartments AP2 and AP6 exhibited highly significant results ($p < 0.001$), while no significant differences were observed in Rome. In New York, the Wilcoxon test indicated that U-values significantly added to total energy demand in all apartments ($p < 0.001$). Specifically,



a) Beijing b) Rome c) Wellington

Figure 7. Total mean energy demand (kWh/m^2·year) per apartment, with 95 percent confidence intervals, categorized by U -value (W/m^2·K) in a) Beijing, b) Rome, and c) Wellington.

Table 9
Kruskal-Wallis and Wilcox test results on total energy demand across the eight apartments in Ankara, Beijing, New York, Rome, and Wellington, highlighting the statistical significance of WWR. Statistically significant results are indicated at $p < 0.001$.

	Ankara	Beijing	New York	Rome	Wellington
AP1	-	-	-	e	-
AP2	e	b,c,d,e,f,g,h,i,j	c,d,e,g,h,j	c,d,e,h	-
AP3	c,d,e,g,h,j	b,c,d,e,f,g,h,i,j,k	c,d,e,f,g,h,i,j,k	b,c,d,e,f,g,h,j	b,c
AP4	c,d,e,g,h,i,j,k	b,c,d,e,f,g,h,i,j,k	b,c,d,e,f,g,h,i,j,k	b,c,d,e,f,g,h,i,j,k	a,b,c,d,e,f.g,h
AP5	c,d,e,g,h,j	b,c,d,e,f,g,h,i,j,k	c,d,e,f,g,h,i,j,k	b,c,d,e,f,g,h,j	b,c,d
AP6	e	c,d,e,f,g,h, j	c,d,e,g,h	d,e,h	c
AP7	-	-	-	e	-
AP8	-	-	-	-	-

Comparison between groups: a: Group 10 by Group 20, b: 10, by Group, 30, c: 10, by Group, 40, d: 10, by Group, 50, e: 10, by Group, 60, f: 20, by Group, 40, g: 20, by Group, 50, h: 20, by Group, 60, i: 30, by Group, 50, j: 30, by Group, 60, k: 40, by Group, 60.

comparisons between U-values of 0.1 and 0.6 W/m^2·K consistently yielded significant differences, whereas no significance was found in comparisons between 0.2 and 0.6 W/m^2·K for apartments AP2, AP3, and AP6. In Wellington, the Wilcoxon test yielded surprising results. It revealed that U-value variations were statistically significant across all apartments ($p < 0.001$), except for apartment AP4, where a comparison yielded a value of $8{\cdot}10^{-2}$ W/m^2·K. This finding further supports the hypothesis that the U-value remains consistent across all apartments, except for AP4. In the remaining apartments, comparisons between U-values from 0.1 to 0.6 W/m^2·K, did not allow the rejection of the null hypothesis, suggesting stable energy demand across these apartments. Similarly, in apartments AP1, AP2, AP6, AP7 and AP8 comparisons between 0.1 and 0.5 as well as 0.2 and 0.6 W/m^2·K, were not statistically significant. In apartments AP1, AP6, AP7, and AP8, the hypothesis could not be rejected when comparing 0.1 with 0.4, and 0.3 with 0.6 W/m^2·K. Furthermore, in apartments AP1, AP7, and AP8, it was not feasible to reject the comparisons between 0.1 and 0.3, 0.2 and 0.4, and 0.3 and 0.5 W/m^2·K. These results suggest that energy demand remains consistent in these apartments, indicating that apartments AP1, AP7, and AP8, are more sensitive to changes in U-values compared to the other apartments (10 out of 15 possible). In contrast, apartment AP4 exhibits a lack of responsiveness to U-value variations. Table 8.

3.3. Window-to-Wall Ratio (WWR)

This study analysed the impact of the window-to-wall ratio (WWR) on total energy demand in the eight apartments across the cities of Ankara, Beijing, New York, Rome, and Wellington (Figure S3.1, supplementary material). Figure 8 shows the mean total energy demand values, along with their 95% confidence intervals, for each apartment, employing the WWR as the categorical variable for the three representative cities. The results indicated a strong correlation between energy demand and WWR in most cities, except for the city of Wellington, where no significant correlation was observed ($p > 0.001$). In this city, the effect of WWR is negligible in south- facing apartments, and in the north-facing ones, although lower WWR result in higher energy demands, the correlation cannot be stated as significant.

Table 8
Kruskal-Wallis and Wilcox test results for total energy demand across the eight apartments in Ankara, Beijing, New York, Rome, and Wellington, highlighting the statistical significance of U-values. Statistically significant results are indicated at $p < 0.001$.

	Ankara	Beijing	New York	Rome	Wellington
AP1	-	c,d,g	d,g	-	a,b,c,d,e,f,g,h,i
AP2	d	d	d	-	c,d,g
AP3	d,g	-	d	-	d
AP4	c,d,g, i	-	d,g	-	-
AP5	d,g	-	d,g	-	d
AP6	d	d,g	d	-	b,c,d,f,g, i
AP7	d	c,d,g,i	d,g	-	a,b,c,d,e,f,g,h,i,j
AP8	d	d,g	d,g	-	a,b,c,d,e,f,g,h,i,j

Comparison between groups: a: 0.1, by Group, 0.3, b: 0.1, by Group, 0.4, c: 0.1, by Group, 0.5, d: 0.1, by Group, 0.6, e: 0.2, by Group, 0.4, f: 0.2, by Group, 0.5, g: 0.2, by Group, 0.6, h: 0.3, by Group, 0.5, i: 0.3, by Group, 0.6, j: 0.4, by Group, 0.6.

Kruskal-Wallis and Wilcox tests were conducted to assess differences in total energy demand across the eight apartments in Ankara, Beijing, New York, Rome, and Wellington under varying WWR (Table 10). The findings indicated a significant impact of WWR on energy demand in several apartments, with some exceptions. In Beijing, WWR was found to be significant in apartments AP2, AP3, AP4, and AP5 ($p<0.001$). In Ankara, New York, and Wellington, the Wilcoxon test indicated significant differences in most apartments when comparing WWR values of 10% and 60%. However, apartments AP3 and AP4 in Wellington also showed significant differences. Apartment AP5 was identified as the most sensitive to WWR variations across all cities. Overall, a larger number of significant differences were identified in apartments AP2, AP3, AP4, and AP5 with differences observed in 9 out of 15 comparisons conducted in Beijing, Rome, and New York. In Rome, WWR was found to be significant in most apartments, except for apartments AP1, AP7, and AP8. Conversely, in Wellington, WWR did not attain statistical significance in most apartments, except for apartment AP4. Notably, significant differences were observed in apartment AP4 for the 40% - 60% WWR comparison in Beijing, Rome, and New York.

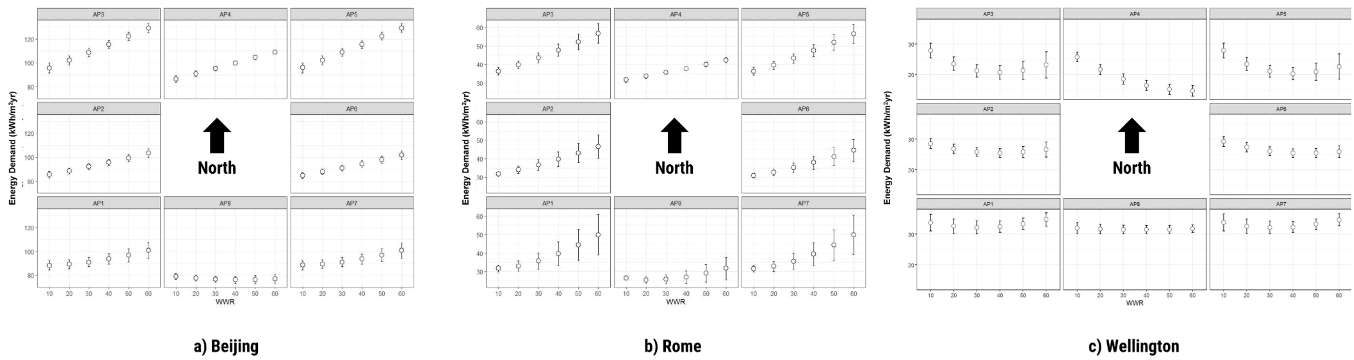


Figure 8. Total mean energy demand (kWh/m^2·year) per apartment, with 95 percent confidence intervals, categorized by WWR in a) Beijing, b) Rome, and c) Wellington.

3.4. *Energy demand considering a movable shading device*

Given that shading devices exhibited the greatest number of statistically significant discrepancies and considering that the implementation of movable shading consistently reduced total energy demand across all apartments, a focused analysis of this specific scenario was deemed necessary. In this context, the WWR was considered a key variable, as U-values showed lower sensitivity in certain apartments under the tested hypothesis. This analysis evaluated Beijing and Wellington in terms of total, heating and cooling energy demand, considering various U-values and WWR (additional analysis can be found in Figures S4.1, S4.2 and S4.3 (supplementary material).

Figure 9 illustrates the total energy demand in Beijing across the eight apartments, considering the use of movable shading devices, with WWR as the primary variable and U-values ranging from 0.1 to 0.6 W/m^2·K. It is noticeable that, in general, total energy demand decreases across all apartments as U-values improve although this effect varies depending on the apartment. North-facing apartments (AP3 and AP5) exhibit a strong influence of WWR. In contrast, in south-facing apartments (AP1 and AP7), a coupling effect between WWR and U-values is observed, where the influence of WWR varies depending on the specific U-value applied. An optimal WWR value was identified in apartment AP7, with a similar pattern noted in apartment AP1. However, the optimal WWR shifts according to the U-value: 10%, 23%, 30%, 38%, and 51% for U-values of 0.1, 0.2, 0.3, 0.4 and 0.5 W/m^2·K, respectively.

To examine the effect of insulation (U-value) and solar gains (WWR) on the total energy demand, an analysis of both heating and cooling demand was conducted, considering various U-values and WWR. Figure 10 presents the average cooling and heating demand per apartment in Beijing, considering movable shading, a U-value of 0.1 W/m^2·K, and varying WWR across apartments. It should be noted that the U-value for windows is 1.06 W/m^{2}K, so as the window area increases, there will

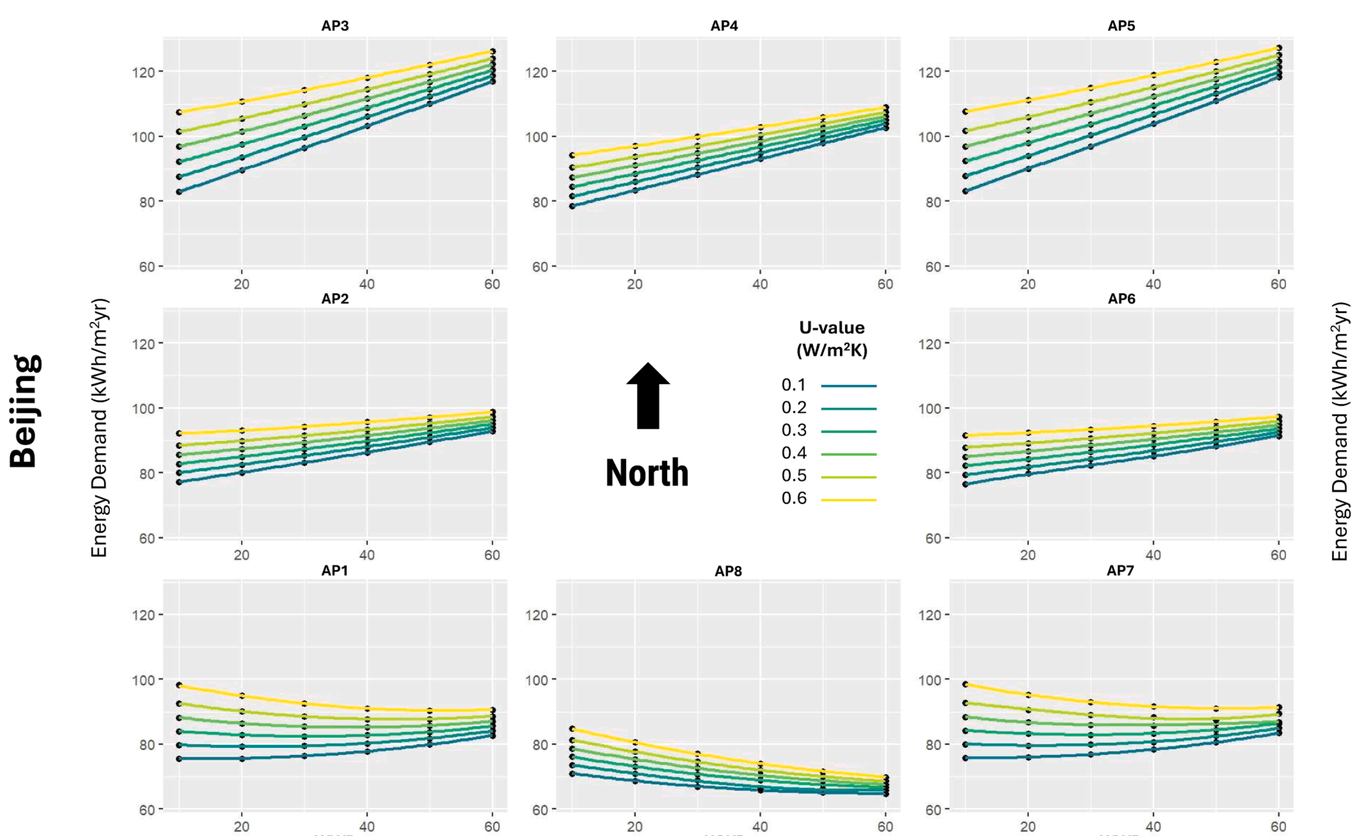


Figure 9. Total energy demand (kWh/m^2·year) per apartment in Beijing, considering a movable shading device and using WWR as a key variable.

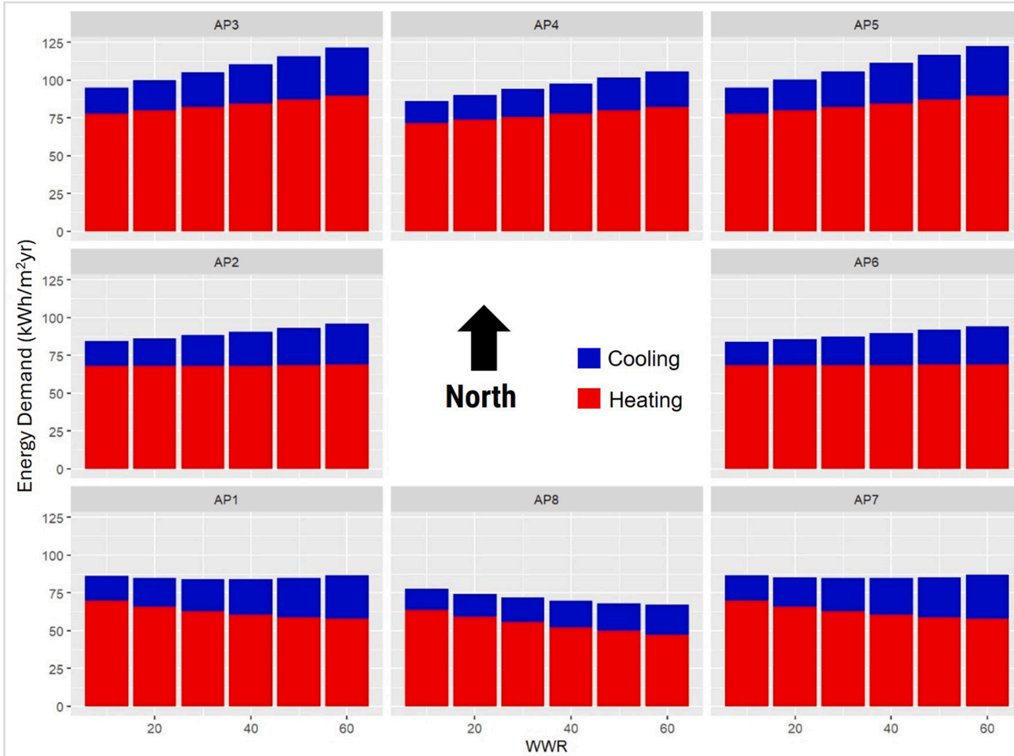


Figure 10. Average cooling and heating energy demand (kWh/m^2·year) per apartment in Beijing, considering movable shading, a U-value of 0.1 W/m^2·K, and varying WWR across apartments.

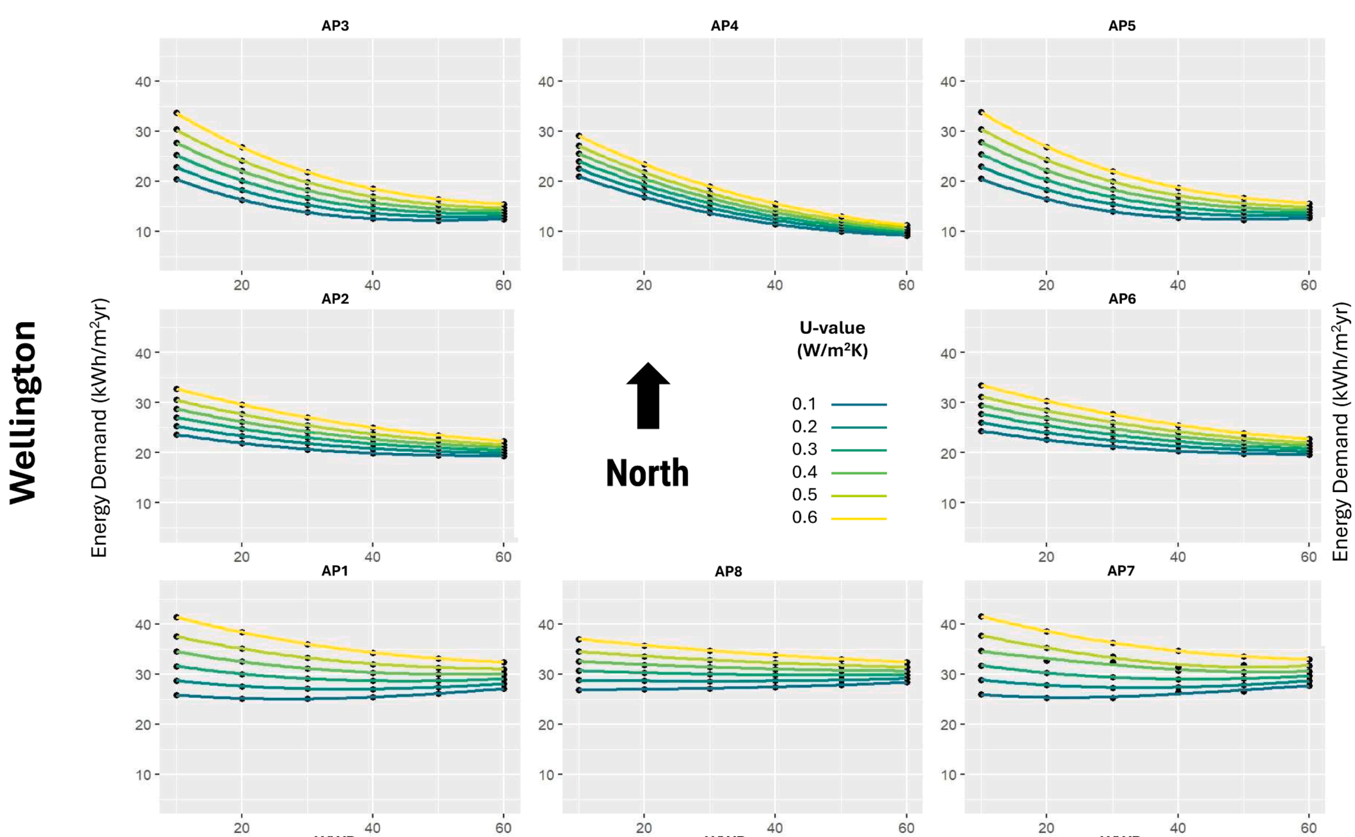


Figure 11. Total energy demand (kWh/m^2·year) per apartment in Wellington, considering the use of a movable shading device using WWR as a variable.

be a greater effect of solar gains and heat flow. For this reason, the results showed that cooling energy demand increased with higher WWR, a trend that was consistent across all apartments. Conversely, the heating demand exhibited apartment-specific behaviour. Apartments AP2 and AP6 displayed relatively constant heating demand, likely due to increased exposure to direct winter sunlight and the associated benefits of passive solar heating. South-facing apartments (AP1, AP7, and AP8) showed a decrease in heating demand as WWR increased. AP7 and AP8 (east/southeast exposures) show moderate energy demands and were less affected by increases in WWR, likely due to their shorter periods of solar exposure throughout the day.

Figure 11 presents the total energy demand in relation to the use of a movable shading device in Wellington, with the WWR as a variable across specific apartments. A general reduction in total energy demand is observed across all apartments as the U-value decreases although it the effect of WWR varies by apartment. North-facing apartments (AP3, AP4, and AP5), show strong sensitivity to changes in WWR. In south-facing apartments, (AP1, AP7, and AP8), a coupling effect between WWR and U-value is observed, with the influence of WWR shifting depending on the specific U-value. Total energy demand decreases for U-values above 0.2 W/m^2·K and higher WWR values in south-facing apartments (AP1, AP7, and AP8). However, for U-values of 0.2 W/m^2·K, an optimal WWR of 30% is identified in AP1 and AP7.

Figure 12 presents the average cooling and heating demand per apartment in Wellington, considering movable shading, a U-value of 0.1 W/m^2·K, and varying WWR across apartments. The analysis revealed that although cooling demand approaches zero, a slight increase is observed in most apartments when the WWR exceeds 40%. In contrast, heating demand exhibited apartment-specific behaviour. South-facing apartments (AP1, AP7, and AP8), maintained relatively constant heating demand across different WWR values, whereas the remaining apartments showed a decreasing trend in heating demand as the WWR increased.

As established in the analysis of shading strategies, insulation levels, and WWRs, an optimal configuration was assessed for each apartment and city. Thus, Figure 13 illustrates the optimal WWR for each apartment across the five cities, considering movable shading strategy and a U-value of 0.1 W/m^{2}K for energy and lighting demand pattern. As can be observed, a clear pattern emerges for Ankara, Beijing, New York and Rome, which generally share similar optimal WWRs configurations, in contrast to Wellington, which displays a markedly different behaviour. The impact of WWR on lighting demand becomes progressively negligible once WWR reaches 30%. Concurrently, an augmentation in the WWR engenders an escalation in cooling demand, thereby counterbalancing the initial lighting energy savings [17]. It is evident that the maximum permissible limit for the representation of optimum has been restricted to 30%, with the objective of ensuring the optimal level of daylight comfort. For the north-facing apartments (AP2 to AP6), the optimal WWR is consistently 10% in all cities except Wellington, where significantly higher values are observed, ranging from 49% in AP3 and AP5, to 60 % in AP4. The full south-facing apartment (AP8) achieves optimal performance with a 60% WWR in Ankara, Beijing and New York, while lower values are observed in Rome (35% WWR) and Wellington (10% WWR). On the other hand, apartments 1 (AP1) and 7 (AP7), which are west and east-facing respectively, exhibit the greatest variation in optimal WWR. In these orientations, Beijing shows the lowest optimal value (10% WWR), followed by Rome (18% WWR), Wellington (26% WWR), Ankara (29% WWR) and New York (30% WWR).

4. Discussion

The findings of this study highlight the significant influence of WWR and shading strategies on annual energy demand across different climates, insulation levels (U-value), and orientations. Typically, larger WWR values led to higher energy demands, with the effect being most pronounced in cities with extreme seasonal temperatures, such as Beijing and New York, where the lack of adequate shading exacerbated this effect, as previously noted by Li et al. [25].

The analysis also confirmed that lower U-values consistently resulted

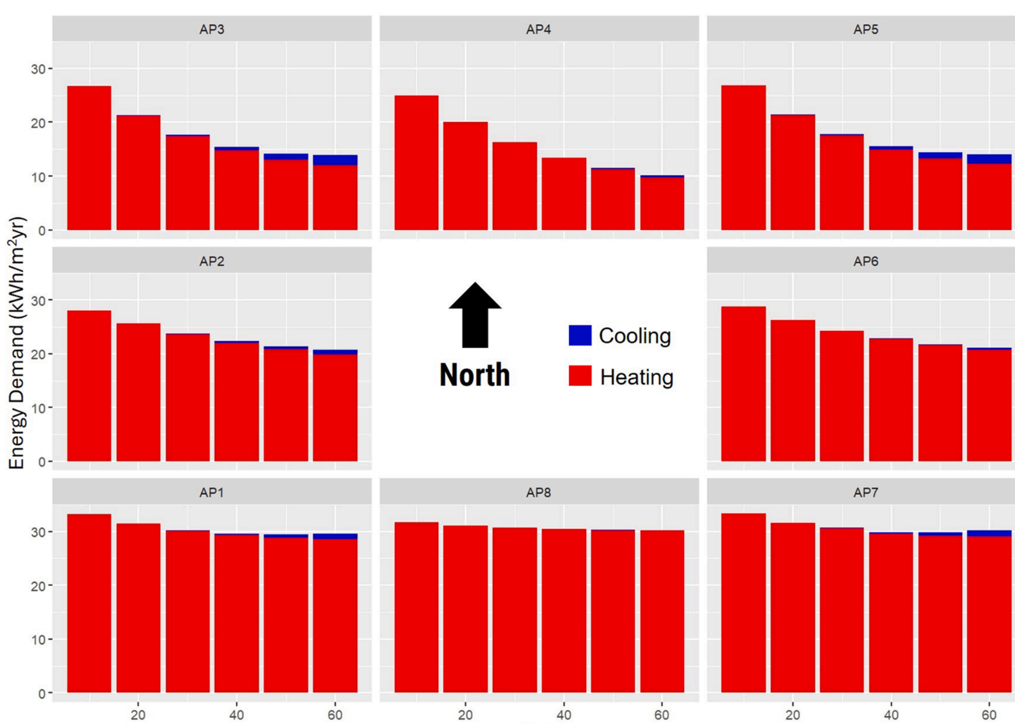


Figure 12. Average cooling and heating energy demand (kWh/m^2·year) per apartment in Wellington, considering movable shading, a U-value of 0.1 W/m^2·K, and varying WWR across apartments.

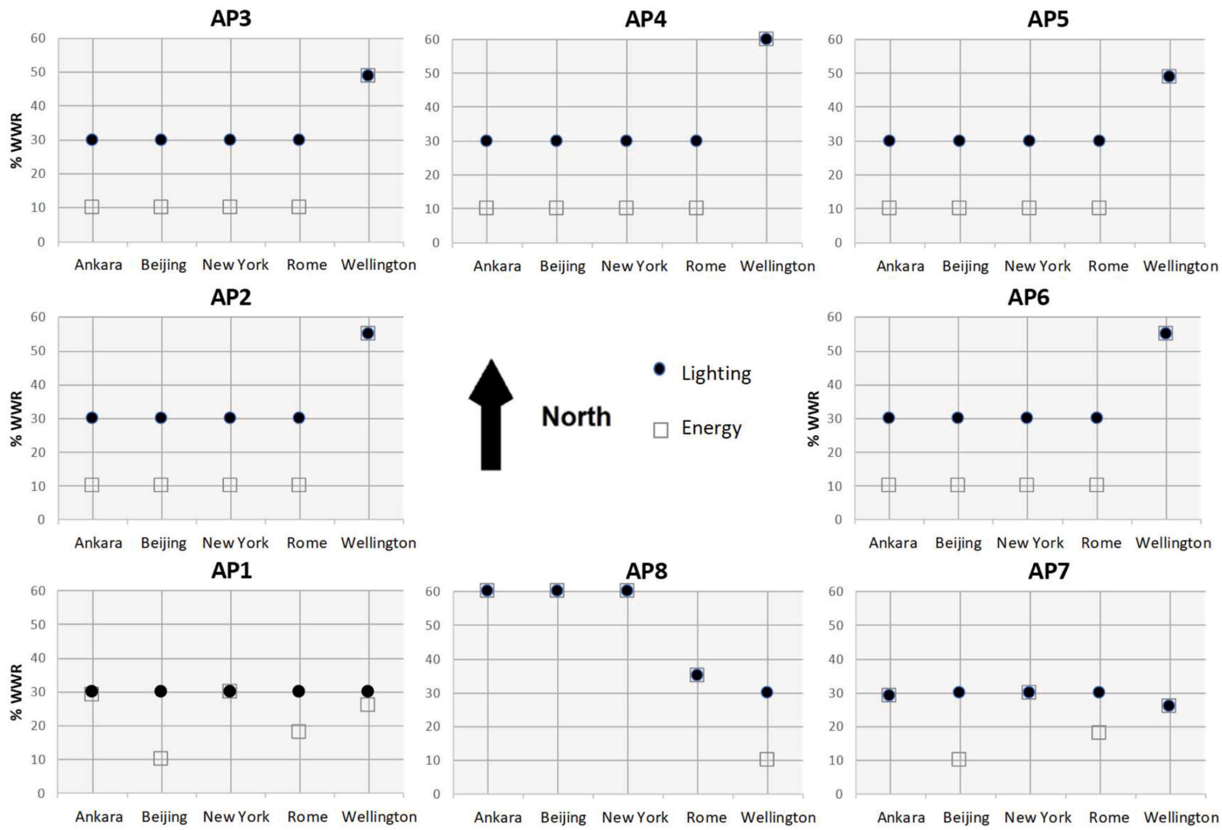


Figure 13. Optimal WWR for each apartment under the movable shading strategy across the five cities, considering U=0.1 W/m^{2}K and energy or lighting demand pattern.

in reduced annual energy demand due to the direct relationship between U-value and energy demand, which is consistent with previous findings [9]. Among the shading strategies, movable shading proved to be the most effective in reducing both heating and cooling loads. This is because these systems can block unwanted solar radiation during warmer months while allowing beneficial solar heat gains during colder periods, a phenomenon also analysed by Lee et al., [26] and further confirmed by Heidarzadeh et al., who demonstrated that optimised external shading in highly glazed façades can substantially reduce cooling demand and improve daylight performance in warm climates [47].

Optimal configurations for each apartment and city were further analysed, and results confirmed the strong interdependence between WWR, orientation, and climatic context. Sayadi et al. found that optimal WWR values are highly dependent on climate conditions, orientation, and window thermal properties [48]. North-facing apartments generally performed best with minimal WWR (10%) when only energy demand is considered, a result consistent with previous work by Cheng et al., who estimated an optimal WWR value of 10% for north-facing apartments [22]. In contrast, south-facing apartments benefited from larger WWR values (up to 60%) when combined with high insulation and movable shading. Notably, Wellington exhibited a smaller overall impact on annual energy demand, reflecting its milder climate and reduced need for heating or cooling control. This study highlights the importance of climate-responsive design strategies and the critical role of orientation and shading in warmer climates, echoing Chiesa et al. [49]

The lowest energy demands occurred in south-facing AP8 with movable shading and a 60% WWR. Fully south-facing apartments (such as AP8), take advantage of passive solar gains in winter, while movable shading prevents overheating in summer. Unlike fixed shading, movable shading allows seasonal and even daily adjustment, optimizing performance throughout the year. For warmer climates such as Rome or Ankara, effective solar control significantly reduces cooling demand.

Among the limitations, this study assumes a fixed overhang of 70 cm for the fixed shading, which was based on a 30% WWR, as estimated in prior research [9]. This configuration resulted in a 9% reduction in daylighting, a threshold justified by previous findings [39]. Since the effectiveness of fixed shading depends heavily on window size and position, future work should consider adjusting overhang length proportionally to WWR to enable more accurate performance comparisons. Moreover, daylight performance was not directly assessed in this study. While artificial lighting was assumed to activate below a defined radiation threshold, ensuring visual comfort, a more detailed daylighting analysis would require coupling TRNSYS with specialized tools such as Radiance or Daysim, as commonly done in the literature [14,39]. Future studies should therefore integrate daylighting simulations and test a wider range of shading geometries (i.e., vertical fins for east-west façades, deeper overhangs for south façades), to explore trade-offs between WWR, shading devices, daylight, and energy demand.

In summary, this work focused on the interplay between WWR, U-values, and horizontal shading devices across multiple orientations and climates, with the main objective of identifying configurations that minimize energy demand. While daylighting analysis was beyond the scope, this remains an important area for further research to strengthen the integration of thermal and visual comfort in residential design [14,17,49].

5. Conclusions

This comprehensive study underscores the profound impact of shading devices, insulation levels (U-value), window-to-wall ratio (WWR) and apartment orientation on shaping building energy demand across diverse climates to reduce energy demand and promote sustainability. Through rigorous statistical analyses, including Kruskal-Wallis and Wilcoxon tests, our research reveals substantial variations in energy demand triggered by the interplay of WWR, shading devices, and U-values in residential buildings with different apartment typologies across five cities near 40° latitude: Beijing, Ankara, New York, Rome, and Wellington.

The findings unequivocally demonstrate that movable shading devices are highly effective in mitigating energy demand across most regions. U-values also exhibit a strong correlation with energy demand, except in Rome, where this relationship appears statistically insignificant. Additionally, significant differences between shaded and unshaded configurations were detected in nearly all cities, with particularly marked contrasts in Beijing, Rome, and New York.

Specifically, the key findings include:

- **Movable shading devices** are highly effective in reducing energy demand in most climates and orientations. Compared to unshaded configurations, they achieved reductions ranging from 22% in Beijing to 56% in Rome in south-facing apartments with 60% WWR and U-value of 0.3 W/m^2·K. Their ability to dynamically respond to seasonal and daily solar conditions makes them a superior, low-cost alternative to static shading strategies.
- **U-values** exhibit a strong correlation with energy demand across most cases, emphasizing the importance of thermal insulation. The effect is particularly noticeable at lower WWRs, with reductions up to 28% in north-facing apartments (AP3 and AP5) in Beijing when movable shading and 10% WWR were applied. Rome was the only exception, where this correlation appeared statistically insignificant.
- **WWR** profoundly impacts energy demand, especially in apartments facing north or partially north (AP2 to AP6) in northern hemisphere cities, where excessive glazing increases heat losses. The optimal WWR for north-facing apartments was consistently 10% in all cities except Wellington, whereas south-facing apartments benefited from higher WWRs: 60% WWR in Ankara, Beijing and New York, 35% in Rome and only 10% in Wellington.
- **Apartment orientation is** essential, as sensitivity to shading and insulation varies by zone, demanding tailored solutions. North-facing apartments showed limited sensitivity to shading strategies, while south-facing apartments achieved the lowest energy demand when combining movable shading and optimal insulation. For example, Apartment 8 (south-facing) in Rome achieved energy savings up to 55% compared to northeast and west-facing apartments (AP3 and AP5) under the same conditions.

Based on these findings, climate-sensitive policy recommendations can be formulated to align with shading strategies, envelope insulation (U-value), WWRs and orientation:

- Temperate continental climates: mandate external or movable shading devices for SE and SW façades to reduce cooling loads in summer and allow passive solar gains win winter. Limit WWR on north façades to $< 30\%$. Enforce low U-values (< 0.3 W/m^2·K) for building envelopes, especially in north-facing apartments.
- Mediterranean climates: encourage south-facing apartment layouts with moderate WWRs (35-45%) and shading to balance daylight and thermal comfort. Incentivize architectural designs that reduce exposure of east and west façades, which are more prone to overheating. Ensure U-values comply with regional regulations (0.4-0.6 W/m^{2}K).
- Semi-arid climates: enforce low U-values (< 0.3 W/m^2·K) across all orientations to mitigate extreme temperatures. Promote high WWRs (50-60%) on south façades with shading to optimize passive solar heating and cooling.
- Oceanic climates: allow larger WWR (north façades up to 40%) for daylight and winter gains. Ensure U-values comply with regional regulations.

These findings reinforce the need for zone and orientation specific strategies, as the sensitivity to shading, insulation, and WWR varies notably depending on climate and layout. Furthermore, orientation emerges as a decisive factor, underscoring the importance of context-aware architectural planning.

The insights from this study offer valuable implications for policy-making, and urban planning, providing actionable knowledge for reducing energy demand and combat climate change. By integrating these findings into urban development and building practices, cities can become more energy-efficient and environmentally sustainable.

In conclusion, this study provides a robust foundation for future research and policy development, highlighting the urgent need for climate-specific and context-specific approaches to sustainable building design and adaptative urban planning.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Ali Rafat Gigasari: Writing – original draft, Software, Methodology, Investigation, Data curation. **Mar Cañada-Soriano:** Writing – review & editing, Visualization, Supervision, Conceptualization. **Carolina Aparicio-Fernández:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **José-Luis Vivancos:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Supplementary materials

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Data availability

No data was used for the research described in the article.

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