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Original Article

Assessment of window renovation potential in an apartment with an energy performance approach

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Abstract

Windows are of great importance in improving the energy efficiency of buildings. It is possible to achieve this with the help of the regeneration of window design. The amount of energy used, the expense of heating and cooling, and the emissions of greenhouse gases that contribute to climate change can all be significantly reduced by improving the energy efficiency of windows. For this, computer modeling and BIM-based simulation programs provide significant timesaving in simultaneously evaluating design variations' visual and thermal results. This study selected a four-story residential building to analyze the energy load and thermal comfort of the windows redesign and examine the energy-saving potential for residential buildings. To analyze the renewed window design strategies, a four-story apartment building is selected as a case study in Izmir/Turkey (38° 4′, 27° 2′). This apartment is built on a 90 m^2 gross floor area. The existing indoor environmental conditions of the flat are generally observed as cool and low illuminated by the occupants, so the window design options must be compared and renewed. As the first option, current conditions are simulated. The second option is to simulate different patterns for window-to-wall ratio (WWR). Moreover, the third option is to simulate different types of glass in each window. Currently, the WWR of the selected flat in the north, east and south directions is around 10%. But more is needed to provide daylight to the apartment. This article used Autodesk Revit and Green Building Studio simulations to investigate WWR and glass types and evaluate energy use intensity's (EUI) impact. As a result, this study shows that a 10% WWR on all building facades leads to an EUI of 993.9 MJ/m^2/year. In contrast, increasing the WWR to 95% significantly increased EUI, reaching 2121 MJ/m^2/year. In addition, it has been shown that the use of low U-value glasses, such as translucent wall panels and super-insulated three-pane clear Low-E, can provide energy savings of up to 5% per year, and especially the super-insulated three-pane Low-E glass type provides the highest efficiency on all facades.

Keywords: redesign; simulation-based design; energy use; window-to-wall ratio; residential building

1. Introduction

Windows are of great importance in improving the energy efficiency of buildings. It is possible to achieve this with the help of the regeneration of window design. The amount of energy used, the expense of heating and cooling, and the emissions of greenhouse gases that contribute to climate change can all be significantly reduced by improving the energy efficiency of windows. In the broader context of global environmental challenges, improving the energy efficiency of building components such as windows is crucial in reducing overall energy consumption and mitigating climate change impacts. Window-to-wall ratio (WWR) is a significant indicator for calculating energy load. The WWR is a term used in the design and construction industry, which refers to the amount of habitable area found within each facade (window) as perceived on its exterior. This can be of great importance in improving the energy efficiency of buildings from a thermal technical point of view. Different aspects of daylight levels and energy must be considered to find the optimum range of windows concerning the dimensions of the façade. The WWR should not be reduced to the point where the natural light (daylight) and perspective are adversely affected. Also, the ratio should not be too high because solar radiation can produce excessive heat gain and increase the chance of glare in the region near the windows. Every workplace requires an outward-facing window to allow natural light, which should be between 1/10 and 1/8 the size of the room's floor plan. This vantage point is considered the minimum daylight requirement for this article. This point of view is seen as a basic limitation of the optimization process. Minimal energy usage for heating, cooling, and lighting is assessed from an energy perspective. In line with the energy performance analysis, a study in Izmir/Turkey emphasized that the WWR is an important criterion for thermal comfort [1]. In addition, in a study evaluating adaptive thermal conditions in the same climate zone, the importance of window sizes is in line with the studies in the literature [2]. Previous studies [3–8] have extensively investigated energy efficiency in various contexts and underlined the importance of comprehensive analyses in improving environmental sustainability.

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Many research activities point to the importance of window orientation, type of glazing, and WWR on the energy performance of buildings. A study conducted in Algeria by Mehaoued and Lartigue [9] indicated that increasing the WWR in hot regions leads to a rise in cooling demand due to a higher ambient temperature around the building caused by the reflection of heat flow. However, the effect of WWR on energy consumption was found to be less significant in regions located toward the north, as per the findings of Lahmar *et al.* [10]. Recent research emphasizes the decisive role of WWR and window types on building energy performance. In his study, Mahmoud [11] modeled how different glazing types and WWR affect energy consumption in a hot and arid climate. He found that certain glazing types and WWR ratios can significantly reduce total annual energy use. Shaik *et al.* [12] examined the impact of various glazing types, WWR, and wall thicknesses on buildings' energy-saving potential and carbon emissions. They stated the importance of these factors on energy performance. Li *et al.* [13] and Sayadi *et al.* [14] investigated in detail the impact of WWR on the energy performance of buildings in different climatic conditions and found that this ratio is directly related to energy efficiency. Other studies, such as Albatayneh [15], Zhang *et al.* [16], and Naili *et al.* [17], also analyzed the impact of WWR and window type on both cooling and heating loads, showing that these variables are critical in improving the thermal performance of buildings.

Researchers have extensively studied the design optimization problem of window sizes and facade orientations in buildings using many simulation programs regarding energy and comfort criteria. Calculations were made using DesignBuilder, Tas EDSL, Rhino for Diva, and Autodesk Revit integrated Autodesk Green Building Studio (GBS) program. In addition, studies have been carried out in tropical regions in general, and there are simulation studies on the effect of WWR ratio and window directions.

The study statistically investigated the accuracy of energy consumption estimates made by Autodesk GBS using Autodesk Revit on eight different parameters. According to this study, univariate linear regression models have high accuracy among the regression models developed [18]. Fitriani *et al.* explore the potential of BIM for building energy performance assessment in Indonesia and examine energy use scenarios for building energy assessment using the Revit integrated GBS interface. As a result, it is stated that BIM for energy use analysis can be used as a guide for its potential [19]. Kim *et al.* created scenarios to investigate the effect of window size and orientation on the energy load created by Autodesk Revit. GBS was used to calculate the total energy load. It shows that the building needs the lowest load when the windows in all directions are positioned at mid-height, and the positioning of the east windows affects the total energy load the most [20].

Some of these studies investigated the energy performance and thermal comfort with different glazing generally in office buildings (Table 1). The article discusses the effect of PCM glazing on energy performance and occupant comfort in an office building with experimental measurements in Chile. PCM has helped reduce the cooling requirement for sunny and partly cloudy days. It has also been noted to increase thermal comfort significantly. Regarding glare, there was no change in the hours when the PCM melted [22]. A study in Izmir/Turkey, on integrating phase change materials into building materials significantly reduced CO_2 emissions, especially in the hottest months [27]. In this study, Ichinose experimentally investigated an office building in a tropical climate zone, and the relationship between thermal comfort and glare variables was evaluated. Accordingly, it can be said that the perceived temperature affects the annoying glare, and the perceptible glare affects the thermal comfort [23]. Also, another study is about the effect of tinted glasses on thermal and visual comfort. It has been observed that overall comfort correlates positively with both visual and thermal comfort, comparable to both [28].

Another simulation program to simulate daylight and energy load is Rhino for Diva and TAS EDSL. Daylight and thermal analysis were performed using Rhino for Diva to examine the effect of window glass type on energy consumption in Refaat's study. This study discusses six different glass types, and the necessity of choosing the type that can prevent glare, reduce heat gain, and save more energy is emphasized. It has been stated that glasses with a high U value benefit energy saving, especially in hot climates [24]. Lelardi *et al.* analyzed the extent to which window glass type affects the energy performance and indoor comfort of buildings in an office building in a Mediterranean climate. Different glazing was applied to the building and compared with the current situation via simulation. According to the results, Low-E solar control windows provided the best thermal comfort indoors and slightly outperformed reflective glass regarding electricity demand [25]. Alwetaishi examines the effect of WWR and shading elements on the thermal insulation of the residential building. It has been observed that it reduces the heating load in winter due to passive solar heating, which saves up to 100 W in winter. In addition, according to this study, a 20% reduction in WWR improved energy consumption by 15% [21]. Pino *et al.* simulated the effect of WWR on heating and cooling demand for an office building in Santiago. Accordingly, it is calculated that in a building with 20% WWR, external sun protection and selective glazing, the demand can be as low as 25 kWh/m^2 per year. It has also been noted that a WWR of 20% is sufficient to maintain useful daylight about 80% of the time throughout the year [29]. Also, in this study by Poirazis, energy efficiency was questioned by making simulations on different office buildings with a WWR ratio of 30, 60, and 100, and the office building with a WWR ratio of 30% provides an acceptable level of thermal comfort compared to the others [26].

This article analyzes the relationship between WWR and window type of energy performance in residential buildings. Its primary objective is to provide a quantitative description of the effect of the WWR on energy use intensity (EUI). A secondary objective is to quantify the relationship between the two by developing an analytic model for the relationship between these two variables. For this, using computer modeling and BIM-based simulation programs provides significant timesaving for simultaneously evaluating the visual and thermal results of design variations. Also, this article investigated window type and window sizes to evaluate the effect of energy consumption. It evaluated both energy performance and daylight analysis with the current situation. Here, the WWR and the glass type are important variables. In addition, this research questions the effect of each variable on the structure. Autodesk Revit and GBS were used for energy analysis to analyze selected cases.

Table 1. Overview of the past reviews.

References	Year	Climate	Types of building	Methodology
[18]	2022	Humid subtropical climate	Office building	Simulation with Revit-Green Building Studio
[19]	2022	Tropical rainforest climate	Office building	Simulation with Revit-Green Building Studio
[10]	2022	Mediterranean climate	Office building	Simulation with TAS EDSL
[21]	2022	Mediterranean climate	Residential building	Simulation with TAS EDSL
[22]	2021	Mediterranean climate	Office building	Experimental
[23]	2020	Tropical rainforest climate	Office building	Experimental
[9]	2019	Warm, humid continental climate	Office building	Experimental
[24]	2018	Tropical and subtropical desert climate	Office building	Simulation with DIVA for Rhinoceros 3D
[25]	2017	Mediterranean climate	Office building	Simulation with Designbuilder
[20]	2016	Marine West Coast Climate	Residential building	Simulation with Revit-Green Building Studio
[26]	2008	Marine West Coast Climate	Office building	Simulation with IDA ICE 3.0

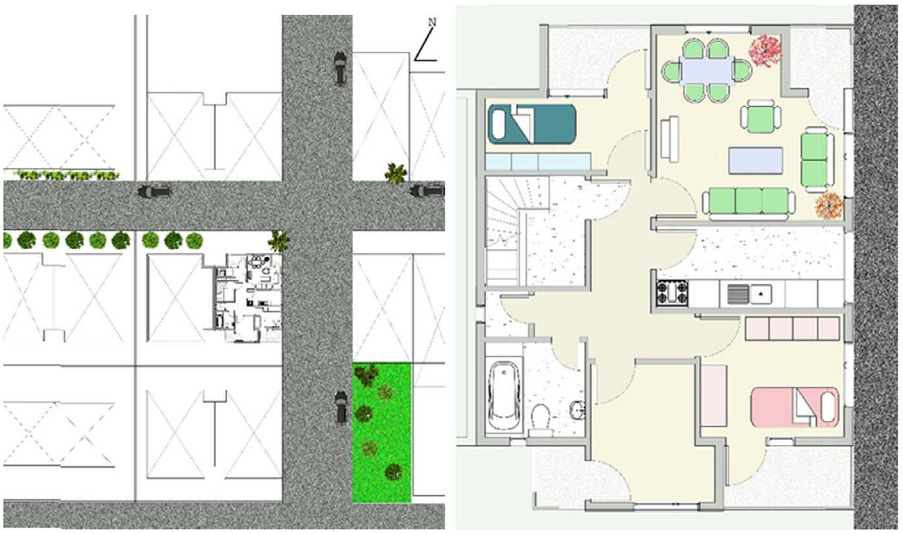

Figure 1. Plan view of case building (out of scale).

2. Materials and method

2.1. Case study

This study selected a four-story residential building to analyze the energy load of the windows redesign and examine the energy-saving potential for residential buildings. To analyze the renewed window design strategies, a four-story apartment building is selected as a case study in Izmir (38° 4′, 27° 2′). The building was constructed in 1995. The main entrance faces north, and the building is developed four levels above the ground at elevation ±0.00; one shop, in elevations +3.00, +6.00, and + 9.00, are standard floors. Each standard floor is envisaged to be one flat; at elevation +12.00 is the flat roof. This apartment is built on a 90 m^2 gross floor area with a balcony (Fig. 1). There are three flats of approximately equal square meters on each floor. Each flat has the same plan: a living area, two bedrooms, a kitchen, and a bathroom. Single-glazed window types are on the building's north, south and east facades. The heating system of the building is central heating with natural gas. The existing indoor environmental conditions of the flat are generally observed as cool and low illuminated by the occupants, so the window design options must be compared and renewed.

As a first option, the current situation was simulated. Then, the first option is to simulate different patterns of WWRs. This is the second case. Then, there is option 3, where each window has a different type of glass. Currently, the WWR of the selected apartment is ~10% north-facing and 10% east-facing. That is a low value for daylight. However, this is not enough to provide the apartment with natural light. This article investigated WWR and glass type to assess the impact of EUI. Furthermore, this study questions the impact of each variable structure. For energy analysis, selected cases were analyzed using Autodesk Revit and Green Building Studio.

The structure is forecasted to be a monolithic reinforced structure, with bearing reinforced concrete beams, columns, and slabs. The external and internal walls are built with single bricks 19 cm and 9 cm (Fig. 2). The roof is constructed with a reinforced concrete structure. The choice of materials used in the building relates to the function of space. External and internal walls consist of a final coat of plaster. Also, the floor is built with 15 cm reinforced concrete and wood floor finishing. Table 2 shows the thickness, conductivity, specific heat, density, and thermal absorptance of the floor and walls [30, 31].

The reliability and validity of this study are ensured under the specific conditions under which the research was conducted. The assumptions in Table 3 form the basis of the energy modeling and analysis process. These assumptions cover various factors such as the climatic characteristics of Izmir, building design, the materials' thermal properties, the heating and cooling system, and the accuracy of the simulation tools. When analyzing the building considered in this research, these assumptions are important for scientific consistency and

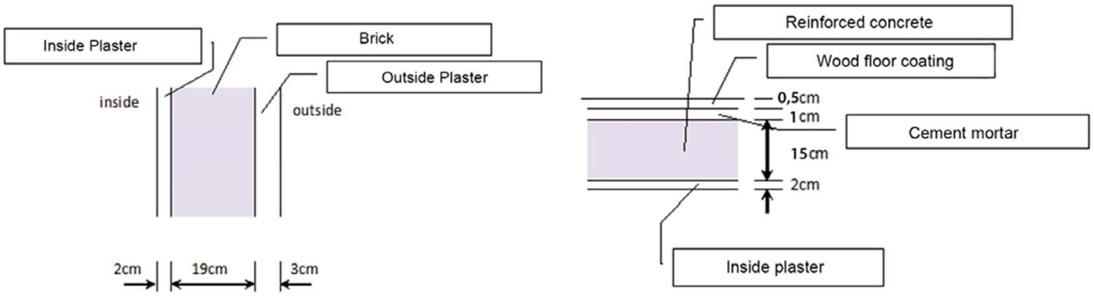

Figure 2. Section of the building elements of case building with dimensions.

Table 2. Case building finishing works materials and their features [30, 31].

Wall	Thickness (m)	Conductivity (w/m-k)	Specific heat (j/kg-k)	Density (kg/m^3)	Thermal absorptance
Inside plaster	0.02	0.5	1000	1300	0.9
Brick	0.19	0.62	800	1700	0.9
Outside plaster	0.03	0.5	1000	1300	0.9
Floor/ceiling	Thickness (m)	Conductivity (w/m-k)	Specific heat (j/kg-k)	Density (kg/m^3)	Thermal absorptance
Wood coating	0.005	0.138	2805	500	0.9
Cement/plaster	0.01	1.5	840	1900	0.9
Concrete	0.15	2.3	1000	2300	0.9
Inside plaster	0.02	0.5	1000	1300	0.9

Table 3. Modeling assumptions.

Assumptions	Assumption description
Climate conditions	The study was based on the climatic conditions of Izmir, Turkey. These conditions include a temperate climate, high humidity levels, heavy rainfall, and little temperature difference between seasons
Building design	A consistent design and construction are assumed across all units of the four-story residential building used in the study, which includes uniform glazing, insulation levels, and building materials
WWR	The initial WWR is assumed to be 10% for the north, east, and south facades. The west façade has no windows as it is adjacent to another building
Heating system	The natural gas-fired central heating system for each apartment is assumed to be standard throughout the building, with no significant differences in efficiency or maintenance status
Occupant behavior and internal load	Internal loads from appliances and electronics and user behavior are assumed to be standard for typical regional residential units. There are no significant deviations in energy use patterns
Solar radiation gain	Considering the sunny climate of Izmir, solar radiation gain through windows is assumed to affect the thermal performance of the building significantly
Thermal properties of building materials	Thermal properties of building construction materials are assumed to be compatible with standard materials typically used in the region
Accuracy of simulation tools	The simulation tools used in the study, Autodesk Revit and Green Building Studio, are assumed to accurately reflect the real-world energy performance of the building by comparing them with studies in the literature

relevance to real-world scenarios. Each assumption is critical in interpreting the modeling results and drawing general conclusions.

2.2. Climate

This research focuses on Izmir, located in Turkey, which has a mild climate characterized by high humidity levels, heavy rainfall, and hot weather with little temperature variation between winter and summer. Izmir's average high temperature is 30 °C in June, whereas the average low temperature is 20 °C. The province lies at 38° 4′ latitude and 27° 2′ longitude, with an elevation of 25 m above sea level. According to Fig. 3, the region experiences the highest average temperature between July and January. Moreover, the minimum sunshine duration in Izmir is 12 hours per day on average [32].

2.3. Energy modelling in Revit green building studio

The Green Building Studio plugin is an energy analysis program integrated into Autodesk Revit. GBS can perform a wide variety of calculations regarding building energy use. The Green Building Studio program can perform calculations such as whole-building energy consumption analysis, CO$_2$ emissions analysis, daylight analysis, and energy cost analysis. LEED includes, but is not limited to, credit analysis. Improvements to the GBS program include the ability to simulate building orientation, interior loads, and efficiency of different heating, ventilation, and air conditioning (HVAC) systems and integration with various simulation engines. According to various studies, the analysis results obtained from the GBS program were reliable and accurate, depending on the

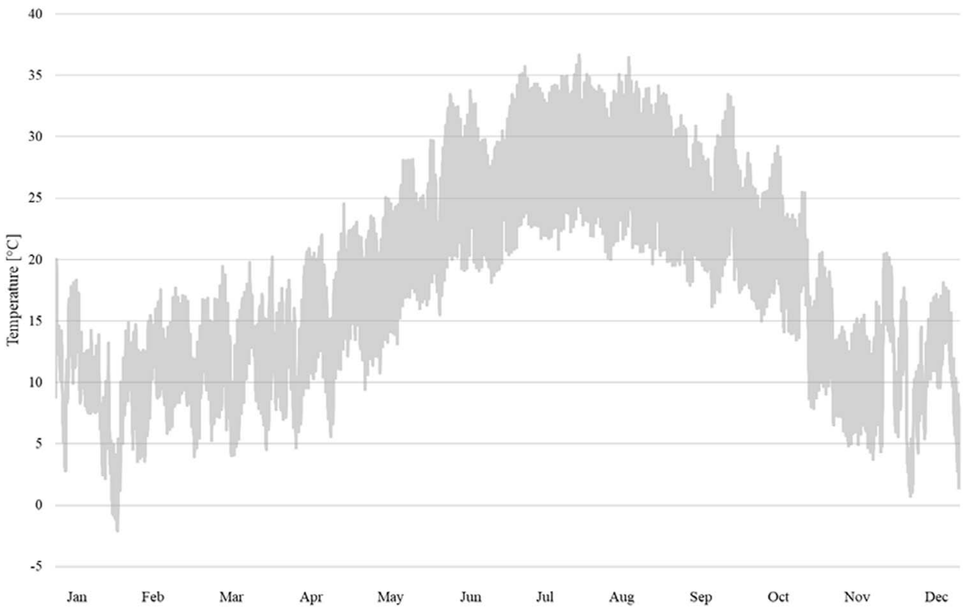

Figure 3. İzmir highest and lowest temperatures throughout the year (2005–2016) [32].

complexity of the building models [33, 34]. While performing the energy analysis, especially the dimensions, plan, areas and volumes of the different building areas, building direction, thermal characteristics of the construction units, operational use of the building, device loads, lighting, HVAC systems, and location information should be given.

The use of the GBS software is as follows step by step (Fig. 4):

- Step 1. Start opening the Revit project to be analyzed.
- Step 2. Navigate to the analyze tab and click on energy analysis
- Step 3. Choose energy settings and define the building's occupancy, HVAC systems, construction materials, and other characteristics.
- Step 4. Create a new energy model in Green Building Studio.
- Step 5. Run the energy analysis in Green Building Studio, automatically generating a report with various energy and analysis metrics.
- Step 6. Review and analyze the report to identify areas where energy savings can be made and make improvements as necessary.
- Step 7. Make improvements.

3. Generation of the alternatives

Considering the current state of the building, 41 simulations were carried out, including the existing case. These simulations, whose names and properties are listed in Table 4, only include WWR and window type change. The case building has a 10% opening on each side and is adjacent to another building on the west.

Therefore, there is no opening on the western façade. 95%, 80%, 60%, 50%, 40%, 30%, 15%, and a wall with no openings were also tested on the north, south, and east façades with openings. These values were performed on the existing noninsulated wall and aim to calculate the effect of window openings and window type for this article. Combinations were tried on 3 different fronts for WWR, and 32 simulations were obtained. Run 34–41, on the other hand, has been applied to facades for glass components with different window properties such as U value and solar heat gain coefficient (SHGC), and the window in the existing case is Single-glazed windows (U-5.74 W/(m^2-K), SHGC: 0.86). In addition, the Translucent Wall Panel (U-0.10 W/(m^2-K), SHGC 0.06), first called Type-1, was tried in simulations, and this glass was simulated separately for each facade was tested on all facades, and EUI

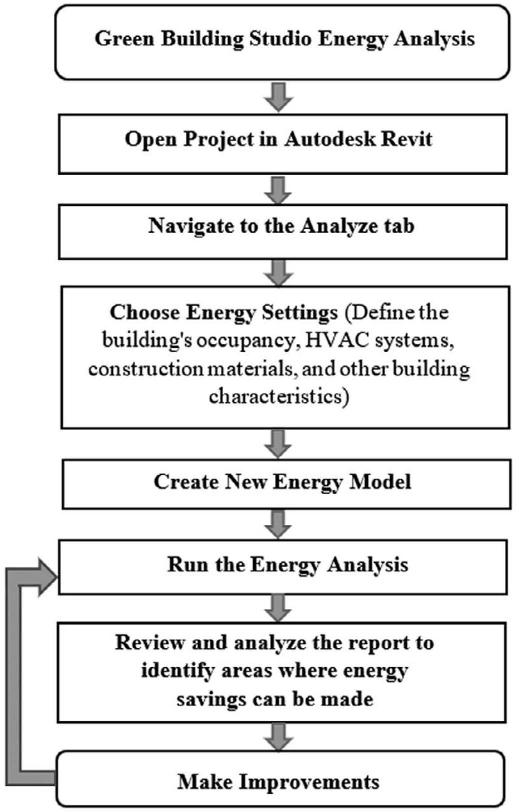

Figure 4. The flowchart for GBS.

Table 4. Run names for various WWR and window-type patterns.

Simulation run names	Window types			WWR		
	Northern walls	Southern walls	Eastern walls	Northern walls	Southern walls	Eastern walls
Run 1	Single-glazed windows	Single-glazed windows	Single-glazed windows	10%	10%	10%
Run 2	–	–	–	95%	–	–
Run 3	–	–	–	80%	–	–
Run 4	–	–	–	65%	–	–
Run 5	–	–	–	50%	–	–
Run 6	–	–	–	40%	–	–
Run 7	–	–	–	30%	–	–
Run 8	–	–	–	15%	–	–
Run 9	–	–	–	0%	–	–
Run 10	–	–	–	–	95%	–
Run 11	–	–	–	–	80%	–
Run 12	–	–	–	–	65%	–
Run 13	–	–	–	–	50%	–
Run 14	–	–	–	–	40%	–
Run 15	–	–	–	–	30%	–
Run 16	–	–	–	–	15%	–
Run 17	–	–	–	–	0%	–
Run 18	–	–	–	–	–	95%
Run 19	–	–	–	–	–	80%
Run 20	–	–	–	–	–	65%
Run 21	–	–	–	–	–	50%
Run 22	–	–	–	–	–	40%
Run 23	–	–	–	–	–	30%
Run 24	–	–	–	–	–	15%
Run 25	–	–	–	–	–	0%
Run 26	–	–	–	95%	95%	95%
Run 27	–	–	–	80%	80%	80%
Run 28	–	–	–	65%	65%	65%
Run 29	–	–	–	50%	50%	50%
Run 30	–	–	–	40%	40%	40%
Run 31	–	–	–	30%	30%	30%
Run 32	–	–	–	15%	15%	15%
Run 33	–	–	–	0%	0%	0%
Run 34	Type 1			–	–	–
Run 35		Type 1		–	–	–
Run 36			Type 1	–	–	–
Run 37	Type 1	Type 1	Type 1	–	–	–
Run 38	Type 2			–	–	–
Run 39		Type 2		–	–	–
Run 40			Type 2	–	–	–
Run 41	Type 2	Type 2	Type 2	–	–	–

has been calculated. The second simulated glass type is called type 2. This glass type is super insulated 3-pane Clear Low-E (U-0.22 W/(m^2-K), SHGC 0.47). This type of glass has also been applied to all applicable façades, and its combinations have also been simulated.

4. Results and discussion

In the previous sessions, the results obtained in different climatic zones using different programs related to WWR and window type, which affect the energy consumption on the facade of the building, were discussed. According to the results of the studies mentioned above, it is seen that it is an effective strategy according to the changes made on the building facade. In this section, the results obtained from the examined building are discussed and compared with the studies done.

The Patterns 2–33 simulations indicate that the energy consumption behavior of the apartment is highly influenced by its WWR. This is because windows transmit more solar radiation into the interior than opaque facade elements, resulting in greater energy gains or losses. The apartment's location in Izmir means high solar heat gain from the windows due to the mild climate, intense rainfall, high humidity, and hot weather. The graph shows that energy consumption is higher on the west-facing walls than on the north and south. Window surface enhancement in all directions leads to the highest energy loss compared to enhancing just one facade. The south-facing wall of the apartment experiences high solar radiation, while the north-facing wall leads to the least annual total energy consumption.

One way to reduce energy consumption in an apartment is to reduce the WWR rate. It is an effective solution to reduce WWR, especially in the west direction, which causes the most energy consumption. In this study, only the effect of WWR on energy consumption was simulated, and simulating changes in wall material, structures, and combinations will provide more effective results. According to the EUI value

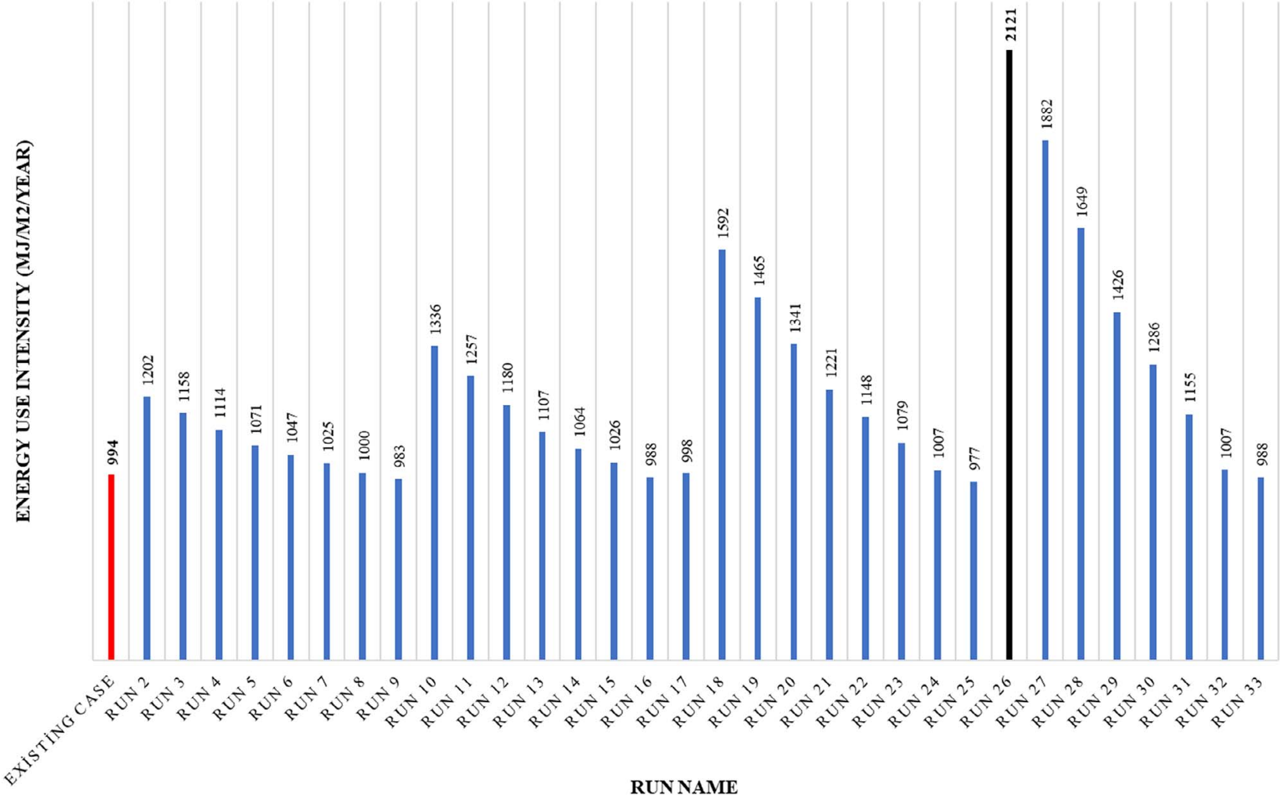

Figure 5. Comparison of the energy use intensity for 41 runs.

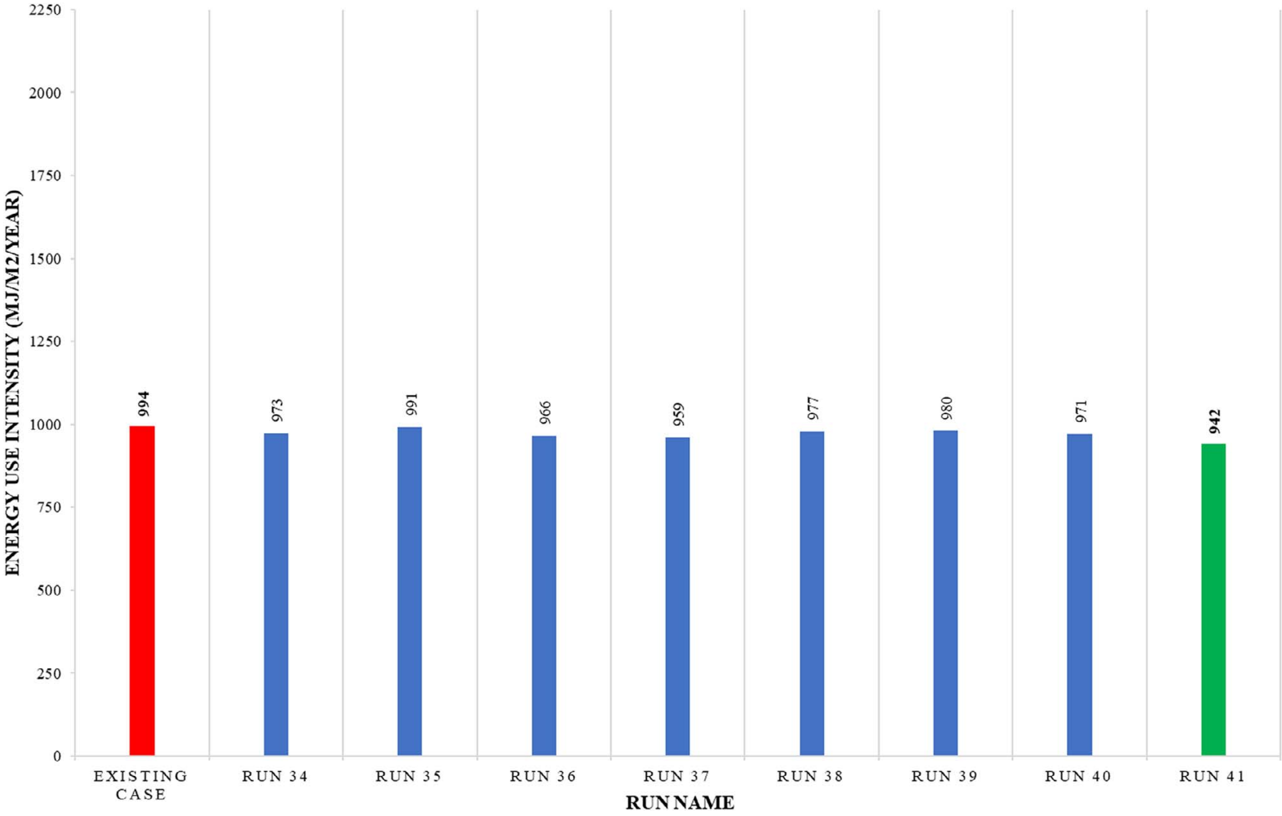

Figure 6. Energy use intensity results for window glass types runs.

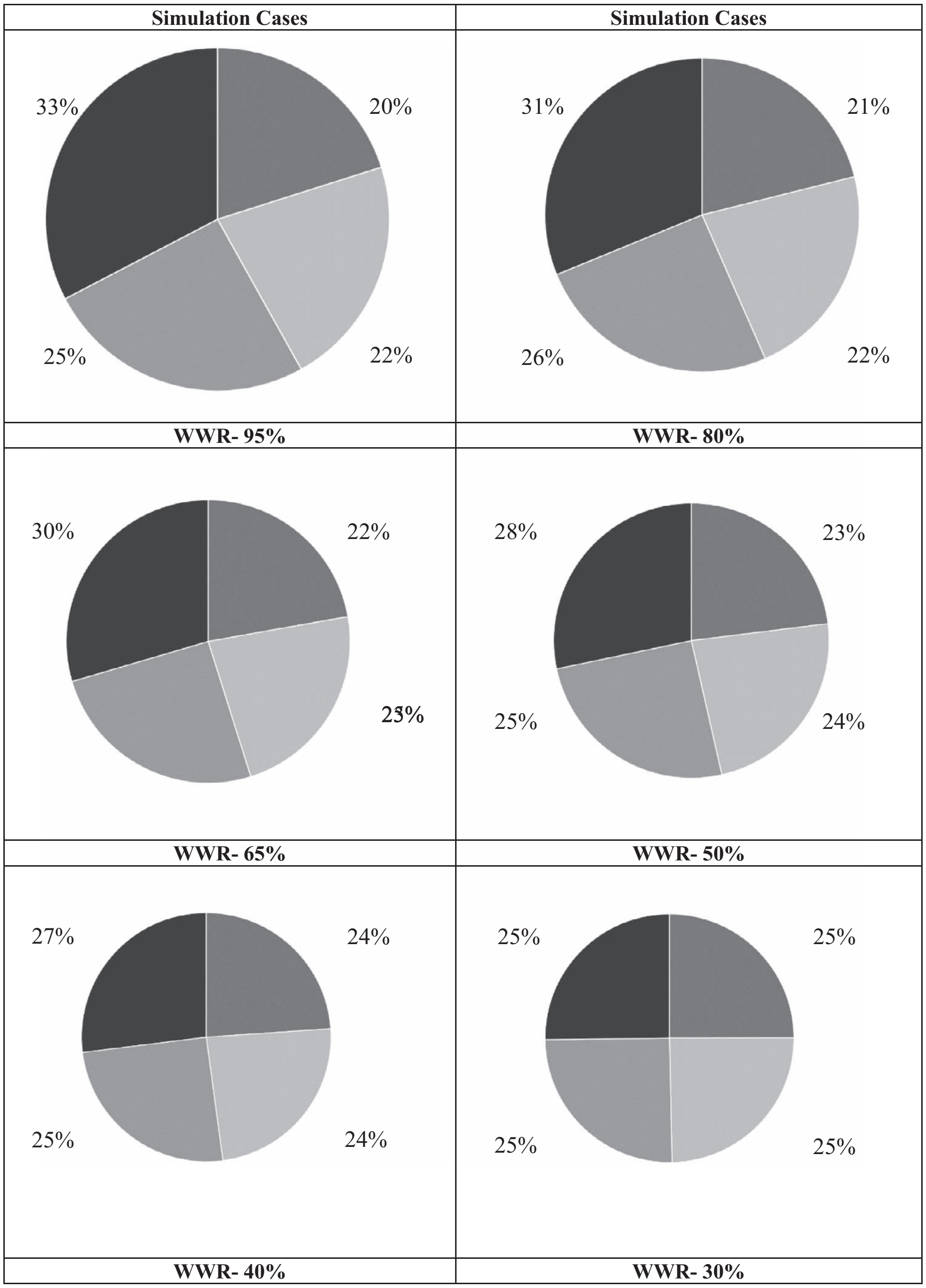

Figure 7. Overall yearly energy use intensity results for WWR and window glass type simulations.

comparison, the EUI value is 993.9 MJ/m^2/year with 10% WWR on all building facades. However, the simulated pattern 26, applying 95% WWR on all facades, has the highest value of 2121 MJ/m^2/year (Fig. 5).

The lowest value was obtained by changing the glass types obtained here. Run 34–41 patterns are simulated with two different types of glass. Again, it has been tried separately on each facade and using the selected glass type on all facades has also been simulated. The energy consumption values obtained for various window glass types are given in Fig. 6. Although the existing case is single-glazed, two different glasses with low U-value, such as Translucent Wall Panel and Super Insulated 3-pane Clear Low-E, were tried. Using translucent and super-insulated glass in the examined structure provides 2% and 5% energy savings in annual energy consumption. The simulation pattern with the lowest energy consumption in the simulations was to use Super Insulated 3-pane Clear Low-E on all glasses.

Figure 7, created after the simulation, shows WWR and glass types, the annual energy use per square meter of walls. Shapes scaled to scale are arranged from the pattern with the highest energy use to the pattern with the lowest energy use. The first given figure is the pattern with the highest EUI value in all directions, with a ratio of WWR-95%. When used in all directions, it causes an average of 8% and 33% of usage, while it has an average of 20% in the north direction, 25% in the east direction, and 23% in the south direction. The average for this case is 1440 MJ/m^2/year. These pie charts are scaled over

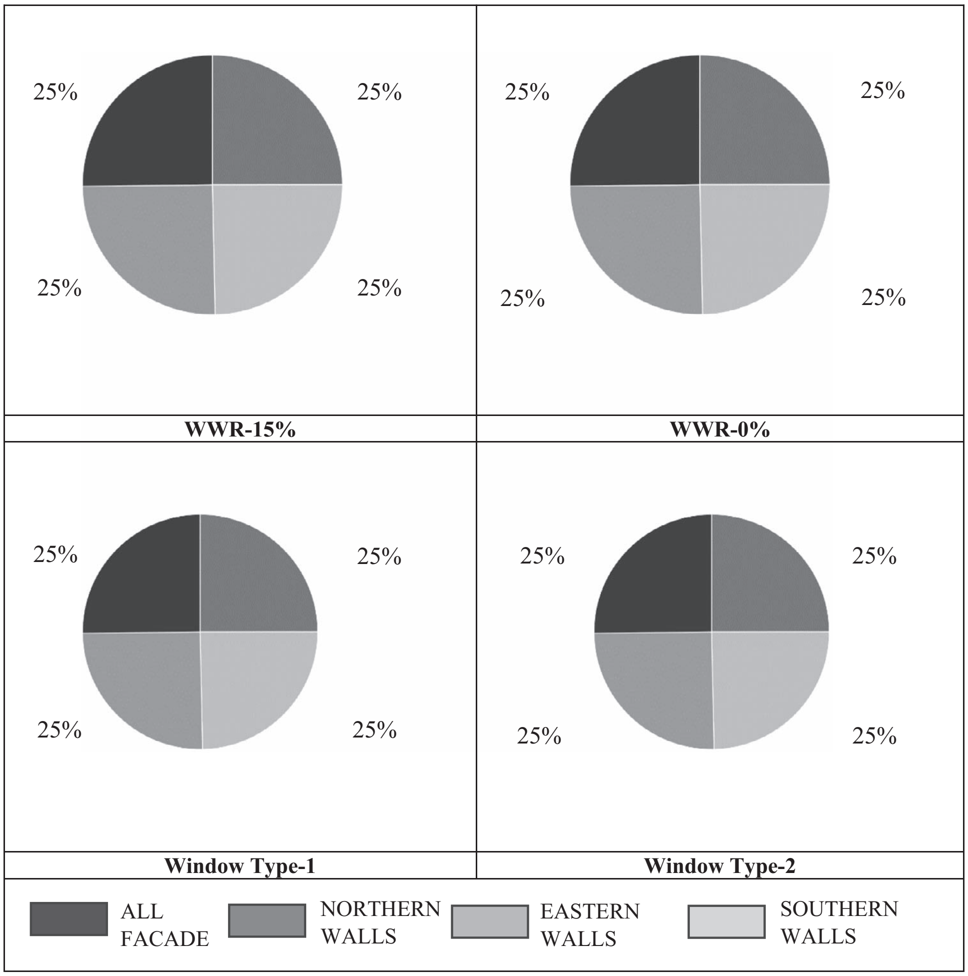

Figure 7. Continued.

the highest heat loss, which is assumed to be 100%. The glass-type replacement configuration, which causes the lowest heat loss, is scaled with a 70% difference and is 967 MJ/m^2/year on average.

Younis *et al*. [35] found that the building envelope has a significant effect on saving energy, with the most efficient improvements being a 15% WWR, triple glazing Low-E windows, wall insulation, and roof insulation, resulting in energy savings of 45.43%, 19.8%, 13.4%, and 30%, respectively. According to a study conducted in Bangladesh [36], replacing the windows in the examined building with low-E windows with single-glazed windows provides 3.77% energy savings in annual energy consumption and 4.03% energy savings by using triple-glazed Low-E. Looking at the results of a study conducted in Cyprus [37], replacing windows reduced all occupied spaces' energy consumption by 6% because of the high thermal transmittance of U-value 1.1 W/m^{2}K (double glazing with a low-emissivity coating). Simulations in Malaysia showed that double-coated reflective glass could improve energy efficiency by ∼10–14%, although the precise result varies depending on the other improvements made to the building facade. However, this result changes with different improvements (insulation, etc.) to be made on the facade of the building. Finally, a study comparing the performance of one green building to one conventional building found a 15% reduction in annual energy costs for the former, consistent with the other research mentioned.

5. Conclusion

Designing energy-efficient and high-performance buildings requires integrated work with simulation tools that calculate building performance. This research aimed to document the effect of the WWR and different types of windows on energy use with Green Building Studio, which performs a rigorous energy simulation in Autodesk Revit's infrastructure. The energy analysis of a four-story apartment building in 1995 and in use was analyzed and simulated with GBS. The 41 simulations performed in this study examined the effect of WWR and window types on building EUI. Passive design strategies have an important place in energy efficiency. The building EUI values were compared by integrating the best passive model among the different combinations, and a difference of up to 30% can be observed with the WWR variable. Another variable can save 5% in the examined building by changing the glass type. The results show that increasing the WWR from 10% to 95% increases the EUI of the building from 993.9 to 2121 MJ/m^2/year. This large increase highlights the critical role of window design in energy efficiency, especially in areas such as Izmir, where sunlight is intense. The simulated super-insulated 3-pane clear Low-E glass resulted in the lowest EUI (967 MJ/m^2/year) on all facades. In addition, the analysis revealed significant differences in the EUI values of facades with different WWR ratios; in particular, the western facades had the highest energy consumption, while the northern facades showed the lowest energy consumption.

These results show that the WWR and the window type determine building energy performance. These findings provide the basis for our future work, which aims to provide a wider range of understanding and applications in energy efficiency and sustainable building design. This research reveals how effective the choice of WWR and window type, which is one of the effective and applicable options that designers, contractors, suppliers, property owners, and researchers should consider for the retrofit and design phase, is effective in energy saving. The next step of this research is to extend the simulations across the whole building, create a case study, compare energy models with different software, and work for different climatic conditions and building types.

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Author contributions

Tugce Pekdogan (Conceptualization [equal], Data curation [equal], Validation [equal], Writing—original draft [equal]), Hasan Yildizhan (Conceptualization [equal], Methodology [equal], Validation [equal], Writing—original draft [equal]), Mohammad Hossein Ahmadi (Validation [equal], Writing—review and editing [equal]), Mohsen Sharifpur (Supervision [equal], Writing—review and editing [equal]).

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