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Article

Comparison of Glazing Types in Terms of Cost Efficiency and Total Energy Consumption

İşıl İplik¹ , Gülçin Gülsüm Konuk Taştan¹ , Hızır Gökhan Uyduran² , Mehmet Nuri İlgürel¹ 

¹Department of Architecture, Yıldız Technical University Faculty of Architecture, İstanbul, Türkiye

²Konu Merdiven, İzmir, Türkiye

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ABSTRACT

Energy efficiency in buildings has become an increasingly important design criterion in the context of sustainable architecture. In this context, building envelope components such as window systems must be thoroughly evaluated in terms of energy performance, initial costs, and long-term total cost. This study draws attention to the limitations of the commonly adopted one-dimensional approaches in selecting window glazing systems and offers a comprehensive analysis across three key parameters: Investment cost, energy consumption, and life cycle cost. A total of 64 scenarios are developed for a theoretical residential building located in İstanbul. Comparisons are made across three key performance criteria, taking into account different facade orientations (north/south) and window-to-wall ratios (30%/60%). The results reveal that the optimal window systems differ across the performance criteria, suggesting that selecting a system based solely on energy consumption or investment cost may result in suboptimal or misleading outcomes. Systems with low energy consumption often come with higher investment costs, which may limit the potential to minimize overall life cycle cost. Double-glazed systems with solar low-e coatings tend to yield more favorable life cycle cost outcomes, thanks to their relatively low investment costs and balanced overall performance. The study underscores the importance of adopting a multidimensional approach in window system selection and offers practical guidance to decision-makers aiming for cost-effective design strategies.

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*Corresponding author

*E-mail address: isil.iplik@std.yildiz.edu.tr



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INTRODUCTION

Global energy demand continues to rise and is still predominantly met by non-renewable fossil fuels such as coal, oil, and natural gas (International Energy Agency, 2022). These resources are limited in quantity and geographically concentrated in only a few regions, which makes them a major import dependence for many countries (Huo & Peng, 2023; Yadav & Mahalik, 2024). This situation poses a significant long-term risk to energy security, as it increases dependence on external energy sources and heightens supply risks during periods of political and economic instability (Anwar, 2016; Carfora et al., 2022). Buildings contribute to global energy consumption significantly—both directly and indirectly—throughout their life cycle, from construction to demolition (Sharma et al., 2011). As energy control in buildings contributes not only to environmental sustainability goals but also to energy supply security, political authorities have issued directives to encourage energy conservation in the building sector (Gaglia et al., 2017). These measures are intended to limit energy consumption in buildings and reduce the environmental impacts associated with fossil fuel use. In this context, the European Commission (2002) issued the Energy Performance of Buildings Directive (EPBD) to reduce energy consumption in buildings. Under this directive, it has become mandatory in EU member states and candidate countries to determine the energy consumption of buildings during the design phase and to certify them based on their energy performance levels (European Commission, 2002). Parallel to the EPBD, legal regulations on energy efficiency were introduced in Turkey, and the “Regulation on Energy Performance in Buildings” came into force in 2008, making the Energy Performance Certificate mandatory for all buildings (Turkish Standards Institution, 2008).

Since the early 1990s, it has been recognized that the environmental impacts and energy consumption of a product need to be assessed not only during its production or use phases, but across its entire life cycle. This recognition has given rise to the concept of life cycle assessment (LCA) in energy analyses (Carfora et al., 2022; Keoleian, 1993; Tillman et al., 1994). Moreover, the economic dimension of energy efficiency has also gained importance, with the objective of achieving maximum energy performance at the lowest total cost over the life cycle of buildings, and the concept of life cycle cost (LCC) emerged in the early 2000s (Bogenstätter, 2000; Durairaj et al., 2002; Norris, 2001; Sterner, 2000; Wen & Kang, 2001a, 2001b). In light of these developments, the directive issued by the European Commission was revised in 2010, stating that energy-efficient design must be carried out in accordance with cost-optimal scenarios (European Commission, 2010).

Life cycle cost (LCC) is an analytical method used to evaluate the economic performance of a building over its entire

life span, encompassing the construction, operation, maintenance, and demolition phases (Dwaikat & Ali, 2018). Since investment cost, maintenance and repair costs, and operating costs are considered collectively in the calculations, energy-efficient design strategies can be evaluated from a long-term economic perspective (Islam et al., 2015).

Residential buildings account for approximately 40% of global primary energy consumption, making them a key focus of energy conservation efforts (Atmaca, 2016). According to sectoral data on final energy consumption provided by the International Energy Agency (IEA), the share of residential buildings in total energy use is 24.6% in Europe (International Energy Agency, 2022) and 21.6% in Turkey (International Energy Agency, 2023). Primary energy consumption in the residential sector mainly arises from heating, cooling, and artificial lighting loads (Turkish Statistical Institute, 2025; U.S. Energy Information Administration, 2025). Transparent elements of the building envelope have a significant impact on energy-efficient design decisions, as they directly influence heating, cooling, and artificial lighting loads through heat losses, daylight gains, and ventilation effects (Hee et al., 2015; Li & Wu, 2025; Wang & Greenberg, 2015). Therefore, appropriate glass selection is a critical factor in energy-efficient building design. However, in architectural practice, glazing selection is often driven by investment cost, while long-term economic and environmental impacts tend to be overlooked.

In the literature, a number of studies addressing life cycle cost focus on only one or two parameters rather than evaluating heating, cooling, and artificial lighting loads comprehensively (Li & Wu, 2025; Solmaz, 2016; Tushar et al., 2022; Villaplana, 2020). The existing research on the transparent components of energy-efficient building envelopes indicates that some scholars investigate design-related features such as window location, orientation, and window-to-wall ratio (WWR) (Baş & Kazanasmaz, 2020; Pathirana et al., 2019; Uç & Dokuzer Öztürk, 2022; Yassin et al., 2017), while others focus on technical parameters including U-value, solar heat gain coefficient (SHGC), daylight transmittance, film coating, and cavity fill (Aguilar-Santana et al., 2020; Cuce et al., 2021; Heydari et al., 2021; Krarti, 2023). Studies investigating the types of glass used in architectural practice generally include a limited number of samples, which hinders a comprehensive analysis of glazing performance under different WWRs, orientations, and technical specifications. While most studies on architectural glazing include a limited number of samples, some focus on advanced or experimental glazing systems that are not commonly used in practice (De Masi et al., 2022; Niu et al., 2022; Sun et al., 2021). On the other hand, studies examining glass used in architectural applications generally include a limited number of samples (Sadzadehrafiei et al., 2012; Tahmasebi et al., 2011; Yıldız et al., 2011). A substantial proportion of research on the energy performance of

glazing focuses on heating and cooling load calculations, while life cycle analyses remain largely overlooked (Cengiz et al., 2024; Hart et al., 2019; Heydari et al., 2021). However, as LCC-focused studies investigate long-term performance, the short-term burden of investment cost is not examined as an independent variable. Nevertheless, investment cost remains a decisive factor in the decision-making process of investors. Therefore, energy performance assessments need to adopt a holistic approach that considers both life cycle cost and investment cost.

In this study, multiple glazing alternatives with different technical properties, commonly used in architectural practice, are compared in accordance with EU directives in terms of life cycle cost, investment cost, and energy consumption, using rooms with varying orientations and window-to-wall ratios (WWRs). The analyzed room is assumed to be located in Istanbul, and its function is defined as residential, a typology in which energy efficiency plays a significant role. This study aims to contribute to energy-efficient design by proposing a cost-effective approach for glass selection and by analyzing the advantages and disadvantages of glazing systems commonly used in architectural practice, considering both life cycle cost and investment cost.

METHODOLOGY

The parameters defined as fixed conditions and design variables are systematically addressed within the scope of this study. In this stage, the volumetric dimensions of the calculation room, facade orientations, window-to-wall ratios (WWRs), wall section types, and insulation thicknesses are defined first, and then the technical properties of the glazing are evaluated.

The calculation room is defined based on the BESTEST (Building Energy Simulation Test) models. This widely applied method for testing and validating building energy simulations also serves as a reference for the development of ASHRAE Standard 140 (Hao et al., 2023; Şahin et al., 2013). In the BESTEST model, room geometry and material properties are deliberately kept as simple as possible to minimize the risk of user error, and rectangular single-zone rooms without internal partitions are analyzed (Taffese, 2012). In this study, the calibrated BESTEST Case 600 model, which is frequently used in scientific research, is utilized (Fan, 2022; Fan et al., 2021; Judkoff & Neymark, 1995; Kyrou et al., 2023; Piccioni et al., 2024; Taveres-Cachat & Goia, 2021; Walker et al., 2022). The BESTEST Case 600 model is diversified in terms of WWR and orientation to evaluate glazing design under different conditions. Analyses are carried out for the south facade, which has the highest potential for solar radiation utilization, and for the north facade, which has the lowest.

The provisions of TS 825:2024 Thermal Insulation Rules for Buildings, issued by the Turkish Standards Institute, are

taken into account in determining WWR values. According to the standard, for buildings with a WWR of 60% or higher on heat-loss vertical exterior surfaces, the total thermal transmittance coefficient of the window system (U_{wi}) must not exceed 1.60 W/(m²·K). If this ratio is exceeded, other heat-loss components of the building (e.g., external walls, floors, ceilings) must be designed with U-values that are 25% lower than those recommended in the standard (Turkish Standards Institution, 2024). Considering these provisions, two WWR alternatives—30% and 60%—are evaluated in the study to represent both groups defined in the standard and to reflect common market applications (Figure 1).

In the opaque parts of the model, the simplest wall composition is selected, consisting of exterior plaster, insulation, horizontally perforated brick, and interior plaster layers. The insulation thickness is determined to satisfy the minimum U-values specified in the standard for Istanbul (0.30 W/(m²·K) for 60% WWR and 0.40 W/(m²·K) for 30% WWR). Accordingly, an insulation thickness of 10 cm is used for 60% WWR and 6 cm for 30% WWR (Table 1).

The glazing types included in the study are determined through a systematic analysis of glass systems. The analysis covers glazing configuration (double and triple-glazing), film coatings, cavity fill materials, and glass thicknesses.

Glazing systems are classified into three main groups based on coating type: Uncoated, low-e coated, and solar low-e coated glazing. As preliminary calculations presented in Table 2 show, uncoated glazing does not meet the minimum values recommended in the standard. Therefore, it is not included in the study. Low-e coated glazing reduces heat loss by reflecting long-wave infrared (IR) radiation, thereby contributing to thermal insulation (Mohelnikova, 2009). Solar low-e glazing incorporates multilayer coatings that provide both low-emissivity and solar-control functions simultaneously (Saidur et al., 2008). These glazing systems restrict a significant portion of short-wave solar radiation, which in turn reduces solar gains transmitted to the interior and lowers cooling loads during summer (Dachselt et al., 1982). However, their daylight transmittance and total solar energy transmittance are lower than those of low-e coated glazing (Berardi, 2019). Since both coating types significantly affect energy performance and life cycle cost (LCC), their comparison is considered appropriate within the scope of this study.

In the market, glazing products with thicknesses of 3, 4, 5, 6, 8, 10, and 12 mm are commercially available (Şişecam, 2025). Glass with a thickness of 3 mm is excluded from window applications due to its limited mechanical strength. Glass thicknesses of 5, 8, 10, and 12 mm are generally sold as full sheets rather than by area (m²), which leads to a higher material waste ratio. Therefore, glazing thicknesses of 4 mm and 6 mm are the most commonly used in architec-

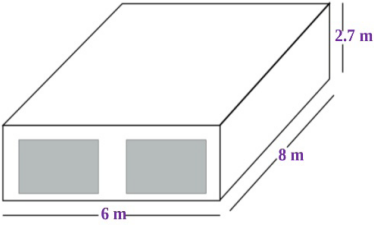
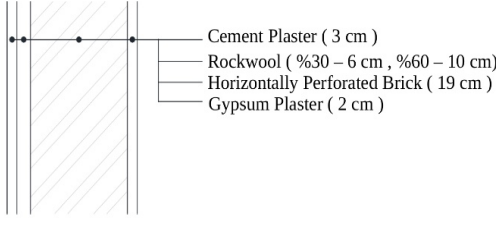
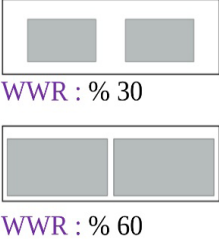
Basic Parameters	Model
<p>Dimensions : 6 m x 8 m x 2.7 m WWR : %30 , %60 Orientation: South, North</p>	
Wall Section	WWR
 <p>Cement Plaster (3 cm) Rockwool (%30 – 6 cm , %60 – 10 cm) Horizontally Perforated Brick (19 cm) Gypsum Plaster (2 cm)</p>	 <p>WWR : % 30 WWR : % 60</p>

Figure 1. Technical parameters.

tural applications. Accordingly, the study considers glazing combinations formed by 4 mm and 6 mm glass thicknesses to be sufficient for evaluation.

The cavity between glass panes is another critical parameter in double and triple-glazing systems, typically ranging from 9 to 24 mm (Şişecam, 2025). The U-values of the window alternatives decrease as the cavity width increases up to 16 mm and remain nearly constant beyond this point (Table 3). Considering its balanced thermal performance and frequent use under market conditions, a cavity width of 16 mm is deemed appropriate for the evaluation of all glazing combinations.

The cavity between glass panes in glazing systems is typically filled with air or argon to improve thermal insulation performance. The U-value of argon-filled systems is lower than that of air-filled systems (Cuce, 2018). However, the investment cost of argon-filled systems is higher than that of air-filled systems (Aruk, 2023; Şişecam, 2024). Therefore, both cavity fill materials are included in the life cycle cost (LCC) calculations to enable a comparison of their cost and performance characteristics.

Based on these selections, double glazing configurations of ‘4-16-4’ and ‘6-16-6’, which are commonly used in the market, are defined together with the triple-glazing configurations of ‘4-16-4-16-4’ and ‘6-16-6-16-6’, following a parallel logic. By combining low-e and solar low-e coating types with argon- and air-filled cavity alternatives, a total of 16 glazing configurations are defined, consisting of 8 double-glazing and 8 triple-glazing options (Table 4). For each

alternative, the thermal transmittance (U-value), solar heat gain coefficient (SHGC), and daylight transmittance are calculated to be used in total energy consumption analyses.

Each glazing alternative is assigned an ID code for reference in the analyses. In these codes, DG denotes double glazing, TG denotes triple-glazing, LEC represents low-e coated glass, and SLEC represents solar low-e coated glass. The numerical values following the glass type indicate the glass thickness in millimeters, whereas the letters A and Ar denote air and argon cavity fillings, respectively. As the cavity thickness is fixed at 16 mm for all alternatives, it is not included in the ID codes. Each ID code is entered into Excel as a data row, and the technical attributes corresponding to that code are recorded in the relevant columns (Table 4).

Energy calculations are performed using the Rhinoceros 8 / Grasshopper platform with the Ladybug and Honeybee v1.8 plugins. The parametric coding process is carried out in four main steps: (i) Defining the fundamental parameters, (ii) introducing the wall and glazing sections into the program, (iii) preparing the energy calculation scripts, and (iv) organizing the cost data (Figure 2).

In the first phase, the simulation model is developed based on the BESTEST Case 600, and the climate data of Istanbul are incorporated into the system. The surfaces of the room are classified as floor, ceiling, and walls. As the building is assumed to be a mid-floor unit, the ceiling and floor surfaces are defined as adiabatic to prevent exposure to outdoor conditions. To represent the two window-to-wall ratios (WWR) under investigation, openings with 30% and 60% WWR are

Table 1. Thermal transmittance coefficient (U) of wall systems with varying insulation thicknesses

Exterior plaster	Insulation	Wall material	Interior plaster	U (W/m ² ·K)
	3 cm rockwool			0.606
	5 cm rockwool			0.450
2 cm cement plaster	6 cm rockwool	19 cm horizontal perforated brick	2 cm gypsum plaster	0.399
	8 cm rockwool			0.325
	10 cm rockwool			0.274

Table 2. Thermal transmittance coefficient (U) of uncoated glass types (Şişecam, 2024)

First glass	Cavity width and cavity fill	Second glass	U (W/m ² ·K)
4 mm clear glass	16 mm air	4 mm clear glass	2.7
6 mm clear glass	16 mm air	6 mm clear glass	2.7

created in separate layers within the Rhinoceros interface, and north and south orientations are assigned to the room.

The technical data of the wall and glazing sections (e.g., SHGC, daylight transmittance, etc.) are organized in MS Excel and imported into Grasshopper using the keywords defined in the column headers. Since each selected material can be either double- or triple-layered, the number of layers is not identical across all materials. This results in the presence of empty cells in certain data rows within the Excel file.

A custom code is developed to eliminate the empty cells. The physical state of each material (solid or gas) is defined in Grasshopper using the appropriate components. After filtering out the irrelevant data, a material definition block is created using the remaining physical parameters and introduced into the system to model each wall and glazing layer. These layers are then combined to generate the complete wall and glazing sections (Figure 2 – Phase 2).

The Honeybee model, together with the climate data and building operation schedules, is incorporated into Grasshopper to generate the energy calculation scripts. As a result of the simulations, the annual energy demand for heating, cooling, and artificial lighting is obtained (Figure 3).

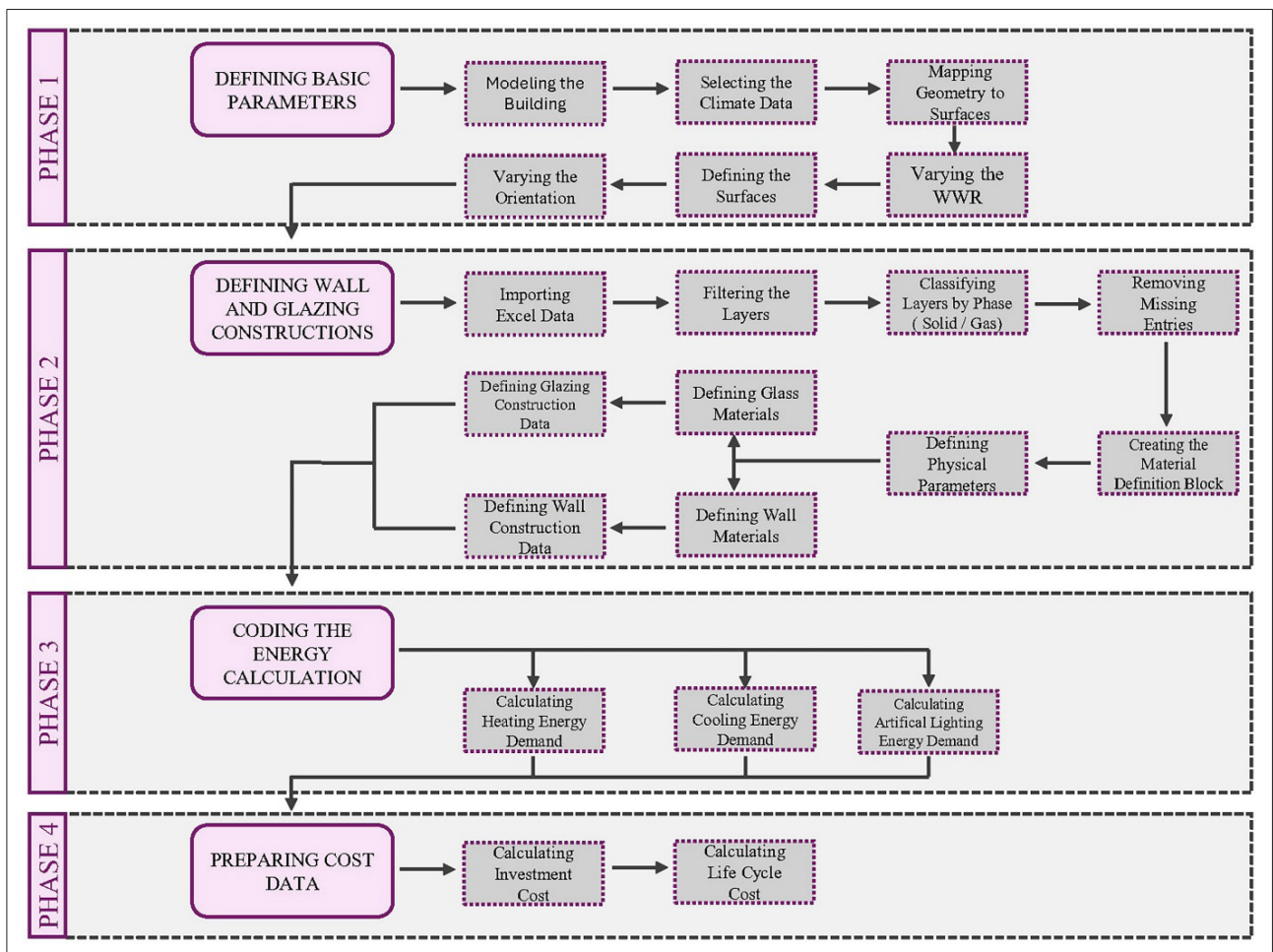


Figure 2. Parametric workflow.

The life cycle cost (LCC) analysis consists of investment, operation, maintenance, repair, and replacement costs (Mangan, 2015; Manioğlu, 2002).

The investment cost (C_i) is calculated using Equation (1), where S_m represents the area of the material and C_m represents the unit cost of the material (in this study, cost per square meter). Since variations in the window-to-wall ratio (WWR) alter the transparent and opaque surface areas, the investment cost is directly affected by these changes. This issue is addressed in the algorithm by adopting a unit-area-based calculation approach. Unit prices of the materials, including labor costs, are obtained from manufacturers and contractors operating in the market. The average of the quotations is used to calculate the investment cost per unit area for each ID code. In Rhinoceros/Grasshopper, a parametric code is developed to calculate surface areas corresponding to different window-to-wall ratios (WWR). The investment

cost for each ID code is then determined by multiplying the calculated surface area by the investment cost per unit area.

$$C_i = \sum S_m \times C_m \tag{1}$$

The operation cost is calculated using Equation (2), where C_e denotes the energy cost, CO_f indicates the fuel consumption, C_f defines the fuel cost, P_{PV} represents the amount of energy generated by photovoltaic (PV) panels, and C_{PV} refers to the unit price of the energy produced by PV panels. Since PV systems are not included in this study, the second part of the equation is disregarded. Accordingly, the operation cost is calculated by multiplying the heating, cooling, and artificial lighting loads obtained from the workflow shown in Figure 3 by their respective unit energy prices. The unit energy price, obtained from the local distribution company in Istanbul, is incorporated into the calculation and multiplied by the total energy consumption through an algorithm developed in Rhinoceros/Grasshopper (Energy Market Regulatory Authority, 2025).

$$C_e = \sum(CO_f \times C_f) - \sum(P_{PV} \times C_{PV}) \tag{2}$$

The maintenance and repair cost (C_{mr}) includes cleaning and preventive maintenance expenses. However, due to the significant variability of these costs even within the same city, sufficient data are not available; therefore, this component is excluded from the scope of the study.

According to the Directive 2010/31/EU of the European Parliament and of the Council (2010), LCC analysis for residential buildings are to be conducted over a 30-year period.

Table 3. Thermal transmittance coefficient (U) for different cavity widths (Şişecam, 2024)

First glass	Cavity width and cavity fill	Second glass	U (W/m ² ·K)
4 mm low-e coated glass	9 mm air	4 mm clear glass	1.9
	12 mm air		1.6
	16 mm air		1.4
	20 mm air		1.4
	24 mm air		1.4

Table 4. Technical properties of glazing alternatives

ID	System	Cavity fill	U (W/m ² ·K)	SHGC	Daylight transmittance (%)
DG_LEC_04_A	4-16-4	Air	1.4	0.56	0.79
DG_SLEC_04_A	4-16-4	Air	1.4	0.45	0.72
DG_LEC_04_Ar	4-16-4	Argon	1.1	0.56	0.79
DG_SLEC_04_Ar	4-16-4	Argon	1.1	0.45	0.72
DG_LEC_06_A	6-16-6	Air	1.4	0.55	0.78
DG_SLEC_06_A	6-16-6	Air	1.4	0.44	0.71
DG_LEC_06_Ar	6-16-6	Argon	1.1	0.55	0.79
DG_SLEC_06_Ar	6-16-6	Argon	1.1	0.44	0.71
TG_LEC_04_A	4-16-4-16-4	Air	1.1	0.52	0.72
TG_SLEC_04_A	4-16-4-16-4	Air	1.1	0.41	0.66
TG_LEC_04_Ar	4-16-4-16-4	Argon	0.9	0.52	0.72
TG_SLEC_04_Ar	4-16-4-16-4	Argon	0.9	0.41	0.66
TG_LEC_06_A	6-16-6-16-6	Air	1.0	0.50	0.70
TG_SLEC_06_A	6-16-6-16-6	Air	1.0	0.40	0.64
TG_LEC_06_Ar	6-16-6-16-6	Argon	0.8	0.50	0.70
TG_SLEC_06_Ar	6-16-6-16-6	Argon	0.8	0.40	0.64

Since annual operation costs recur each year throughout the analysis period, the total cost is calculated by considering the present value factor (PVF), as presented in Equation (3). In this formula, r denotes the discount rate, and n represents the life cycle period (years). In this study, the life cycle period is assumed to be 30 years, with a discount rate of 10%. Accordingly, the present value of the operation cost ($C_{op,t}$) is calculated using Equation (4).

$$PVF = \frac{1}{(1+r)^n} \tag{3}$$

$$C_{op,t} = (C_e \times \sum_{n=1}^n \frac{1}{(1+r)^n}) \tag{4}$$

Finally, the life cycle cost (C_{lc}) is calculated using Equation (5) through a parametric code developed in Rhinoceros/Grasshopper (Figure 4).

$$C_{lc} = C_i + C_{op,t} \tag{5}$$

As a result, the initial investment cost, life cycle cost, and total energy consumption values for 64 scenarios—derived from 16 glazing alternatives (8 double- and 8 triple-glazed alternatives), two transparency ratios (30% and 60%), and two orientations (north and south)—are calculated within a total computation time of 70 minutes using the parametric code developed in Rhinoceros/Grasshopper.

FINDINGS

The scenarios examined within the scope of the study are evaluated in terms of investment cost, total energy consumption, and life cycle cost. For each parameter, the results are listed from the highest- to the lowest-performing systems, and the evaluations are made accordingly. In addition, the performance of different design alternatives—namely, the number of glass panes (double/triple-glazing), coating type (low-e/solar low-e), cavity fill (air/argon), and

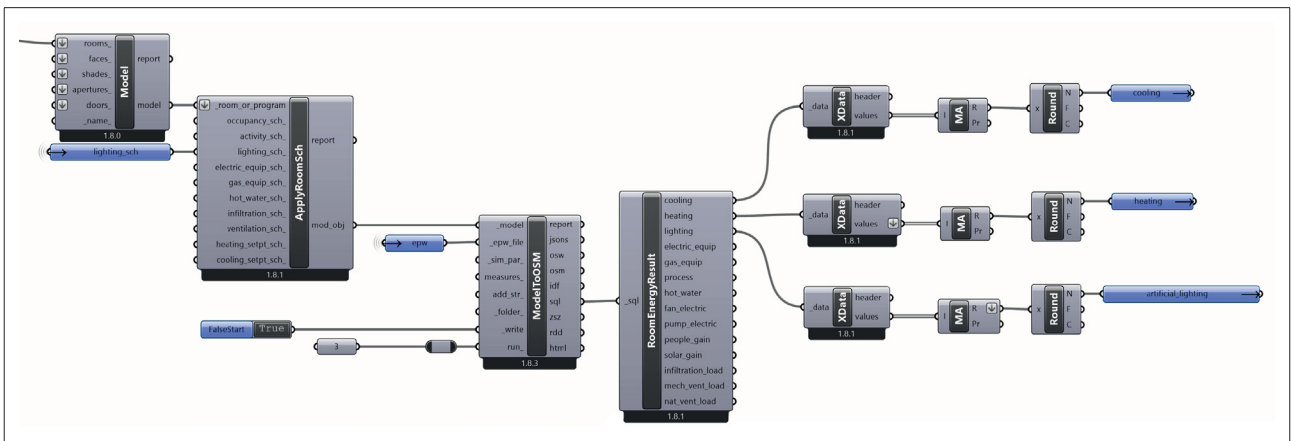


Figure 3. Energy simulation codes for parametric analysis.

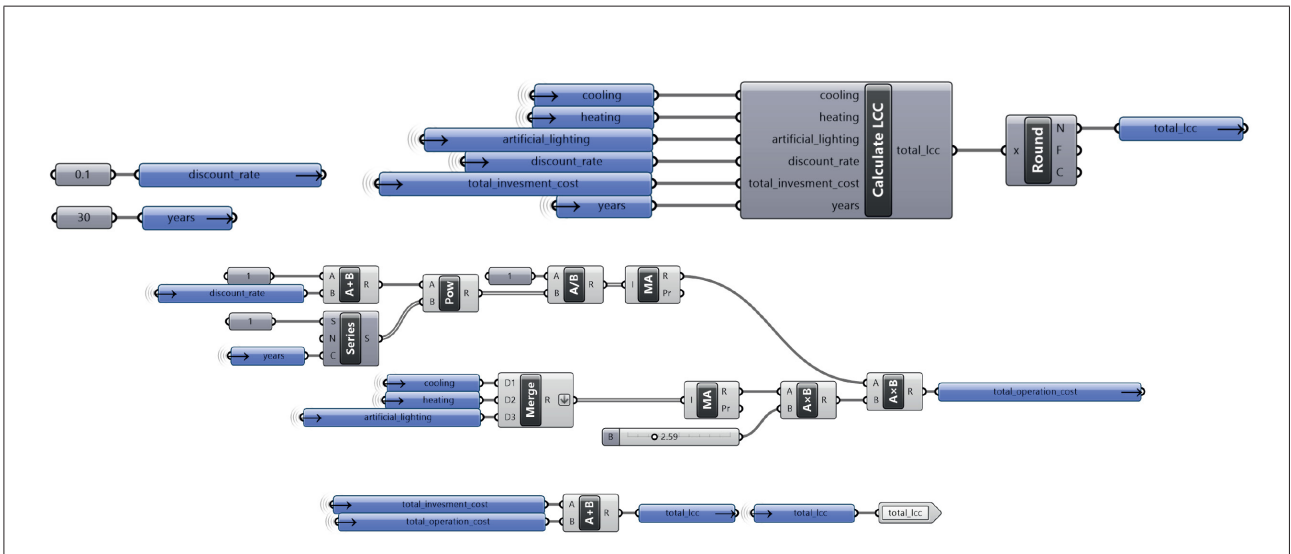


Figure 4. Parametric calculation code for life cycle cost.

glass thickness (4/6 mm)—is analyzed with respect to the selected evaluation parameters.

The investment cost increases significantly for all glazing systems as the window-to-wall ratio increases. In scenarios with a 30% window-to-wall ratio, the investment cost ranges from \$390.25 (DG_LEC_04_A) to \$805.51 (TG_SLEC_06_Ar), while in the 60% WWR scenarios, this range increases to between \$776.17 and \$1602.21 for the same systems. Since orientation (north/south) does not have a significant impact on the investment cost, the analyses are conducted based on the technical characteristics of the glazing systems, including the number of layers, coating type, cavity fill, and glass thickness. The number of layers appears to be the most influential factor affecting the investment cost. All double-glazing alternatives are found to be less costly than triple-glazing systems. Subsequently, the effects of cavity fill and glass thickness also appear to have a measurable impact on the investment cost. Although neither variable demonstrates a clear dominance over the other, cavity fill shows a slightly greater influence on the investment cost ranking (Table 5). For example, the sample with the ID code TG_LEC_04_Ar has a higher investment cost than TG_LEC_06_A due to the use of argon as the cavity fill. Thus, despite having a thinner glass thickness, it ranks lower in the investment cost comparison. The component with the least impact on investment cost is the low-e (LEC)/solar low-e (SLEC) film coating. Under all conditions, low-e coated (LEC) alternatives are consistently less costly than solar low-e coated (SLEC) options.

The analysis of the energy performance of window systems reveals that TG_SLEC_06_Ar achieves the highest efficiency in all scenarios, while DG_LEC_04_A shows the lowest performance. Triple-glazing systems provide better energy performance, whereas double-glazing alternatives lead to higher energy consumption. Since buildings constructed in accordance with the TS 825:2024 regulation are generally well-insulated against heat loss, solar low-e coatings tend to stand out in terms of total energy consumption, regardless of whether the orientation is north or south. Regarding the cavity fill variable, argon provides a slight performance advantage over air-filled systems; however, this difference remains limited in terms of energy consumption. A similar pattern is observed for the glass thickness parameter. Although the 6 mm alternatives show a minor improvement in certain scenarios, the differences in annual energy consumption do not indicate a significant advantage.

Energy consumption varies significantly depending on facade orientation and window-to-wall ratio. In scenarios with a 30% window-to-wall ratio, annual energy consumption ranges between 2477 and 2645 kWh on the north facade and between 2663 and 2926 kWh on the south facade. As the window-to-wall ratio increases to 60%, energy consumption rises noticeably, reaching 2814–3194 kWh on the north facade and 3191–3601 kWh on the south facade.

Table 5. Investment cost-based performance ranking

Ranking	ID	Investment Cost (\$)	
		30%	60%
1	DG_LEC_04_A	390.25	776.17
2	DG_SLEC_04_A	427.40	850.08
3	DG_LEC_04_Ar	435.27	865.79
4	DG_SLEC_04_Ar	472.45	939.71
5	DG_LEC_06_A	483.14	960.97
6	DG_SLEC_06_A	520.32	1034.89
7	DG_LEC_06_Ar	528.19	1050.57
8	DG_SLEC_06_Ar	565.34	1124.52
9	TG_LEC_04_A	622.51	1238.18
10	TG_SLEC_04_A	659.69	1312.10
11	TG_LEC_06_A	678.25	1349.08
12	TG_LEC_04_Ar	712.62	1417.41
13	TG_SLEC_06_A	715.43	1422.99
14	TG_SLEC_04_Ar	749.77	1491.32
15	TG_LEC_06_Ar	768.36	1528.26
16	TG_SLEC_06_Ar	805.51	1602.21

A comparison of scenarios with the same orientation and window-to-wall ratio reveals significant differences in the energy performance of the window systems. In the 30% window-to-wall ratio scenario, the annual energy consumption difference between glazing types is 263 kWh on the south facade and 168 kWh on the north facade. In the 60% window-to-wall ratio scenarios, these differences become more pronounced, reaching 410 kWh on the south facade and 380 kWh on the north facade. These findings indicate that, for buildings located in Istanbul with different window-to-wall ratios and orientations, an annual energy saving of 6.78% to 13.50% can be achieved through the appropriate selection of number of layers, coating type, cavity fill, and glass thickness (Table 6).

Across all scenarios, the glazing system with the highest performance is DG_SLEC_04_A, whereas the lowest-performing system is TG_LEC_06_Ar. As no significant variations are observed in the rankings with respect to orientation or window-to-wall ratio, glazing systems demonstrate comparable performance across north/south facades and 30%–60% window-to-wall ratios. In other words, while glazing systems exhibit similar performance across different orientations and window-to-wall ratios, their technical properties exert a considerably stronger influence on life cycle cost performance. In terms of the number of glass panes, double-glazing systems demonstrate considerably higher performance than triple-glazing systems. Solar low-e coating and a 4 mm glass thickness stand out with respect to life

Table 6. Total energy consumption-based performance ranking

Ranking	ID (Energy Consumption-kwh.y)			
	30%		60%	
	South	North	South	North
1	TG_SLEC_06_Ar (2663)	TG_SLEC_06_Ar (2477)	TG_SLEC_06_Ar (3191)	TG_SLEC_06_Ar (2814)
2	TG_SLEC_06_A (2680)	TG_SLEC_04_Ar (2492)	TG_SLEC_04_Ar (3227)	TG_SLEC_04_Ar (2851)
3	TG_SLEC_04_Ar (2684)	TG_SLEC_06_A (2501)	TG_SLEC_06_A (3237)	TG_SLEC_06_A (2856)
4	TG_SLEC_04_A (2702)	TG_SLEC_04_A (2517)	TG_SLEC_04_A (3277)	TG_SLEC_04_A (2894)
5	DG_SLEC_06_Ar (2748)	DG_SLEC_06_Ar (2533)	DG_SLEC_06_Ar (3344)	DG_SLEC_06_Ar (2946)
6	DG_SLEC_04_Ar (2758)	DG_SLEC_04_Ar (2536)	DG_SLEC_04_Ar (3360)	DG_SLEC_04_Ar (2960)
7	DG_SLEC_06_A (2770)	TG_LEC_06_Ar (2548)	TG_LEC_06_Ar (3383)	TG_LEC_06_Ar (2987)
8	DG_SLEC_04_A (2785)	DG_SLEC_06_A (2567)	DG_SLEC_06_A (3393)	DG_SLEC_06_A (3009)
9	TG_LEC_06_Ar (2810)	TG_LEC_06_A (2570)	DG_SLEC_04_A (3414)	TG_LEC_06_A (3022)
10	TG_LEC_06_A (2825)	TG_LEC_04_Ar (2572)	TG_LEC_04_Ar (3428)	DG_SLEC_04_A (3024)
11	TG_LEC_04_Ar (2847)	DG_SLEC_04_A (2574)	TG_LEC_06_A (3440)	TG_LEC_04_Ar (3036)
12	TG_LEC_04_A (2857)	TG_LEC_04_A (2594)	TG_LEC_04_A (3490)	TG_LEC_04_A (3074)
13	DG_LEC_06_Ar (2890)	DG_LEC_06_Ar (2606)	DG_LEC_06_Ar (3534)	DG_LEC_06_Ar (3119)
14	DG_LEC_04_Ar (2908)	DG_LEC_04_Ar (2617)	DG_LEC_04_Ar (3548)	DG_LEC_04_Ar (3135)
15	DG_LEC_06_A (2916)	DG_LEC_06_A (2642)	DG_LEC_06_A (3588)	DG_LEC_06_A (3179)
16	DG_LEC_04_A (2926)	DG_LEC_04_A (2645)	DG_LEC_04_A (3601)	DG_LEC_04_A (3194)
Greatest difference (kWh)	263	168	410	380
Greatest difference (%)	9.88	6.78	12.85	13.50

cycle cost performance. The comparison between air- and argon-filled cavities reveals minimal variation, indicating a balanced performance.

At a window-to-wall ratio of 30%, life cycle cost values range from \$2785.98 to \$3148.10 on the south facade, and from \$2607.28 to \$2926.22 on the north facade. When the window-to-wall ratio increases to 60%, the range rises to \$3741.34–\$4393.27 on the south facade and \$3411.06–\$4057.92 on the north facade. Among the four scenarios that employ the same glazing type, life cycle cost varies between 43.5% and 50.1% (Table 7; Rows 1 and 16). For instance, the life cycle cost of the TG_LEC_06_Ar glazing is \$2926.22 in the scenario with a 30% window-to-wall ratio on the north facade, whereas it increases to \$3148.10 on the south facade under the same configuration. At a 60% window-to-wall ratio, the corresponding values are \$4057.92 on the north facade and \$4393.27 on the south facade.

Evaluating each facade orientation and window-to-wall ratio group individually shows that life cycle costs are vary between 12.23% and 18.96%. This variation indicates that, even in scenarios with the same orientation and window-to-wall ratio, the technical components of glazing sys-

tems—such as the number of panes, coating type, cavity fill, and glass thickness—have a decisive impact on total cost.

The results reveal that double-glazing systems and 4 mm glass thickness alternatives constitute the most advantageous glazing combinations in terms of investment cost and life cycle cost. While triple-glazing systems and 6 mm glass thickness options demonstrate strong energy efficiency performance, their high investment costs cannot be economically tolerated over the life cycle period. Solar low-e coated glazing systems are achieved as the most advantageous alternatives both in north or south facade orientation. These results demonstrate that, the thermal insulation thicknesses offered in TS825:2024 increases the thermal performance of the building, so the cooling-related energy demand is seems to become more prominent. Argon-filled systems present a disadvantage in terms of investment cost while offering advantages in terms of energy consumption; conversely, the opposite situation applies to air-filled cavity systems. From a life cycle cost perspective, no distinct superiority is observed between the two cavity fill alternatives, and economically advantageous glazing sections can be achieved using either option. Considering all three performance criteria, investment cost, energy consumption and

Table 7. Life cycle cost-based performance ranking

Ranking	ID (Life Cycle Cost - \$)			
	30%		60%	
	South	North	South	North
1	DG_SLEC_04_A (2785.98)	DG_SLEC_04_A (2607.28)	DG_SLEC_04_A (3741.34)	DG_SLEC_04_A (3411.06)
2	DG_SLEC_04_Ar (2808.18)	DG_SLEC_04_Ar (2620.15)	DG_SLEC_04_Ar (3785.25)	DG_SLEC_04_Ar (3446.47)
3	DG_SLEC_06_A (2866.21)	DG_LEC_04_A (2630.28)	DG_LEC_04_A (3825.80)	DG_LEC_04_A (3481.13)
4	DG_LEC_04_A (2868.22)	DG_LEC_04_Ar (2651.57)	DG_LEC_04_Ar (3870.55)	DG_LEC_04_Ar (3520.77)
5	DG_SLEC_06_Ar (2892.57)	DG_SLEC_06_A (2694.27)	DG_SLEC_06_A (3908.35)	DG_SLEC_06_A (3583.17)
6	DG_LEC_04_Ar (2898.02)	DG_SLEC_06_Ar (2710.50)	DG_SLEC_06_Ar (3956.50)	DG_SLEC_06_Ar (3619.45)
7	TG_SLEC_04_A (2947.97)	DG_LEC_06_A (2720.60)	DG_LEC_06_A (3999.61)	DG_LEC_06_A (3653.24)
8	DG_LEC_06_A (2952.65)	DG_LEC_06_Ar (2735.17)	DG_LEC_06_Ar (4043.46)	DG_LEC_06_Ar (3692.02)
9	DG_LEC_06_Ar (2975.68)	TG_SLEC_04_A (2791.29)	TG_SLEC_04_A (4087.33)	TG_SLEC_04_A (3764.29)
10	TG_SLEC_06_A (2985.08)	TG_LEC_04_A (2819.32)	TG_SLEC_06_A (4164.37)	TG_LEC_04_A (3841.51)
11	TG_SLEC_04_Ar (3022.82)	TG_SLEC_06_A (2833.50)	TG_LEC_04_A (4193.82)	TG_SLEC_06_A (3841.69)
12	TG_LEC_04_A (3042.07)	TG_LEC_06_A (2854.73)	TG_SLEC_04_Ar (4224.21)	TG_SLEC_04_Ar (3905.79)
13	TG_SLEC_06_Ar (3060.77)	TG_SLEC_04_Ar (2860.21)	TG_LEC_06_A (4262.36)	TG_LEC_06_A (3908.35)
14	TG_LEC_06_A (3070.69)	TG_LEC_04_Ar (2890.80)	TG_SLEC_06_Ar (4304.64)	TG_SLEC_06_Ar (3985.36)
15	TG_LEC_04_Ar (3123.72)	TG_SLEC_06_Ar (2903.26)	TG_LEC_04_Ar (4320.53)	TG_LEC_04_Ar (3988.55)
16	TG_LEC_06_Ar (3148.10)	TG_LEC_06_Ar (2926.22)	TG_LEC_06_Ar (4393.27)	TG_LEC_06_Ar (4057.92)
Greatest difference (\$)	362.12	318.94	651.93	646.86
Greatest difference (%)	13.00	12.23	17.42	18.96

life cycle cost, together, double-glazed systems with solar low-e coatings and argon or air fills exhibit balanced performance and stand out in terms of life cycle cost.

These findings highlight the importance of incorporating cost data alongside energy performance, emphasizing that energy-focused evaluations alone are insufficient to achieve truly sustainable solutions. The analyses clearly demonstrate the necessity of assessing facade orientation, window-to-wall ratio, glass thickness, and window components in a holistic manner.

CONCLUSION

In recent years, energy efficiency has become one of the core components of sustainability goals and building sector policies. Window components, as integral parts of facade systems, require detailed evaluation since they have a direct impact on energy consumption and often entail high investment and operational costs. In this study, a multidimensional approach is adopted in evaluating window systems, focusing not on a single performance criterion, but on the integration of three key parameters: Investment cost, annual energy consumption, and life cycle cost.

The analyses indicate that energy consumption varies between 2477 and 3601 kWh annually, while life cycle cost ranges from \$2607.28 to \$4393.27, depending on the glazing configuration. Appropriate selection of glazing systems can provide annual energy savings of 6.78%–13.50%. Architectural parameters such as facade orientation (north/south) and window-to-wall ratio (30%/60%) also influence system performance, although the ranking of glazing alternatives remains relatively stable across these variations.

From an applied perspective, the results provide a clear decision-support framework for architects and investors by demonstrating how commonly used glazing systems perform under varying design conditions in terms of both energy efficiency and long-term cost. The findings reveal that different glazing systems stand out depending on which of the three parameters, investment cost, energy consumption, and life cycle cost, is prioritized. The study demonstrates that, in terms of investment cost, double-glazing systems, 4 mm glass thickness, low-e coatings, and air-filled cavities are the most advantageous options. From an energy consumption perspective, triple-glazing systems combined with 6 mm glass thickness, solar low-e coatings, and argon-filled cavities provide superior performance. With regard to life

cycle cost, double-glazing systems, 4 mm glass thickness, and solar low-e coatings emerge as the most favorable alternatives, while air- and argon-filled cavity options exhibit a balanced performance with no clear dominance.

In conclusion, this study indicates that glazing selection in buildings cannot be based solely on investment cost, which is commonly emphasized under free market conditions. Likewise, academic evaluations that focus exclusively on energy consumption may lead to misleading interpretations. Therefore, the results highlight the necessity of adopting a life cycle cost-based approach to ensure appropriate and sustainable glazing selection. The study contributes to the literature by linking parametric energy analysis with life cycle cost assessment, thereby supporting more informed and sustainable facade design decisions.

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