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Optimizing the Thermal Performance of Double-Glazed Window Systems Using Response Surface Methodology: A Case Study of a High-Rise Office Building

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ABSTRACT

This study investigates the optimization of the thermal performance of double-glazed window systems under Tehran climatic conditions with the aim of minimizing the building's energy consumption. Four key design parameters, including glass thickness (2, 4, 6, and 8 mm), glass type (ordinary, reflective, spectrally-selective, and blue-tinted glass), air-gap thickness between glazing layers (3, 6, 8, and 13 mm), and the type of filling gas (air, argon, krypton, and xenon), were considered. The modeling and optimization process was carried out using the Response Surface Methodology (RSM) in the Design-Expert software. The results demonstrated that increasing the air-gap thickness between the glazing layers significantly reduced the building's energy consumption. Similarly, increasing the glass thickness improved the thermal insulation performance and decreased energy usage. Among the investigated gases, xenon exhibited the best thermal performance and resulted in the lowest energy consumption. In addition, reflective glass showed superior performance compared with other glass types in terms of reducing energy demand. The optimization results indicate that the optimum configuration for achieving minimum energy consumption consists of reflective glass, xenon gas filling, an air-gap thickness of 12.75 mm, and a glass thickness of 2.825 mm. Under these optimal conditions, the minimum building energy consumption was obtained to be 161.46 kWh/m². The findings of this study provide useful insights for the design and optimization of energy-efficient double-glazed window systems in a high-rise office building located in climates similar to Tehran's.

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1. Introduction

Energy consumption in the building sector has increased significantly in recent decades due to rapid urbanization, population growth, and the rising demand for indoor thermal comfort. Buildings account for a considerable portion of global energy use, with a major share associated with heating and cooling systems[1]. Therefore, improving the thermal performance of building envelopes has become an important strategy for reducing energy consumption and greenhouse gas emissions[2, 3]. Among the various components of a building envelope, windows play a critical role in heat transfer because they are generally less thermally resistant than opaque walls and roofs. As a result, substantial energy losses occur through windows, particularly in regions with extreme climatic conditions. Double-glazed window systems are widely used to improve the thermal insulation performance of buildings and reduce energy demand. The thermal behavior of these systems depends on several parameters, including glass type, glass thickness, cavity thickness, and the type of gas filling between glazing layers[4]. Selecting appropriate combinations of these parameters can significantly reduce heat transfer and improve the energy efficiency of the building. Different glazing materials, such as reflective and spectral glasses, can affect solar heat absorption and thermal insulation performance, while inert gases such as argon, krypton, and xenon provide lower thermal conductivity compared with air, thereby reducing conductive heat transfer through the glazing cavity[5, 6].

Previous studies have shown that increasing the air-gap thickness between glazing layers can improve thermal resistance to an optimum level, beyond which natural convection effects may reduce the insulation performance. This behavior occurs because a larger cavity initially decreases the conductive heat transfer between the glazing layers by increasing the thermal resistance of the enclosed gas layer. However, when the cavity thickness exceeds a critical value, buoyancy-driven air circulation develops inside the gap, enhancing convective heat transfer and consequently reducing the overall insulating capability of the window system[7]. Therefore, determining the optimum cavity thickness is essential for achieving maximum thermal efficiency in double-glazed windows. In addition, the thermal performance of the cavity strongly depends on the type of the filling gas used between the glazing layers. The study conducted by Onatayo et al. [8] investigates the thermal performance of double-glazed windows with and without inert gas filling using a data-driven method for calculating the window's U-factor. Since experimental and computational approaches have several limitations, the research proposes an alternative method for evaluating the thermal transmittance of installed windows under real conditions. The analysis focused on double-glazed windows filled with air and different concentrations (75 %, 85 %, and 95 %) of argon. The results have showed that the center of glazing significantly affects the thermal performance of the window system and the emissivity of the glass is closely related to the U-factor of center of the glass. Moreover, the proposed data-driven approach demonstrated high accuracy and reliability when compared with NFRC 100-certified U-factor values. The findings highlight the importance of the glazing design and inert gas filling in improving energy efficiency and reducing the building's energy consumption. Air and argon gas fillings are among the most commonly used options in double-glazed window systems, while krypton gas is also utilized in some advanced glazing applications. Inert gases such as argon, krypton, and xenon possess lower thermal conductivity than air, which can further suppress heat transfer and improve insulation performance[9]. Several studies have also reported that the combined effects of cavity thickness, gas type, and glazing material significantly influence the overall energy performance of buildings, particularly in climates with high cooling and heating demands[10]. Consequently, optimizing these parameters simultaneously can lead to substantial reductions in the annual energy consumption of buildings and improve indoor thermal comfort[11]. Similarly, increasing glass thickness generally decreases heat transfer through the window system. In addition, reflective glazing has been reported as an effective solution for reducing solar radiation transmission and cooling loads in buildings located in hot and semi-arid climates. Therefore, optimizing the characteristics of double-glazed windows is essential for achieving higher energy efficiency in buildings[12].

Various numerical, experimental, and statistical approaches have been applied to evaluate and optimize the thermal performance of glazing systems[13]. Among these methods, the Response Surface Methodology (RSM) is recognized as an efficient statistical and optimization technique for investigating the interaction effects among multiple variables and determining the optimum operating conditions with a reduced number of experiments. Although previous studies have examined the effects of glazing type, cavity thickness, gas filling, and glass thickness on building energy performance, most have focused on evaluating these parameters individually or through limited comparative analyses. Moreover, studies that systematically investigate the combined and interactive effects of these variables and determine their optimum combination for high-rise office buildings under Tehran's climatic conditions remain limited. Therefore, the present study employs RSM and the Design-Expert software to develop predictive models and optimize the thermal performance of double-glazed window systems in a high-rise office building located in Tehran. Four influential parameters, namely glass thickness, glass type, cavity thickness, and filling gas type, were simultaneously analyzed to quantify both their individual and interactive effects on the building's energy consumption. The main contribution of this research is the integration of these glazing design variables within a comprehensive statistical optimization framework to identify the optimum window configuration that minimizes energy consumption. The obtained results provide practical guidelines for improving the thermal performance of building envelopes and enhancing energy efficiency in high-rise office buildings located in climates similar to Tehran's.

2. Case-base model

In the present study, an office room equipped with a double-glazed window was considered to investigate the effect of various window parameters on the building's energy consumption. Four main variables, including the air-gap thickness between the two glass layers, the type of filling gas, the glazing material, and the glass thickness, were examined. The required thermal and physical properties corresponding to 6 mm glass thickness were obtained from the study conducted by Peyman Pilechiha and used as reference data for the simulation and optimization process. The simulated office room had dimensions of 4m×4m×3.2 m. The external walls were assumed to be made of 22 cm thick brick masonry, which is commonly used in office buildings in Tehran. The wall construction from the exterior to the interior consisted of 2.5 cm cement mortar, 17.5 cm brick layer, and 2 cm gypsum plaster. In this study, a transparent double-glazed window with a 3 mm air gap filled with air was selected as the reference case. All investigated configurations were double-glazed systems, and each glazing unit consisted of two panes made of the same glass. The investigated variables included the glass thicknesses of 2, 4, 6, and 8 mm; different glazing types including ordinary, blue, reflective, and spectral glass; air-gap thicknesses of 3, 6, 8, and 13 mm; and filling gases including air, argon, krypton, and xenon[14]. The thermal and performance data for the glass thicknesses of 2, 4, 6, and 8 mm were obtained through dynamic building energy simulations using Energy Plus. The simulation model was developed in accordance with the methodology and validated assumptions reported in the study by Pilechiha [14]. The required input data for the simulation are presented in Table 1.

Table 1.
Simulation parameters of the heating, cooling, and heating, ventilation, and air conditioning (HVAC) systems used in the study.

Parameter	Value
HVAC system type	Ideal air system
Occupancy density	1 person
Heating setpoint (occupied hours: 7:00 AM–7:00 PM)	21 °C
Heating setpoint (unoccupied hours)	15.6 °C
Cooling setpoint (occupied hours: 7:00 AM–7:00 PM)	24 °C
Cooling setpoint (unoccupied hours)	26.7 °C
Lighting power density	10.76 W/m^2
Equipment power density	6.92 W/m^2
Air changes per hour (ACH)	1 h^{-1}
Infiltration rate	0.3 $L/s \cdot m^2$
Ventilation rate	6.44 L/s·person
Sensible heat fraction (cooling load)	0.7

Indeed, the simulation model adopted in this study was developed based on the methodology and assumptions reported by Pilechiha et al. [14], who investigated the influence of double-glazed window parameters on building energy performance under similar climatic conditions. The occupancy schedules, HVAC operation, internal loads, infiltration rates, and thermal comfort settings were implemented according to the validated framework presented in that study. Furthermore, the trends obtained from the present simulations are in agreement with previous research, which reported that increasing cavity thickness, employing reflective glazing, and using inert gases with low thermal conductivity improved thermal insulation and reduce the building's energy consumption.

3. Design of experiments

The experimental design of this study was developed using RSM in Design-Expert 11.1. A systematic design of experiments approach was employed to evaluate the effects of four key independent variables, including glass thickness, glazing type, air-gap thickness, and filling gas type, on the building's energy consumption. A structured experimental matrix was generated to define different combinations of input parameters within their specified ranges. The glass thickness levels were selected as 2, 4, 6, and 8 mm, while the glazing types included ordinary, reflective, spectrally-selective, and blue-tinted glass. The air-gap thickness varied between 3, 6, 8, and 13 mm, and the filling gases considered to be air, argon, krypton, and xenon. The design was carried out to ensure adequate coverage of the design space and to capture possible interaction effects between variables. For each experimental run, the corresponding energy performance was evaluated through simulation results. In this study, a two-factor interaction (2FI) regression model was selected to describe the relationship between input variables and the response. The general form of the model is given as:

$$y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ij} x_i x_j \qquad (1)$$

Where y represents the response (energy consumption), x_i and x_j are the independent variables, and the β terms are the regression coefficients. This model captures the main effects and interactive effects between variables without including quadratic terms.

Table 2.
Actual levels of the investigated variables used in the experimental design.

Name	Units	Type	Levels	L[1]	L[2]	L[3]	L[4]
Air gap thickness	mm	Discrete	5	3	6	8	13
Glass thickness	mm	Discrete	4	2	4	6	8
Glass type		Nominal	4	Ordinary glass	Blue-tinted glass	Reflective glass	Spectrally selective glass
Gas filling type		Nominal	4	Air	Argon	Krypton	Xenon

Table 2 presents the investigated variables and their corresponding levels used in the experimental design of the present study. Four independent parameters affecting the thermal performance and energy consumption of the double-glazed window system, including the air-gap thickness, glass thickness, glass type, and filling gas type, were considered. The air-gap thickness was defined as a discrete variable with four levels of 3, 6, 8, and 13 mm in order to evaluate the influence of cavity spacing on thermal insulation performance. Similarly, the glass thickness was considered at four different levels, including 2, 4, 6, and 8 mm, to investigate the effect of glazing thickness on heat transfer reduction. In addition, the glass type and filling gas were treated as nominal variables. Four glazing materials were examined, namely ordinary glass, blue-tinted glass, reflective glass, and spectrally selective glass, each having different optical and thermal properties. Moreover, four different filling gases, including air, argon, krypton, and xenon, were investigated to analyze their influence on the thermal resistance of the glazing cavity.

4. Results and discussion

4.1. Results of RSM

Table 3 presents the experimental matrix generated using the Central Composite Design (CCD) method within the framework of RSM. The table includes all simulation runs considered in the present study along with the corresponding combinations of the investigated variables and the resulting the building's energy consumption values. Four independent variables were examined in the experimental design: air-gap thickness (Factor A), glass thickness (Factor B), glass type

(Factor C), and gas filling type (Factor D). The air-gap thickness and glass thickness were treated as discrete numerical variables, while the glass type and gas filling type were considered categorical variables. The response variable of the study was the annual energy consumption of the building expressed in kWh/m².The generated design matrix consisted of 77 simulation runs covering different combinations of the selected parameters. The investigated air-gap thicknesses ranged from 3 to 13 mm, whereas the glass thicknesses varied between 2 and 8 mm. Four glazing materials, including ordinary glass, blue-tinted glass, reflective glass, and spectrally selective glass, were evaluated together with four filling gases: air, argon, krypton, and xenon.

The results presented in Table 3 indicate that the energy consumption strongly depends on the combination of the glazing properties and filling gas. In general, reflective glass and xenon gas demonstrated superior thermal performance, compared with other alternatives, resulting in lower energy consumption values. In contrast, ordinary glass combined with air filling exhibited the highest energy demand among the investigated cases. Moreover, increasing the air-gap thickness and glass thickness generally contributed to reducing the annual energy consumption of the building. The minimum energy consumption obtained in the experimental design was approximately 164 kWh/m², corresponding to the configurations incorporating reflective glazing and xenon gas filling, while the highest energy consumption exceeded 200 kWh/m² for ordinary glass filled with air. These results demonstrate the significant influence of window design parameters on the thermal and energy performance of buildings.

Table 3.
Range of variables in the CCD experimental design.

Run	A:Air gap thickness	B:Glass thickness	C:Glass type	D: Gas filling type	Energy consumption
	mm	mm			kWh/m²
1	8	6	Blue-tinted glass	Air	182.8
2	8	8	Blue-tinted glass	Air	181.2
3	8	4	Spectrally selective glass	Krypton	172.4
4	8	8	Reflective glass	Air	169.1
5	3	6	Spectrally selective glass	Krypton	174.5
6	13	6	Ordinary glass	Argon	178.6
7	3	8	Spectrally selective glass	Argon	175.6
8	8	2	Ordinary glass	Argon	189.8
9	8	2	Blue-tinted glass	Air	185.5
10	3	2	Reflective glass	Air	175.6
11	3	4	Spectrally selective glass	Xenon	174.8
12	8	2	Blue-tinted glass	Xenon	182.6
13	3	8	Reflective glass	Xenon	170.5
14	13	6	Spectrally selective glass	Krypton	169.3
15	8	6	Ordinary glass	Argon	187.8
16	13	6	Reflective glass	Xenon	164.2
17	8	4	Ordinary glass	Air	188
18	8	8	Ordinary glass	Xenon	187.2
19	8	4	Ordinary glass	Xenon	176.6
20	6	2	Reflective glass	Argon	171.8
21	8	4	Reflective glass	Air	170.2

22	3	6	Reflective glass	Air	173.7
23	8	8	Reflective glass	Argon	168.5
24	3	4	Reflective glass	Xenon	173.5
25	8	6	Spectrally selective glass	Argon	177.5
26	3	2	Spectrally selective glass	Krypton	179.4
27	13	2	Spectrally selective glass	Argon	181.4
28	3	6	Reflective glass	Argon	173.9
29	8	8	Spectrally selective glass	Air	172.8
30	3	6	Blue-tinted glass	Krypton	183.6
31	8	4	Spectrally selective glass	Air	174.5
32	8	8	Blue-tinted glass	Krypton	180.7
33	8	4	Ordinary glass	Xenon	179.8
34	3	6	Blue-tinted glass	Argon	184.8
35	3	8	Blue-tinted glass	Air	180.7
36	8	8	Blue-tinted glass	Argon	181.8
37	3	2	Ordinary glass	Xenon	195.6
38	3	2	Ordinary glass	Krypton	199.5
39	8	4	Ordinary glass	Air	187.8
40	8	4	Ordinary glass	Krypton	181.5
41	3	8	Spectrally selective glass	Xenon	174.1
42	8	8	Spectrally selective glass	Krypton	170.5
43	6	2	Blue-tinted glass	Krypton	184.4
44	3	6	Ordinary glass	Xenon	196.8
45	8	4	Blue-tinted glass	Argon	183.7
46	3	2	Blue-tinted glass	Argon	186.5
47	13	8	Blue-tinted glass	Air	177.8
48	3	2	Spectrally selective glass	Air	182
49	3	4	Blue-tinted glass	Xenon	182.2
50	8	2	Spectrally selective glass	Argon	185.5
51	8	6	Blue-tinted glass	Xenon	177.8
52	3	2	Spectrally selective glass	Argon	185.2
53	13	4	Reflective glass	Argon	167.8
54	13	4	Blue-tinted glass	Krypton	178.9
55	3	6	Ordinary glass	Air	198.5
56	8	8	Reflective glass	Krypton	166.9
57	3	4	Ordinary glass	Argon	192.7
58	3	6	Reflective glass	Krypton	172.5
59	3	6	Ordinary glass	Krypton	197.5
60	8	6	Spectrally selective glass	Xenon	171.2
61	8	2	Reflective glass	Xenon	167.1
62	8	8	Ordinary glass	Air	184.9
63	13	4	Reflective glass	Argon	167.4
64	3	6	Spectrally selective glass	Air	178.8
65	3	8	Ordinary glass	Argon	188.6
66	13	8	Spectrally selective glass	Argon	178.5
67	3	2	Reflective glass	Krypton	174.8
68	3	2	Blue-tinted glass	Air	187.8
69	3	2	Ordinary glass	Air	202
70	13	2	Blue-tinted glass	Air	181.2
71	8	6	Reflective glass	Xenon	167.3
72	8	2	Spectrally selective glass	Xenon	172
73	8	8	Ordinary glass	Krypton	180.7

74	13	4	Blue-tinted glass	Krypton	179.2
75	8	4	Reflective glass	Krypton	168.7
76	3	8	Blue-tinted glass	Xenon	180.5
77	8	4	Reflective glass	Air	170.4

Table 4 presents the statistical evaluation of different regression models developed for predicting the building's energy consumption using RSM. Several statistical indicators, including the sequential p-value, lack-of-fit p-value, adjusted coefficient of determination (Adjusted R^2), and predicted coefficient of determination (Predicted R^2), were used to assess the adequacy and predictive capability of the developed models. The linear model showed a statistically significant sequential p-values of lower than 0.0001, indicating that the model terms were significant. However, the relatively lower Adjusted R^2 (0.8374) and Predicted R^2 (0.8131), together with a significant lack-of-fit value (0.0054), suggested that the linear model was not sufficiently accurate for describing the response behavior. The Two-Factor Interaction (2FI) model demonstrated substantial improvement in the model's performance. The model exhibited a highly significant sequential p-value (< 0.0001) and a non-significant lack-of-fit p-value (0.0689), indicating good agreement between the model and the simulation data. In addition, the high values of Adjusted R^2 (0.9492) and Predicted R^2 (0.9127) confirmed the strong predictive capability of the 2FI model. Therefore, this model was selected as the most appropriate model for the present study. Although the quadratic model also showed acceptable statistical indicators, the sequential p-value of 0.9681 indicated that the addition of quadratic terms did not significantly improve the model's performance compared with the 2FI model's. Furthermore, the cubic model was identified as aliased, meaning that the available experimental data were insufficient to independently estimate all cubic model terms. Consequently, the cubic model was not considered suitable for the analysis. Based on these statistical results, the 2FI model was selected for further analysis and the optimization of the double-glazed window system due to its high accuracy, good predictive capability, and statistical reliability.

Table 4.
Statistical summary and adequacy evaluation of the developed RSM models.

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Linear	< 0.0001	0.0054	0.8374	0.8131	
2FI	< 0.0001	0.0689	0.9492	0.9127	Suggested
Quadratic	0.9681	0.0626	0.9469	0.9043	
Cubic	0.0112	0.9168	0.9893		Aliased

Table 5 presents the sequential sum of squares analysis used to evaluate the significance and adequacy of the developed regression models in the RSM analysis. The statistical parameters include the sum of squares, degrees of freedom (df), mean square, F-value, and p-value for each model's level. The linear model showed a highly significant effect on the response variable with an F-value of 49.92 and a p-value of lower than 0.0001, indicating that the primary variables significantly influenced the building's energy consumption. However, the addition of interaction terms in the Two-Factor Interaction (2FI) model considerably improved the model's performance. The 2FI model produced a significant F-value of 7.79 and a p-value of below 0.0001, confirming that the interactive effects between the investigated variables played an important role in predicting the response. Therefore, the 2FI model was suggested as the most appropriate model for the present analysis. The quadratic model did not provide any statistically significant improvement over the 2FI model, as indicated by its very high p-value (0.9681) and extremely low mean square contribution. This result suggests that the quadratic terms had negligible influence on the response variable. Although the cubic model showed statistical significance, it was identified as aliased, meaning that the experimental design was insufficient to estimate all cubic terms independently. Consequently, the cubic model was not considered reliable for prediction and optimization purposes. Overall, the statistical analysis demonstrated that the 2FI model achieved the best balance between model accuracy, significance, and predictive capability, making it the most suitable model for evaluating and optimizing the thermal performance of the double-glazed window system.

Table 5.
Sequential model sum of squares analysis for the developed RSM models.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Mean vs Total	2.481E+06	1	2.481E+06			
Linear vs Mean	4736.27	8	592.03	49.92	< 0.0001	
2FI vs Linear	635.90	22	28.90	7.79	< 0.0001	Suggested
Quadratic vs 2FI	0.2509	2	0.1254	0.0324	0.9681	
Cubic vs Quadratic	164.87	37	4.46	5.70	0.0112	Aliased
Residual	5.47	7	0.7817			
Total	2.487E+06	77	32292.23			

Table 6 presents the analysis of variance (ANOVA) results for the selected Two-Factor Interaction (2FI) model developed to predict the building's energy consumption. The statistical analysis confirms that the developed model is highly significant, with an F-value of 48.29 and a p-value of lower than 0.0001. Moreover, the lack-of-fit test was found to be statistically non-significant (p = 0.0689), indicating good agreement between the developed model and the simulation data. Among the investigated parameters, the glass type (Factor C) showed the strongest influence on energy consumption, with the highest F-value of 322.51. the air-gap thickness (Factor A) was identified as the second most influential variable, followed by the filling gas type (Factor D) and glass thickness (Factor B). The results indicate that all main factors significantly affect the thermal and energy performance of the double-glazed window system. Regarding interactive effects, the interactions between the air-gap thickness and the glass type (AC), the air-gap thickness and the filling gas type (AD), the air-gap thickness and the glass thickness (AB), the filling gas type and the glass thickness (BD), and the glass type and the filling gas type (CD) were statistically significant. However, the interaction between the glass thickness and the glass type (BC) was not statistically significant, as indicated by its p-value of greater than 0.05. Overall, the ANOVA results demonstrate that the selected 2FI model is statistically reliable and suitable for analyzing the combined effects of the glazing parameters on the building's energy consumption.

Table 6.
Analysis of variance (ANOVA) for the selected 2FI model.

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	5372.17	30	179.07	48.29	< 0.0001	significant
A-Air gap thickness	532.44	1	532.44	143.57	< 0.0001	
B-Glass thickness	136.95	1	136.95	36.93	< 0.0001	
C-Glass type	3588.06	3	1196.02	322.51	< 0.0001	
D-D	216.42	3	72.14	19.45	< 0.0001	
AB	29.12	1	29.12	7.85	0.0074	
AC	359.26	3	119.75	32.29	< 0.0001	
AD	88.67	3	29.56	7.97	0.0002	
BC	19.23	3	6.41	1.73	0.1744	
BD	41.59	3	13.86	3.74	0.0174	
CD	93.94	9	10.44	2.81	0.0101	
Residual	170.59	46	3.71			
Lack of Fit	165.31	41	4.03	3.81	0.0689	not significant
Pure Error	5.29	5	1.06			
Cor Total	5542.76	76				

According to Figure 1, the residuals generally follow the reference straight line, which indicates that the model's errors are approximately normally distributed. Most of the points clustered closely around the line in the central region, suggesting that the normality assumption is reasonably satisfied for the majority of observations. There is some deviation in the tails, particularly one strong negative residual on the far left and a few larger positive residuals on the right. These tail deviations suggest the presence of possible outliers or mild non-normality at the extremes, but not enough to severely violate normality overall. The regression model appears acceptable with respect to residual normality, though a few unusual observations may warrant further examination.

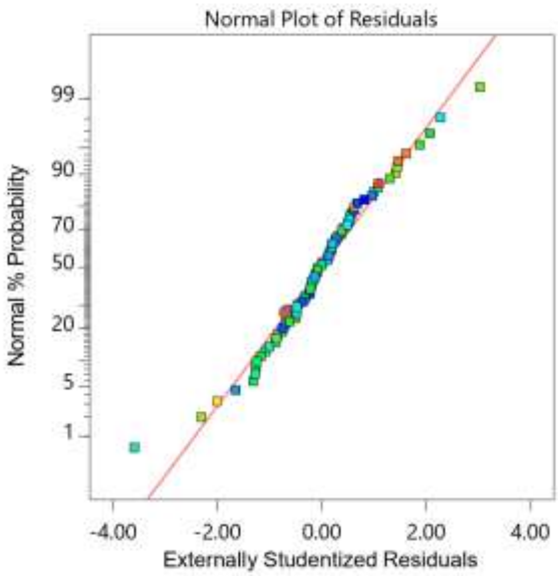


Figure 1. Normal Probability Plot of Residuals.

According to Figure 2, the scatter points lie very close to the 45-degree reference line, indicating strong agreement between predicted and actual values. This pattern suggests high predictive accuracy and good model's fit. There is no obvious systematic bias (e.g., consistent overprediction or underprediction) across most of the range. Minor deviations appear at some higher actual values, but these are relatively small. The spread remains fairly tight, implying stable performance across the dataset.

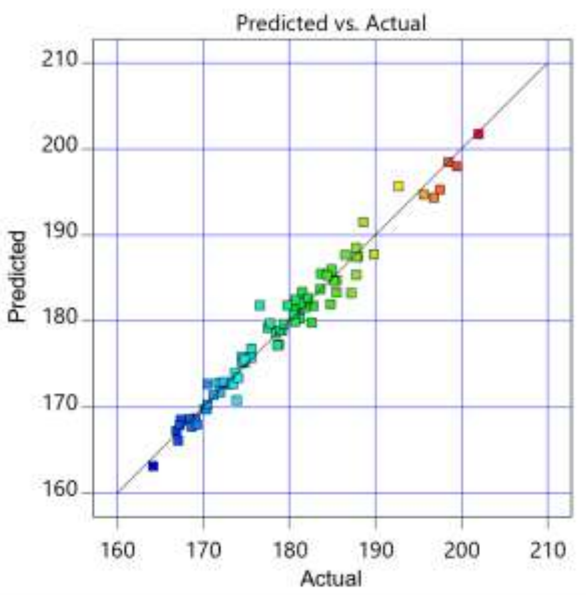


Figure 2. Predicted vs. Actual Values.

Figure 3 presents the influence of the key glazing system parameters, including air gap thickness, glass thickness, glazing type, and gas fill material, on the building energy consumption. As shown in Figure 3(a), increasing the air gap thickness from 3 mm to 13 mm significantly reduces energy consumption from approximately 199 kWh/m² to 175 kWh/m², indicating that wider air gaps substantially improve thermal insulation and reduce heat transfer through the window system. This suggests that the air gap thickness is a critical design parameter for enhancing building energy efficiency. Figure 3(b) illustrates the effect of the glass thickness on energy consumption. Increasing the glass thickness from 2 mm to 8 mm results in only a slight reduction in energy consumption, from about 185.5 kWh/m² to 183.8 kWh/m². Compared with that of the air gap thickness, the impact of the glass thickness is relatively minor, indicating that increasing the pane thickness alone offers limited improvements in the overall thermal performance. Figure 3(c) compares different glazing types, including ordinary glass, blue-tinted glass, reflective glass, and spectrally selective glass. Reflective glass exhibits the lowest energy consumption, followed by spectrally selective glass, while ordinary and blue-tinted glasses show comparatively higher consumption levels.

These findings demonstrate that advanced glazing technologies with improved solar control properties can significantly enhance building energy performance by minimizing unwanted solar heat absorption. Figure 3(d) evaluates the influence of the gas fill type within the glazing cavity. Among the gases analyzed, Xenon provides the greatest reduction in energy consumption, followed by Krypton, while Air and Argon show higher energy use. The superior performance of Xenon and Krypton is attributed to their lower thermal conductivity, which improves insulation efficiency. Overall, Figure 3 demonstrates that air gap thickness, glazing type, and gas fill material have substantial effects on reducing the building's energy consumption, whereas the glass thickness has a comparatively smaller impact. These results highlight the importance of optimizing multiple glazing parameters to achieve maximum energy efficiency in the building envelope design.

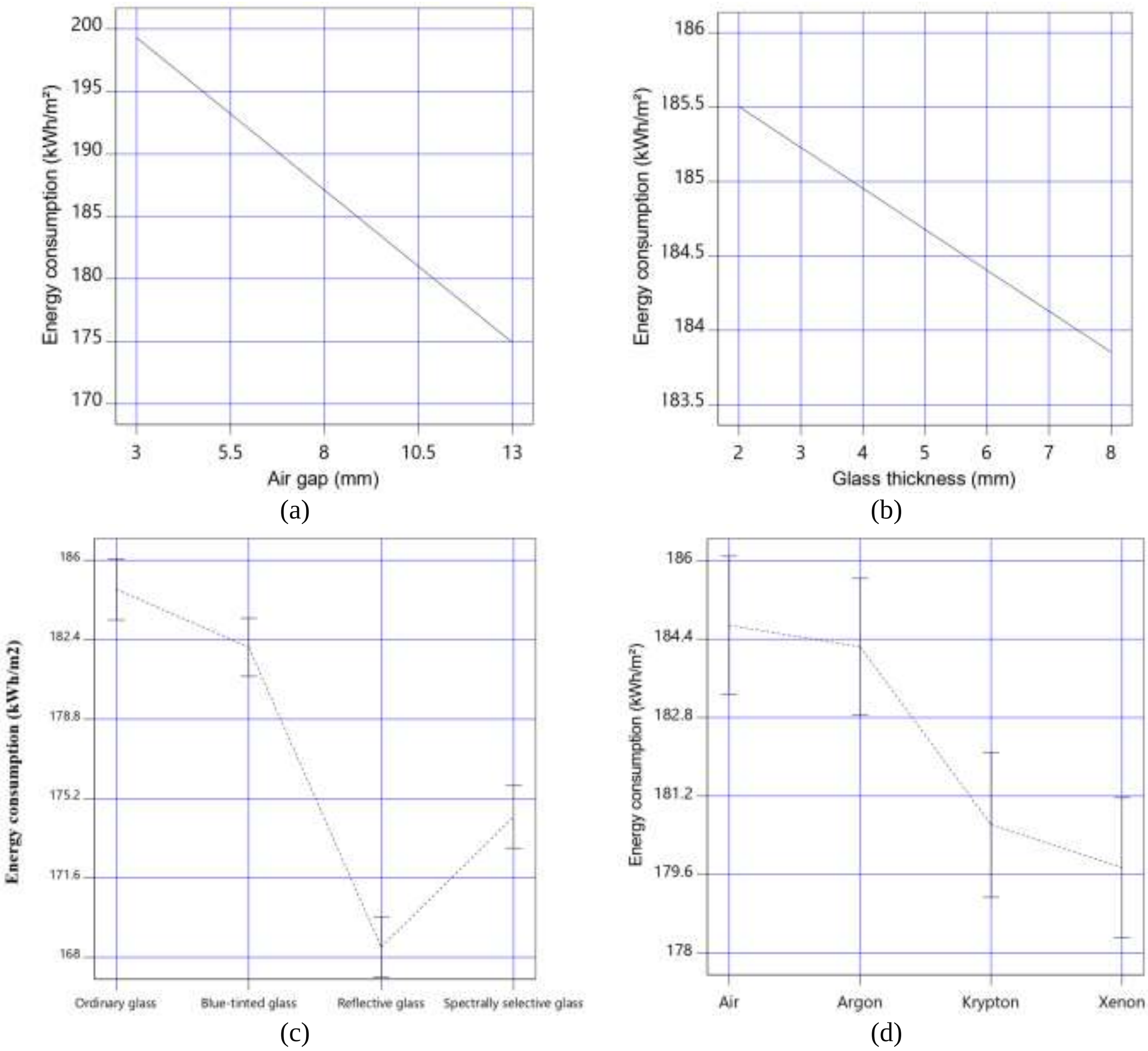
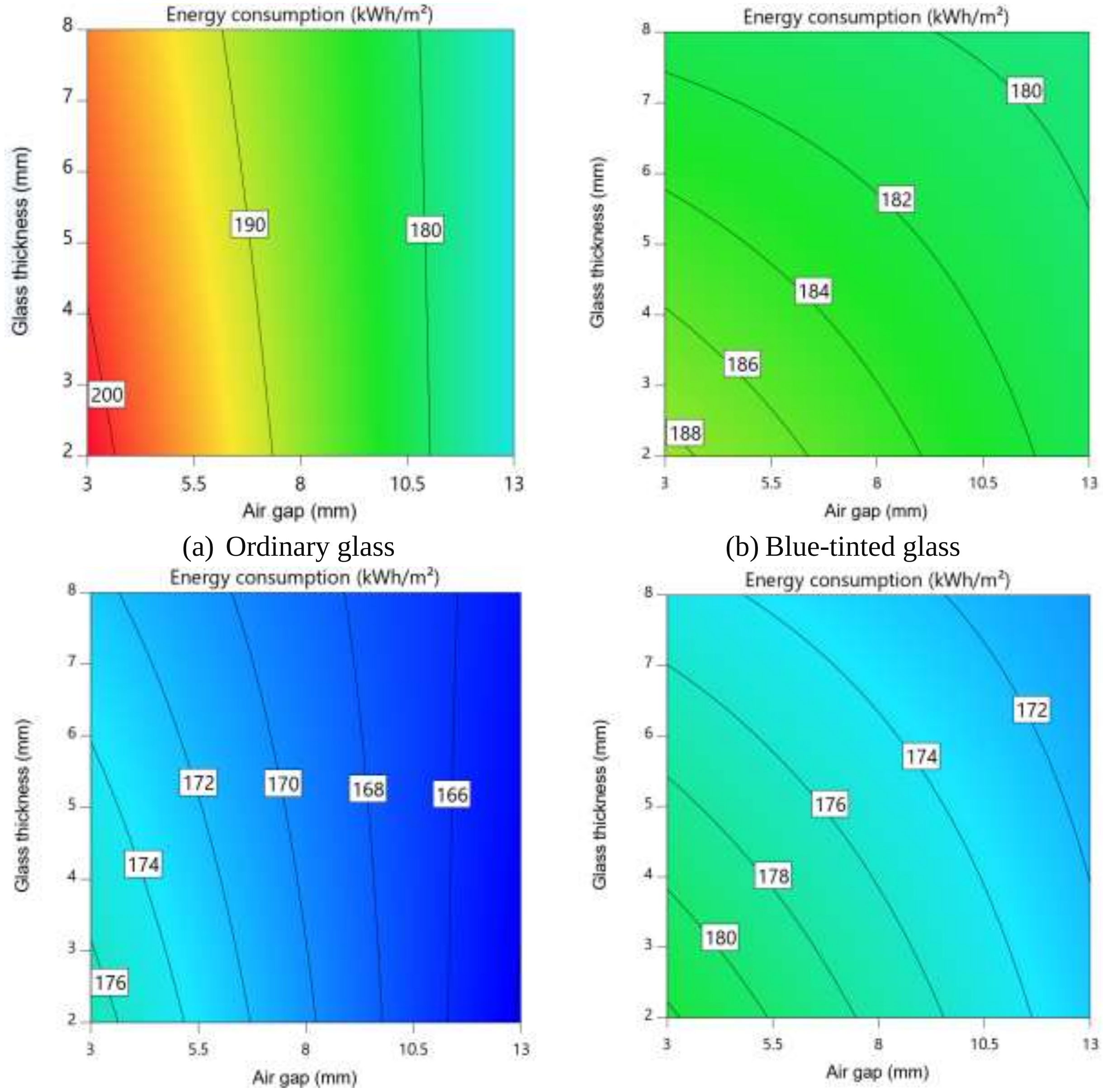


Figure 3. Influence of window system design parameters, including the (a) air gap thickness, (b) glass thickness, (c) glazing type, and (d) cavity gas type, on the building's energy consumption.

Figure 4 illustrates the combined two-dimensional effect of the air gap thickness and glass thickness on the building's energy consumption. The results demonstrate that the air gap thickness has a much stronger influence on reducing energy consumption than the glass thickness. As the air gap thickness increases, the building's energy consumption decreases significantly, reflecting the improved thermal resistance provided by a wider insulating cavity between glazing layers. In contrast, variations in the glass thickness produce comparatively smaller changes in energy consumption, indicating that increasing the pane thickness alone offers only marginal thermal benefits. The interaction between these two parameters suggests that the optimal reduction in energy consumption is achieved when larger air gaps are combined with appropriate glass thickness. Overall, the figure highlights that while both factors contribute to the window's thermal performance, optimizing the air gap thickness is considerably more effective than increasing the glass thickness for enhancing building energy efficiency.



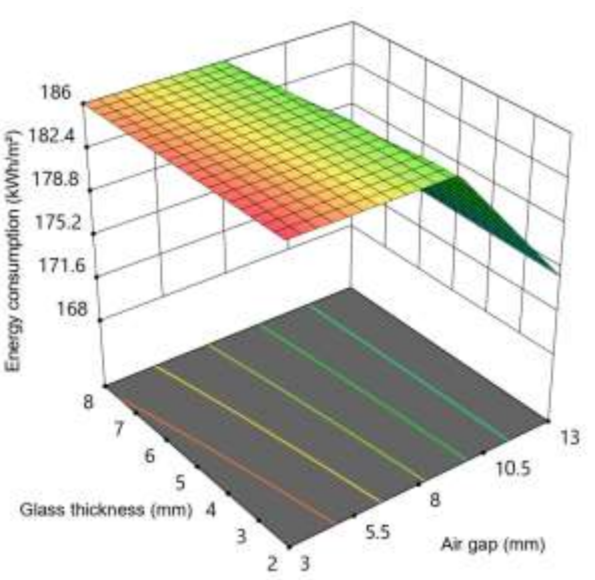
(a) Ordinary glass (b) Blue-tinted glass

(b) Reflective glass (c) Spectrally selective glass

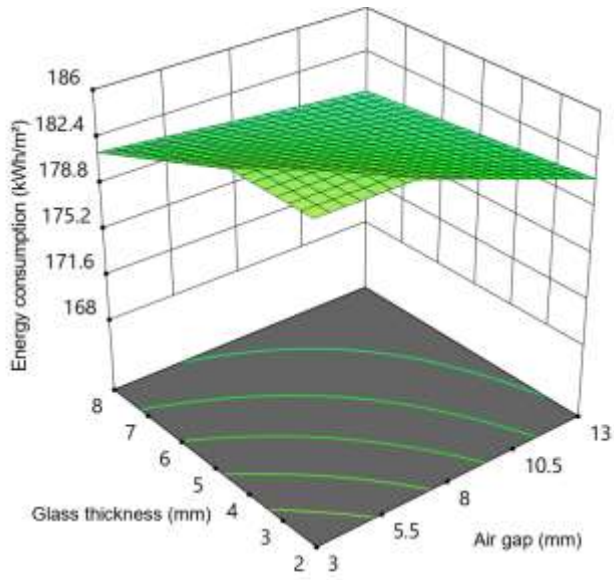
Figure 4. Two dimensional plot of the effect of the air gap thickness and glass thickness on the building's energy consumption.

Although the primary variables in Figure 4 are the air gap and glass thickness, the thermal performance of the glazing system is strongly influenced by the selected glass material. Advanced glass types such as reflective and spectrally selective glasses generally provide lower energy consumption compared with ordinary or blue-tinted glasses due to their enhanced ability to control solar heat absorption and improve insulation performance. Reflective glass reduces solar radiation transmission, thereby lowering cooling loads, while spectrally selective glass allows visible light transmission while blocking excessive infrared heat. In contrast, conventional ordinary glass and blue-tinted glass tend to exhibit higher energy consumption because of their relatively lower thermal efficiency. Therefore, when interpreting the combined effects of the air gap and glass thickness, the selection of high-performance glazing materials can further enhance energy savings and maximize the benefits of optimized window designs. This indicates that the best overall energy performance of buildings is achieved through an integrated approach that combines the suitable air gap thickness, appropriate glass thickness, and advanced glass type.

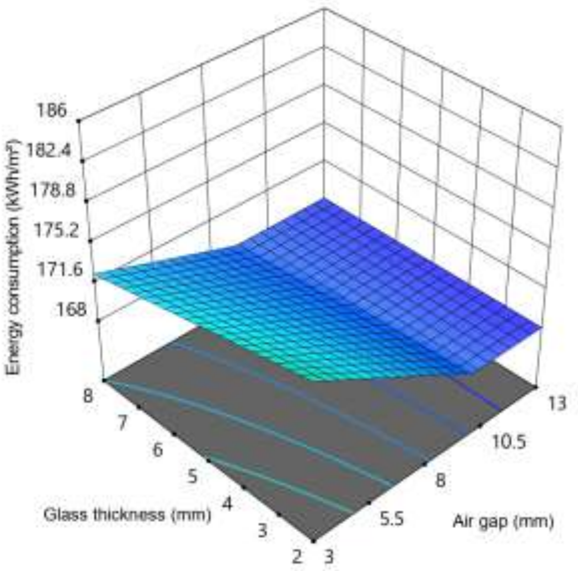
Figure 5 presents the three-dimensional relationship between air the gap thickness, glass thickness, and building's energy consumption, providing a more comprehensive visualization of the combined effects of these two design parameters. The surface plot demonstrates that increasing the air gap thickness leads to a substantial reduction in energy consumption, confirming its dominant role in improving thermal insulation and minimizing heat transfer through the glazing system. As the air gap widens, the insulating performance of the window system improves, resulting in lower overall energy demand of buildings. In comparison, increasing the glass thickness has a relatively smaller effect on energy consumption. While thicker glass contributes slightly to improved insulation, its influence is modest when compared to the pronounced impact of the air gap thickness. The three-dimensional surface therefore slopes more steeply along the air gap axis than along the glass thickness axis, clearly illustrating that the optimizationof the air gap is more critical for energy savings. The figure also implies that the lowest energy consumption of the building is achieved when larger air gaps are combined with thicker glass panes, although the marginal gains from increasing the glass thickness remain limited. Additionally, the effectiveness of these physical parameters can be further enhanced by selecting advanced glazing materials such as reflective or spectrally selective glasses, which provide superior solar control and thermal performance compared to ordinary glazing types. Figure 5 highlights the interactive effects of the air gap thickness and glass thickness on the building's energy performance and emphasizes that optimizing the air gap thickness is the most effective strategy for reducing energy consumption, while the glass thickness serves as a secondary factor. These findings support the importance of integrated glazing designs in achieving energy-efficient building envelopes.



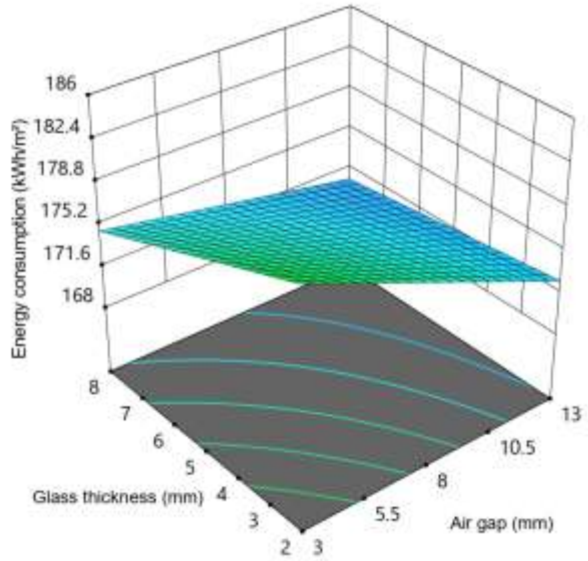
(a) Ordinary glass



(b) Blue-tinted glass



(b) Reflective glass



(c) Spectrally selective glass

Figure 5. Three dimensional plot of the effect of the air gap thickness and glass thickness on the building's energy consumption.

Table 7 summarizes the optimization criteria and design constraints applied in this study for minimizing the building's energy consumption through enhancing the performance of double-glazed window systems. Four primary independent variables were considered in the optimization process: air gap thickness (A), glass thickness (B), glass type (C), and filling gas type (D), each of which was assigned equal importance with a weighting factor of 3. The air gap thickness was evaluated within a range of 3 to 13 mm, while the glass thickness varied between 2 and 8 mm. For the glazing material, the optimization range extended from ordinary glass to spectrally selective glass, and for the filling gas, the range included air to xenon. The objective of the optimization was to minimize the building's energy consumption within the specified response range of 164.2 to 202 kWh/m². Equal lower and upper weights were assigned to all variables and the response, ensuring the balanced consideration of all factors during the numerical optimization process. These optimization constraints allowed the RSM model to systematically identify the most efficient combination of glazing parameters while maintaining realistic design boundaries. The range of selected parameters reflects the practical limitations of construction and commercially available materials, ensuring that the optimized solutions are both technically feasible and applicable to real-world building designs. Overall, this optimization framework provided a structured approach for evaluating the combined effects of multiple glazing parameters and enabled the identification of an optimal double-glazed window configuration that significantly reduces the building's energy consumption under Tehra'sn climatic conditions.

Table 7.
Optimization goals, design variable constraints, and importance levels for double-glazed window system parameters used in the RSM analysis.

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Air gap thickness	is in range	3	13	1	1	3
B:Glass thickness	is in range	2	8	1	1	3
C:Glass type	is in range	Ordinary glass	Spectrally selective glass	1	1	3
D:Filling gas	is in range	Air	Xenon	1	1	3
Energy consumption	minimize	164.2	202	1	1	3

Table 8 presents the optimal solutions generated through the RSM numerical optimization process for minimizing the building's energy consumption in double-glazed window systems under Tehran's climatic conditions. The table includes multiple design configurations that satisfy the optimization criteria with a desirability value of 1.000, indicating that all listed solutions fully meet the defined optimization objectives and constraints. The optimized solutions demonstrate that low energy consumption values can be achieved through different combinations of the air gap thickness, glass thickness, glass type, and filling gas. Most of the optimal configurations are associated with the relatively large air gap thicknesses, generally ranging from approximately 12.75 mm to 14.97 mm, confirming that wider glazing cavities significantly improve thermal insulation and reduce energy demand. Similarly, glass thickness values vary across the solutions, suggesting that while the glass thickness contributes to thermal performance, it provides flexibility within the optimized range. Reflective glass appears in the majority of the optimal solutions, highlighting its superior ability to reduce the building's energy consumption through enhanced solar heat control. This finding confirms the effectiveness of reflective glazing in improving the overall energy efficiency of buildings. In terms of the filling gas, Xenon and Krypton generally produce the lowest energy consumption values due to their superior thermal insulation properties, although some solutions with Air also achieve highly favorable results when combined with optimized structural parameters. Among all proposed solutions, Solution 9 achieved the lowest energy consumption value of 161.469 kWh/m² with an air gap thickness of 12.75 mm, glass thickness of 2.825 mm, reflective glass type, and Xenon gas filling. This configuration represents the most energy-efficient design identified in the study. Other solutions with slightly different parameter combinations also demonstrated similarly low energy consumption, indicating that multiple practical design alternatives can achieve near-optimal performance. Table 8 highlights the effectiveness of the optimization model in identifying several high-performance double-glazed window configurations. The results emphasize that maximizing the air gap thickness, selecting reflective glass, and utilizing advanced inert gases such as Krypton or Xenon are the most effective strategies for minimizing the building's energy consumption. These findings provide valuable design guidance for developing energy-efficient glazing systems in climates similar to Tehran's.

Table 8.
Optimal design solutions generated by RSM for minimizing the building's energy consumption in double-glazed window systems under Tehran's climatic conditions.

Number	Air gap thickness	Glass thickness	Glass type	D	Energy consumption	Desirability	
1	13.593	6.891	Reflective glass	Xenon	163.437	1.000	
2	14.261	7.247	Reflective glass	Air	163.702	1.000	
3	14.932	7.368	Reflective glass	Air	163.188	1.000	
4	14.806	2.417	Ordinary glass	Xenon	163.004	1.000	
5	14.367	4.836	Reflective glass	Air	162.886	1.000	
6	13.773	6.902	Reflective glass	Air	164.021	1.000	
7	14.578	6.173	Reflective glass	Air	163.094	1.000	
8	13.949	3.946	Reflective glass	Air	163.087	1.000	
9	***12.750***	***2.825***	***Reflective glass***	***Xenon***	***161.469***	***1.000***	**Selected**
10	14.300	4.450	Reflective glass	Air	162.842	1.000	
11	14.965	2.199	Ordinary glass	Xenon	162.362	1.000	
12	13.350	6.875	Reflective glass	Xenon	163.634	1.000	
13	14.690	6.575	Reflective glass	Air	163.124	1.000	
14	14.646	3.730	Reflective glass	Air	162.232	1.000	
15	14.771	3.512	Ordinary glass	Xenon	164.158	1.000	

16	14.955	2.012	Ordinary glass	Krypton	164.157	1.000
17	14.525	7.775	Reflective glass	Air	163.650	1.000
18	13.749	7.000	Reflective glass	Air	164.066	1.000
19	13.915	3.018	Reflective glass	Air	162.883	1.000
20	12.800	4.600	Reflective glass	Krypton	161.944	1.000

4.2. Practical Implications for Building Designs

The optimized glazing configurations identified in this study have important implications for the design and operation of high-rise office buildings. The results demonstrate that the appropriate selection of the glazing type, cavity thickness, and filling gas can significantly reduce the building’s energy consumption and improve the thermal performance of the building envelope. In practical applications, these improvements can contribute to lower heating and cooling loads, reduced HVAC system capacity requirements, and improved indoor thermal comfort for occupants. The findings may assist architects and façade designers during the early design stages by providing guidance on the selection of high-performance window systems. In particular, the use of the reflective glazing combined with an optimized cavity thickness can be readily implemented in commercial buildings to reduce solar heat absorption and improve energy efficiency. Furthermore, the developed optimization framework can support decision-making processes by enabling designers to evaluate the combined effects of multiple glazing parameters rather than considering each parameter independently. Although the optimum configuration identified in this study included krypton gas filling, the practical implementation should consider factors such as material availability, installation costs, maintenance requirements, and project-specific energy performance targets. Therefore, the results should be interpreted as a technical benchmark for high-performance glazing designs, while the final material selection should account for both thermal and economic considerations.

5. Conclusion

This study successfully optimized the thermal performance of double-glazed window systems under Tehran climatic conditions to minimize the building’s energy consumption through the application of the Response Surface Methodology. By evaluating the effects of the glass thickness, glass type, air-gap thickness and filling gas type, the research identified the most effective window design parameters for enhancing the building’s energy efficiency. The results confirmed that the air-gap thickness is one of the most significant factors influencing thermal performance, with larger air gaps substantially reducing the building’s energy consumption due to improved insulation properties. The glass thickness also contributed positively to reducing energy demand, although its impact was less pronounced than that of the air-gap thickness. Among the filling gases investigated, xenon demonstrated the highest thermal resistance and provided the greatest reduction in energy consumption. Similarly, reflective glass outperformed ordinary, blue-tinted, and spectrally selective glass types by offering superior solar heat control and minimizing cooling loads. The optimization process revealed that the most energy-efficient double-glazed window configuration consists of reflective glass, xenon gas filling, an air-gap thickness of 12.75 mm, and a glass thickness of 2.825 mm. This optimized design achieved the minimum energy consumption of 161.46 kWh/m² in buildings, representing the best thermal performance among all evaluated combinations. Overall, the findings highlight the critical importance of integrating multiple glazing parameters in window system designs to maximize the building's energy savings. The study provides valuable practical guidance for architects, engineers, and policymakers in designing energy-efficient building envelopes, particularly in climates similar to Tehran's. By adopting optimized double-glazed window configurations, substantial reductions in heating and cooling energy demand can be achieved, contributing to more sustainable building practices and lower environmental impacts. Future studies may expand this work by examining the economic feasibility, long-term durability, and performance under different climatic conditions to further advance sustainable glazing technologies.

The findings demonstrate that integrating the Response Surface Methodology with the building energy analysis provides an effective framework for optimizing the glazing systems and improving the energy performance of high-rise office buildings. By evaluating both the individual and interaction effects of glazing parameters, the proposed approach offers practical guidance for energy-efficient window designs. Future research should investigate the economic feasibility and life-cycle performance of optimized glazing systems, as well as their impacts on the thermal comfort, daylight availability, and occupant satisfaction across different building types and climatic conditions.

Nomenclatures		**Unit**
Abbreviations		
ANOVA	Analysis of Variance	-
BE-PCM	Binary-eutectic phase change materials	-
CCD	Central Composite Design	-
DOE	Design of Experiments	-
EC	Energy consumption	(kWh/m^2)
HVAC	Heating, Ventilation, and Air Conditioning	-
RSM	Response Surface Methodology	-

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