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Decision support for energy-efficient façade design

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Research Paper

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Decision support for energy-efficient façade design

This study aimed to evaluate the impact of façade design parameters in north-oriented residential buildings, where scenic views take priority over ideal climatic orientation, and develop design strategies that ensure optimal energy performance under these specific contextual limitations. A decision-support model is proposed to analyse the sensitivity of façade design parameters to heating and cooling loads as well as CO₂ emission values, and to identify optimal façade solutions through three main stages: creating the building model, applying the sensitivity analysis method, and applying the optimisation method.

Key words:

residential buildings, energy-efficient façade, energy modelling, sensitivity analysis, optimisation

Prethodno priopćenje

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Potpora odlučivanju o energetske učinkovitosti projektiranja pročelja

Cilj ovog istraživanja bio je procijeniti utjecaj parametara projektiranja pročelja stambenih zgrada orijentiranih prema sjeveru, čija slikovita vizura ima prednost pred klimatski najpovoljnijom orijentacijom, te razviti projektne smjernice kojima se, unatoč prostornim ograničenjima, može postići optimalna energetska učinkovitost. U tu je svrhu razvijen model za potporu odlučivanju kojim se analizira osjetljivost projektnih parametara pročelja na potrebe za grijanjem i hlađenjem te na emisije CO₂, uz istodobno određivanje optimalnog rješenja za pročelje. Model se temelji na trima osnovnim fazama: izradi modela zgrade, primjeni analize osjetljivosti te postupku optimizacije.

Ključne riječi:

stambene zgrade, energetske učinkovito pročelje, energetske modeliranje, analiza osjetljivosti, optimizacija

1. Introduction

The energy problems experienced in meeting the needs for housing inevitably make it necessary to ensure energy efficiency in housing production. Different alternatives must be defined and compared during the design stage to provide the desired performance in terms of energy efficiency. Decision support systems are important tools for improving the energy performance of buildings, particularly during the early design stages [1]. At this stage, when decisions have the highest impact on final performance and costs, it is important to support decision-making and guide the design to increase performance [2]. Because of the need to predict the results of decisions made at the design stage, the use of sensitivity analysis in building energy performance analysis has increased [3]. Sensitivity analysis, which is used to determine the key parameters affecting the performance of a building, is a measure of the effect of an input on the output. To provide decision support during the design stage, sensitivity analysis has been integrated into multi-criteria decision-making systems and multi-objective optimisation processes to investigate the parameters affecting the energy consumption of buildings and the value ranges for these parameters [4, 5]. The study conducted by Ulukavak Harputlugil [6] proposed a design guideline model that provides decision support for designers to improve building performance by analysing different climate zones in Türkiye. Tian stated that a sensitivity analysis can be used to identify the key variables affecting the energy performance of a building from both energy simulation models and observational studies [5]. Yildiz et al. used a sensitivity analysis to investigate the annual cooling energy load for low-rise apartment buildings in hot-humid climates in Türkiye [7]. Gerçek and Arsan used a sensitivity analysis to determine the most important parameters for annual heating and cooling energy loads for residential buildings in a hot-humid climate region under current and future climate conditions [8]. In decision support system studies, along with sensitivity analysis, the optimisation approach plays an important role with its potential to simultaneously fulfil conflicting objectives regarding building energy performance. In his study of the three most common housing prototypes in Vietnam, Nguyen [9] obtained the best design strategy combinations for each climate zone through a simulation-based optimisation method using the results of the most effective design variables revealed in the sensitivity analysis. Şenel Solmaz [10] developed a simulation-based multi-objective optimisation method to optimise the envelope parameters of an office building located in İzmir, Turkey, and evaluated the results within the framework of a holistic decision support approach. Mangan developed a Web-based decision support tool focused on energy and cost that can provide positive feedback on low awareness levels in the housing sector to support the development and adoption of sustainable residential buildings [11]. The decision support tool that analyses design alternatives that meet conflicting goals in Mangan's study has become a starting point for providing

effective guidance to decision makers. In optimisation studies, a large body of research has focused on optimising façade design. Gagne and Andersen used a genetic algorithm to optimise the values of glazing material parameters, façade openings, and the geometric properties of shading elements according to the daylighting performance of the façade design [12]. The optimisation model created by Jin [13] determined the optimal façade solutions that performed better than the solutions obtained from the traditional façade design process in terms of CO₂ emission value and cost. Kültür et al. [14] presented a holistic decision support tool based on the interdependent relationships among façade performance, façade parameters, and conditions, developed to guide decisionmakers in the early stages of façade design. To support decisions to be made for building performance optimisation, they developed software such as BEopt, GenOpt, Op-E-Plus, MOBO, and jEPlus+EA, as well as various optimisation tools in areas such as passive building design, energy consumption, and environmental impact. Tokarik et al. optimised the passive energy-efficiency parameters of a high-performance house in Toronto in a multi-objective optimisation environment created using the jEPlus program to search for configurations that provide optimal building performance and life-cycle costs [15, 16]. Kahsay et al. aimed to reduce energy consumption using simulation-based optimisation in a jEPlus+EA environment to determine the optimal window sizing and configuration of a high-rise building. [17].

Numerous studies have emphasised the importance of providing decision support tools during the early design stages to improve the energy performance of buildings, as design decisions made during this phase have a significant and long-lasting impact on the overall building energy use [18, 19]. However, a noticeable gap exists in decision support when contextual constraints limit the implementation of climate design strategies. In particular, when environmental or locational parameters restrict the ability to make optimal orientation decisions, the potential for reducing energy losses through passive design is also constrained [20, 21]. A relevant example can be observed in the northern regions of Turkey (e.g. the Black Sea Region), where houses are often oriented north because of scenic sea views. As a result, the north-facing façade becomes the primary interface that affects the energy performance. Given that the building envelope, particularly the façade, accounts for the majority of the heat transfer between indoor and outdoor environments, early design decisions regarding façades in such contextually constrained buildings are crucial for optimising the thermal performance [22-24]. Therefore, understanding the influence of façade design parameters on energy loads in buildings with orientation constraints is critical for achieving energy efficiency during the operational phase. In this regard, this study aims to evaluate the impact of façade design parameters in north-oriented residential buildings and develop design strategies that ensure optimal energy performance under these specific contextual limitations.

2. Material and methods

The model aims to develop a decision support system that optimises façade design solutions by evaluating façade design parameters and ensuring informed decision-making in residential building designs to enhance energy performance. In this context, the following are intended:

- Reaching design alternatives to provide optimal benefits for improving the energy performance of residential buildings.
- Producing houses with optimal energy performance through the application of the model at the design stage.

The stages of the approach, which aim to evaluate the energy performance of residential buildings in terms of façade design parameters, are given below and schematically explained in Figure 1 [25].

- Creating a building model
- Application of the sensitivity analysis method
- Applying the optimisation method.

The approach developed for assessing the energy performance of residential buildings can be considered as a subprocess within the design phase and is applicable to newly designed buildings. Therefore, the developed approach was based on a building model designed for residential use.

2.1. Creating the building model

The stage of creating a building model involves defining the building model and developing alternatives. To define the building model stage, parameters related to users, climate, and buildings were considered [26]. A building model was proposed for the Province of Samsun, located in the Black Sea region of Turkey, with a dominant north orientation. The DesignBuilder program was used to create the building model. It is an interface program developed to measure the building energy performance using EnergyPlus software [27].

For the user-related parameters, based on official research data on family structures in Samsun, a user scheme was created in which a household consisted of three users: two parents (one of whom was employed) and one child [28]. The user activity level was defined as 110 W/person

[29]. The user clothing type was set to 1 clo during the heating period, and 0.5 clo during the cooling period. For the climate-related parameters, a Typical Meteorological Year (TMY) file was used to analyse the external climate conditions in Samsun [30]. Samsun has a moderately humid climate. In Samsun, the annual average minimum temperature occurs in February and is 3.9 °C, while the annual average maximum temperature is recorded in August at 27.1 °C. The overall annual average temperature is approximately 14.6 °C [31]. As a part of the climate-related parameters for the indoor climate, the heating system was determined as a natural gas heating system to maintain an indoor air comfort temperature of 20 °C between 07:00 and 23:00 and a set temperature of 13 °C

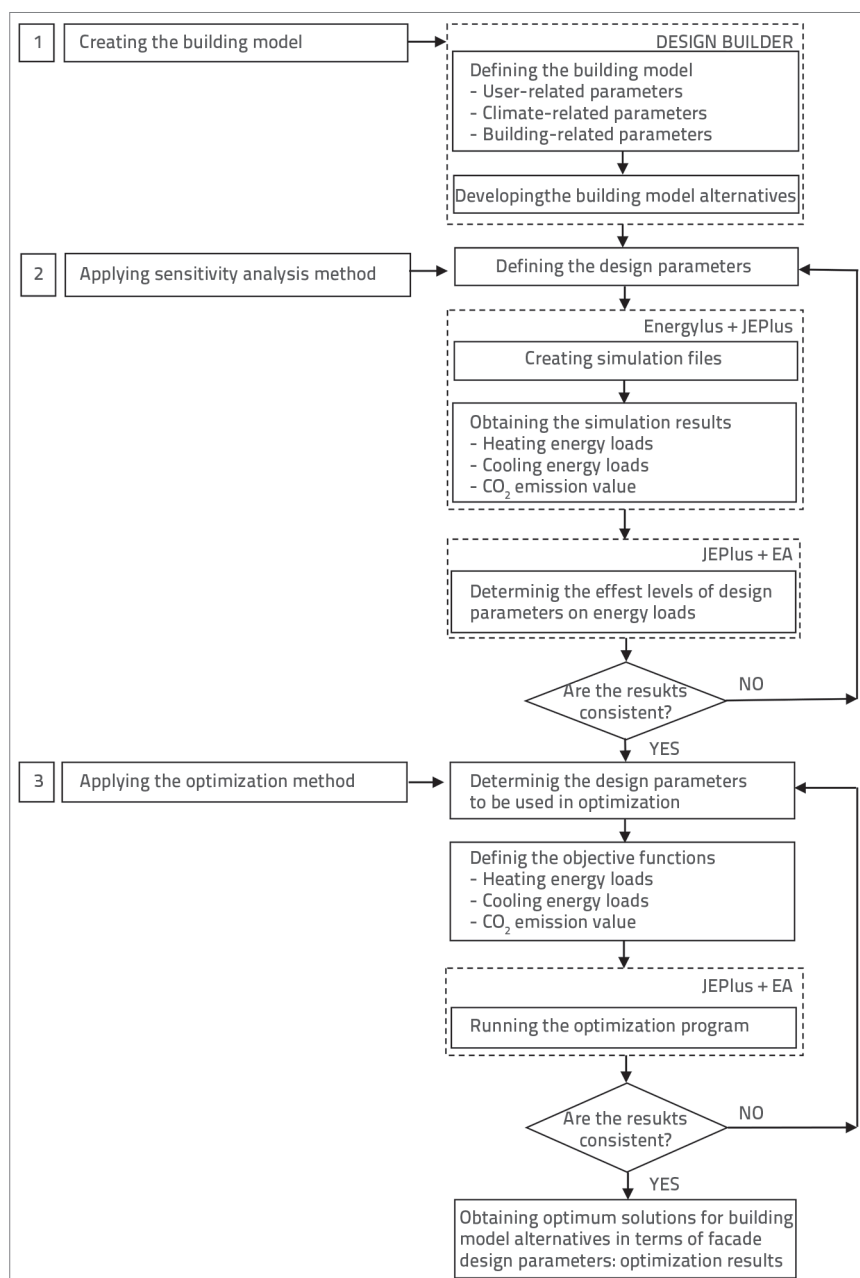


Figure 1. Schematic description of the proposed method [25]

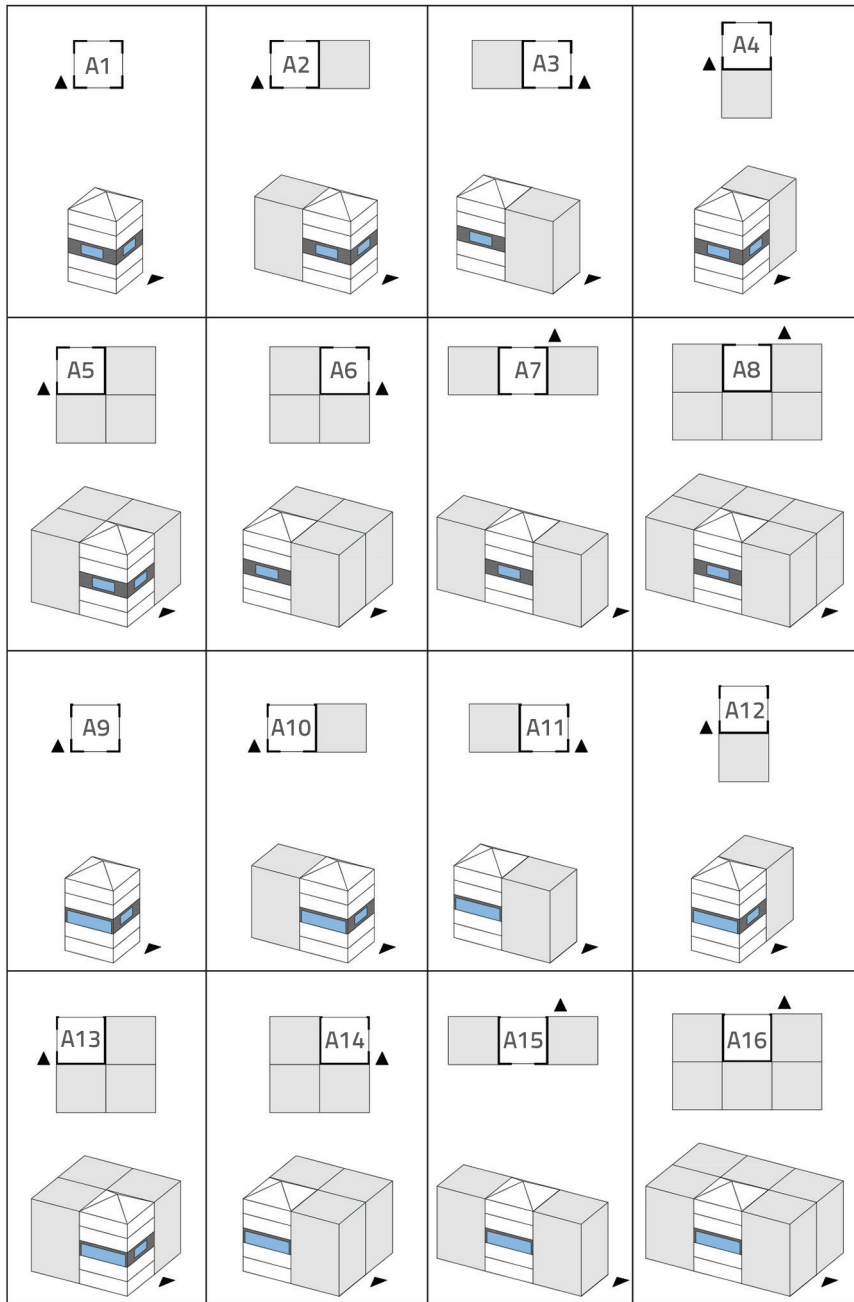


Figure 2. Building model alternatives

during the periods when heating is desired, whereas the cooling system was determined as a wall-type split air conditioner to provide an indoor air comfort temperature of 26 °C between 07:00 and 23:00, and a set temperature of 32 °C during the periods when heating is not desired [32]. A coefficient of performance (COP) of 0.85 was assigned to the heating system, while a COP of 4.50 was assigned to the cooling system, which utilises electricity as its energy source [33]. For building-related design parameters, it was assumed that the building was in a flat area with no surrounding buildings. The building was 10 × 10 m in size, and the floor height was 3 m. The roof was hipped. It had façades in four directions. The

building was modelled as having five floors [34], with one apartment on each floor, and each floor was considered a thermal zone. The study was based on calculations for the 3rd floor, which is the intermediate floor of a building. The layering details and calculated U values for the opaque and transparent components of the building model were 0.59 W/m²K for the exterior wall, 0.53 W/m²K for the floor slab, 0.36 W/m²K for the roof, and 2.40 W/m²K for the window [35]. A 7.5 W/m² LED lamp was used in the artificial lighting system, which had a gradual lighting control that worked in integration with the daylight brightness level. The electrical equipment power was set to 5 W/m² in accordance with residential usage. A blind integrated to the outside of the window was used as a shading element.

The generated building model was called Alternative 1 (A1). Building model alternatives were developed to analyse the impact of the north façade on building performance (Figure 1).

To conduct this analysis, attention was paid to ensure that in each alternative, the north façade featured openings, while the blind façades were placed on the south, east, and west façades in different configurations. Building model alternatives were developed in three steps.

1. The building model defined in the first stage is Alternative 1 (A1).
2. Models (A2–A8) were developed by applying different opaque façade configurations to the first model (A1).
3. Models (A9–A16) were developed by setting the transparency ratio of the northern façades to 80 % in models A1–A8 (Figure 2).

In the first step, the building model designated as Alternative 1 (A1) features all four façades as open, with no fully opaque façades.

In the second step, a series of models (A2–A8) were developed based on the A1 model by assuming the application of different opaque façades. In these variations, the east façade is fully opaque in model A2; the west façade in A3; the south façade in A4; both the south and east façades in A5; the south and west façades in A6; the east and west façades in A7; and the south, east, and west façades in A8. During the development of these models, commonly

used residential building types in Samsun were considered. Although these models adopt a default transparency ratio of 30 % in the building model created using DesignBuilder, during the analysis process, the transparency ratios of all façades vary within an approximate range of 10 % to 80 % based on the parameter values defined during the sensitivity analysis stage. To evaluate the impact of other façades on the overall building performance when the north façade exhibited a high level of transparency, as exemplified in the Samsun case, an additional set of building models was developed in which the transparency ratio of the north façade was kept constant. Models A9 through A16 replicate the fully opaque façade configurations of models A1 through A8, respectively; however, in these models, the north façade was fixed at a high transparency ratio of 80 %. In the third step, models A9–A16 were generated by incorporating large transparent openings on the northern façades of models A1–A8. Model A9 features open façades on all four sides with no fully opaque surfaces. Model A10 features a fully opaque east façade, model A11 a fully opaque west façade, and model A12 a fully opaque south façade. Model A13 includes fully opaque south and east façades, whereas model A14 includes opaque south and west façades. In model A15, the east and west façades were opaque, and in model A16, the south, east, and west façades were entirely opaque. In all models, from A9 to A16, the transparency ratio of the north façade was fixed at 80 %. In these models, while the transparency ratios of the other façades varied, the transparency ratio of the north façade remained constant.

2.2. Applying the sensitivity analysis method

Applying the sensitivity analysis method involves defining the design parameters, creating simulation files, obtaining simulation results, and determining the effect levels of the design parameters on the energy loads. In the first stage of sensitivity analysis, the design parameters were defined in the categories of orientation, window, exterior wall, shading element, and air infiltration rate. The parameters defined under the window category are window width, window height, window solar heat gain coefficient (SHGC), and window U-value. Within the exterior wall category, the parameters were the wall insulation material thickness, wall insulation material specific heat value, and wall insulation material thermal conductivity value. For the shading element category, the parameters were shading element depth and shading element angle. The orientation and air infiltration rate categories were not further subdivided into subparameters. Moreover, while all parameters were defined for each façade (north, south, east, and west), the orientation and air infiltration rate were applied to the entire building and, therefore, were not specified in the façade direction. The value ranges of the parameters were determined based

on the ranges used in previous studies, the boundary values of commonly used construction materials in the building industry, and the Turkish standard TS 825 [35]. Because the values of the defined parameters directly affected the results of the sensitivity analysis, the parameters were assigned as many values as possible, and this was considered when interpreting the results. Table 1 lists the names of the 38 design parameters used in the sensitivity analysis, the façades they affect, their abbreviations, units, and the minimum and maximum values that define the range of each parameter [36].

Among the generated models, the A1 model incorporates values for all 38 parameters, whereas the alternative models produced with different opaque façade configurations include values for a smaller subset of these parameters.

After defining the design parameters and determining their value ranges, jEPlus was used to assign parameter values to each file during the creation of the simulation file. This software defines the parameters within the EnergyPlus model and manages the simulations of the generated parametric inputs [16]. A sample set was produced using the Latin hypercube sampling method by entering the parameters and their value ranges into jEPlus. The Latin hypercube sampling method is a stratified sampling technique designed to provide a better coverage of parameter ranges. In this method, each design parameter is divided into a certain number of intervals and values are generated within these intervals [37, 38]. The sample size was determined according to the commonly recommended practice for the Latin hypercube sampling method, which suggests using a sample size of 1.5 to 10 times the number of parameters. Thus, the sample size was set to eight times the number of parameters ($38 \times 8 = 304$) [39]. This sample size applies only to the A1 model, in which all parameters are assigned values. As the number of opaque façades increases with different façade configurations, models with fewer assigned parameters are simulated with a reduced sample size. Simulation results were obtained by simultaneously varying each parameter of each model. The outputs considered as performance indicators at this stage included the annual heating energy load (kWh), annual cooling energy load (kWh), and CO₂ gas emissions (kg). The heating and cooling energy loads represent the energy required to satisfy the building's thermal comfort setpoints throughout the year, that is, the building's annual energy requirement for space heating and cooling. To determine the effects of the design parameters on the energy loads, the effect of each parameter on the output was assessed separately using the jEPlus+EA program [40].

An additional tool, jEPlus+EA, was developed to optimise jEPlus projects through the use of genetic algorithms [40]. Although relatively new to the research community, the program has demonstrated the ability to produce reliable multi-objective optimisation results with a user-friendly interface and low computational effort [41–44].

Table 1. Parameters used in the sensitivity analysis [35]

Design parameter	Façade	Abbreviation	Unit	Value range
Orientation		(ORI)	degree	0. 45. 315
Window width	North façade	(WW-N)	m	1.5 – 8.5
	South façade	(WW-S)	m	1.5 – 8.5
	East façade	(WW-E)	m	1.5 – 8.5
	West façade	(WW-W)	m	1.5 – 8.5
Window height	North façade	(WH-N)	m	1.5 – 2.5
	South façade	(WH-S)	m	1.5 – 2.5
	East façade	(WH-E)	m	1.5 – 2.5
	West façade	(WH-W)	m	1.5 – 2.5
Window solar heat gain coefficient	North façade	(SHGC-N)	-	0.51 – 0.86
	South façade	(SHGC-S)	-	0.51 – 0.86
	East façade	(SHGC-E)	-	0.51 – 0.86
	West façade	(SHGC-W)	-	0.51 – 0.86
Window U value	North façade	(Uw-N)	W/m ² K	0.8 – 2.4
	South façade	(Uw-S)	W/m ² K	0.8 – 2.4
	East façade	(Uw-E)	W/m ² K	0.8 – 2.4
	West façade	(Uw-W)	W/m ² K	0.8 – 2.4
Wall insulation material thickness	North façade	(IT-N)	m	0.01 – 0.1
	South façade	(IT-S)	m	0.01 – 0.1
	East façade	(IT-E)	m	0.01 – 0.1
	West façade	(IT-W)	m	0.01 – 0.1
Wall insulation material specific heat value	North façade	(ISHV-N)	J/kg-K	600 – 2000
	South façade	(ISHV-S)	J/kg-K	600 – 2000
	East façade	(ISHV-E)	J/kg-K	600 – 2000
	West façade	(ISHV-W)	J/kg-K	600 – 2000
Wall insulation material thermal conductivity value	North façade	(ICV-N)	W/mK	0.03 – 0.04
	South façade	(ICV-S)	W/mK	0.03 – 0.04
	East façade	(ICV-E)	W/mK	0.03 – 0.04
	West façade	(ICV-W)	W/mK	0.03 – 0.04
Shading element depth	North façade	(SED-N)	m	0.1 – 0.2
	South façade	(SED-S)	m	0.1 – 0.2
	East façade	(SED-E)	m	0.1 – 0.2
	West façade	(SED-W)	m	0.1 – 0.2
Shading element angle	North façade	(SEA-N)	stupanj	10 – 90
	South façade	(SEA-S)	stupanj	10 – 90
	East façade	(SEA-E)	stupanj	10 – 90
	West façade	(SEA-W)	stupanj	10 – 90
Air infiltration rate		(AIR)	ach	0.1 – 1.2

Table 2 presents the top five most effective parameters when the façade design parameters are ranked according to their level of effect on the heating and cooling energy loads and CO₂ emission values (A1–A16). The parameters in these tables are listed using the abbreviations listed in Table 1. The table shows that with respect to the heating energy load, the air infiltration rate (AIR) is consistently identified as the most influential parameter across all models. When the top five parameters influencing heating energy load are examined, it is observed that they predominantly include the air infiltration rate (AIR), orientation (ORI), and, within the window category, window width (WW), solar heat gain coefficient (SHGC), and window U-Value (U_w), as well as wall insulation material thickness (IT) from the wall category. When the impact of these parameters on the cooling energy load was examined, it was found that the window width (WW) consistently ranked among the most influential parameters across all models. The top five parameters influencing cooling energy load most

frequently include the air infiltration rate (AIR), orientation (ORI), and, within the window category, window width (WW), window height (WH), solar heat gain coefficient (SHGC), and window U -Value (U_w). When the impact of the parameters on CO₂ emissions was examined, the air infiltration rate (AIR) is found to be the most influential parameter across all models. The top five parameters affecting CO₂ emissions are most commonly air infiltration rate (AIR), orientation (ORI), and, within the window category, window width (WW), solar heat gain coefficient (SHGC), window U-Value (UW), as well as wall insulation material thickness (IT) for the wall category. The sensitivity analysis results presented in Table 2 indicate that the relative importance of the design parameters influencing the heating and cooling energy loads and CO₂ emissions varied. However, across all cases, the top five parameters consistently included the air infiltration rate, orientation, window width, solar heat gain coefficient, window U-value, and wall insulation material thickness.

Table 2. Effect levels of parameters on heating and cooling loads and CO₂ emissions

	Four façades		Three façades					
	A1	A9	A2	A10	A3	A11	A4	A12
Required energy								
Heating	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)
	(WW-S)	(WW-S)	(WW-S)	(WW-S)	(WW-S)	(WW-S)	(WW-E)	(Uw-N)
	(SHGC-S)	(Uw-N)	(ORI)	(ORI)	(ORI)	(ORI)	(WW-W)	(WW-E)
	(WW-E)	(SHGC-S)	(SHGC-S)	(Uw-N)	(SHGC-S)	(Uw-N)	(SHGC-E)	(SHGC-E)
	(IT-W)	(WW-E)	(WW-W)	(SHGC-S)	(WW-E)	(SHGC-S)	(SHGC-W)	(SHGC-W)
Cooling	(WW-E)	(WW-E)	(WW-S)	(WW-S)	(WW-E)	(WW-E)	(WW-E)	(WW-E)
	(WW-S)	(SHGC-N)	(WW-N)	(SHGC-N)	(WW-S)	(SHGC-E)	(WW-W)	(ORI)
	(SHGC-E)	(WW-S)	(AIR)	(WW-W)	(SHGC-E)	(WW-S)	(WW-N)	(SHGC-N)
	(AIR)	(SHGC-E)	(SHGC-S)	(AIR)	(WW-N)	(SHGC-N)	(SHGC-E)	(SHGC-E)
	(WW-W)	(AIR)	(WW-W)	(SHGC-S)	(SHGC-S)	(AIR)	(AIR)	(WW-W)
CO ₂ Emission	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)
	(WW-E)	(WW-E)	(WW-N)	(ORI)	(ORI)	(WW-E)	(WW-N)	(Uw-N)
	(WW-N)	(SHGC-N)	(WH-N)	(Uw-W)	(WW-E)	(SHGC-N)	(WW-E)	(ORI)
	(SEA-S)	(WW-W)	(ORI)	(SEA-N)	(WW-N)	(SHGC-E)	(IT-E)	(WW-E)
	(IT-W)	(SHGC-E)	(IT-W)	(Uw-N)	(IT-N)	(ORI)	(SEA-W)	(IT-E)

Table 2. Effect levels of parameters on heating and cooling loads and CO₂ emissions - continuens

Required energy	Two façades						One façade	
	A5	A13	A6	A14	A7	A15	A8	A16
								
Heating	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)
	(ORI)	(ORI)	(ORI)	(ORI)	(WW-S)	(WW-S)	(Uw-N)	(Uw-N)
	(WW-E)	(Uw-N)	(WW-E)	(WW-E)	(SHGC-S)	(Uw-N)	(IT-N)	(SHGC-N)
	(Uw-N)	(SHGC-N)	(SHGC-E)	(Uw-N)	(WH-S)	(SHGC-S)	(SHGC-N)	(IT-N)
	(Uw-W)	(WW-W)	(IT-N)	(SHGC-N)	(Uw-S)	(Uw-S)	(WW-N)	(ORI)
Cooling	(WW-N)	(SHGC-N)	(WW-E)	(WW-E)	(WW-S)	(SHGC-N)	(WW-N)	(SHGC-N)
	(WW-W)	(WW-W)	(WW-N)	(ORI)	(WW-N)	(WW-S)	(AIR)	(ORI)
	(AIR)	(ORI)	(ORI)	(SHGC-N)	(SHGC-S)	(AIR)	(SHGC-N)	(Uw-N)
	(SHGC-N)	(AIR)	(SHGC-E)	(SHGC-E)	(AIR)	(SHGC-S)	(ORI)	(AIR)
	(SHGC-W)	(Uw-N)	(AIR)	(AIR)	(SHGC-N)	(WH-S)	(WH-N)	(SEA-N)
CO ₂ Emission	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)	(AIR)
	(ORI)	(ORI)	(ORI)	(ORI)	(WW-N)	(SHGC-N)	(IT-N)	(Uw-N)
	(Uw-N)	(Uw-N)	(WW-N)	(Uw-N)	(WW-S)	(Uw-N)	(WW-N)	(ORI)
	(Uw-W)	(Uw-W)	(WW-E)	(Uw-E)	(Uw-S)	(WH-S)	(Uw-N)	(SEA-N)
	(WW-N)	(IT-W)	(IT-N)	(WW-E)	(WH-N)	(SEA-S)	(ORI)	(ISHV-N)

2.3. Applying the optimisation method

The optimisation method includes determining the design parameters to be used in the optimisation, defining the objective function, running the optimisation program, and obtaining optimum solutions for the building model alternatives in terms of façade design parameters (optimisation results). The parameters used in the optimisation were determined by further detailing the design parameters defined in the initial stage of the sensitivity analysis based on the results of the sensitivity analysis. The sensitivity analysis results demonstrated that the importance ranking of the design parameters affecting the heating and cooling energy loads and CO₂ emissions varied across the models. However, the air infiltration rate and orientation affected the entire building, together with the window solar heat gain coefficient, window width, window U-value, and wall insulation material thickness evaluated per façade, which consistently ranked among the top five influential parameters (Table 2). In the optimisation stage, the significant parameters from the sensitivity analysis were further specified using different material types and layers, particularly within the window and wall categories, to allow the evaluation of various material alternatives. Additionally, the air infiltration rate parameter, which ranged between 0.1 and

1.2 in the sensitivity analysis, was fixed at a value of 0.5 and included in the optimisation process due to its dominant role in the sensitivity analysis results.

Notably, the solar heat gain coefficient (SHGC) and window U-value (U_w) parameters identified during the sensitivity analysis were combined to form a glass-type (GT) parameter for optimisation (Table 3). Similarly, the insulation material type (IMT) parameters in the optimisation were created by integrating the wall insulation material thickness (IT), thermal conductivity (ICV), and specific heat value (ISHV) from the wall category (Table 4). Whereas the sensitivity analysis assessed the independent effect of each parameter (with a total of 38 parameters), the optimisation stage analysed the combined material alternatives, reducing the parameter count to 25. Table 3 lists the glass-type parameters used in the optimisation, whereas Table 4 lists the insulation material-type parameters [45]. The glass type and insulation material type parameters were determined based on construction materials commonly used in the building industry and the Turkish standard TS 825 [35]. The values of the orientation, window width, window height, shading element depth, shading element angle, air infiltration rate, and the values of the materials defined in the glass- and insulation-material-type parameters were analysed in the optimisation stage. Table 5 lists the names of the design

Table 3. Glass type parameter values

No.	Glass type	Layers	Surface	Filling	SHGC Value	UW
1	Uncoated	4+16+4	Clear glass	16 mm argon	0.78	2.6
2		4+12+4+12+4	Clear glass	12 mm air	0.71	1.9
3		4+16+4+16+4	Clear glass	16 mm argon	0.71	1.7
4	Heat control coated	4+12+4	Low-E glass	12 mm air	0.55	1.6
5		4+16+4	Low-E glass	16 mm argon	0.55	1.1
6		4+12+4+12+4	Low-E glass	12 mm air	0.48	0.9
7		4+16+4+16+4	Low-E glass	16 mm argon	0.48	0.6
8	Heat and sun control coated	4+12+4	Solar low-E glass	12 mm air	0.44	1.6
9		4+16+4	Solar low-E glass	16 mm argon	0.44	1.1
10		4+12+4+12+4	Solar low-E glass	12 mm air	0.4	0.9
11		4+16+4+16+4	Solar low-E glass	16 mm argon	0.4	0.6

Table 4. Insulation material type parameter values

No.	Insulation material type	Thickness [mm]	Thermal conductivity value [W/m K]	Specific heat value [J/kg K]
1	Rockwool	50	0.037	840
2		60	0.037	840
3		80	0.037	840
4		100	0.037	840
5	Expanded polystyrene foam (EPS)	50	0.039	1500
6		60	0.039	1500
7		70	0.039	1500
8		80	0.039	1500
9		100	0.039	1500
10		120	0.039	1500
11	Extruded polystyrene foam (XPS)	50	0.035	1500
12		60	0.035	1500
13		70	0.035	1500
14		80	0.035	1500
15		100	0.035	1500
16		120	0.035	1500

parameters, the façades they affect, and their abbreviations. After determining the design parameters to be used in the optimisation, it is necessary to define the project goals and building performance criteria to be improved during the formulation of the objective function. In this study, heating energy load, cooling energy load, and CO₂ emission values were set as the three objectives to be minimised simultaneously within the multi-objective optimisation problem. The jEPlus+EA program was used to simultaneously optimise these functions. The CO₂ emissions were calculated using a formula based on the annual heating and cooling energy-load values generated the jEPlus+EA program. The total annual CO₂ emissions were obtained by multiplying the heating and cooling energy loads by

a CO₂ conversion coefficient of 0.234 for natural gas energy and 0.418 for electrical energy, which is related to the type of fuel consumed in Türkiye [33, 11].

The optimisation program was run once the design parameters to be used in the optimisation were determined and the objective function was defined. The NSGA-II algorithm within the jEPlus+EA program was used for the optimisation process, with parameter settings including population size, crossover rate, mutation rate, and iteration number. The NSGA-II integrated with jEPlus+EA provides an effective approach and optimisation framework for architectural design. The recommended value range of the population size is 10–200, the crossover rate is 0.4–0.99, the mutation rate is 0.0001–0.1 and

Table 5. Defining the parameters to be used in optimisation

Design parameter	Façade	Abbreviation	unit	Value range
Orientation		(ORI)	stupanj	0. 45. 315
Window width	North façade	(WW-N)	m	1.5 – 8.5
	South façade	(WW-S)	m	1.5 – 8.5
	East façade	(WW-E)	m	1.5 – 8.5
	West façade	(WW-W)	m	1.5 – 8.5
Window height	North façade	(WH-N)	m	1.5 – 2.5
	South façade	(WH-S)	m	1.5 – 2.5
	East façade	(WH-E)	m	1.5 – 2.5
	West façade	(WH-W)	m	1.5 – 2.5
Glass type (SHGC)–(UW–W/m ² K)	North façade	(GT-N)	-	-
	South façade	(GT-S)	-	-
	East façade	(GT-E)	-	-
	West façade	(GT-W)	-	-
Insulation material type (IT–m)–(ISHV–J/kg–K)–(ICV–W/m K)	North façade	(IMT-N)	-	-
	South façade	(IMT-S)	-	-
	East façade	(IMT-E)	-	-
	West façade	(IMT-W)	-	-
Shading element depth	North façade	(SED-N)	m	0.1 – 0.2
	South façade	(SED-S)	m	0.1 – 0.2
	East façade	(SED-E)	m	0.1 – 0.2
	West façade	(SED-W)	m	0.1–0.2
Shading element angle	North façade	(SEA-N)	stupanj	10 – 90
	South façade	(SEA-S)	stupanj	10 – 90
	East façade	(SEA-E)	stupanj	10 – 90
	West façade	(SEA-W)	stupanj	10 – 90

the maximum generation is less than 1000 [46,47]. In this study, the population size was selected as 20, the crossover rate was 0.9, and the mutation rate was 0.1 in order to obtain the best balance between calculation time and reliable solutions. The optimisation program terminated once the optimal solutions were obtained according to the defined objective function and algorithm. The 16 models produced in this study yielded solution sets that minimised the building's heating and cooling energy loads and CO₂ emissions.

3. Results

The optimisation results were examined based on the heating and cooling energy loads (kWh), CO₂ emission values (kg), and façade design parameter values of the models. Based on the obtained results, the performance ranges obtained from the Pareto-optimal solutions demonstrated considerable variation in heating and cooling energy loads as well as CO₂ emissions.

For the four-open-façade configurations (A1 and A9), the A1 model had an annual heating energy load ranging between 211 and 2080, while the cooling energy load varied between 1071 and 8510, and the annual CO₂ emissions ranged from 292 to 1019. The A9 model had an annual heating energy load ranging between 222 and 2401, the cooling energy load varied between 1645 and 9136, and the annual CO₂ emissions ranged from 367 to 1094.

For the three open-façade configurations, the performance ranges varied depending on which façade was opaque. When the east façade was opaque (A2 and A10), The A2 model exhibited heating loads ranging from 214 to 2172, cooling loads between 749 and 7018, and CO₂ emissions between 240 and 1048. A10 model has heating loads ranged between 230 and 2242, cooling loads between 1173 and 7601, and CO₂ emissions between 311 and 1075. For the west-opaque configuration (A3 and A11), A3 model has heating loads ranged between 168 and 2396, cooling

loads between 1026 and 9290, and CO₂ emissions between 265 and 1102. A11 model has heating loads ranged between 210 and 2273, cooling loads between 1458 and 9361, and CO₂ emissions between 338 and 1146. When the south façade was opaque (A4 and A12), A4 model has heating loads ranged between 275 and 2259, cooling loads between 968 and 9245, and CO₂ emissions between 387 and 1095. A12 model has heating loads ranged between 250 and 2458, cooling loads between 1396 and 9337, and CO₂ emissions between 424 and 1183.

For the two-open-façade configurations, the east- and south-opaque configuration (A5 and A13), A5 model showed heating loads between 380 and 2322, cooling loads between 699 and 5456, and CO₂ emissions between 302 and 1053. A13 model showed heating loads between 417 and 2422, cooling loads between 1113 and 6095, and CO₂ emissions between 376 and 1107. The west- and south-opaque configuration (A6 and A14), A6 model exhibited heating loads ranging from 194 to 2298, cooling loads from 866 to 9147, and CO₂ emissions from 359 to 1116. A14 model exhibited heating loads ranging from 210 to 2648, cooling loads from 1293 to 9781, and CO₂ emissions from 539 to 1190. Similarly, in the east- and west-opaque configurations (A7 and A15), the A7 model resulted in heating loads ranging from 174 and 2067, cooling loads of 686 and 6652, and CO₂ emissions of 215 and 930. The A15 model resulted in heating loads ranging from 185 and 2083, cooling loads of 1240 and 6801, and CO₂ emissions of 301 and 1001.

Finally, for the single-open-façade configuration, in which east, west, and south façades were opaque (A8 and A16), A8 model has heating loads ranged between 1137 and 2257, cooling loads between 651 and 5646, and CO₂ emissions between 504 and 937. A16 model has heating loads ranged between 1152 and 2280, cooling loads between 1095 and 5950, and CO₂ emissions between 510 and 1014.

In addition to pairwise comparisons, the overall analysis of all 16 models (A1–A16) provides a broader understanding of the energy behaviour of buildings with different façade configurations. As the number of opaque façades increased, the total energy demand exhibited a clear upward trend. Models with only one opaque façade (A2–A10, A3–A11, A4–A12), achieved the most balanced performance, as solar gains remained sufficient, while cooling loads remained within a controllable range. Double-opaque-façade models (A5–A13, A6–A14, A7–A15) tended to exhibit higher heating loads depending on orientation. The three-opaque-façade models (A8–A16), which had openings only on the north side, exhibit higher heating loads owing to reduced solar exposure, whereas diffuse daylight during summer also contributed to increased cooling requirements. Consequently, CO₂ emissions followed a similar pattern.

Directional differences also played a crucial role in the energy balance. When the east façade was opaque (A2–A10), the morning solar gains were lost, leading to a slight

increase in the heating load. In contrast, when the west façade was opaque (A3–A11), the afternoon solar radiation was effectively reduced, thus lowering the cooling loads and improving the overall energy performance. Blocking the south façade (A4–A12) resulted in the most pronounced increase in heating demand as winter solar gains were eliminated. East-west opaque configurations (A7–A15) reduced daily radiation asymmetry, producing the lowest CO₂ emissions within their category. When the paired models with different north façade transparency ratios are evaluated, it is evident that increasing the transparency of the north façade generally led to higher heating energy loads and CO₂ emissions, while its effect on cooling loads remains more limited and configuration-dependent. Furthermore, as the number of open façades decreases, the impact of façade parameters became more pronounced, and the sensitivity of the energy performance to transparency variations increased. Overall, these findings highlight that both the transparency level and the number and orientation of open façades must be considered in optimisation processes to achieve balanced and energy-efficient design outcomes.

Subsequently, the analysis was extended to examine the parameter values and the corresponding results for the cases that achieved the minimum performance outcomes (Table 6), focusing specifically on the parameter configurations associated with the minimum values within the performance ranges. Table 6 summarises the design parameter values selected from the Pareto-optimal set that correspond to the minimum heating load, cooling load, or CO₂ emission obtained for each of the functionally related model pairs. A solution was considered Pareto-optimal if it is not possible to minimise one objective without worsening at least one other objective. In Table 6, building models (A1–A16) are positioned in the same row according to the number of façade openings and transparency ratio of the north façade. Thus, the models with openings on four façades are grouped as A1–A9; models with openings on three façades as A2–A10, A3–A11, A4–A12; models with openings on two façades as A5–A13, A6–A14, A7–A15; and models with clear openings on one façade as A8–A16 [24]. This table includes three representative complete solutions selected from the Pareto front of each model. Each solution consisted of a coherent set of parameter values belonging to the same individual, along with the corresponding values for three objective functions: the minimum annual heating energy load, minimum annual cooling energy load, and minimum annual CO₂ emissions. A comparison between models A1–A8 and A9–A16 indicates that while certain parameter values remain consistent across different configurations, others vary depending on the façade arrangement and design conditions. These findings indicate that when the south façade is opaque, the building can achieve minimum values at orientations of 45° and 315°, whereas when the south façade is open,

Table 6. Selected Pareto-optimal solutions minimising heating load, cooling load and CO₂ emissions [24]

	(ORI)	(WW-N)	(WW-S)	(WW-E)	(WW-W)	(WH-N)	(WH-S)	(WH-E)	(WH-W)	(GT-N)	(GT-S)	(GT-E)	(GT-W)	(IMT-N)	(IMT-S)	(IMT-E)	(IMT-W)	(SED-N)	(SED-S)	(SED-E)	(SED-W)	(SEA-N)	(SEA-S)	(SEA-E)	(SEA-W)	Heating [kWh]	Cooling [kWh]	CO ₂ [kg]
A1 	315	1.5	7.5	1.5	8.5	1.70	2.30	1.5	2.50	10	3	7	7	16	11	10	10	0.14	0.1	0.16	0.1	10	10	20	20	211	5.725	590
	0	1.5	1.5	1.5	1.5	1.70	1.5	1.5	1.5	10	4	6	8	1	10	10												
	0	1.5	8.5	1.5	1.5	1.70	2.50	1.5	1.5	10	4	6	8	16	10	10	10	0.20	0.1	0.16	0.16	10	10	10	10	391	1.986	292
	0	-	8.5	1.5	3.5	-	2.50	1.60	1.90	11	3	11	7	15	16	16	15	0.20	0.1	0.16	0.14	10	10	30	10	222	3.743	409
	0	-	2.5	1.5	1.5	-	1.90	1.60	1.80	8	4	10	6	14	16	16	3	0.16	0.1	0.16	0.14	10	10	10	10	1.724	1.645	627
A9 	0	-	8.5	1.5	1.5	-	1.70	1.60	1.90	11	3	11	7	15	16	16	15	0.20	0.1	0.16	0.14	10	10	10	10	324	2.990	367
	0	1.5	8.5	-	1.5	1.5	2.50	-	1.5	6	3	-	6	3	10	-	9	0.1	0.1	-	0.12	20	10	-	10	214	2.270	270
	0	1.5	1.5	-	1.5	1.5	2.30	-	1.5	6	8	-	9	5	14	-	2	0.1	0.20	-	0.12	20	10	-	10	1.940	749	604
	0	1.5	8.5	-	1.5	1.5	2.50	-	1.5	6	5	-	6	3	10	-	10	0.1	0.1	-	0.12	20	10	-	10	276	1.768	240
	315	-	7.5	-	8.5	-	2.40	-	1.70	11	7	-	11	3	10	-	10	0.12	0.16	-	0.14	10	10	-	10	230	4.324	465
A10 	0	-	1.5	-	1.5	-	1.60	-	1.5	8	8	-	8	6	10	-	15	0.12	0.14	-	0.18	10	10	-	10	2.076	1.173	681
	0	-	8.5	-	1.5	-	2.10	-	1.60	11	7	-	11	3	16	-	9	0.12	0.16	-	0.1	10	10	-	10	324	2.389	311
	0	1.5	8.5	8.5	-	1.70	2.50	2.30	-	6	3	11	-	15	14	16	-	0.12	0.16	0.1	-	10	10	20	-	168	5.371	545
	0	1.5	1.5	-	1.5	1.5	1.5	1.5	-	11	10	11	-	1	14	16	-	0.16	0.16	0.1	-	80	10	20	-	1.733	1.026	573
	0	1.5	8.5	1.5	-	1.90	2.30	1.5	-	8	7	10	-	15	14	16	-	0.12	0.16	0.1	-	10	10	20	-	289	1.995	265
A11 	0	-	8.5	1.5	-	-	2.40	1.5	-	11	3	10	-	9	15	15	-	0.20	0.20	0.16	-	10	10	20	-	210	3.387	372
	0	-	1.5	1.5	-	-	1.5	1.5	-	8	8	10	-	1	1	16	-	0.12	0.20	0.16	-	10	10	10	-	2.060	1.458	702
	0	-	8.5	1.5	-	-	2.30	1.5	-	10	7	10	-	3	4	16	-	0.1	0.12	0.16	-	10	10	10	-	326	2.679	339
	45	1.5	-	8.5	1.5	2.20	-	2.50	2.10	11	-	1	7	16	-	10	9	0.1	-	0.14	0.12	10	-	10	20	275	5.517	588
	315	1.5	-	1.5	1.5	1.60	-	1.80	1.80	11	-	10	8	16	-	10	10	0.16	-	0.16	0.12	10	-	10	10	1.815	968	590
A12 	45	1.5	-	6.5	1.5	1.60	-	2.30	1.60	10	-	7	7	16	-	10	9	0.16	-	0.14	0.12	10	-	10	10	466	2.791	387
	45	-	-	8.5	1.5	-	-	2.40	1.5	11	-	3	10	16	-	16	4	0.20	-	0.1	0.18	10	-	10	10	250	6.657	687
	315	-	-	1.5	1.5	-	-	1.5	1.60	8	-	5	8	15	-	13	7	0.12	-	0.20	0.18	10	-	20	10	2.318	1.396	768
	315	-	-	1.5	8.5	-	-	1.5	2.50	11	-	11	7	12	-	16	14	0.18	-	0.14	0.18	10	-	10	10	564	2.893	424

Table 6. Selected Pareto-optimal solutions minimising heating load, cooling load and CO₂ emissions [24] - continuens

	(ORI)	(WW-N)	(WW-S)	(WW-E)	(WW-W)	(WH-N)	(WH-S)	(WH-E)	(WH-W)	(GT-N)	(GT-S)	(GT-E)	(GT-W)	(IMT-N)	(IMT-S)	(IMT-E)	(IMT-W)	(SED-N)	(SED-S)	(SED-E)	(SED-W)	(SEA-N)	(SEA-S)	(SEA-E)	(SEA-W)	Heating [kWh]	Cooling [kWh]	CO ₂ [kg]
 A5	315	1.5	-	-	8.5	2.30	-	-	2.50	7	-	-	3	16	-	-	16	0.16	-	-	0.16	10	-	-	10	380	2.596	346
	315	1.5	-	-	1.5	1.5	-	-	1.70	8	-	-	8	13	-	-	16	0.12	-	-	0.18	10	-	-	10	1.833	699	569
	315	1.5	-	-	8.5	1.60	-	-	2.50	10	-	-	7	16	-	-	16	0.12	-	-	0.18	10	-	-	10	460	1.891	302
	315	-	-	-	8.5	-	-	-	2.50	7	-	-	7	12	-	-	16	0.16	-	-	0.18	10	-	-	10	417	2.963	390
	315	-	-	-	1.5	-	-	-	1.5	8	-	-	8	7	-	-	9	0.12	-	-	0.16	10	-	-	10	2087	1113	678
 A13	315	-	-	-	8.5	-	-	-	2.50	11	-	-	7	16	-	-	10	0.18	-	-	0.20	10	-	-	10	430	2770	376
	45	1.5	-	8.5	-	1.80	-	2.50	-	10	-	3	-	16	-	3	-	0.18	-	0.20	-	30	-	10	-	194	5299	546
	315	1.5	-	1.5	-	1.5	-	1.60	-	10	-	11	-	3	-	16	-	0.12	-	0.16	-	10	-	10	-	1909	866	606
	45	1.5	-	8.5	-	1.5	-	1.70	-	11	-	11	-	16	-	16	-	0.20	-	0.20	-	10	-	10	-	485	2.432	359
	45	-	-	8.5	-	-	-	2.50	-	7	-	7	-	8	-	15	-	0.14	-	0.12	-	10	-	20	-	210	6.341	647
 A14	315	-	-	1.5	-	-	-	1.60	-	8	-	8	-	6	-	10	-	0.12	-	0.14	-	10	-	10	-	2.251	1.293	740
	45	-	-	8.5	-	-	-	1.5	-	11	-	11	-	16	-	15	-	0.1	-	0.14	-	10	-	10	-	491	4.350	539
	0	1.5	8.5	-	-	1.70	2.40	-	-	7	3	-	-	4	15	-	-	0.18	0.14	-	-	20	10	-	-	174	2.271	259
	0	1.5	1.5	-	-	1.5	2.00	-	-	10	8	-	-	5	9	-	-	0.18	0.16	-	-	10	10	-	-	1732	686	541
	0	1.5	8.5	-	-	1.5	2.20	-	-	7	7	-	-	10	4	-	-	0.18	0.14	-	-	10	10	-	-	241	1606	215
 A15	0	-	8.5	-	-	-	2.40	-	-	11	3	-	-	15	12	-	-	0.12	0.14	-	-	10	10	-	-	185	3.089	338
	0	-	1.5	-	-	-	1.60	-	-	8	5	-	-	11	13	-	-	0.1	0.12	-	-	10	10	-	-	1.879	1.240	632
	0	-	8.5	-	-	-	2.30	-	-	11	7	-	-	8	10	-	-	0.1	0.20	-	-	10	10	-	-	227	2.566	301
	45	8.5	-	-	-	2.50	-	-	-	7	-	-	-	16	-	-	-	0.20	-	-	-	60	-	-	-	1137	4084	692
	0	1.5	-	-	-	1.5	-	-	-	8	-	-	-	2	-	-	-	0.1	-	-	-	10	-	-	-	1.914	651	587
 A16	315	6.5	-	-	-	2.50	-	-	-	7	-	-	-	16	-	-	-	0.1	-	-	-	10	-	-	-	1.380	1.337	504
	45	-	-	-	-	-	-	-	-	7	-	-	-	16	-	-	-	0.20	-	-	-	90	-	-	-	1.152	4.247	712
	315	-	-	-	-	-	-	-	-	8	-	-	-	5	-	-	-	0.14	-	-	-	10	-	-	-	2.068	1.095	671
	315	-	-	-	-	-	-	-	-	7	-	-	-	16	-	-	-	0.1	-	-	-	10	-	-	-	1.312	1.598	510

optimum results were obtained at an orientation of 0° . In terms of window width, except for models with a single open façade on the north side, minimum performance was generally achieved with the lowest width values on the north façade, while for the south, east, and west façades, widths of approximately 8.5 m minimise heating load and about 1.5 m minimise cooling load. Regarding façade height, it is observed that higher values are preferred in solutions minimising the heating load and lower values in those minimising the cooling load for the north, east, and west façades, with the north façade generally exhibiting the lowest height values. In terms of glazing type, as the size of the north façade increased, glazing with lower U-values was selected to minimise the heating load, whereas glazing with higher U-values was preferred to minimise the cooling load. Comparisons between model pairs with different north façade transparency ratios suggest that changes in transparency influenced the selection of parameter values associated with minimum performance outcomes..

4. Conclusion

This study comparatively analysed various façade scenarios using a multi-objective optimisation approach to reveal the impact of façade design parameters on building energy performance. Sixteen residential building models (A1–A16), categorised according to façade orientation and transparency ratio, were evaluated to minimise heating and cooling energy loads and CO₂ emissions. The transparency ratio of the north façade was increased as a design constraint, reflecting real architectural conditions, where buildings with scenic views often have wider openings on the north façade. Models with the north façade fixed at 80 % transparency (A9–A16) were used to examine how this inevitable design condition affected the energy performance. Minimising heating and cooling energy loads and CO₂ emissions requires a decision-support model that identifies optimal combinations of holistically evaluated design parameters. Therefore, multi-objective optimisation strategies are essential for achieving successful outcomes and providing valuable guidance for architects, designers, and decision makers aiming to enhance building performance. The key findings are summarised as follows:

- Sensitivity analysis establishes a framework that clarifies how façade design parameters influence building energy performance. This revealed the significance of specific variable shifts in models with wide north-facing openings, guiding designers toward more informed parameter prioritisation.
- Within Samsun's temperate humid climate, wide north-facing façades were found to substantially affect energy behaviour, particularly through glazing characteristics. These results emphasise that façade design strategies must be context-specific and adapted to both climatic

conditions and user needs, highlighting the sensitivity of façade performance to the climatic context.

- The parameter values determined based on sensitivity analysis results were used in the optimisation process, yielding the most efficient solutions for heating, cooling, and CO₂ performance for each model. The findings indicate that façade design decisions should vary depending on orientation: south-facing openings play a critical role in reducing heating loads, while limiting the east and west façades reduces cooling loads and solar gains. When the south façade is opaque, it was observed that achieving optimal values requires not only changes in façade-related parameters, but also a modification of the façade orientation itself. In this context, the façade achieved optimal performance by adopting orientation values of 45° and 315° . When the building is opaque on all façades except the south façade, it can generally be oriented at 0° .
- As the number of openings decreases, energy-related design decisions become more sensitive, further amplifying the critical role of optimisation in the overall design process. Compared to the model with openings on all four façades, the model with only a north-facing opening showed an approximately 419 % increase in heating demand, a 33.4 % decrease in cooling demand, and a 39 % increase in CO₂ emissions. This configuration represents the most constrained scenario, requiring precise calibration of the glass-type and insulation materials to achieve balanced energy performance.
- Parametric flexibility in façade openness, glazing, and insulation offers the greatest advantages. Incorporating the north façade opening as a variable parameter enhances the feasibility of balanced solutions, whereas keeping it fixed complicates the optimisation and amplifies the role of other parameters.

Therefore, multi-objective optimisation is essential for achieving well-balanced and high-performance design solutions. This study highlights the critical role of optimisation, even under fixed architectural limitations.

The analyses in this study were conducted using the current climate data. Considering the changes that global warming will bring, it is important to generate new optimal solutions, as the design approach and application methods will change over time. It has been stated that temperatures will increase rapidly in Türkiye after the 2030s [49]. Because this situation will be reflected in the energy performance of buildings as an increase in cooling energy loads and a decrease in heating energy loads, it is critical for future studies to consider the possibility that climate change will extend the duration of the desired cooling period. The aim of the following processes is to expand the scope of the developed model by applying it to different climate zones along with future climate scenarios and cost calculations, as well as to develop guiding tools for designers, producers, and decision-makers. Thus, it is

possible to contribute to the development of sustainable environments by designing and implementing houses that can adapt to changing climatic conditions by considering the cost calculations of buildings in energy-efficient housing design processes for different climatic regions of Türkiye.

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