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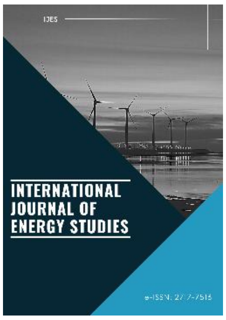

Research Article

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Enhancing summer thermal comfort and energy performance in university office spaces using DesignBuilder's parametric optimization: The role of window openings, solar shading, and HVAC systems

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Highlights

- Up to 62% energy savings achieved through optimized design parameters.
- Summer thermal comfort improved by up to 54% in faculty offices.
- Parametric BPO tested 5–50% openings, 10 shades, and 5 HVAC systems.
- Study offers practical insights for summer comfort and energy use.

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ABSTRACT

Improving energy efficiency, reducing consumption, and enhancing indoor thermal comfort are key concerns in sustainable architecture. While much research has addressed minimizing heating demands during winter, fewer studies have explored strategies to improve thermal comfort and reduce cooling loads during summer. This study aims to bridge that gap by analyzing the combined effects of window opening ratios, solar shading devices, and HVAC systems on summer energy performance and indoor comfort in faculty offices at Bingöl University.

The hypothesis suggests that optimizing window openings, implementing suitable shading strategies, and selecting effective HVAC systems can significantly enhance thermal comfort and lower cooling energy use. The study explores four main questions: (1) How effective is natural ventilation through varying window openings? (2) How much can solar shading reduce overheating and cooling loads? (3) How do mechanical systems interact with passive design strategies? (4) What is the combined effect of all three parameters on performance?

A parametric simulation approach was applied using DesignBuilder software. Scenarios included window openings from 5% to 50%, ten solar shading configurations, and five HVAC types. A total of 498 simulations generated a robust dataset for performance analysis. Results show that integrated optimization can reduce cooling energy use by up to 62% and improve thermal comfort by up to 54% compared to the base case. These findings confirm the initial hypothesis and underscore the value of holistic design strategies. In conclusion, this research offers a structured framework for improving summer thermal performance in educational office spaces. It provides actionable insights for architects, engineers, and policymakers seeking to enhance indoor environmental quality and energy efficiency in warm climate zones.

Keywords: BIM, BEM, BES, Building performance optimization, Natural ventilation and cooling energy in buildings, Building energy efficiency through sensitivity and pareto analysis.

1. INTRODUCTION

Buildings are the primary living spaces where people spend approximately 90% of their time. Therefore, to achieve an energy-efficient society, building designs should not only enhance energy efficiency but also provide a comfortable and healthy environment for occupants [1]. In its 2021 report, the International Energy Agency (IEA) highlights that energy consumption in buildings accounts for one-third of the total global energy use [2]. The World Green Building Council, in its advancing Net Zero project call-to-action report, stated that buildings are responsible for 39% of global energy-related carbon emissions, with 28% of these emissions originating from the energy used for heating, cooling, and power supply [3]. Heating, ventilation, and air conditioning (HVAC) systems account for a significant portion of energy consumption in the building sector [4], with some sources emphasizing that more than 50% of building energy consumption is attributed to HVAC systems [5,6]. In particular, energy use by air conditioning systems and electric fans constitutes 20% of the total consumption and is identified as one of the fastest-growing sectors [7]. The increasing energy demand is driving up building operating costs while straining electrical systems and environmental sustainability [1]. In response to this rising energy demand, strategies aimed at reducing energy consumption and improving indoor comfort have become crucial. To reduce the load on HVAC systems and enhance energy efficiency, passive methods such as natural ventilation and solar control can make significant contributions. Additionally, the use of energy-efficient HVAC systems is of great importance. Natural ventilation is one of the most effective technologies for passive cooling in buildings. In fact, natural ventilation not only reduces indoor air temperatures during summer but also improves indoor air quality (IAQ), enhances thermal comfort, and lowers building energy consumption costs [8]. Natural ventilation relies on pressure differences caused by natural forces to ensure airflow within buildings. Studies in this field have shown that the use of natural ventilation can lead to energy savings of 8% to 78% for cooling, depending on local weather conditions and air quality [9]. Similarly, natural ventilation can achieve savings of up to 54.4% in electricity required for cooling during hot weather [10] and reduce the operation time of mechanical ventilation by 90% in temperate countries during summer [1,11]. In this context, one of the significant approaches to reducing building energy consumption is to develop designs that support natural ventilation. The role of window opening ratios in optimizing natural ventilation has a decisive impact on building energy performance and indoor comfort. Careful management of window opening ratios can enhance the effectiveness of natural ventilation in buildings and reduce reliance on HVAC systems. This, in turn, can ensure thermal comfort while optimizing energy consumption. Increasing the opportunities for natural ventilation through windows, along with the use of sunshades to control solar radiation on building facades, is an effective method to reduce cooling loads and achieve summer thermal comfort. The comfort and energy efficiency of a building are significantly influenced by control components such as window systems and shading elements [12]. Solar shading elements improve thermal comfort by preventing indoor overheating and reducing energy consumption associated with cooling loads. As they reduce solar radiation, external shading elements on a building's facade are a critical component of passive design [13]. To enhance thermal comfort and achieve significant energy savings, shading elements block solar radiation from entering buildings during summer while allowing necessary solar gains during winter [14]. In hot and humid climates, it is crucial to protect indoor spaces from solar rays that can penetrate building walls and increase cooling energy demands [15,16].

Numerous studies have been conducted on the relationship between the energy performance of solar shading devices and thermal comfort. Perera et al. [17] investigated the effectiveness of passive design strategies (PDS) in reducing energy costs in high-rise residential buildings in tropical regions. The study analyzed fixed projections and side fins made of reinforced concrete in three tropical sub-climates defined by ASHRAE, revealing their energy-saving potentials. Yin and Muhieldeen [18] examined the impact of vertical shading systems on cross-ventilation performance in office buildings and demonstrated that shading devices serve as a practical architectural strategy for improving natural ventilation. Abdeen et al. [19] conducted parametric simulations to enhance the energy performance of residential buildings in the UAE, emphasizing the significance of design variables such as wall-roof insulation, glazing, and window shading in energy conservation. Albatayneh [20] optimized the thermal performance of a residential building in Ajlun, Jordan, by analyzing building envelope design variables and comparing the effects of local shading elements such as overhangs, louvres, and side fins on thermal performance under different scenarios. El Sherif [21] highlighted the importance of adopting passive techniques in tropical climates, demonstrating that eaves and side panels oriented differently in summer and winter reduced solar gains by 13%-55%, leading to up to 27.5% energy savings. Ebrahimpour and Maerefat [22] evaluated the effects of advanced glazing and projections on solar energy transmission in typical residential buildings in Tehran using the EnergyPlus™ software. Similarly, Bojić [23] aimed to optimize cooling loads in a 20-story high-rise residential building in Hong Kong by incorporating overhangs and side fins. These studies primarily focus on residential buildings and tropical climates. However, research on academic office buildings in regions like Bingöl, which has a climate characterized by hot and dry summers and cool winters, remains limited. Therefore, this study aims to address this research gap by investigating the impact of different solar shading devices on the energy performance and thermal comfort of office buildings, particularly those used by academics.

Additionally, there are limitations or deficiencies in the use of natural ventilation and solar control in buildings. The effectiveness of natural ventilation largely depends on external wind conditions; typically, an outdoor wind speed of over 3.0 m/s is required to create a noticeable cooling effect in naturally ventilated buildings [24]. Natural ventilation is not always a viable option, especially on rainy days, when windows remain open, or in situations where outdoor air quality is compromised due to pollution or excessive heat, making it challenging to maintain optimal indoor air quality and thermal comfort. Conversely, relying entirely on mechanical ventilation can lead to higher energy consumption and, in some cases, pose health risks for building occupants [25]. A more efficient approach is hybrid ventilation (HV), which integrates the benefits of both natural and mechanical systems, ensuring ventilation as needed while minimizing energy use [8,26]. Compared to traditional air-conditioned buildings, structures utilizing hybrid ventilation systems can achieve notable reductions in total energy consumption and carbon emissions [8]. Reducing the increasing energy demand of buildings and improving user comfort can be achieved through the integration of heating, ventilation, and air conditioning (HVAC) systems with natural ventilation strategies. When combined with appropriate window opening ratios, natural ventilation can reduce the energy load on HVAC systems. However, this process requires the optimization of design parameters such as window opening ratios, solar shading elements, and HVAC systems. Particularly during summer, the effective management of window opening ratios and natural ventilation plays a critical role in ensuring indoor thermal comfort. In this context, the use of solar shading elements, the optimization of window opening ratios, and the proper management of HVAC systems are crucial for enhancing building energy performance and ensuring indoor comfort. The combined implementation of these strategies is essential for both improving energy efficiency and creating a comfortable indoor environment for occupants. This study aims to improve energy consumption and thermal comfort during summer by analyzing the interaction between window opening ratios, solar shading elements, and HVAC systems. In this scope, DesignBuilder software was utilized to evaluate building energy performance and optimize different design parameters. DesignBuilder is a simulation software based on the EnergyPlus engine, enabling comprehensive analyses of building energy performance, energy consumption, thermal comfort, and environmental impacts [27-29]. DesignBuilder (DB) simulation software is applicable throughout various project stages and is widely recognized for its comprehensive simulation capabilities [30]. For example, Avendaño-Vera et al. [31] employed DB to analyze the thermal inertia of construction materials across different climatic zones in Chile. Similarly, Fouad et al. [32] used DB to evaluate the energy consumption and carbon footprint of a sustainable net-zero energy community. In another study, Zhu and Bao [33] leveraged DB's simulation features to examine the influence of window and shading configurations on Building Energy Codes (BEC) and construction costs across diverse climate zones in China [34].

The literature emphasizes the need for a comprehensive examination of the effects of window opening ratios on natural ventilation and indoor temperatures [35]. Similarly, studies have reported that solar shading devices contribute to improved energy performance and thermal comfort in hot climates [36]. Research on the relationship between energy design parameters and energy demand in buildings across Turkey's different climatic regions is crucial for energy efficiency and sustainable architectural design. Many studies have been conducted in this context, and further research continues to evolve [37-39].

However, studies specifically addressing the effects of these design parameters in faculty offices located in hot and dry summer climates, such as Bingöl, remain limited. The DesignBuilder software used in this study provides a comprehensive simulation framework to bridge this research gap and propose optimized design solutions. In the academic offices located in the additional building of Bingöl University Faculty of Engineering and Architecture, thermal comfort cannot be achieved during summer due to the limited ventilation capacity of windows and high solar radiation exposure. This situation reduces the productivity of academic staff and increases energy consumption, as individuals rely on personal fans for cooling.

Research Aim and Questions:

This study aims to analyze the effects of various passive and active design parameters on improving thermal comfort in faculty offices during summer at Bingöl University and to propose optimal design solutions. It investigates how window opening ratios, solar shading devices, and HVAC systems influence cooling energy consumption and indoor thermal comfort in office spaces. The primary research question guiding this study is:

How do window opening ratios, solar shading, and HVAC systems interact to improve thermal comfort and reduce cooling loads in office spaces?

To address this, the study explores the following specific research questions:

1. To what extent can the type and rate of window opening increase the effectiveness of natural ventilation?
2. To what extent can solar shading devices alleviate overheating and reduce cooling loads?

3. What is the relationship between mechanical solutions, energy performance, and design strategies?
4. How do these three parameters collectively affect building energy performance and indoor comfort conditions?

Hypothesis and Validation Criteria

This study is based on the hypothesis that an optimized combination of window opening ratios, solar shading strategies, and HVAC systems can significantly enhance summer thermal comfort while reducing cooling energy consumption. To test this hypothesis, the following sub-hypotheses are proposed:

- H1: Increasing window opening ratios enhances natural ventilation efficiency and improves indoor comfort conditions.
- H2: The use of solar shading devices reduces overheating and decreases cooling loads in office spaces.
- H3: The selection of an appropriate HVAC system significantly influences the balance between energy performance and thermal comfort.
- H4: The integration of all three parameters provides an effective approach to optimizing indoor environmental conditions.

Hypothesis Validation Process

To validate these hypotheses, a structured approach was adopted, combining dynamic simulations and analytical comparison methods. The validation process consisted of the following key steps:

1. Parametric Building Performance Simulations:
   - Dynamic thermal simulations were conducted using DesignBuilder software, generating a comprehensive dataset for cooling loads and thermal discomfort levels under different design configurations.
2. Pareto Analysis for Key Parameter Selection:
   - The dataset was analyzed using Pareto analysis to identify the most influential design parameters affecting cooling loads and thermal comfort.
3. Pairwise Sensitivity Analysis:
   - A pairwise sensitivity analysis was conducted to assess the individual impact of window opening ratios, solar shading devices, and HVAC systems on cooling energy demand and indoor thermal conditions.

These validation methods provided a robust framework for confirming the hypotheses, demonstrating how passive and active design strategies can be optimized to enhance indoor environmental conditions in academic offices. In conclusion, this research seeks to fill gaps in the literature by examining the effects of passive and hybrid HVAC strategies on thermal comfort and cooling loads in hot and dry climates like Bingöl. Furthermore, it aims to provide practical solutions to improve indoor comfort conditions while ensuring energy efficiency in academic office spaces.

2. METHODOLOGY

In the faculty offices located in the additional building of Bingöl University Faculty of Engineering and Architecture, it has been observed that inadequate thermal comfort conditions during summer significantly reduce work efficiency. Discomfort arises due to the limited ventilation provided by windows during summer (Figure 1a, b) and excessive exposure to sunlight and heat through the southwest-facing windows (Figure 1c, d [40]). These issues emphasize the necessity of improving indoor design. In this context, the aim of this study is to analyze the effects of various design parameters on improving summer thermal comfort conditions in the faculty offices and to develop optimal design solutions based on these analyses.

Figure 1 (a) Natural ventilation in the current window system, **(b)** Enhancement of natural ventilation, **(c)** The impact of solar radiation on the indoor environment, **(d)** Schematic representation of solar control systems.

The main questions addressed in this study are as follows:

- To what extent can changing the type and ratio of window openings improve the effectiveness of natural ventilation?
- How much can this problem be mitigated by using solar shading devices?
- What kind of relationship can be established between mechanical solutions, energy performance, and design strategies?
- To what extent do these three parameters affect building energy performance and indoor comfort conditions?

To systematically address these questions, this study is based on the hypothesis that an optimized combination of window opening ratios, solar shading strategies, and HVAC systems can significantly enhance summer thermal comfort while reducing cooling energy consumption. The following sub-hypotheses are tested:

- H1: Increasing window opening ratios enhances natural ventilation efficiency and improves indoor comfort conditions.
- H2: The use of solar shading devices reduces overheating and decreases cooling loads in office spaces.
- H3: The selection of an appropriate HVAC system significantly influences the balance between energy performance and thermal comfort.
- H4: The integration of all three parameters provides an effective approach to optimizing indoor environmental conditions.

Methodology Steps:

In this context, alternative scenarios based on the current situation and different design parameters were created, and these scenarios were evaluated in terms of thermal comfort and energy performance. The research was conducted in the following steps:

1. Developing a model of the existing building and analyzing current thermal comfort conditions:

- A parametric model of the office space at Bingöl University Faculty of Engineering and Architecture was created using DesignBuilder software.
- The existing thermal comfort conditions were analyzed based on temperature distributions, PMV-PPD values, and cooling loads.

2. Identifying alternative design parameters:

- Alternative window opening ratios (5% to 50%), solar shading devices (10 configurations), and HVAC system types (5 different models) were defined as key variables.

3. Conducting simulations based on the defined design parameters:

- Dynamic energy simulations were performed to assess the impact of these parameters on cooling loads and indoor comfort.
- A dataset comprising 498 simulation results was generated.

4. Analyzing and comparing the simulation results and proposing the most suitable design strategies:

- The dataset was first analyzed using Pareto analysis to identify the most influential design parameters.

- A pairwise sensitivity analysis was conducted to isolate the effects of window openings, solar shading, and HVAC systems on thermal performance.
- The optimal configuration of design parameters was determined based on energy efficiency and thermal comfort improvements.

This study adopts a simulation-based approach that is widely used in building performance analyses. Various studies in the literature have demonstrated that building simulations provide accurate and reliable results. In the study by Liu et al., the parameters of a BIM-DB simulation were input into the software, and the resulting simulation data were compared with actual building data derived from energy consumption bills. The comparisons revealed that building simulations performed using DB are accurate and reliable [34]. In the literature, the relationship between window properties and building energy performance has been extensively studied [41-44]. The window opening ratio significantly affects indoor comfort conditions and cooling capacity. Opening windows is an effective method to ventilate the air and reduce indoor temperatures. Research has shown that the act of opening windows is one of the most effective and economical ways to establish a connection between indoor climate and occupant comfort [45]. Natural ventilation, under favorable weather conditions, can reduce indoor temperatures, save energy, and simultaneously improve indoor air quality [46]. For example, during summer, when outdoor air temperatures are suitable, opening windows helps cool the space and reduces cooling energy consumption [47]. Furthermore, window opening behaviors significantly impact occupant comfort perceptions; occupants tend to open windows to lower indoor temperatures when they feel warm [48]. Therefore, designers must consider both energy efficiency and occupant comfort when designing window openings [49]. Ultimately, the window opening ratio combines indoor comfort conditions with cooling loads as a critical factor. An appropriate window opening ratio not only saves energy but also enhances indoor comfort. This system plays a significant role in improving the efficiency of natural ventilation systems in building design [50]. In addition to window opening ratios, the use of shading elements on windows is another critical parameter for improving summer comfort conditions. Shading elements have a significant impact on the energy performance and thermal comfort conditions of spaces. By preventing direct sunlight from entering indoor spaces, these elements help lower indoor temperatures during summer. The study by Canan and Geyikli [51] investigated the effects of external shading elements on microclimate conditions and demonstrated their role in improving thermal comfort. In their study, outdoor thermal comfort conditions were calculated using the PET (Physiological Equivalent Temperature) index, and the effects of shading elements were discussed in detail. Şenyurt and Altun [52] extensively studied the impact of environmentally adaptive building envelope designs for office buildings on energy consumption, revealing that appropriate shading designs can significantly enhance energy performance and reduce cooling loads. Additionally, Yaman and Arpacıoğlu [53] investigated the effects of dynamically controlled shading systems on energy performance, noting that such systems, when adjusted based on solar intensity, enhance energy efficiency.

In conclusion, shading elements play a critical role in energy management and thermal comfort. Properly designed shading systems not only regulate indoor temperatures and reduce cooling loads to save energy but also make significant contributions to achieving thermal comfort conditions. Therefore, the effective use of shading elements in architectural design is essential for creating sustainable and comfortable living spaces. Window opening ratios and shading elements have been identified as key design parameters in this study, and different HVAC systems have been considered to evaluate their impact on cooling loads. Studies analyzing the combinations of these parameters in hot and dry summer climates are limited. Therefore, this study aims to fill this gap in the literature. The combined effects of natural ventilation, solar shading elements, and mechanical ventilation systems on summer thermal comfort were addressed based on similar studies in the literature. However, studies analyzing the combined effects of these parameters in climates like Bingöl, characterized by cold winters and hot, dry summers, are limited. This study addresses existing thermal comfort issues and proposes effective design solutions to improve summer thermal comfort.

3. MATERIALS AND METHODS

3.1. Reference Building Characteristics and Climate Conditions

This study was conducted in the academic offices of the Faculty of Engineering and Architecture at Bingöl University. The reference building examined in this study is located in Bingöl Province, situated in the Eastern Anatolia Region of Turkey (Figure 2). According to the Köppen climate classification, Bingöl exhibits the characteristics of a "Dsa" climate type, which is a continental climate with hot and dry summers (Figure 2). In this classification:

- The letter "D" represents continental (microthermal) climates, where the average temperature of the coldest month is below -3°C, and the average temperature of the hottest month exceeds 10°C.
- The letter "s" indicates dry summers, with the average precipitation in the driest month being below 30 mm.

- The letter "a" signifies hot summers, where the average temperature of the hottest month is above 22°C.

Thus, the "Dsa" climate type is characterized as a continental climate with mild winters and hot, dry summers. In Bingöl, winter temperatures are generally low, while summer temperatures are high. Precipitation is concentrated mainly in winter and spring, with summers being relatively dry [54]. These climatic features are critical factors in building design and energy consumption. Particularly during the summer months, ensuring indoor thermal comfort necessitates the use of natural ventilation strategies, solar control elements, and appropriate insulation materials. For the simulations, a local climate file in EPW format was utilized. The reference building used in the study is located within the campus of Bingöl University in Bingöl Province (Figure 2).

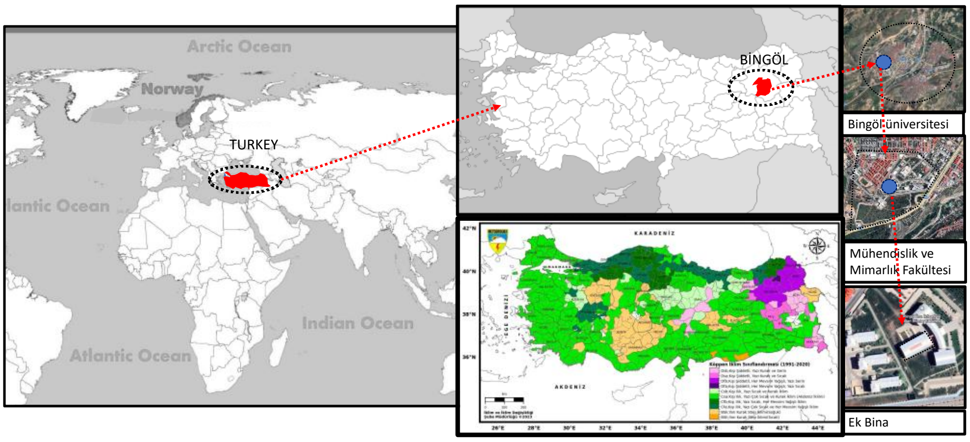


Figure 2. Map representation of the reference building and its climate condition on the Köppen climate map

The campus consists of a main building (Block A) constructed in 2010 and an additional building (Block B) built in 2014 [55]. The research was conducted in Block B, where the offices of the faculty members of the Faculty of Engineering and Architecture are located. Block B has a rectangular geometry and is oriented in the Northeast-Southwest direction (Figure 2). The transparent surfaces on the exterior facade of the reference building are composed of insulated glass curtain wall systems, while the opaque surfaces consist of insulated composite cladding systems (Figure 3a). The building is heated by a central natural gas heating system. While no additional heating systems are used in the academic offices during the winter months, it has been observed that some offices require the use of fans during the summer. The building comprises a basement and a ground floor plus three additional floors. The spaces within the building are organized as offices aligned along the long facade and are connected to vertical circulation areas via a central corridor (Figure 3b). On the fourth floor, there are faculty offices facing the interior corridor (Figure 3c, d). Passive ventilation in the offices facing the exterior facade is provided by windows that open to outdoor conditions (Figure 3e, f), while for offices facing the interior corridor, ventilation is achieved through doors and windows opening to the corridor [55].

It has been determined that ideal thermal comfort conditions for working environments cannot be achieved in the building during the summer months. In a study conducted by Yaman et al. [55], thermal comfort measurements were carried out in the faculty offices within this building, revealing that office temperatures reached an average of 33.2°C during the summer. The same study emphasized the necessity of examining thermal comfort parameters during the summer months and highlighted the need for comprehensive studies aimed at improving thermal comfort parameters to protect the health of individuals working in these spaces and enhance their work efficiency. In this context, this study addresses recommendations for improving summer thermal comfort conditions in the mentioned building.

Figure 3 (a). Insulated glass curtain wall system on the exterior facade of the reference building, **(b)** The layout of office spaces along the building's long facade and their connection to the central corridor, **(c)** Faculty offices facing the interior corridor on the fourth floor, **(d)** Interior view of the offices facing the central corridor, **(e)** Windows providing passive ventilation for offices facing the exterior façade, **(f)** Doors and windows enabling ventilation for offices facing the interior corridor.

In previous studies conducted by Yaman et al. [55], the thermal comfort conditions in these spaces were investigated using the Testo 480 measuring device. The measurement results indicated that the spaces did not meet summer thermal comfort conditions, emphasizing the necessity of improvements. In this context, based on the findings from this building, solution proposals can be developed for building typologies with similar characteristics.

3.2. Determination of Alternative Design Parameters

In the study, baseline and alternative scenarios were defined to analyze the comfort conditions and cooling loads of the spaces. The baseline scenario includes the current windows, which can open by 5%. Three parameters were identified as alternative scenarios: window opening ratios, shading elements, and ventilation strategies.

For the window opening ratio scenarios, nine scenarios were created by increasing the current opening ratio of 5% (Figure 4a) in increments of 5% for comparison. The upper limit for the opening ratio was set at 50%. These limitations were determined based on the sections of the existing window. The current window consists of six casements, with two vertical and one horizontal section (Figure 4b). The upper sections are high and difficult to open; therefore, to reflect realistic usage, the upper limit of 50% was defined as the scenario where the three lower sections are fully open (Figure 4c).

Windows without shading elements allow excessive solar radiation into a building, which can lead to thermal problems and visual issues such as glare, impacting user comfort [56, 16]. In this context, the second variable parameter involves creating scenarios where shading elements are added to the windows. The schematic representation of the solar shading types defined in the DesignBuilder software is shown in Figure 4d.

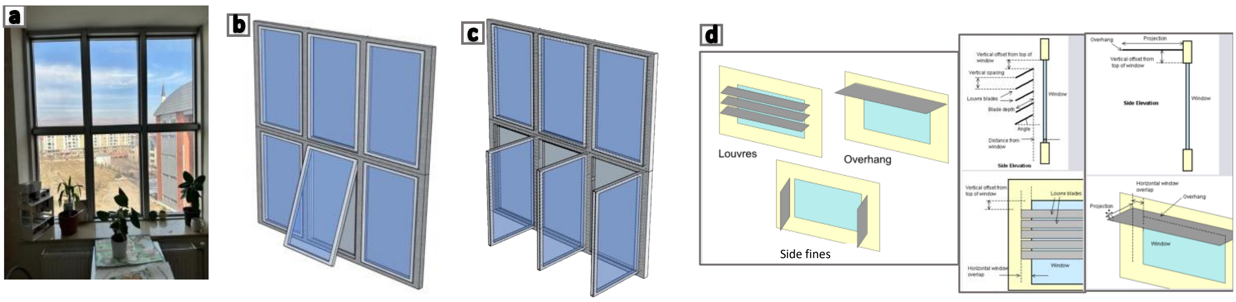
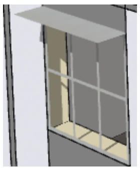
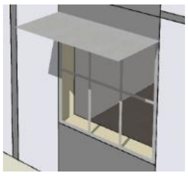
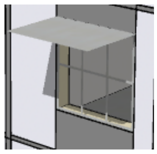
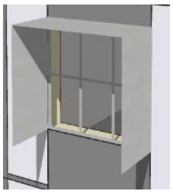
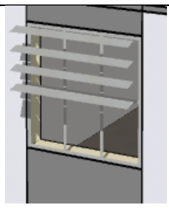
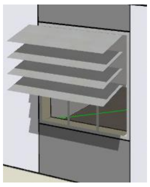
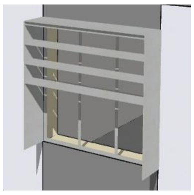
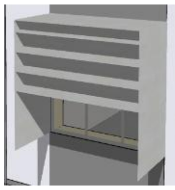


Figure 4(a) Current window system with a 5% opening ratio representing the baseline scenario, **(b)** Existing window structure with six casements, including two vertical and one horizontal section, **(c)** Maximum window opening scenario with 50% opening, where the three lower sections are fully open, **(d)** Impact of shading elements on reducing solar radiation entering through the windows (Taken from the DesignBuilder software interface).

During the summer months, solar energy has a significant impact, particularly on the southwest-facing facade. The types of shading elements determined as parameters for this scenario are presented in Table 1.

Table 1. Types of shading elements used for the southwest-facing facade and their parameters.

SE-1. No Shading	**SE-2.** 0.5m Overhang	**SE-3.** 1m Overhang	**SE-4.** 1.5m Overhang	**SE-5.** Overhans and side fines (0.5m projection)
				
SE-6. Overhans and side fines(1m projection)	**SE-7.** 0.5m projection Louvre	**SE-8.** 1m projection Louvre	**SE-9.**Louvre, 0,5m projection+0,5 overhans and side fines	**SE-10.**Louvre, 1 m projection+1 overhans and side fines
				

As part of the study, the effects of solar shading elements that can be integrated into windows were examined for 10 different scenarios, including systems with horizontal elements of varying widths, vertical elements, horizontal segmented elements, and combinations of horizontal and vertical systems. In this study, HVAC systems were considered as the third variable parameter. In addition to passive methods, the study aimed to analyze the effects of different HVAC systems if a climate control system is used. For this purpose, five different HVAC systems were defined. Their abbreviated names and types, for ease of explanation, are presented in Table 2.

Table 2. Abbreviations and types of HVAC systems analyzed in the study.

Called	HVAC Type
VT-1	Natural ventilation
VT-2	Packaged DX
VT-3	Radiator Heating, Boiler HW, Mixed mode Nat vent, Local comfort cooling
VT-4	VAV, Air-cooled Chiller, HR, Outdoor air reset-mixed mode
VT-5	VRF (Air-cooled), Heat recovery, Doas, DCV

For the reference building, natural ventilation was defined as the first scenario. For the other four scenarios, mechanical ventilation systems were defined, including hybrid ventilation systems with mixed-mode operations. Hybrid ventilation combines the advantages of both natural and mechanical ventilation [8]. Hybrid ventilation systems, which combine natural ventilation with mechanical support, can significantly lower energy costs for building owners while ensuring a comfortable indoor environment for occupants. The thermal efficiency of these buildings is notably higher than that of purely naturally ventilated structures, as mechanical cooling supplements natural airflow when outdoor conditions are unfavorable. Offering advantages such as reduced energy consumption and enhanced indoor air quality, hybrid ventilation presents a viable solution for promoting both building sustainability and occupant well-being [57]. The ventilation systems defined in Table 2 represent different types of ventilation strategies in the study.

- VT-1 represents natural ventilation and describes a condition where no mechanical system is present.
- VT-2 and VT-5 include two different HVAC systems that provide only mechanical ventilation.
- VT-3 and VT-4 are hybrid (mix-mode) ventilation systems that combine natural and mechanical ventilation, offering more flexible indoor air quality control.

In the study, VT-1, VT-3, and VT-4 were selected to analyze the impact of window opening rates on the results. Additionally, the effect of shading devices on all systems will be evaluated. This approach allows for a comprehensive examination of the impact of different ventilation strategies on energy consumption.

3.3. Building Energy Modeling and Simulation Methodology

In this study, the aim is to improve the thermal comfort conditions of these spaces while also ensuring energy savings through optimization solutions. Therefore, an energy model of these spaces has been created. The architectural plan details obtained from Yaman et al. [55] were used to generate 2D plan drawings in AutoCAD software. These drawings were imported into the DesignBuilder software as DXF files to serve as a reference for energy model creation. All building elements, such as walls, doors, and windows, were modeled in DesignBuilder. Except for the variable parameters specified in the previous section, the characteristics of other building elements were defined in the model.

In the study, the energy model of the reference building was first developed, covering the faculty offices in the additional building of Bingöl University's Faculty of Engineering and Architecture. The building energy model was created using the DesignBuilder software (Version 7.0.2.006). DesignBuilder was chosen for its detailed simulation features in building energy modeling and thermal comfort analysis. The software operates based on the EnergyPlus dynamic building energy simulation engine and is widely used to obtain highly reliable building simulation datasets. Although dynamic simulation tools such as EnergyPlus generate results, inaccuracies in input parameters may lead to errors. To mitigate this issue, the Building Energy Simulation Test functions as a comparative diagnostic method endorsed by ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers). This assessment verifies that DesignBuilder software demonstrates high precision in diagnostic performance [58]. In this context, the energy modeling of the study was carried out using DesignBuilder based on EnergyPlus.

Using DesignBuilder software, annual simulations are conducted by accurately defining the climatic characteristics of the buildings for which the energy model is created. These simulations produce various energy performance outputs, including heating load, cooling load, and solar gain. Through this process, a single building model is included in the simulation. Modeling and simulating each of the design variable scenarios defined in the previous section separately is a long and challenging process. Therefore, the Parametric Optimization feature of the program was utilized. By restricting the parameters and outputs for the building model created in the software, multiple simulations can be performed. In this approach:

- The defined parameters and their ranges were assigned to the software to conduct optimization simulations.
- The results of these simulations were recorded as a dataset in CSV format.
- Due to software limitations, simulations could not be conducted with all parameters simultaneously.
- Therefore, simulations were performed in separate parts, and the obtained data were later merged.

To perform simulations and parametric optimizations accurately, it is essential to define the building data correctly in the software. For the model, the activity schedule was set to 'Office-OpenOff-Occ,' and the activity type was defined as 'Light Office Work/Standing/Walking.' Other activity-related settings are provided in Table 3.

Table 3. Activity-related settings used in the energy model of the faculty offices.

Factor (Men:1.00, Women:0.85, Childeren:0.75)	0.90
Occupancy density (people/m2)	0.1110
Heating (ºC)	22.0
Heating set back (ºC)	12.0
Cooling (ºC)	24.0
Cooling set back (ºC)	28.0

After developing the energy model of the existing building and defining the fixed design parameters, multiple simulations of the variable parameters were conducted using the building performance optimization feature of DesignBuilder software. In DesignBuilder, building performance optimization involves testing multiple scenarios with different combinations of design parameters. This method is used to analyze the impact of varying parameters on building performance, providing comprehensive insights into how design parameters interact with each other. It is ideal for selecting the optimal design that enhances thermal comfort while reducing energy consumption. This approach allows testing scenarios to observe how small design changes (e.g., increasing the window opening ratio) affect overall building performance. One of the reasons for choosing DesignBuilder is its ability to utilize multi-objective optimization algorithms [59-62]. During the optimization process, the software performs numerous simulations, and the simulation data is obtained directly from the program. Since manually conducting simulations for buildings with varying design parameters can be a long and challenging process, the optimization feature of DesignBuilder was utilized. This feature is suitable for automatically generating optimal or near-optimal design options, making it more efficient than traditional "trial-and-error" design methods, which largely depend on the knowledge and experience of designers [63,64]. In this context, variable design parameters and their parameter ranges were defined to perform building performance optimizations using DesignBuilder (Table 4).

Table 4. Variable design parameters and their defined ranges used for building performance optimization.

Variable type	Min. Value	Max. Value	Step (parametric)	Options list
External window opening	5.00	50	5	-
Local Shading type	-	-	-	10 options
HVAC template	-	-	-	5 options

Among these variables, External window opening, as schematically described in Figures 4b and 4c, was defined as 10 different window opening ratios: 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, and 50%. The second parameter, Local shading type, was defined as a variable parameter range in the software, based on 10 different solar shading types specified in Table 1. For the third parameter, 5 options were included in the parametric optimization process, representing the HVAC systems listed in Table 2. Using the parametric optimization method, a total of 498 different scenarios were generated, and the multi-simulation feature of the software was used to compile the results into a single dataset. Each simulation included a combination of specific HVAC systems, window opening ratios, and solar shading devices. The methods used in this study were applied within the context of academic offices at Bingöl University. However, the DesignBuilder software and simulation methodology employed in this study can also be adapted to other building types in similar climatic conditions.

In the DesignBuilder software, after defining the variable parameters and their ranges for optimization simulations, the outputs were specified and analyzed. In this study, discomfort hours were evaluated using two internationally recognized standards: ASHRAE 55 and CEN 15251. ASHRAE 55 was selected due to its adaptability to occupant behavior and climatic conditions, providing a flexible approach for dynamic thermal environments. Conversely, CEN 15251 was chosen for its stricter criteria, representing high-performance indoor environments. These two standards were employed to highlight the differences in discomfort hour assessments based on varying methodological approaches. The choice of these standards aims to offer a comprehensive perspective on thermal comfort evaluations under different frameworks. Additionally, for the accuracy of summer comfort evaluations, discomfort hours were also assessed based on summer clothing conditions.

ASHRAE 55 [65]: This standard is widely used worldwide and provides comprehensive criteria for evaluating thermal comfort, making it a key reference. It is particularly suitable for assessing indoor thermal comfort in office environments.

CEN 15251 [66]: Since this standard was specifically developed for European climate regions, it is particularly useful for evaluating natural ventilation strategies. Given that this study evaluates natural ventilation parameters, this standard was selected as an appropriate comparison tool.

Since both standards have different temperature and humidity tolerance ranges, their use enhances the diversity of the analysis results. This diversity offers a broader perspective on how thermal comfort conditions are assessed across different geographical and climatic contexts. In this study, the different metrics provided by ASHRAE 55 and CEN 15251 allow for the analysis of the same thermal comfort data using varied evaluation criteria. Therefore, these standards were incorporated as output parameters in the simulation program for multi-simulation analyses. These outputs include:

Discomfort Hours (hr) Based on Summer Clothing: Determines the thermal discomfort hours of building occupants during the summer, in compliance with ASHRAE 55 standards.

- Discomfort Hours (hr) According to CEN 15251 Category I: Indicates the duration for which indoor thermal comfort does not meet the highest category standards as defined by European standards.

- Discomfort Hours (hr) Based on ASHRAE 55 Adaptive 80% Acceptability: Reflects the duration exceeding acceptable limits based on ASHRAE's adaptive thermal comfort model.
- Cooling Load (kWh): Represents the amount of energy required to cool the building's indoor environment.

At this stage, the aim was to conduct numerous simulations for each building model during the optimization process and obtain data from these simulations. Building Performance Optimization (BPO) has been extensively studied due to its potential to enhance building performance and design efficiency. However, studies on its application to support early-stage design decisions are relatively limited, raising questions about its real effectiveness [67]. These outputs were used to comprehensively evaluate building energy performance and indoor comfort conditions, as well as to compare the impacts of different design parameters. Additionally, an EPW-format dataset representing the local climate conditions of Bingöl Province was used for the optimization simulations. With these configurations, energy performance optimization simulations for the reference building were conducted. A total of 498 scenario simulations were performed, and the data was collected.

3.4. Two-Step Sensitivity Analysis: Pareto Impact Assessment and Heatmap Pairwise Comparisons

To evaluate the effects of design parameters on thermal comfort and cooling load, a two-step sensitivity analysis was conducted. The methodology included:

- Pareto Impact Assessment: Identifying and ranking the most influential design parameters.
- Heatmap-Based Pairwise Comparisons: Evaluating interactions between selected parameters to confirm and refine the initial findings.

This two-step approach ensured a structured and comprehensive analysis, allowing us to prioritize the key parameters while also capturing their interdependencies.

The first step involved a Pareto-based impact assessment to determine which parameters had the highest influence on discomfort hours and cooling loads. Pareto analysis is based on the 80/20 rule, which states that a significant portion of results stems from a small portion of inputs. In a Pareto chart: Bars: Represent the impact of each variable, arranged in descending order of magnitude. Line: Indicates the cumulative effect. This analysis provides a quick visualization of the most influential variables [68]. The Pareto principle (80/20 rule) was used to identify the key contributors to indoor thermal conditions [69-71]. The assessment was conducted for three main design variables:

1. Window Opening Percentage (%)
2. Shading elements
3. HVAC System

A dataset of 498 parametric simulations was generated using DesignBuilder's parametric simulation feature. The cumulative impact of each variable on cooling loads and discomfort hours was analyzed. The Pareto ranking provided a preliminary prioritization, forming the basis for further sensitivity analysis.

In the second step, pairwise sensitivity comparisons using heatmaps were conducted to further analyze the interactions between the listed parameters. Pairwise sensitivity analysis using heatmaps has been widely applied in energy performance studies to visualize complex parameter interactions [72-74]. This analysis allowed for a more detailed evaluation of how the selected parameters influence cooling loads and discomfort hours.

In particular, this method was chosen to better observe the effects of passive design parameters such as window opening ratios and shading elements. To visualize sensitivity interactions, heatmaps were generated using Python.

Pairwise Comparisons Include:

- Pairwise parameter comparisons of window opening ratio, shading elements, and HVAC systems regarding thermal discomfort for summer clothing conditions.
- Pairwise parameter comparisons of window opening ratio, shading elements, and HVAC systems regarding cooling load effects.

Each heatmap effectively visualized parameter sensitivity by colorizing changes in discomfort hours.

Key Findings from the Two-Step Sensitivity Analysis:

- Pareto Impact Assessment, which identifies dominant parameters by ranking their individual contributions to thermal comfort and cooling loads.
- Heatmap-Based Pairwise Comparisons, which verify and refine the initial Pareto findings by confirming complex interactions between variables.

The combination of these two methods enhanced the reliability of the study's findings, ensuring a systematic assessment of the impact of design parameters. This two-step sensitivity analysis provided a structured approach to parameter evaluation, facilitating the identification of critical design factors and a better understanding of their interdependencies.

The methods used in this study were applied within the specific context of academic offices at Bingöl University. However, the DesignBuilder software and analysis methodology employed in this research can also be adapted to other buildings with different climatic conditions or functional purposes.

4. RESEARCH RESULTS AND DISCUSSION

4.1. Evaluation of the Climate Data for Bingöl Province

In this study, the analysis of outdoor weather conditions for Bingöl Province was conducted based on the premise that variables such as solar radiation and temperature provide essential inputs for energy simulations and urban planning studies. The evaluation included meteorological parameters such as outdoor air temperature, dew point temperature, wind speed and direction, solar radiation components (direct and diffuse radiation), and atmospheric pressure. These data were analyzed to understand the impact of seasonal variations and environmental factors on building performance, energy consumption, and thermal comfort. The site analysis data for Bingöl Province in DesignBuilder is presented in the graph below (Figure 5). For these analyses, an EPW file containing climate data for Bingöl from 2009 to 2023 was used, and climate simulations were performed for the year 2023. However, it is important to note that climate data obtained from EPW files is based on historical weather records and may not fully capture extreme weather variations or long-term climate trends. Additionally, the simulation results are subject to uncertainties due to potential inaccuracies in climate projections, assumptions regarding internal loads, and simplifications in the building model.

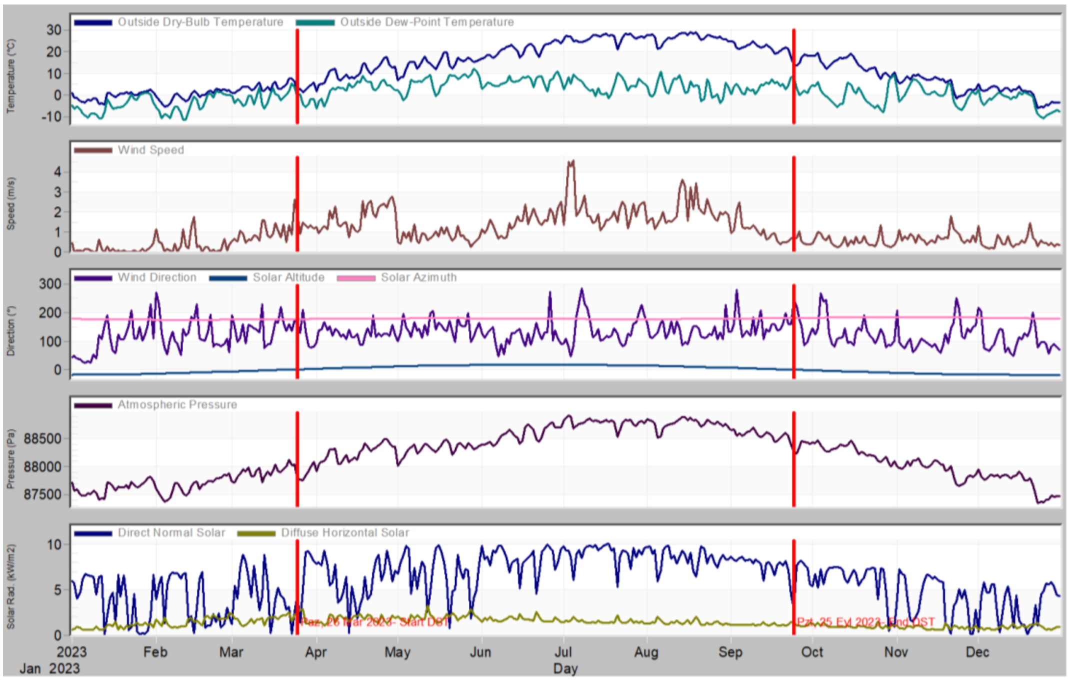


Figure 5. Climate data analysis for Bingöl Province, including outdoor air temperature, solar radiation, wind speed, and other meteorological parameters, based on the EPW dataset (2009–2023).

These graphs illustrate various parameters of outdoor weather conditions throughout the year. The first graph displays Outside Dry-Bulb Temperature (°C) and Outside Dew-Point Temperature (°C) data. During the summer months (June–August), the outside air temperature increases, while it decreases in the winter months (December–February). The maximum temperature in summer is around 20–28°C, whereas in winter, it ranges between 0 and -3°C. The Dew-Point Temperature**,** related to humidity levels, increases during the summer along with the temperature but remains lower than the outside air temperature. Particularly in winter, this value approaches or falls below 0°C, indicating high humidity levels. In the study by Demir et al. (2015), it was determined that water deficiency and evaporation reached their highest levels during the summer months, particularly in July, August, and September. Additionally, the study found that while water deficiency occurred in the summer, moderate water surplus was observed in the winter [77]. This situation can be attributed to the dominance of drought effects in the summer and heavy snowfall in the winter. The second graph presents Wind Speed (m/s)**.** Irregular fluctuations in wind speed are observed throughout the year. In summer, especially in August, a sharp increase in wind speed is noticeable, reaching approximately 3 m/s. In winter, wind speeds remain generally low. In Alashan's (2020) study, it is stated that wind speed data for Bingöl varies significantly depending on the wind direction and that the city is primarily influenced by northwesterly winds [78]. The third graph shows Wind Direction (°) and Solar Altitude and Azimuth Angles**.** Wind Direction varies significantly throughout the year with no distinct trend. Solar Altitude (°) reaches its highest-level during summer (June), correlating with longer daylight hours. In winter (December), solar altitude is very low. Solar Azimuth (°), which indicates the angle of the sun on the horizontal plane, varies throughout the year and plays a crucial role in influencing daylight duration and solar radiation. The fourth graph illustrates Atmospheric Pressure (Pa)**.** Slight fluctuations in atmospheric pressure are observed throughout the year. Pressure tends to increase during spring and summer while decreasing in autumn and winter. These changes are related to seasonal air movements and pressure systems. The fifth graph displays Direct Normal Solar Radiation (kWh/m²) and Diffuse Horizontal Solar Radiation (kWh/m²)**.** Direct solar radiation reaches its highest values in summer (June–August), indicating longer sunlight hours and direct sunlight reaching the surface. In winter (December–February), direct solar radiation decreases. Diffuse horizontal solar radiation remains at lower levels throughout the year but shows slight increases in winter due to cloud cover.

These graphs clearly demonstrate the effects of seasonal variations throughout the year. While temperatures and solar radiation increase during the summer, these values decrease in winter. Fluctuations in wind speed and changes in atmospheric pressure are linked to seasonal transitions. The direct and diffuse components of solar radiation provide critical data for energy analyses and evaluating the seasonal potential for solar energy. These graphs visualize seasonal and daily variations in meteorological data, forming an important foundation for studies related to energy analysis, building performance, and environmental impacts. Solar radiation and outdoor temperature values, in particular, play a critical role in energy consumption and thermal comfort calculations. The analyzed data can be used to assess changes in building energy requirements across different seasons. For example, increased solar radiation and temperature in summer raise cooling loads, whereas lower temperatures in winter increase heating demands. This analysis is especially useful for building energy simulations or urban planning studies.

The data in these graphs are consistent with the climate conditions described in Section 3.1 and the information provided according to the Köppen climate classification [54]. Bingöl is located in the eastern part of Türkiye, far from the sea, and exhibits cold and snowy winters along with continental climate characteristics in the summer. As a result, low temperatures are observed in winter, while significant temperature variations occur in summer. The high altitude of the region accentuates day-night temperature differences, making climatic conditions more pronounced. In line with the general climate characteristics of the Eastern Anatolia Region, high-pressure systems dominate during winter, intensifying the impact of cold air masses. In summer, dry and hot air currents prevalent in inland areas shape the region's temperature dynamics. Seasonal variations in wind speed are also a crucial factor influencing the climatic characteristics of the region. While wind speeds tend to remain low in winter over landlocked areas, they become more variable in summer due to the influence of thermal winds. These climatic dynamics form a fundamental basis for understanding seasonal changes in temperature, solar radiation, and wind speed in Bingöl.

4.2. Analysis of the Relationship Between Thermal Discomfort and Variable Parameters

This section presents the analyses of discomfort criteria for the academic offices in the Faculty of Engineering and Architecture at Bingöl University, located in Bingöl Province. Previous studies have investigated the thermal comfort conditions for Bingöl Province [75, 76, 55]. Based on these studies, the importance of thermal comfort conditions has been evaluated. Additionally, this analysis aims to address the gaps in studies linking thermal comfort improvements with design parameters. The analyses in this section are considered within the framework of the window opening ratios explained in Section 3.2, *Determination of Alternative Design Parameters*, the shading devices specified in Table 1, and the HVAC systems defined in Table 22. Additionally, the activity settings specified in Table 3 were used for all scenarios.

One of the primary issues identified in these offices is the use of windows with limited opening ratios. Consequently, the initial focus of this study was to analyze the effect of window opening ratios on different discomfort criteria. These analyses were conducted using bar charts for comparisons and Pareto analysis.

Pareto analysis is based on the 80/20 rule, which states that a significant portion of results stems from a small portion of inputs. In a Pareto chart: Bars: Represent the impact of each variable, arranged in descending order of magnitude. Line: Indicates the cumulative effect. This analysis provides a quick visualization of the most influential variables [68]. It helps identify which factors have the most significant impact on discomfort hours. A graph illustrating the effects of window opening ratios on different discomfort criteria under the SE-1 (No Shading) and VT-1 (Natural Ventilation - No Heating/Cooling) scenarios is presented in Figure 6. Pareto analysis has been used to examine the impact of window opening ratios on discomfort hours and to identify the most effective range. The graph evaluates the effect of different window opening ratios on discomfort hours, determining the range where the most significant reduction occurs. This graph offers valuable insights for optimizing natural ventilation strategies and clearly demonstrates how window opening ratios influence both energy efficiency and thermal comfort.

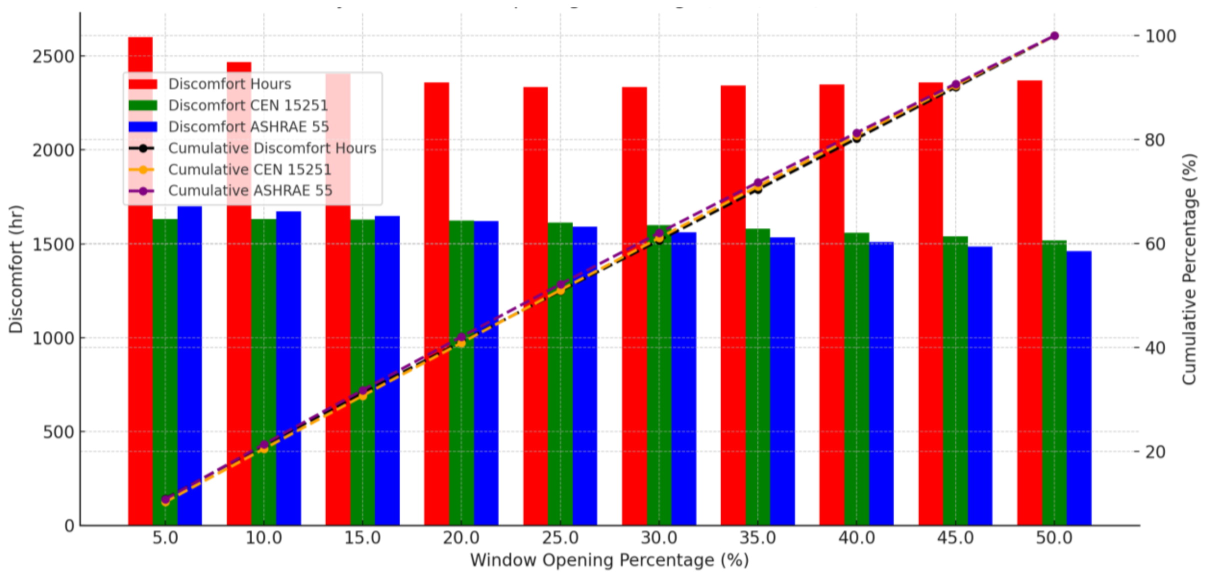


Figure 6. Impact of Window Opening Ratios on Discomfort Criteria under SE-1 (No Shading) and VT-1 (Natural Ventilation - No Heating/Cooling) Scenarios"

Pareto analysis states that a significant portion of the outcome results from a small percentage of inputs. In the graph, the highest discomfort hours are observed at window opening ratios of 5%-20%. When the window opening ratio reaches 35-40%, a significant decrease in discomfort hours occurs. However, beyond 40%, the slope of the decline slows down, indicating a reduction in additional benefits. This situation partially aligns with the Pareto principle. If a large portion of discomfort hours is concentrated at low window opening ratios and no significant improvement occurs beyond a certain threshold (35-40%), the Pareto principle may apply in this context. However, the classic 80/20 ratio is not strictly observed; instead, discomfort hours exhibit a rapid decline initially, followed by a more gradual decrease. In the context of different standards, CEN 15251 shows the highest comfort improvement at a window opening ratio of 30-40%, while ASHRAE standards indicate an effective range of 35-50%. The graph demonstrates that the highest discomfort hours are concentrated at low window opening ratios, with diminishing improvements beyond a certain point. As a result, the optimal window opening ratio is determined to be 30-40%, and this finding provides valuable insights for optimizing natural ventilation strategies.

When the graph is interpreted in the context of Pareto evaluation and comparisons with bar graphs; discomfort Hours (Summer Clothing): The data shows that the window opening ratio was incrementally increased from 5% to 50%. As the window opening ratio increases, a noticeable decrease in discomfort hours is observed. Greater window opening ratios enhance natural ventilation, improving indoor temperature and air quality, which reduces discomfort hours. However, the rate of decrease becomes less pronounced after the window opening ratio reaches

35-40%, suggesting a limited effect of natural ventilation beyond this point. At low window opening ratios (e.g., 5-10%), discomfort hours are notably high. Increasing the window opening ratio improves indoor air quality and reduces perceived heat, effectively lowering discomfort hours. Discomfort CEN 15251 (Discomfort Hours Based on European Standards): The graph also evaluates discomfort hours according to CEN 15251, one of the European thermal comfort standards. At low window opening ratios (e.g., 5-10%), discomfort hours remain high. A more significant reduction in discomfort hours is observed after the window opening ratio reaches 20-25%. This indicates that natural ventilation improves thermal comfort within the building and creates an environment that aligns better with the standard. However, a plateau effect is observed beyond 35-40%, implying a diminishing relationship between window opening ratio and thermal comfort after a certain point. According to the CEN 15251 standard, natural ventilation increases the potential for achieving thermal comfort, with a window opening ratio of 30-40% being an effective range for improving comfort conditions. Discomfort ASHRAE 55 (Adaptive Comfort Approach): The third analysis examines discomfort hours using the adaptive comfort approach outlined in ASHRAE 55. At low window opening ratios (e.g., 5-15%), discomfort hours are high. A more pronounced decrease in discomfort hours occurs as the window opening ratio increases to the 20-30% range. Beyond 35-40%, there is less change in discomfort hours. The adaptive comfort approach shows that natural ventilation improves perceived temperature and reduces discomfort hours. However, high window opening ratios appear to maximize the benefits of the ASHRAE 55 adaptive comfort standard, ensuring that comfort is maintained even at higher opening ratios. The ASHRAE 55 standard demonstrates how natural ventilation allows building occupants to adapt to thermal conditions, maintaining comfort at elevated opening ratios.

In this study, the discomfort criteria defined by ASHRAE 55 and CEN 15251 were used to evaluate thermal comfort conditions. ASHRAE 55 provides globally recognized thresholds for indoor environments, while CEN 15251 is particularly relevant for assessing natural ventilation strategies in European climates [65, 66]. These standards offer different temperature and humidity tolerance ranges, allowing for a more comprehensive evaluation of thermal comfort.

The graph clearly shows that as window opening ratios increase, discomfort hours decrease significantly for all three discomfort criteria. Specifically, while a 5% window opening ratio results in the highest discomfort hours, this value decreases significantly at 50%.

The differences between ASHRAE 55 and CEN 15251 standards are also clearly visible in the graph.

- ASHRAE 55: Due to its wider temperature tolerance, discomfort hours are generally lower.

- CEN 15251: Because of its stricter temperature limits, discomfort hours are higher compared to ASHRAE 55.

In a climate like Bingöl, which experiences hot and dry summers and cool winters, adjusting window opening ratios correctly can significantly reduce discomfort hours. However, stricter thermal comfort targets in standards like CEN 15251 may require tighter control measures, which could lead to increased energy consumption.

The findings provide a foundation for optimizing natural ventilation strategies during the design phase and offer insights into the impact of window opening ratios on energy consumption and thermal comfort.

In the academic offices studied, the second problem causing thermal discomfort during the summer months is the heating effect of solar energy, which is considered a significant source of indoor discomfort. To address this issue, the addition of shading elements was identified as a variable parameter to control the solar energy entering through the windows, and the impact of this parameter on discomfort was analyzed. The graph below (Figure 7) illustrates the effect of different types of shading elements on discomfort hours under a natural ventilation system (VT-1: Natural Ventilation - No Heating/Cooling) at a fixed window opening ratio of 5%. This graph provides a detailed comparison of how shading elements influence discomfort hours according to various standards within the natural ventilation scenario.

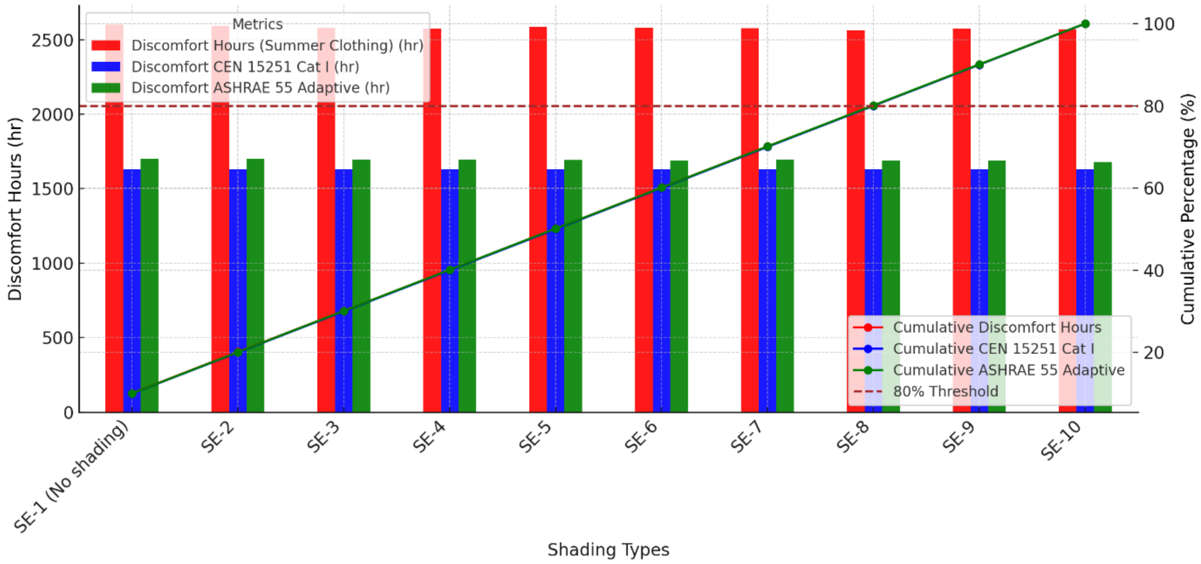


Figure 7. Impact of Different Shading Elements on Discomfort Hours Under Natural Ventilation (VT-1) at a Fixed 5% Window Opening Ratio

This graph illustrates the impact of different types of shading elements on discomfort hours under natural ventilation (VT-1) and a fixed window opening ratio of 5%, based on three different criteria. This graph analyzes the impact of different shading types on discomfort hours and their cumulative distribution, providing an evaluation aligned with the Pareto principle. Pareto analysis states that a significant portion of outcomes stems from a small number of inputs. In this context, the graph illustrates that discomfort hours are concentrated in certain shading types. The cumulative effect line and the 80% threshold help identify which shading types contribute the most to total discomfort hours. The SE-1 (No Shading) scenario exhibits the highest discomfort hours. When shading elements (from SE-2 to SE-10) are applied, discomfort hours decrease. However, the rate of reduction varies across different shading types. Some shading types, particularly SE-10, appear to be more effective than others. The graph shows that shading types from SE-1 to SE-4 account for a significant portion of total discomfort hours. Once the 80% threshold is surpassed, the additional comfort improvement provided by further shading elements diminishes. According to the Pareto principle, most of the total improvement is achieved through a few highly effective shading types. SE-10 emerges as the most effective shading element, while SE-1 (No Shading) performs the worst, significantly increasing discomfort hours. Shading types from SE-2 to SE-6 contribute substantially to reducing total discomfort hours, but the impact of additional shading types beyond SE-7 gradually decreases. This analysis can be used to determine optimal shading design and prevent unnecessary additions. Overall, the Pareto analysis demonstrates that a significant portion of total discomfort hours is reduced by specific shading types. The greatest improvement is achieved with shading elements ranging from SE-2 to SE-6, while SE-10 stands out as the most efficient solution. Considering that the additional benefit of shading elements beyond SE-7 diminishes, selecting the most effective shading elements is crucial for optimizing shading strategies.

When the results of the Pareto analysis evaluation and bar graphs are examined within the framework of the graph, significant differences are observed between shading element types. For example, types like SE-1 (No Shading) increase discomfort hours, whereas all other shading types reduce discomfort hours. Discomfort Hours (Summer Clothing) generally presents the highest values, indicating that this standard considers fewer parameters that contribute to indoor comfort. ASHRAE 55 provides the lowest discomfort hours, highlighting the advantages of the adaptive comfort approach. CEN 15251: Due to its stricter criteria, discomfort hours are higher compared to ASHRAE 55. However, this difference decreases with more effective shading devices such as SE-10. The graph shows that SE-10 (the most effective shading device) reduces discomfort hours to the lowest level and exceeds the cumulative 80% threshold. Although there are small differences between SE-2 and SE-7, these devices also contribute to thermal comfort improvements. The compatibility of CEN 15251 and ASHRAE 55 standards with different shading strategies varies.

While CEN 15251's stricter control requirements necessitate a more careful selection of shading strategies during the design phase, ASHRAE 55 allows for a wider range of applications. In a climate like Bingöl, which has hot and dry summers and cold winters, advanced shading devices such as SE-10 play a crucial role in reducing discomfort hours. Furthermore, the differing requirements of ASHRAE 55 and CEN 15251 highlight the need to establish a balance in building design regarding which shading strategies should be implemented.

This graph clearly demonstrates the importance of shading elements in achieving thermal comfort. The effects of different shading types on discomfort hours underline the critical role of selecting appropriate shading elements in design decisions. According to cumulative lines, the shading types that contribute most to reducing total discomfort hours should be prioritized. If the focus is on a specific standard, such as the European standard or ASHRAE, the shading types that result in the lowest values under that standard should be chosen. The design process can optimize shading element types by considering both individual and cumulative effects.

Another recommendation to reduce thermal discomfort during summer in the studied offices is to provide mechanical cooling with HVAC systems. In this context, discomfort levels for four different HVAC systems were analyzed. Figure 8 compares the effects of different HVAC systems on discomfort levels under a 5% window opening ratio (current scenario) and SE-1 (No Shading). This graph uses Pareto analysis alongside bar charts to compare the impact of HVAC systems on discomfort hours.

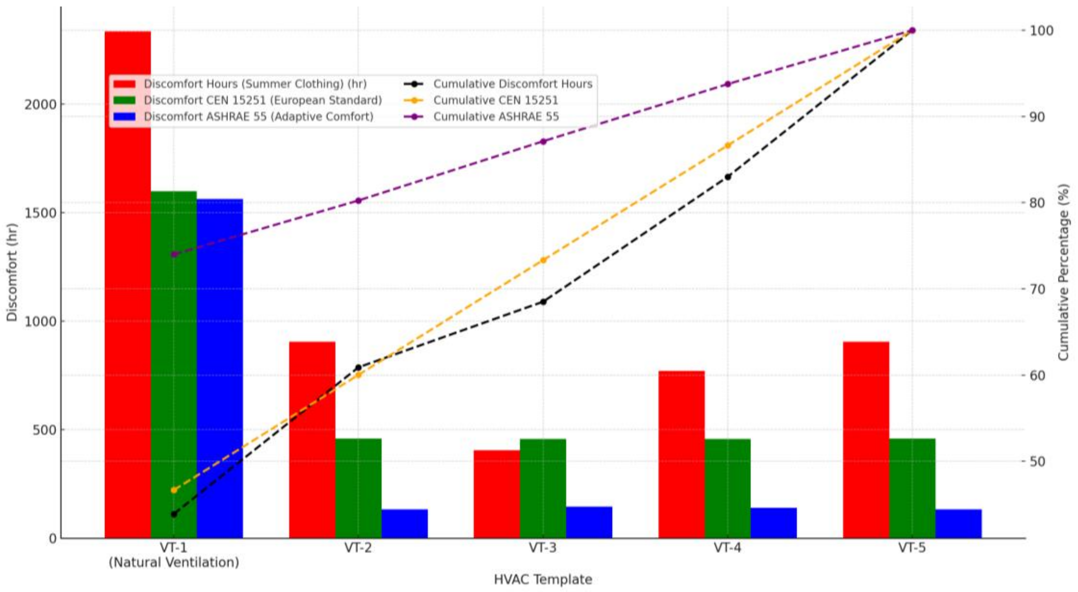


Figure 8: Comparison of Discomfort Hours Across HVAC Systems at 5% Window Opening Ratio and SE-1 (No Shading) Using Pareto Analysis

The graph evaluates the impact of HVAC systems on discomfort hours within the framework of Pareto analysis. According to the Pareto principle, a significant portion of total discomfort hours is determined by a small number of HVAC systems. VT-1 (Natural Ventilation) has the highest discomfort hours, contributing to the majority of total discomfort. The mechanical systems used in VT-2, VT-3, VT-4, and VT-5 significantly reduce discomfort hours; however, this decline slows noticeably after VT-4 and VT-5. Within the context of the Pareto principle, the most substantial improvement is observed when transitioning from VT-1 to VT-3, while the reduction in discomfort hours becomes more limited beyond VT-3 and VT-4. The graph highlights that the difference between HVAC systems is most pronounced between VT-1 and VT-3, but the additional gains become marginal when moving to more advanced systems like VT-4 and VT-5. This aligns with the Pareto effect, where the most significant improvements occur up to a certain point, after which the marginal benefits diminish.

When the results of the Pareto analysis evaluation and bar graphs are examined within the framework of the graph, natural ventilation (VT-1) generally results in higher discomfort hours compared to other systems, as it lacks mechanical support to adapt to environmental conditions. However, even this system can provide acceptable levels of discomfort hours under the ASHRAE adaptive comfort standard. Significant differences in discomfort hours are observed among HVAC systems, with controlled systems effectively reducing discomfort hours. Green bars (CEN 15251 - European Standard) represent discomfort hours according to the European standard. More comprehensive systems (e.g., VT-3 or VT-5) generally offer lower discomfort hours under this standard. Blue bars indicate discomfort hours based on the ASHRAE adaptive comfort standard. Since the adaptive comfort standard accounts for occupant adaptation to environmental conditions, it typically shows the lowest discomfort hours. Even under VT-1 (Natural Ventilation), discomfort hours may appear lower according to ASHRAE 55. Discomfort Hours (Summer Clothing) usually show the highest discomfort values, while ASHRAE 55 generally provides lower values. This variation between standards can guide design decisions depending on which standards are prioritized. HVAC systems like VT-3 or VT-5 may be preferred to reduce discomfort hours and enhance thermal comfort. These systems can provide significantly better thermal comfort. However, low-energy systems like natural ventilation or VT-4 can still deliver acceptable performance under the ASHRAE adaptive comfort standard. If compliance with the European standard is required, systems like VT-3 or VT-5 should be prioritized. CEN 15251 has stricter comfort criteria, which results in higher discomfort hours, especially in low-performance systems such as VT-1 and VT-2. VT-5 is observed to reduce discomfort hours to the lowest level for both standards. However, VT-3 and VT-4 systems have also been noted to effectively reduce discomfort hours in accordance with CEN 15251. The graph also highlights the positive impact of lower-energy-consuming mechanical systems on thermal comfort. Natural ventilation (VT-1) is an insufficient solution for the hot and dry summers of the Bingöl climate. Mechanical systems, particularly advanced systems like VT-5, are shown to be significantly more effective in improving thermal comfort. However, the impact of these improvements on energy consumption should also be taken into consideration.

4.3. Analysis of the Relationship Between Cooling Load and Variable Parameters

The effects of natural ventilation methods for improving summer thermal comfort in university offices were discussed in the previous section, revealing significant potential for improvements. However, improvements achieved solely through natural ventilation are limited, and mechanical systems are also needed to maintain adequate thermal comfort conditions in these spaces. In this context, the energy performance of different HVAC systems was analyzed to enhance the thermal comfort conditions of the offices. The relationship between cooling energy and five selected HVAC systems is presented in the graph in Figure 9. This graph compares the energy performance (cooling loads) of HVAC systems under a 30% window opening ratio and no shading (SE-1) condition. Additionally, it examines the cumulative impact of each system on the total load using Pareto analysis.

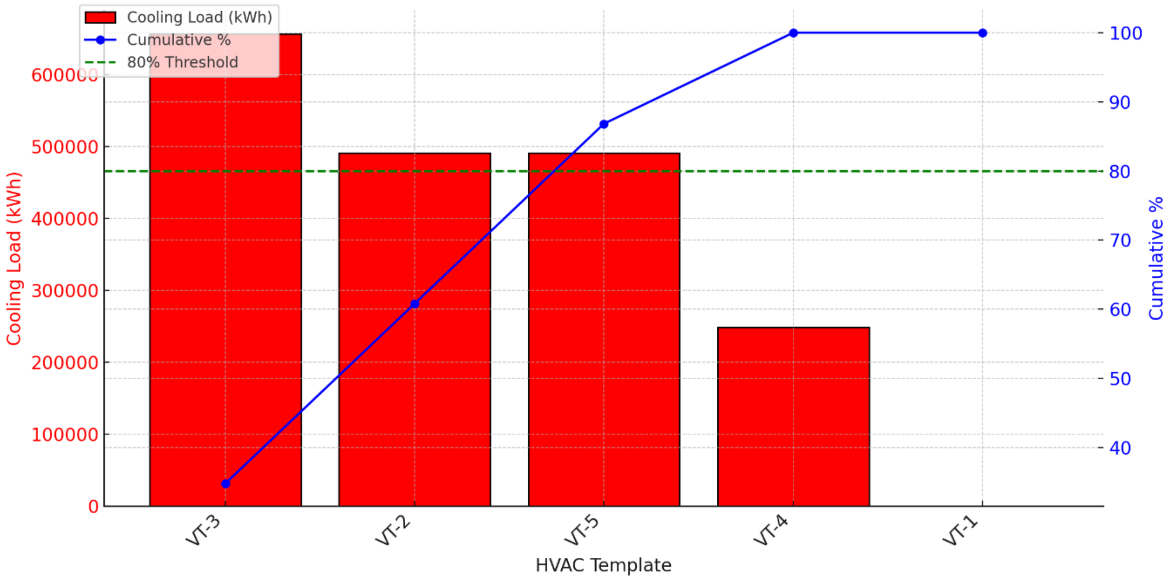


Figure 9. Comparison of cooling loads for five HVAC systems under a 30% window opening ratio and no shading (SE-1) condition, with cumulative impacts analyzed using Pareto analysis.

The Pareto effect in this graph highlights that a significant portion of the total cooling load is dominated by a few HVAC systems. The highest cooling load is observed in VT-3, contributing the most to overall energy consumption. VT-2 and VT-5 also have substantial cooling loads, while VT-4 shows a noticeable reduction. VT-1, representing natural ventilation, has the lowest cooling load. Following the Pareto principle, the majority of the cooling load is concentrated in a few HVAC systems (VT-3, VT-2, and VT-5), accounting for nearly 80% of the total cooling demand. Beyond these, the reduction in cooling load becomes less pronounced, with VT-4 showing moderate energy consumption and VT-1 having minimal cooling demand. This pattern aligns with the Pareto rule, where the most significant portion of energy consumption is driven by a few key systems, while additional improvements yield diminishing returns.

When the results of the Pareto analysis evaluation and bar graphs are examined within the framework of the graph, some HVAC systems result in higher energy consumption compared to others. Systems like VT-2 require greater cooling loads, which may indicate lower energy efficiency or a higher reliance on mechanical cooling. HVAC systems with lower load requirements (e.g., VT-5) are more advantageous in terms of energy savings. These systems may use natural ventilation more effectively or optimize mechanical cooling. Selecting a 30% window opening ratio can optimize the contribution of natural ventilation, although results may vary depending on the HVAC system. The graph provides an opportunity to evaluate the performance of mixed-mode systems (VT-3 and VT-4) compared to other HVAC systems. Such systems combine natural ventilation with mechanical cooling, offering more balanced energy consumption. The lowest energy consumption is observed in the VT-5 system, making it a priority for energy-saving projects due to its minimal cooling load. Systems like VT-2 result in higher energy consumption. If these systems are to be used, measures to enhance natural ventilation should be considered in their design. This analysis significantly contributes to the decision-making process for optimizing the energy consumption of HVAC systems and enhancing energy efficiency.

A graph comparing the cooling loads for different shading element types under the VT-2 HVAC system and a 30% window opening ratio, including Pareto analysis, is presented (Figure 10).

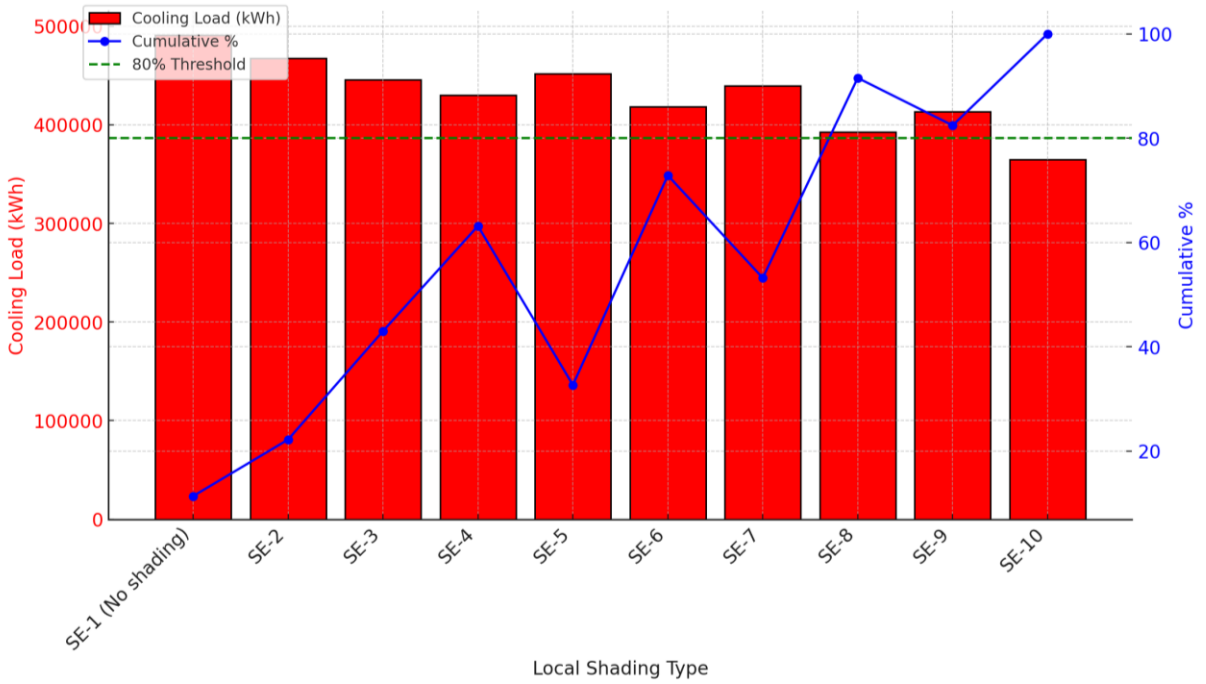


Figure 10. Comparison of cooling loads for different shading element types under the VT-2 HVAC system and a 30% window opening ratio, with cumulative impacts analyzed using Pareto analysis.

The Pareto effect in this graph demonstrates that a significant portion of the total cooling load is primarily influenced by certain shading types. The cooling load remains at similar levels across multiple shading strategies, including SE-1 (no shading). However, when analyzing the cumulative curve, it is evident that approximately 80% of the total cooling load is concentrated in a few shading types (SE-1, SE-2, SE-3, SE-5, and SE-7). According to the Pareto principle, a large portion of energy consumption is concentrated in specific shading strategies. However, some shading types, such as SE-10, exhibit lower cooling loads compared to others. Shading options like SE-4, SE-6, and SE-8 display irregular effects, causing fluctuations in the cumulative impact graph. This suggests that certain shading elements may not be as effective in enhancing energy savings as expected. In conclusion, based on Pareto analysis, the greatest impact on cooling load is achieved by specific shading strategies, while additional improvements yield diminishing marginal benefits. Selecting the most effective shading strategy is a crucial factor in reducing cooling loads efficiently.

When the results of the Pareto analysis evaluation and bar graphs are examined within the framework of the graph, the SE-1 (no shading) condition exhibits the highest cooling load compared to other types. This indicates that it fails to adequately block sunlight, resulting in increased cooling demand. On the other hand, the SE-10 type has noticeably lower cooling loads compared to others, demonstrating its superior shading effectiveness. The differences between shading types are attributed to variations in the size or positioning of the shading elements. Shading types with lower cooling loads (e.g., SE-10) should be prioritized for their energy efficiency advantages. The blue line, representing the Pareto analysis, shows the cumulative percentages. It is used to analyze the shading types contributing the most to 80% of the total cooling load. The first few types (e.g., SE-1, SE-2, SE-3) contribute significantly to the total cooling load. Improving or eliminating these types from the design could lead to energy savings. The green dashed line marks the point where 80% of the cumulative cooling loads are reached. Shading types up to this point indicate high energy demands. Shading types like SE-1, which result in high cooling loads, should be reconsidered in the design. Incorporating shading types like SE-10, which generate lower loads, into design standards can enhance energy efficiency. This graph underscores the need to revisit shading element designs to optimize cooling loads and improve energy savings. Particularly, high-load types such as SE-1 (no shading) should be redesigned or entirely replaced to reduce energy consumption more effectively.

4.4. Heatmap Pairwise Comparisons

In this study, Pareto analysis was used as a fast and effective tool to evaluate the impact of design parameters on energy performance. The primary objective of this analysis is to determine how a small number of key parameters (e.g., 20%) influence the majority of the total outcome (80%) in a complex system. This method provides a significant advantage in prioritizing decision-making processes and focusing on critical design parameters. However, Pareto analysis alone may be insufficient in explaining all interactions between design parameters and their comprehensive effects on energy performance. Therefore, while leveraging the advantages of Pareto analysis, this study also incorporates complementary methods to address its limitations and conduct a more thorough analysis. In this section, the relationships between parameter combinations were examined. This approach allowed for the analysis of both overall trends and detailed interactions. A sensitivity analysis was conducted using pairwise parameter combinations, and heatmaps were generated. Initially, the relationship between thermal discomfort (summer clothing) and parameters was analyzed. The heatmaps below illustrate the interactions of thermal discomfort for summer clothing with various parameters (Figure 11 a, b, c).

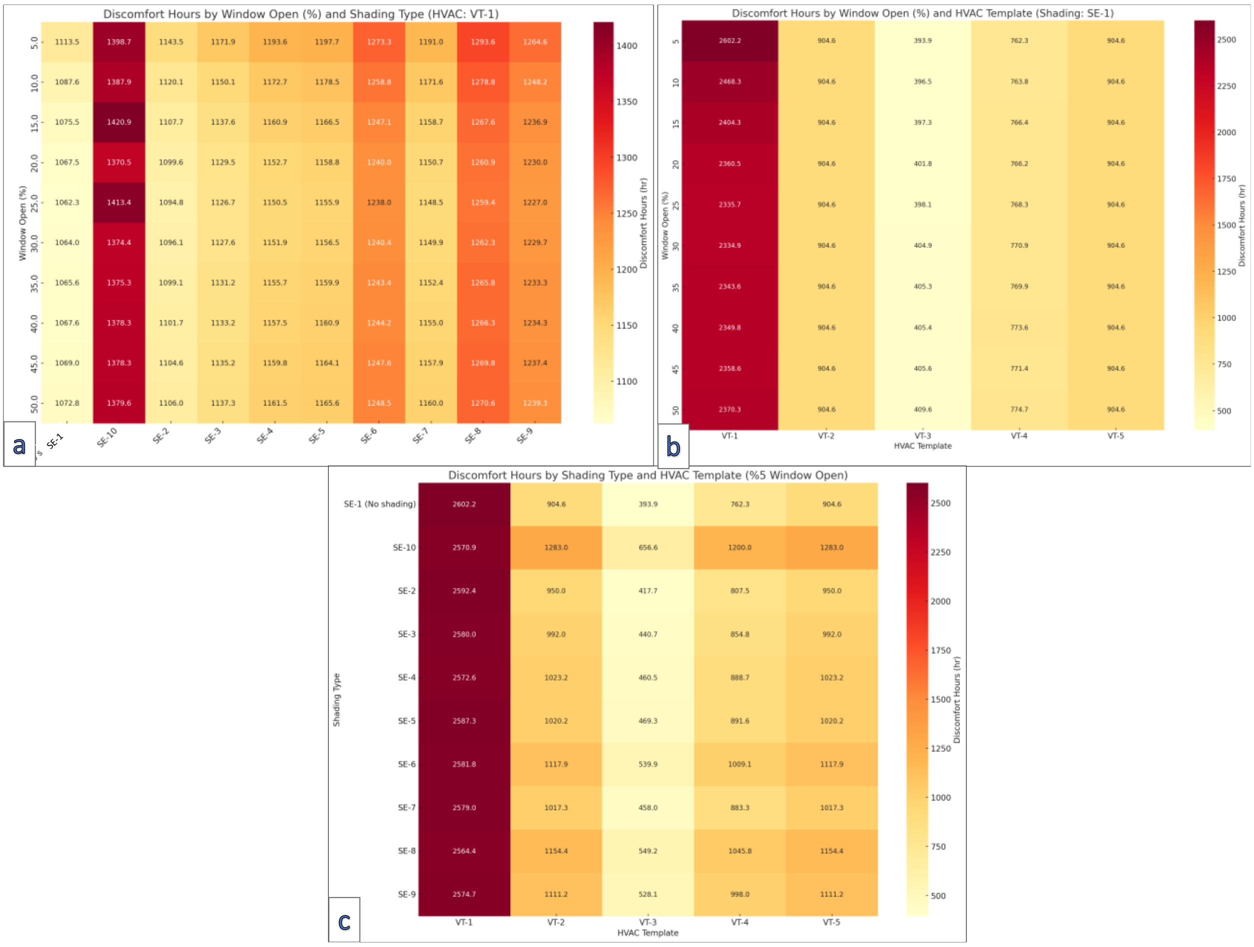


Figure 11 (a). Heatmap of Discomfort Hours by Window Opening Percentage (%) and Shading Type (HVAC: VT-1), **(b).** Heatmap of Discomfort Hours by Window Opening Percentage (%) and HVAC Template (Shading: SE-1), **(c).** Heatmap of Discomfort Hours by Shading Type and HVAC Template (5% Window Open)

Figure 11 (a) is a heatmap showing the effect of window opening percentage and shading type on discomfort hours for summer clothing. The heatmap indicates that lighter colors (yellow) represent lower discomfort hours, whereas dark red tones indicate higher discomfort hours. As the window opening percentage increases from 5% to 50%, a general decrease in discomfort hours is observed, with colors shifting toward yellow. This confirms that higher window opening percentages improve thermal comfort. When the SE-1 (No Shading) type shading element is not used, discomfort hours remain quite high at all window opening percentages (dark red tones). This clearly shows that when no shading elements are used, spaces become overheated and uncomfortable. SE-4 and SE-5 shading elements display more balanced discomfort hours, even at low window opening percentages, with fewer dark red areas. These designs effectively provide shading while also allowing natural ventilation. On the other hand, shading types with higher densities, such as SE-10, tend to result in higher discomfort hours (dark orange and red tones).

This is due to excessive shading limiting natural ventilation, preventing spaces from cooling down. SE-4 and SE-5 shading types, when combined with a window opening percentage of 25% or more, result in the lowest discomfort hours (yellow tones). The combination of SE-1 (No Shading) with low window opening percentages (5%, 10%) shows extremely high discomfort hours (dark red tones), indicating that this combination is unsuitable for summer thermal comfort. However, increasing the window opening percentage above 25% significantly reduces discomfort hours. Shading element design should not only provide shading but also support natural ventilation.

Figure 11 (b) is a heatmap illustrating the effect of HVAC system type and window opening percentage on discomfort hours for summer clothing. As seen in the heatmap, under VT-1 (Natural Ventilation - No Heating/Cooling), discomfort hours remain quite high when window opening percentages are low (5%-20%) (dark red tones). Although discomfort hours decrease at higher window opening percentages (40%-50%), discomfort levels remain generally high under VT-1. HVAC systems such as VT-2 and VT-4 significantly reduce discomfort hours compared to VT-1. Around a 30% window opening percentage, discomfort hours are observed to be at their lowest level (yellow tones) for VT-4. In general, HVAC system type has a major impact on discomfort hours, and more advanced HVAC systems (e.g., VT-4) provide better thermal comfort conditions. Increasing the window opening percentage is particularly important for improving comfort in natural ventilation systems such as VT-1.

Figure 11 (c) is a heatmap showing the relationship between shading element type and HVAC system type. When SE-1 (No Shading) is used, discomfort hours remain high regardless of HVAC system type (dark red tones). This demonstrates that in the absence of shading, the indoor environment fails to provide adequate comfort conditions. For VT-1 (natural ventilation), discomfort hours are high for all shading types. More advanced HVAC systems, such as VT-3 and VT-4, significantly reduce discomfort hours. HVAC systems such as VT-2 and VT-3 are less affected by shading types. Excessive shading, such as SE-10, is effective in reducing discomfort hours for some HVAC systems (e.g., VT-3 and VT-4). Balanced shading types like SE-4 and SE-5 provide optimal discomfort hour reductions.

Following the thermal discomfort analysis, the relationship between cooling load—a key factor in building energy performance—and design parameters was examined. The graphs below illustrate the effects of key parameters on cooling load in detail and discuss their role in energy performance (Figure 12 d, e, f).

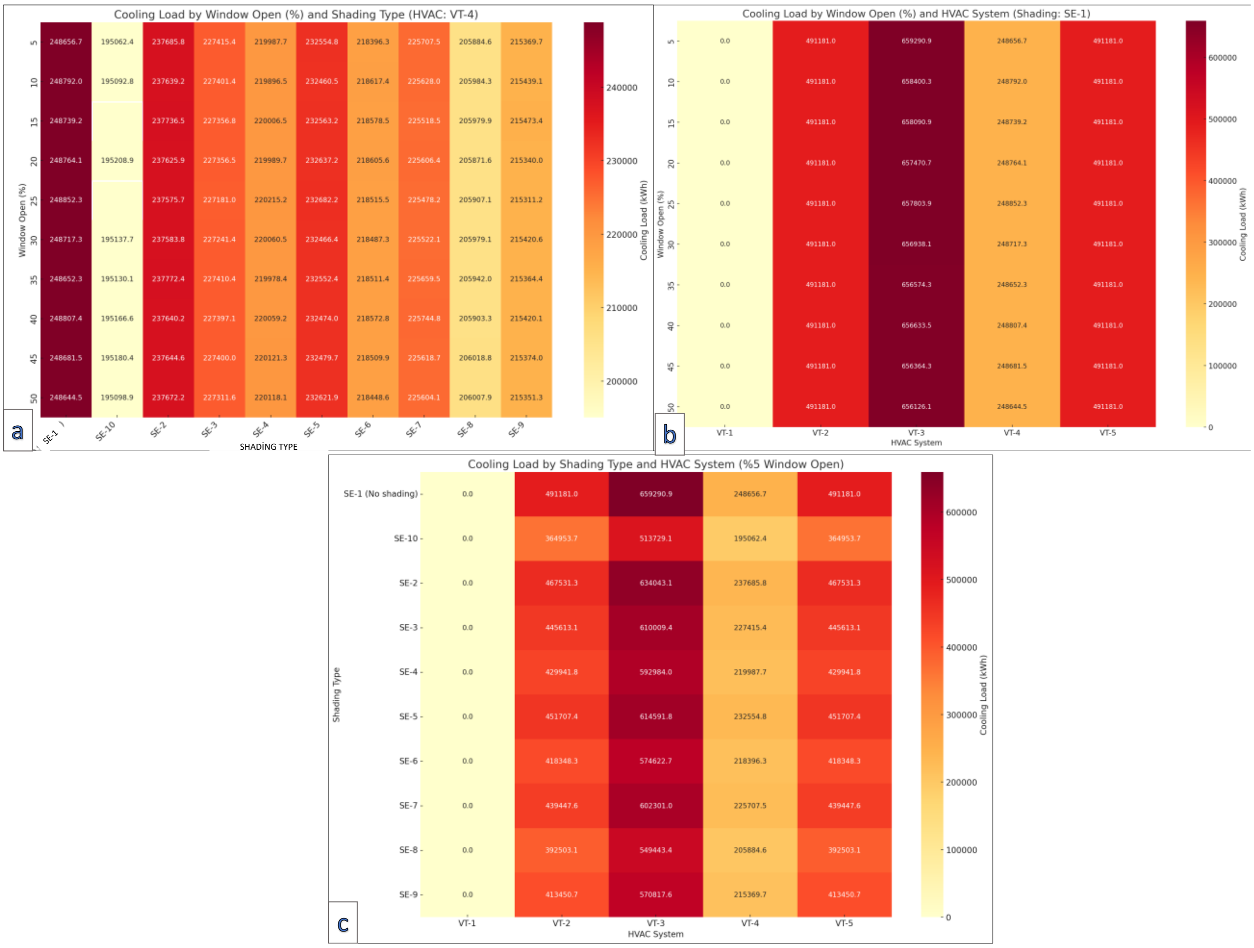


Figure 12 (a). Heatmap of Cooling Load by Window Opening Percentage (%) and Shading Type (HVAC: VT-4), **(b).** Heatmap of Cooling Load by Window Opening Percentage (%) and HVAC System (Shading: SE-1), **(c).** Heatmap of Cooling Load by Shading Type and HVAC System (5% Window Open)

The first heatmap (Figure 12a) examines the effect of window opening percentage and shading type on energy performance. In the current scenario (VT-1), since there is no cooling HVAC system, there is no cooling load. The comparison was conducted based on the mix-mode system, where natural ventilation and mechanical systems coexist (VT-4). As seen in the heatmap, an increase in window opening percentage results in a decrease in cooling load. Cooling load remains higher at low window opening percentages. For SE-1 (No Shading), cooling load remains high across all window opening percentages. In contrast, shading devices that provide more shading (e.g., SE-10) significantly reduce cooling load. Overall, reducing cooling load requires selecting an appropriate shading device and increasing the window opening percentage.

The second heatmap (Figure 12b) illustrates the relationship between the HVAC system and window opening percentage. Among the systems, VT-4 stands out with a lower cooling load.

- VT-1 (Natural Ventilation - No Heating/Cooling) has a fixed and high cooling load since there is no cooling mechanism.
- As the window opening percentage increases, a decreasing trend in cooling load is observed in VT-3 and VT-4 systems.
- VT-2 and VT-5 HVAC systems operate independently of natural ventilation, meaning their cooling load remains constant.

The third heatmap (Figure 12c) represents the relationship between HVAC systems and shading type.

- SE-1 (No Shading): Cooling load is extremely high when shading is absent.
- Shading devices that provide intensive shading, such as SE-10, significantly reduce cooling load, especially in VT-4 and VT-5 HVAC systems.
- Balanced designs (e.g., SE-4, SE-5) yield better results across multiple HVAC systems.

For achieving lower cooling loads, an optimal shading design and advanced HVAC systems (e.g., VT-4, VT-5) should be used together.

4.5. General Evaluation of Findings and Discussion

This study evaluates the effects of window opening percentage, solar shading systems, and HVAC options on improving summer thermal comfort conditions in academic offices. Simulations conducted on academic office spaces at Bingöl University indicate that the effective use of shading devices and natural ventilation strategies can significantly reduce cooling loads. The key findings obtained from the study are summarized below.

Effect of Window Opening Percentages:

- Increasing the window opening percentage from 5% to 50% without adding shading elements and HVAC systems resulted in a 14.2% improvement in ASHRAE 55 Adaptive 80% Acceptability (hr) values.

Performance of Shading Elements:

- The SE-10 shading device demonstrated the best performance among all the examined systems.

Natural Ventilation (VT-1 System):

- When the VT-1 natural ventilation system was used with the SE-10 shading device and a 50% window opening percentage, it resulted in a 23.6% improvement in ASHRAE 55 Adaptive 80% Acceptability (hr) values compared to the baseline scenario.

Discomfort Hours:

- The VT-3 system demonstrated the best comfort performance among different window opening percentages when shading devices were not used.

Cooling Load Performance:

- The VT-4 system was identified as the most energy-efficient HVAC system.
- While VT-3 improved comfort, it exhibited higher energy consumption.
- Without shading devices and at a 50% window opening percentage, the VT-4 system consumed 49–62% less energy than other systems.

Energy and Comfort Balance:

- The VT-1 system is suitable for minimizing energy consumption, but it does not provide an adequate level of comfort.
- When the SE-10 shading device and a 50% window opening percentage were used with the VT-4 system, discomfort hours (summer clothing) improved by 54% compared to the baseline scenario.

Yüksel & Esin (2011) stated in their study that buildings aim to provide a healthy and comfortable indoor living environment while simultaneously protecting occupants from adverse external conditions. The research highlights that natural ventilation methods are effective in reducing building energy loads [79]. In the study conducted by Deng et al. (2022), the impact of façade design on indoor air temperatures was analyzed under both closed and open window conditions. The study confirmed that the positive correlations between the window-to-wall ratio (WWR), residential envelope thermal transmittance value, and indoor air temperature were statistically significant at the 0.05 level. Additionally, indoor thermal comfort was evaluated under scenarios with wind exposure. The results indicate that implementing appropriate façade design strategies can significantly improve indoor thermal comfort [80]. In this context, the findings of this study assess the contributions of natural ventilation strategies, window opening ratios, and passive design solutions to building thermal comfort, while also supporting and expanding upon the findings of previous studies. Additionally, previous studies have emphasized that external shading elements directly affect the solar energy received by a window and the energy transferred into the indoor space through this radiation [22]. In the study conducted by El Sherif [21], the necessity of adopting passive techniques and basic shading elements in tropical climates was highlighted. This study examined the relationship between thermal comfort, visual comfort, and energy consumption. The research was conducted on a building model representing common office types. The performance of different shading elements, such as overhangs and side panels, was analyzed for both summer and winter seasons. The results showed that shading elements reduced solar gains by 13-55% and contributed to energy savings of up to 27.5%. Similarly, the study by Yin & Muhieldeen [18] investigated the impact of window shading systems on natural ventilation. The cross-ventilation performance was evaluated using vertical shading elements, and simulations were conducted with EnergyPlus software. The findings indicated that vertical shading systems could increase ventilation rates by 30.46%. In this context, this study has demonstrated that an appropriate combination of window opening ratios, solar shading systems, and HVAC strategies can reduce energy consumption by 49–62% and improve discomfort hours (summer clothing scenario) by 54% compared to the baseline scenario. These findings align with previous research emphasizing the impact of window shading elements on building energy efficiency and thermal comfort, offering a broader perspective in this field.

Generalization of Findings and Applicability to Different Contexts

When assessed for its broader applicability, the study's findings are relevant not only to academic offices but also to other building types with similar climatic conditions, such as educational facilities, office buildings, and low-density residential projects. In particular, natural ventilation and passive shading strategies hold potential for energy efficiency across a variety of building typologies. However, since the study primarily focuses on academic offices at Bingöl University, this can be considered a limitation. Nonetheless, the findings can be extended to other contexts based on the following considerations:

- Hot and dry climate regions: Increasing the use of natural ventilation strategies can improve air movement and indoor comfort levels.
- Mediterranean and temperate climates: The use of fixed or adjustable shading devices can effectively reduce cooling loads.
- Different building typologies: The proposed strategies are expected to be effective in high-occupancy spaces such as educational buildings, offices, and residential areas.

Further studies are recommended to explore how the proposed solutions can be adapted to different building types and climatic regions. This study can serve as a foundation for broader building stock energy performance analyses in the future.

Limitations and Future Research Directions

The application of the proposed strategies is expected to lead to significant reductions in cooling loads. Additionally, beyond these reductions, the recommended strategies could also decrease energy consumption throughout the building's lifecycle. Optimizing shading devices and natural ventilation strategies can improve both short-term comfort conditions and long-term energy efficiency. Although this study does not include a detailed cost-benefit analysis, preliminary findings indicate that the proposed strategies have the potential to reduce energy consumption and lower operational costs.

Regarding the study's limitations and recommendations for future research, it is important to note that this study focuses on a specific office typology and a single climate region. However, to comprehensively evaluate building energy performance, further research is needed to investigate different building types and various climatic conditions. Future studies could use comprehensive simulations across different building typologies and climate zones to analyze the broader impact of the proposed design strategies.

Additionally, this study does not include a long-term energy performance or cost-effectiveness analysis. Future research should examine how the proposed strategies contribute to energy savings over the building’s lifecycle and assess their economic feasibility. Detailed life-cycle analyses could provide further insights into the long-term sustainability and economic feasibility of these strategies.

In this context, further research should focus on:

- Testing the proposed solutions across various building types and climate regions.
- Supporting this research with a broader case study analysis.
- Incorporating long-term energy savings and economic feasibility assessments.
- Conducting multi-regional comparative studies to determine the performance of the proposed strategies in different climatic zones.

Final Remarks and Research Contributions

Considering the findings and applicability of this study, the research focuses on improving summer thermal comfort and energy performance in academic offices at Bingöl University through parametric building performance optimization. While the findings are specific to this building type and climate, the core principles and methodologies can be extended to broader contexts.

The study’s results are particularly valuable for office buildings and educational facilities with similar occupancy patterns and internal heat gains. Moreover, the proposed passive and active design strategies can be adapted to climates similar to Bingöl. However, the impact of climatic variations and different building typologies on the effectiveness of these strategies should be further investigated. Future research should explore the applicability of these strategies in residential, commercial, and other building types under diverse climatic conditions.

Although this study primarily focuses on historical climate data, it is important to consider potential future climate trends and their implications for thermal comfort and energy performance. Given the expected increase in global temperatures and the potential for more extreme weather conditions, future studies should incorporate climate projection scenarios to assess the long-term adaptability of buildings. Integrating dynamic simulations with future climate datasets can help improve the resilience of building design strategies.

5. CONCLUSIONS AND RECOMMENDATIONS

This study examines the effects of window opening percentage, solar shading systems, and HVAC options on improving summer thermal comfort conditions and reducing cooling loads in academic offices. Simulations conducted for academic offices at Bingöl University indicate that the effective combination of natural ventilation and passive shading strategies can reduce energy consumption and improve comfort conditions.

1. General Findings:

- Optimization of shading devices reduces overheating problems in indoor spaces, thereby decreasing cooling loads.
- Increasing the window opening percentage supports natural ventilation, enhancing indoor thermal comfort conditions.
- Combining HVAC systems with passive design strategies offers an effective solution for reducing energy consumption.
- The best balance between energy efficiency and comfort was achieved using the SE-10 shading device, a 50% window opening percentage, and the VT-4 HVAC system.
- Increasing the window opening percentage improved thermal comfort conditions both in the absence of an HVAC system and in mixed-mode ventilation systems by reducing cooling loads.
- Like window opening percentages, solar shading systems also improved indoor comfort conditions by mitigating the negative effects of solar radiation and contributed to reducing cooling loads in summer conditions.
- The VT-3 system improved comfort but had higher energy consumption, so its application should be carefully considered in terms of energy efficiency.
- The applicability of different strategies should be assessed based on climate and building typology.

2. Generalization of Findings and Application Areas:

This study demonstrates that even without an HVAC system, thermal comfort conditions can be improved through simple passive strategies such as increasing the window opening percentage. Additionally, shading devices and efficient HVAC systems can be integrated to further enhance comfort conditions and reduce cooling loads. The findings of this study are applicable not only to academic offices but also to other building types with similar climatic conditions.

- In hot and dry climate regions, increasing natural ventilation strategies can improve indoor air movement, thereby enhancing comfort levels.
- In Mediterranean and temperate climates, the use of fixed or adjustable shading devices can be effective in reducing cooling loads.
- The proposed strategies can be particularly beneficial for high-occupancy spaces such as educational buildings, offices, and residential areas.

3.Practical Recommendations for Implementation:

The findings of this study highlight the significance of window opening ratios, solar shading strategies, and HVAC system selection in improving thermal comfort and energy efficiency. Based on these results, the following practical recommendations are proposed for architects, engineers, and policymakers:

- Architectural Design: Building designs should integrate solar shading sistems and operable windows to optimize natural ventilation and reduce cooling loads.
- HVAC System Selection: Mixed-mode (hibrit) ventilation systems (e.g., VT-3 and VT-4) should be preferred in regions where natural ventilation can effectively complement mechanical cooling, ensuring both energy efficiency and thermal comfort.
- Policy and Regulations: Urban planning and building codes should encourage the implementation of passive design strategies, particularly in climate regions where overheating is a concern.
- Building Operation Strategies: Occupants should be provided with guidance on how to utilize window openings and shading devices effectively to improve comfort conditions without excessive reliance on mechanical cooling.

These recommendations enhance the applicability of the study’s findings and provide a roadmap for integrating passive and active design strategies into real-world building projects.

4. Recommendations and Future Studies:

- This study analyzed three key parameters: window opening percentage, solar shading systems, and HVAC systems. Design strategies were proposed for each parameter. Future studies with extended simulations covering different building typologies and climate regions could enhance the generalizability of the proposed strategies.
- Future research should also investigate the impact of additional design parameters such as building orientation, building form, and spatial organization on building energy performance.
- A detailed life-cycle analysis should be conducted to evaluate the long-term energy consumption effects of the proposed solutions.

This study focuses on improving summer thermal comfort and energy performance in academic offices through parametric building performance optimization, establishing a structured approach to optimizing energy efficiency while ensuring user comfort. Although the findings are specific to this building type and climate, the core principles and methodologies can be extended to other building types and climate regions. The results enhance existing research on adaptive building strategies and provide valuable guidance for designers and policymakers aiming to improve indoor environmental quality in office spaces.

DECLARATION OF ETHICAL STANDARDS

The author/The authors of the paper submitted declare/declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

All work, including the design, analysis, writing, and review of the manuscript, was carried out by the sole author.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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