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Research paper

The impact of facade geometry on visual comfort and energy consumption in an office building in different climates

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A R T I C L E I N F O

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A B S T R A C T

In recent years, there has been a heightened emphasis improving visual comfort and energy efficiency. Various solutions have been explored to achieve high-performance design. Shading devices play a crucial role in enhancing building performance by redusing solar gains, excessive daylight, and improving both energy efficiency and occupants' visual comfort. This research aims to investigate the effect of facade geometry on visual comfort and energy consumption in four different climates of Iran and categorize each variable based on effectiveness for each location. Parametric office modeling was done by using Grasshopper and Rhino software. Then, the effect of the facade on the interior lighting and energy consumption was analyzed by Radiance, Daysim, and EnergyPlus calculation engines. The Non-Dominated Sorting Genetic Algorithm (NSGA-II) was selected to optimize solutions, minimize energy consumption, maximize useful daylight illuminance, and view quality. In addition, the methodology was used to explore the framework for optimizing office facade design in Iran's diverse climatic zones. The simulation results indicate that window-to-wall ratio and inclined wall were essential for balancing daylighting performance and energy consumption. This research stated that using a self-shading design could increase the quality of view up to 75% while reducing energy consumption and the risk of glare. Results proposed a design framework to improve visual comfort and save energy. The rotating façade's wall 10°-30° reduced cooling energy demand and energy usage intensity in selected models. So, an inclined wall could be an efficient shading device to improve building's performance in Iran.

1. Introduction

About half of the world's population is located in urban areas; by 2030, this proportion is anticipated to reach 80% (Moonen et al., 2012). Large quantities of energy are consumed in the building sector; therefore, it is necessary to consider energy savings and consumption reduction (Nasrollahi, 2015). In Iran, residential, commercial, and office buildings consume approximately 34% of energy (Tabrizikahou and Nowotarski, 2021; Hoseinzadeh et al., 2019). Office buildings in Iran have significantly higher energy consumption indices than other building categories based on application type. In Iran, the average annual energy consumption index for offices is approximately 350 kWh/m^2 (Bagheri et al., 2013). The energy index (350 kWh/m^2) is high because these buildings only work 8–10 h daily. Since most of Iran's office buildings are government or semi-government, energy management has not been performed. Also, the staff in these places are not concerned with energy costs because they do not affect their pay. Therefore, considering energy saving in buildings is important (Jonsson

Abbreviations: ASE, Annual Sunlight Exposure; DA, Daylight Autonomy; EUI, Energy Use Intensity; HVAC, heating, ventilation, and air conditioning; NSGA-II, Non-dominated Sorting Genetic Algorithm-II; PCC, Pearson correlation coefficient; sDA, Spatial Daylight Autonomy; SHGC, Solar heat gain coefficient; UDI, Useful Daylight Illuminance; WWR, Window-to-Wall Ratio.

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and Roos, 2010), and the insufficient non-renewable resources such as oil, coal, and natural gas (Aleklett et al., 2003) have led to greater attention to energy conservation. Due to the high costs of energy and environmental concerns about the building sector, most governments try to improve the sustainability level, particularly in the energy-related fields (Aydin, 2000). Therefore, the importance of saving energy over the last decade has increased attention to building performance. Lighting, heating, and cooling account for most of the building sector's energy use (Omer, 2008).

The building's facade loses more than 40% of the building's energy due to heat loss in winter and excessive heat absorption in summer, which leads to the building's need for air conditioning systems to provide occupants' thermal comfort (Barozzi et al., 2016). Windows are important facade components in saving and wasting a building's energy (Banihashemi et al., 2015). They provide natural light and view outside, increasing occupants' satisfaction and productivity. Therefore, a specific building envelope adapted to the climate can provide thermal comfort for the occupants with minimal fossil energy demand (Mitterer et al., 2012). However, achieving a high-performance facade for design objectives in most climates creates multiple challenges. For example, large windows allow more daylight in the interior, improving the view quality, but they create another problem by increasing unnecessary summer heat and losing winter heat (Yao and Short, 2013). So, defining optimal WWR according to different building conditions is important.

The envelope covers buildings from the outdoors to limit solar insolation, providing occupants' comfort and reducing energy (Rossi et al., 2012). The performance of the facade, which includes windows, insulation elements, and shadings, has a significant effect on heating, cooling, and electric lighting energy requirements, as well as on daylight. The excessive use of windows in facades frequently results in increased cooling and heating loading and glare (Galasiu and Veitch, 2006). However, it reduces the need for artificial lighting (Poirazis et al., 2008). So, visual comfort and energy consumption should be considered in parallel, as their interaction may affect the environment's overall conditions (Van Den Wymelenberg et al., 2010). Although increasing daylight brightness reduces lighting energy consumption, excessive daylight, and solar gain lead to excess heat and glare that disrupt thermal-visual comfort (Aries et al., 2010; Leather et al., 1998). Hence, research has been conducted on the building's facade to prevent excessive sunlight and save energy. The results indicate that employing shading solutions to reduce direct sunlight results in a higher window-to-wall ratio while preserving the environment's internal conditions. Solar shading affects daylight, quality of vision, and the energy used for electric lighting (Heschong, 2002). It controls solar heat and provides daylight, reducing summer cooling and increasing winter heating needs.

The climate is an important factor in building facade design. Adequate lighting and control of excessive solar radiation should be considered in all climatic conditions. Even though more heating is needed in cold climates, excessive solar gain causes high cooling consumption (Grynning et al., 2014). Installation of shading components increases the window size to maximize view quality and daylighting but leads to waste energy. Shade devices have received much attention in hot and dry climates, but their performance has been less investigated in cold, humid, and temperate climates. Numerous researches have studied the different window solutions for office buildings in different climates and shown the impact of different factors on energy consumption. Inanici and Demirbilek's research (Inanici and Demirbilek, 2000) investigated the differences in window-to-wall ratio in different climates of Turkey. According to this research, the lowest window-to-wall ratio (25%) is in hot climates, and the highest (70%) is in cold climates. Bellia et al (Bellia et al., 2013). studied the impact of shading devices on energy consumption for Italian climates. The results showed that shadings have the highest energy saving in the warmest climate.

There are various solutions to improve daylight performance and energy efficiency, for example, kinetic shading (Barozzi et al., 2016), folding shading (Pesenti et al., 2015), overhang (Lee and Tavil, 2007), solar screen (Sherif et al., 2012), and louver shading (Palmero-Marrero and Oliveira, 2010; Mahdavinejad and Mohammadi, 2016) strategies. One of the passive strategies is using a façade as self-shading to prevent direct sunlight and reduce solar heat gain in the interior space (Kandar et al., 2019). During the initial phases of building design, the architect considers the fundamental geometrical aspects associated with the building's shape. In this stage, architects attempt to shape buildings to optimize their performance. This task was accomplished by determining the design of the building's façade to self-control against direct solar radiation and reduce energy waste. However, there are few studies investigating self-shading as a design parameter. Based on this research gap, this research has investigated the performance of façade geometry such as window-to-wall ratio (WWR), window type (separate vertical, continuous horizontal), glazing material (single clear, double clear air, triple clear), and inclined wall as a self-shading geometry in different climates of Iran. According to the sun's radiation and the need for heating or cooling, the efficiency of this system should be investigated. This research examines the effect of the building façade's variables on the design objectives, such as visual comfort, energy consumption, and QV of office buildings in three different climates of Iran. Besides this, view analysis setting based on LEED4 is considered one of the objective goals to determine the effect of variables on the investigated quality of view. The results of this study are used as guidelines for developing thermal-visual comfort for employees, as well as helping reduce energy consumption and improve indoor conditions in office buildings.

2. Background

Due to the occupant's growing demands for comfortable and healthy living conditions, building performance has become a critical issue. For this purpose, the importance of initial design for critical decisions significantly affecting building performance and occupant comfort is highlighted (Taghizade et al., 2019). In this stage, designers must deal with conflicting objectives, such as visual comfort, energy consumption, and indoor environmental quality. Many studies have been carried out on parametric design (Eltaweel et al., 2017), daylight performance (Tabadkani et al., 2019; Shirzadnia et al., 2023), quality of view (Pilechiha et al., 2020a), and energy usage (Abdou et al., 2021; Ebrahimi-Moghadam et al., 2020). All of the mentioned studies had selected different variables, but the studies that stated the window parameters as the effective element were selected as background in this research.

Some scholars have focused on building facades to improve daylight performance. Kharvari (Kharvari, 2020) reveals that the optimum window-to-floor ratio for the south, east, north, and west-facing windows relies on daylighting through multi-objective optimization. Mahdavinejad et al (Mahdavinejad et al., 2012). investigated the optimal window-to-wall ratio to maximize daylight. The results show that the 'daylight efficient ratio' increases with WWR. However, with a WWR above 45%, more than 10% of the work plane is exposed to higher than 2000 lux. So, claimed the most appropriate WWR: %30, %35, and %40 in office buildings in Tehran. A study was performed (de Rubeis et al., 2018) to assess the effect of different room geometry, window shapes, window-to-floor ratio (WFR), and the type of lighting on energy saving. Based on their results, the combination of rectangular classrooms, rectangular south-oriented windows, WFR equal to 12%, and LED lamps is the best energy result for designing academic classrooms in L′Aquila.

Many articles have investigated windows' shape, size, and orientation to reduce energy consumption and visual comfort (Gagne and Andersen, 2012; Krarti et al., 2005; Piotrowska and Borchert, 2017; Vanhoutteghem et al., 2015; Zhai et al., 2019). A study performed in 1998 in Sweden shows the impact of glazing type, and WWR have on cooling and heating demands. Modern glazing, with low solar transmittance and U-values, can mitigate this problem, but it does not necessarily solve it (Bülow-Hübe, 1998). Maleki and Dehghan (2021) presented a study that compared window design variables such as WWR, shape, position, and orientation to reduce annual energy consumption and proper daylight performance. Results show that for the north face window, 40% WWR and 30% WWR with square and horizontal shapes in upper and central positions is the proposed method for other orientations. Mebarki et al. (2021) studied the effect of window size based on the compromise between thermal and visual comfort. The results show that the building envelope is a determining factor that directly influences building energy demand and reduces HVAC system cost and CO_2 emissions. In addition, some studies that have focused on optimizing facade parameters are listed in Table 1. All reviewed studies have stated the importance of increasing useful daylight for energy reduction and visual comfort. Recent studies have highlighted the effect of window properties on improving view quality and energy performance. Pilechiha et al. (2020b)., examining window variables in office buildings, revealed that it is possible to provide a satisfactory QV performance for more than 80% of the reference room points while minimizing energy usage and maximizing daylight. It was concluded that the room's geometry should be considered a variable to increase the quality of view according to official standards.

Despite the above evaluations about building performance, most previous research focuses on external shading systems, while self-shading systems have received less attention. Inclined walls in a few architectural designs are used as a self-shading strategy. Kandar et al. (2019) revealed the relationship between different inclined wall self-shading and solar heat gain. Also found, the optimum inclination angle of self-shading received zero heat conduction through walls and zero solar heat gain through windows. Lavafpour and Sharples (2015) found that implementing an inclined facade could eliminate the risk of overheating in the British climate but simultaneously caused the problem of reducing useful daylight. In previous research, Mohammadi et al (Bakmohammadi and Noorzai, 2020). investigated façade inclination, number of windows, window-to-wall ratio, building orientation, and glazing material as the optimization of light and energy in school classrooms. It was claimed that WWR considerably impacts cooling and heating energy, daylight metrics (UDI and DA), and electric lighting energy, while building orientation highly influences ASE and occupant thermal comfort. Additionally, the wall inclination is also influential in determining DA levels (Bakmohammadi and Noorzai, 2020). Mangkuto et al. (2022) investigated the self-shading mechanism using inclined walls containing windows on two-sided or bilateral daylight openings in classrooms. In both articles, the effectiveness of the parameters has been examined separately, the and influence of selected variables on final goals has not been considered simultaneously. Also, view to outside environment has not been evaluated, which caused the optimal models to have a lower window-to-wall ratio than the original model. In the present research, the mentioned parameters were re-examined in the office to check their effect on outputs, such as glare and QV in the standard office room.

3. Methodology

This research examines the effect of facade geometry in improving visual comfort and saving energy. Based on Bakmohammadi and Noorzai's study (Bakmohammadi and Noorzai, 2020) an inclined wall effectively controlled energy consumption and glare in Tehran's semi-arid climate. The optimization framework in this study was divided into three steps: (1) defining envelopes variable and modeling parametric geometry, (2) verifying the assumption effect of self-shading on visual comfort and energy consumption, (3) optimization offices in different climates of Iran. A flowchart of the conducted research is shown in Fig. 1.

In the first stage, various façade variables were selected based on the mentioned study (Bakmohammadi and Noorzai, 2020) and according to the general conditions of Iran's office buildings. The case study model was developed by Rhinoceros (3D modeling software) with Grasshopper (a visual parametric plugin to Rhinoceros) (Radiance, 2021; EnergyPlus, 2021). In the second stage, the parametric model based on Radiance and Energy-Plus (Radiance, 2021; EnergyPlus, 2021) was simulated for daylight and energy analysis in Ladybug tools and Honeybee (Rhinoceros, 2021; Grasshopper, 2021; Roudsari et al., 2013) tools. In this stage, four cities from different climates of Iran, Tehran (cold semi-arid), Bandar Abbas (hot semi-arid), Rasht (moist mild-latitude), and Ardabil (cold semi-arid), were selected. Then, the assumption of the previous research (Bakmohammadi and Noorzai, 2020) was examined in Tehran and three other cases to determine the influence of an inclined wall and climate on the research objective. After that, the appropriate range for the inclined of the rotating wall and fitness objective was determined. In the third stage, the selected variables were optimized. The Wallacei plugin and Grasshopper software used three-dimension optimization to optimize the office spaces. Quality of view (QV), useful daylight illuminance (UDI), and energy use intensity (EUI) were outputs. NSGA-II algorithms were used to optimize the mentioned modes. Finally, for selected solutions, Annual Sunlight Exposure (ASE) and Spatial Daylight

Table 1
Background.

Ref	Variables For optimization					Performance objectives					
	WWR	Orientation	shading properties	Plan properties	Material	Cooling load	Heating load	Lighting load	EUI	PPD	Daylighting
Tzempelikos and Athienitis (2007) (Tzempelikos and Athienitis, 2007)	✓		✓			✓		✓			
Xu et al. (2015) (Xu et al., 2015)	✓	✓		✓	✓	✓	✓		✓		
Echenagucia et al., 2015)	✓				✓	✓	✓	✓			
Alghoul et al., 2017)	✓	✓				✓	✓		✓		
Li et al. (2018) (Li et al., 2018)		✓		✓					✓		
Sedigh Ziabari et al. (2019) (Sedigh Ziabari et al., 2019)	✓					✓	✓		✓		
Badeche et al., 2020)	✓	✓	✓		✓	✓	✓		✓		
Phillips et al. (2020) (Phillips et al., 2020)	✓									✓	
Yeom et al. (2020) (Yeom et al., 2020)	✓								✓	✓	
Zhao (2021) (Zhao, 2021)	✓	✓							✓		✓
Aksin and Arslan Selçuk (2021) (Aksin and Arslan Selçuk, 2021)	✓		✓	✓	✓				✓	✓	✓
Sahu et al. (2021) (Sahu et al., 2021)	✓	✓							✓		✓
Kim et al. (2021) (Kim et al., 2021)	✓			✓	✓				✓		

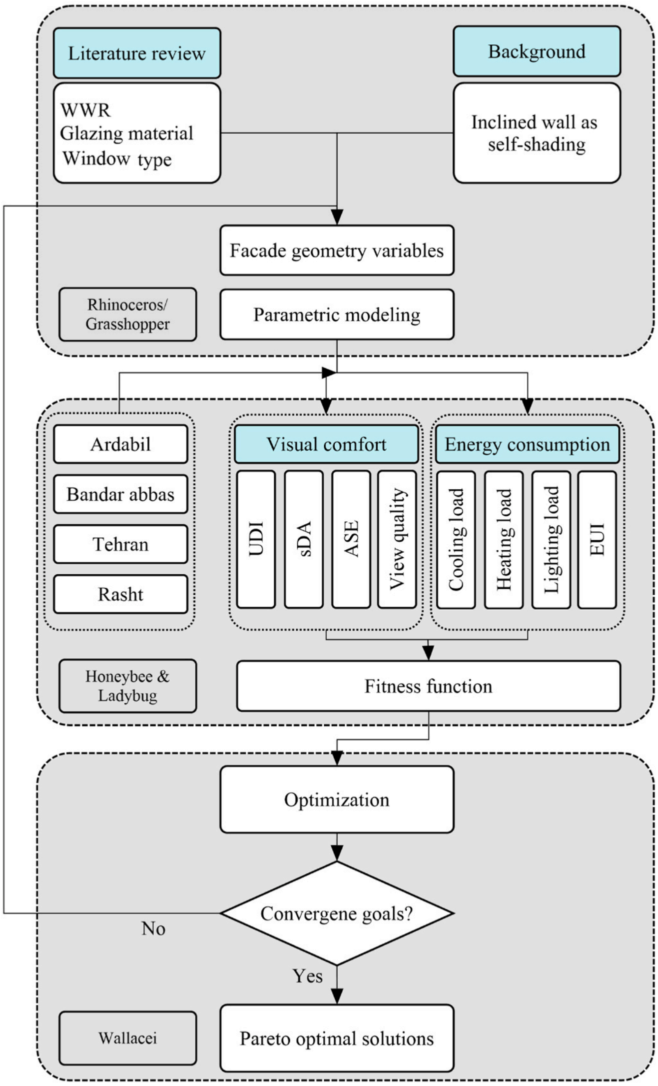


Fig. 1. Research flowchart.

Autonomy (sDA) as visual comfort metrics were calculated to compare the selected solution to the initial model.

3.1. Case study

The reference room in an office building based on Reinhart's model (Reinhart et al., 2013), with dimensions of 3.9 m × 8.5 m × 2.8 m (width × depth × height), as shown in Fig. 2. The direction of the office

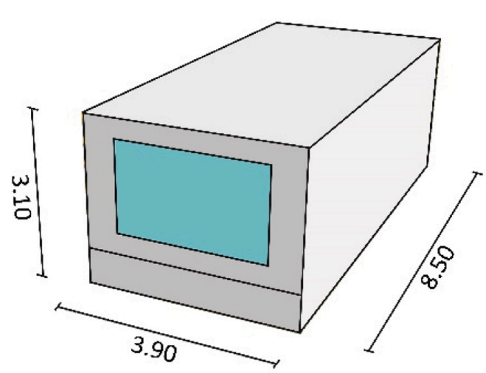


Fig. 2. Base model.

was examined only on the south side, which has more intensity of radiation and glare throughout the year. This model was a single-working space on the middle floor; only the south façade was connected outside with a window. The facade was the only way to exchange heat with outdoor, while other surfaces were adiabatic.

The variables of this research were based on Bakmohammadi and Noorzai's research (Bakmohammadi and Noorzai, 2020) optimized light and energy in school classrooms in Tehran. There were four design variables for optimizing building facades: the inclination of the south wall, window-to-wall ratio, window type, and glazing material. The design variables were marked in Figs. 3 and 4, and the design parameters were summarized in Table 2. In this model, as shown in Fig. 3, the south face, where windows were located, has been divided into two horizontal sections: A) fixed part at the bottom with a distance of 0.7 m from the floor; B) dynamic part at the top able to inclining in both positive and negative directions, within limits of 0–40 degrees. The selected WWR range can be between 20% and 80% with a 10% tolerance. The window types for the horizontal mode were continuous, in the center of the façade. For the vertical mode, four separate vertical windows were considered at 0.7 m from the ground level for all window ratios.

3.2. Climatic data

With a land area of 1648,195 km^2, Iran was the second-largest country in the Middle East and the seventeenth-largest country globally and had a diverse climate. According to the Köppen climate classification, 80% of Iran's areas have a dry climate, whereas 16.7% are warm and 3.2% have cold climates (Fallah Ghalhari et al., 2016). Fig. 5 illustrates the different climates of Iran based on Ghale's study (Ghale, 2014). The objective of identifying and investigating climatic conditions was to investigate the variables of this research on Iranian towns with varying climatic conditions to develop a design framework. In this study, four cities from various climates of Iran were selected as instances for analysis.

a) Tehran, with latitude 35°40'N and longitude 51°18'E, was chosen to symbolize Iran's central region's semi-arid and cold climate; according to the Köppen-Geiger climate classification, it was classified as Bsk category (dry). The average summer temperature was 27°C, while the average winter temperature was 5°C. At around 1190 m above sea level, the relative humidity was 40%. b) Bandar Abbas exemplified the dry climate of the country's southern coast (Köppen: Bsh). The average summer temperature was 34°C, while the average winter temperature was 19°C. Bandar Abbas, located at longitude 56°15' East and latitude 27°15' North at an elevation of approximately 10 m above sea level, has a relative humidity of 80%. c) Rasht has a humid subtropical climate (Köppen: Cfa) at 37°25'E and 49°58'N. This settlement exemplified the Mediterranean climate of the northern coast of the country. Summers were hot and humid, and winters were temperature and humid. The average summer temperature was 25°C, while the average winter temperature was 11°C. The relative humidity was 73%. and d) Ardabil, located approximately 70 kilometers from the Caspian Sea at 38°22'E and 48°32'N. The climate of Ardabil was mainly cold, with semi-arid and cool summers and long, cold winters (Köppen: Bsk). The average summer temperature was 18°C, while the average winter temperature was 0°C. This study is for developing a daylight and energy model in

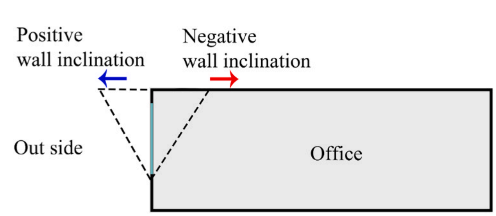
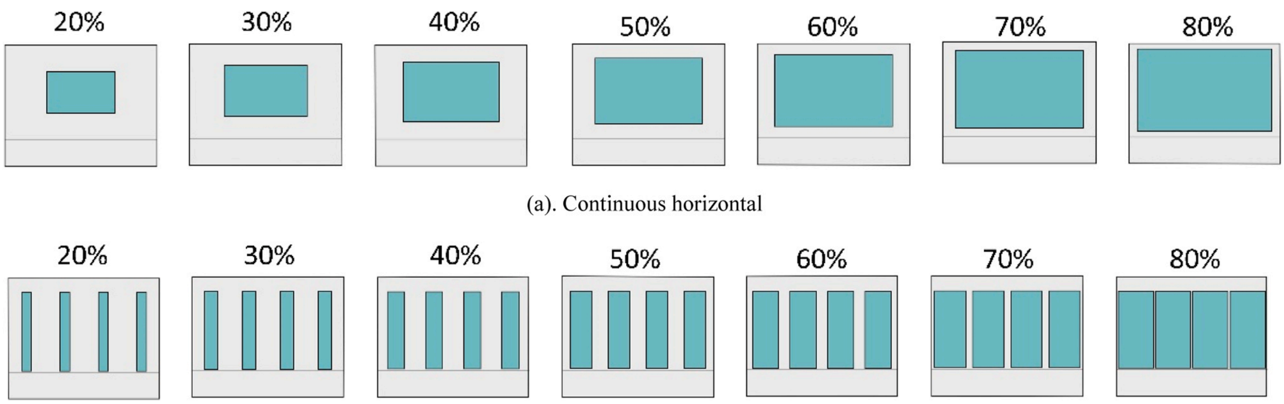


Fig. 3. Inclined wall self-shading.



(a). Continuous horizontal

(b) Separate vertical

Fig. 4. (a) and (b) window type and WWR.

Table 2
Design parameters.

Variable	Attributes	No. of values
slope of south wall	− 40, − 30, − 20, − 10, 0, 10, 20, 30, 40 (°)	9
WWR	20, 30, 40, 50, 60, 70, 80 (%)	7
Window type	Separate vertical, Continuous horizontal	2
Glazing material	Single Clear (U-value: 5.91, SHGC: 0.861), Double Clear Air (U-value: 2.70, SHGC: 0.704), Triple Clear (U-value: 1.74, SHGC: 0.617)	3

simulation analysis using the city's weather data downloaded from the Ladybug Tools website. Fig. 6 illustrates the hourly diffuse horizontal radiation of selected cities. The average monthly dry bulb temperature and relative humidity are shown in Figs. 7 and 8.

3.3. Evaluation indicators

Different metrics have been determined to check the adequacy of daylight and visual comfort. In this study, the selected daylight criteria are useful daylight illuminance (UDI), spatial daylight autonomy ($sDA_{300/50\%}$), and annual sunlight exposure ($ASE_{1000,\ 250}$). ASE indicates the percentage of an area that receives exceeding direct sunlight to cause visual discomfort (glare), and sDA presents the percentage of an area that receives adequate daylight. the $sDA_{300/50\%}$ and $ASE_{1000,250}$ metrics are align with the LEED v4 (Council, 2013). These contain that no more than 10% of space should have direct sunlight of more than 1000 lux for a maximum period of 250 h per year ($ASE_{1000,250} \leq 10\%$), and a percentage of area that meets minimum daylight of 300 lux for at least 50% of the working hours per year($sDA_{300/50\%} \geq 75\%$) (archecology, 2017).

Lastly, the UDI metric was originally suggested in 2005 in a paper by (Nabil and Mardaljevic, 2005). UDI determines the percentage of time in a year that the interior daylight illuminance in a room falls into a certain illuminance range. In brief, UDI represents the annual occurrence of daylight illuminances falling within a given range. Among dynamic models, UDI provides both upper and lower thresholds. Santos et al. utilized the UDI metric with four different bins, including UDI underlit, which there is too little daylight and artificial lighting is necessary (<100 lx). UDI useful, which represents the ratio of time that daylight is useful for functional purposes but needs to be compensated with a certain amount of artificial lighting (100–300 lx). UDI autonomous indicates that the office space could only rely on daylighting to fulfill the light requirements of space without the risk of visual discomfort or excessive heat gains (300– 2000 lx), and UDI overlit, indicates that excessive daylight levels, which might lead to visual discomfort and could give rise to indoor overheating (>2000 lx) (Santos et al., 2018). In 2022, Fang et al. reported illuminance in the "range 300 to around 2000 lux in office space could only rely on daylighting to satisfy the illuminance requirements"; (Fang et al., 2022) therefore, those values were used in the present paper. In this case, the UDI (300–2000 lx) quantifies and evaluates the annual daylight performance. For the daylight simulation, a number of calculator points are executed by the grid of sensors in 0.5 × 0.5 dimensions (total 119 points) that are spread across both floors at a distance of 0.75 m from the floor surface. Furthermore, $UDI_{300–2000\ lx}$ and $sDA_{300/50\%}$ are maximized, while the $ASE_{1000,\ 250}$ is minimized to obtain the optimum solutions.

The energy use intensity (EUI) metric also assesses electricity usage, representing the office energy consumption as a function of its conditioned floor area. So, EUI in this study is the sum of normalized heating, cooling, electric equipment, and electric lighting load in a year (Kwh/m^2/y). The adjusted heating and cooling set points are 21◦c (recommended by Energy Efficiency and Environment in Building (EEEB) in Iran (Nasrollahzadeh, 2021)) and 26°C Building Program and material properties were summarized in Table 3 and Table 4. For an accurate comparison between selected climates, the physical properties of the models are assumed to be the same. But according to Building Code No. 19 of Iran, thermostat heating and cooling set-points were set at 20 °C and 28 °C for Bandar abbas (hot semi-arid climate) and 20 °C and 25 °C for other cases (No.19, 2011). Besides, the view to the outside is assessed. The view analysis setting based on LEED v4 is included to respond to how much the façade's parameters affect the Quality of View. According to the (LEED) version 4.1 (USGBC, 2006), the minimum acceptable rate for view access is 75% of all viewpoints.

The optimization process uses the Wallacei plugin that Mohammad Maki and Milad Shokatbakhsh developed. This is an optimization engine for multi-objective conflicts within the Grasshopper plugin environment (Makki et al., 2020). This study employed this plugin for a three-objective optimization. This plugin operates based on the non-dominated sorting genetic algorithm (NSGA-II) developed by Deb and Agarwal (Deb et al., 2002). The NSGA-II algorithm improves the genetic algorithm-based selection operation for solving the multi-objective optimization problem. This selection should be as broad as possible to encompass the feasible domain based on the problem range and limitation (Yang et al., 2019). Next, rank the population by ascending non-domination (Deb, 2011). After sorting, options with identical non-domination fronts are compared by crowding distance. The average distance of two solutions on either side of solution (i) along each objective determines the population density around solution (i). The crowding distance (d) estimates the circumference of the cuboid with the nearest neighbors as vertices (Deb, 2011). The formula for crowding distance:

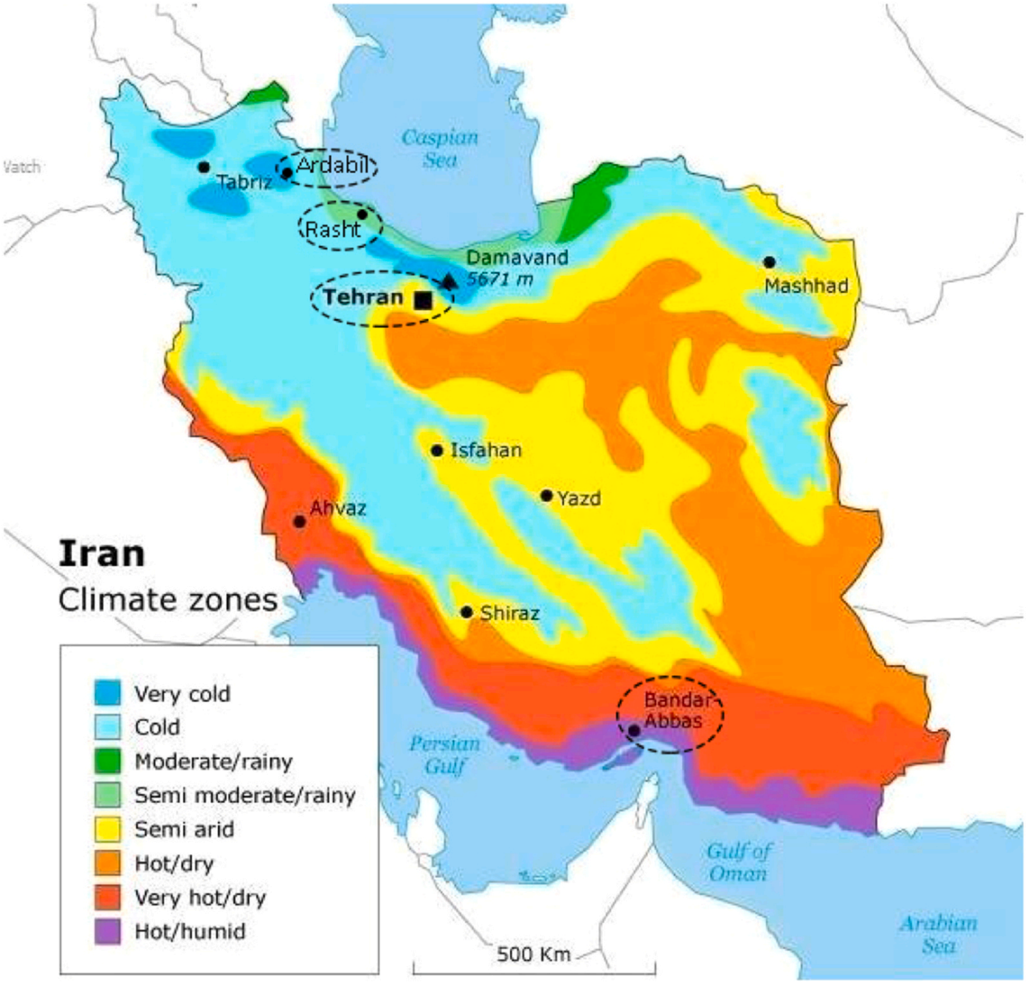


Fig. 5. different climates of Iran (Ghale, 2014).

$$d_i(j) = \sum_{i=1}^{n} = \frac{f_i(j-1) - f_i(j+1)}{f_i^{\max} - f_i^{\min}}$$

Crowding distance stresses less crowded alternatives to maintain diversity (Rappa, 2014; Ghiasi et al., 2011). The border solutions with the lowest and greatest objective function values are assigned unlimited crowding distance values to ensure selection for each objective function (Raquel and Naval, 2005). To meet problem objectives, good (typically above median) solutions will be recognized in a population, and bad answers will be deleted to make numerous copies of good solutions (Ghosh and Das, 2008). Recombination and mutation are used to the parent population to create a population of offspring (Ghiasi et al., 2011). Selection determines next generation members from offspring and current generation populations. Each front fills the new generation until the population exceeds (Yusoff et al., 2011). A user-defined generation limit ends the procedure (Ghiasi et al., 2011).

An efficient search technique must identify optimal trade-off solutions (Pareto front) to present a programmer with the best option based on the unique challenge. An ideal point is a theoretical conception of a real-world objective in which each objective is maximized without regard for the welfare of others. Multi-objective optimization algorithms aim to generate solutions with a well-distributed range near the Pareto optimum front. To compare optimal solution to initial variable, a Pearson correlation coefficient (PCC) was performed to present correlation between variables. PCC has a value between − 1 and 1; the stronger the correlation between two variables, the closer the absolute value of the PCC is to 1. The PCC 1 indicates a positive effect, and the PCC − 1 indicates a negative effect. Eq. (1) defines a Pearson correlation coefficient identically in numeric expressions.

$$Pxy = \frac{\mathrm{cov}(X.Y)}{\sigma x \sigma y} \tag{1}$$

cov is the covariance.
σx is the standard deviation of X.
σy is the standard deviation of Y.

4. Results

4.1. Base model

As mentioned above, the base model was determined according to the reference room in an office building [98]. Based on the ASHRAE 90.1 standard [99], the design variables for the base model were 45% window-to-wall ratio, continuous horizontal window type, single clear window material, and a wall slope of zero; these were assumed to be the same for each location. Daylight and energy consumption analysis of the base model was done. For a comprehensive study of the base model, visual comfort metrics (UDI, sDA, ASE,) energy consumption (EUI, cooling load, heating load, lighting load), and quality of view were measured. Table 5 presented additional information, which showed that Rasht has the lowest and Tehran has the highest UDI distribution, respectively. The minimum and maximum useful daylight illuminance (UDI) varied from 51.1% (Rasht) to 59.9% (Tehran). Rasht and Tehran also had the lowest and highest spatial daylight autonomy (sDA) values.

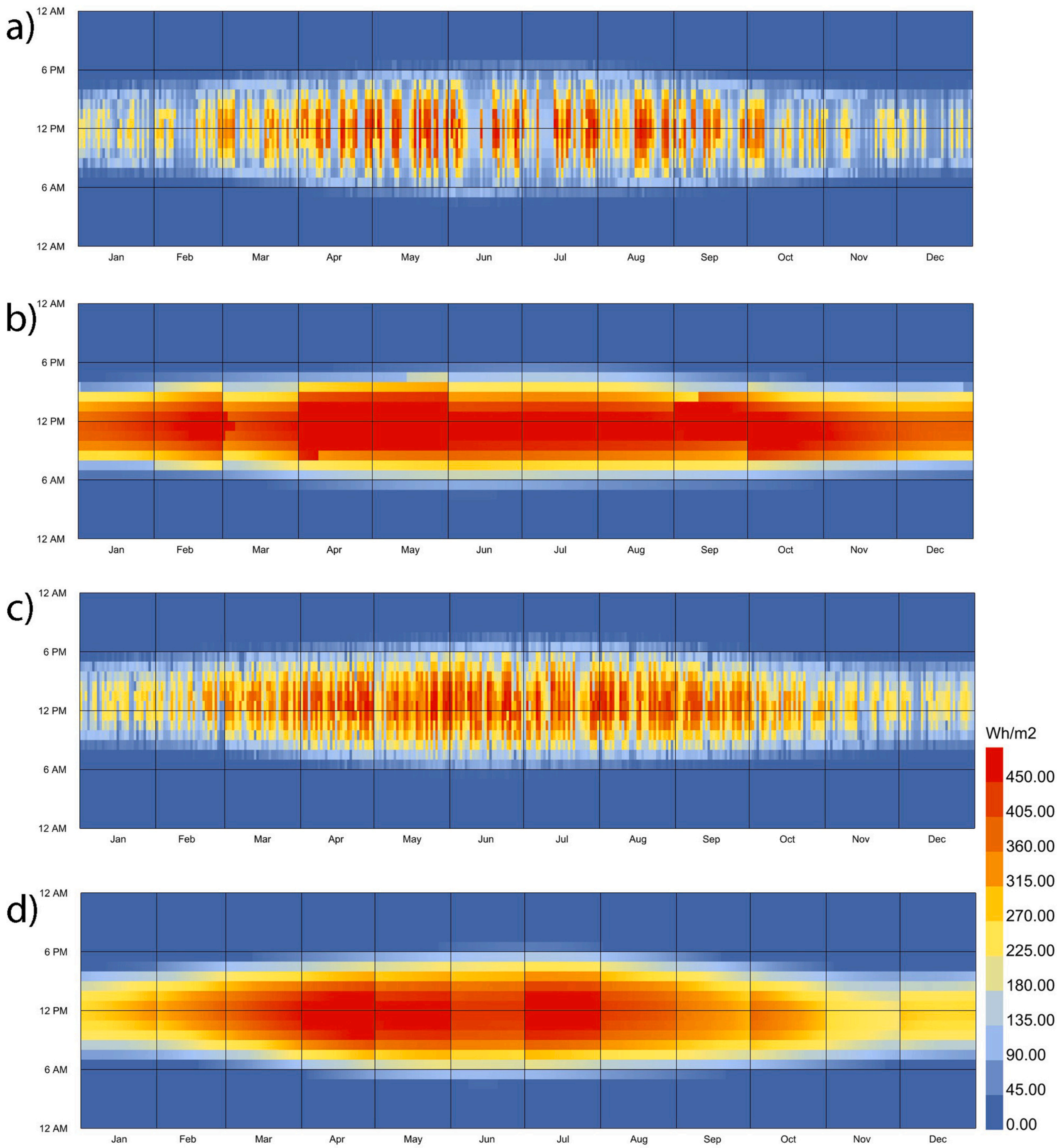


Fig. 6. hourly diffuse horizontal radiation: a) Ardabil, b) Bandar abbas, c)Rash, and d)Tehran.

The sDA ranged from 60.5% (Rasht) to 68.9% (Tehran). ASE ranged between 33% and 42%, a minimum ASE for Bandar abbas and a maximum ASE for Tehran.

Table 5 illustrates the various values of UDI for different selected models. EUI ranged between 104.3(kWh/m^2y) and 142.9(kWh/m^2y), with minimum EUI for Ardabil and maximum for Bandar abbas. The heating load is 0 (kWh) for each location, but there was high difference between cooling loads in different cases. The cooling load ranged between 628.1 (kWh) and 1569.6 (kWh), minimum cooling load for Ardabil and maximum for Bandar abbas. The cooling energy load of Bandar Abbas was significantly higher than other selected locations, which showed that the hot and semi-arid climate needed more cooling demand than the other investigated climates (cold, semi-arid, semi-moderate). The lighting load ranged between 1279.3 (kWh) and 1341.2 (kWh), minimum for Tehran and maximum for Rasht. The difference in lighting energy consumption in different locations was slight and only varied by about 4.8%. The quality of view was the same for each case and was 97.1%.

4.2. Implications of inclined wall on visual comfort and energy consumption

The impacts of the inclined wall, configured based on rotating degrees and location, on visual comfort and energy consumption were

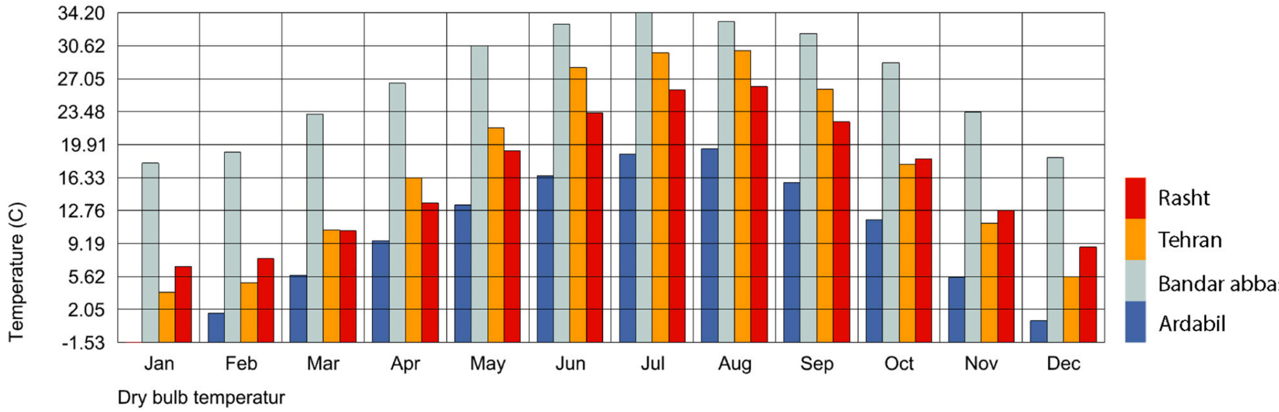


Fig. 7. Average monthly dry bulb temperature.

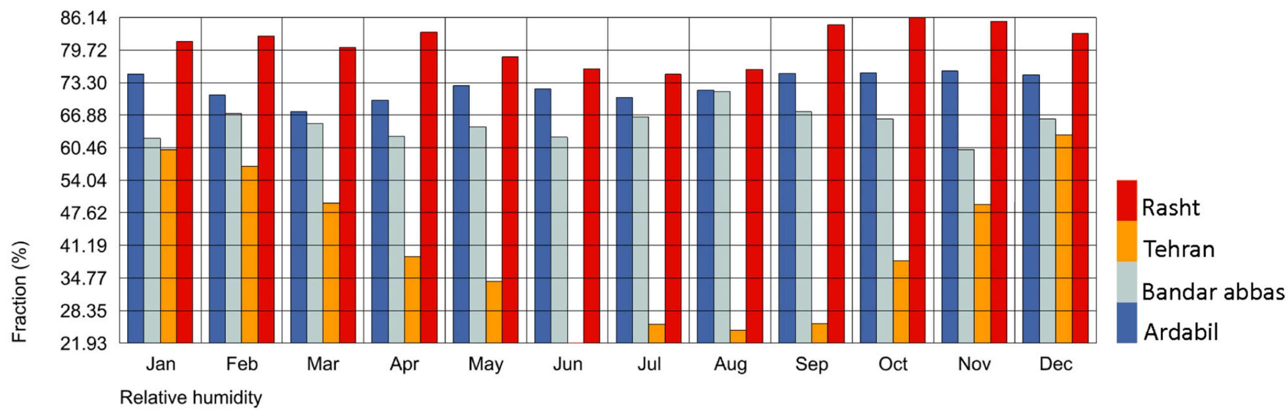


Fig. 8. Average monthly relative humidity.

Table 3
Building Program.

Attributes	Values
Project type	Single Office
Zones program	Closed Office
Working hours	7 AM– 3 PM
People per area	0.025
Metabolic rate	1 (metabolic rate of seated person)
Clothing factor	1 (Three-piece suit)
Equipment load per area	5.33 W/m^2
Infiltration rate per area	0.0002 m^3 /s m^2
Lighting density per area	11.8404 W/m^2
Ventilation per area	0.0003 m^3 /s m^2
HVAC Template	Fan Coil air-cooled chiller with baseboard electric
Heating Setpoint Temperatures (°C)	Heating: 21, Heating set back: 12
Cooling Setpoint Temperatures (°C)	Cooling: 26, Cooling set back: 28

analyzed. Fig. 9 presents the correlation between the inclined wall and visual comfort results. The UDI value increased by rotating the wall from − 40° to 10°, but it decreased when rotating from 10° to 40°. When the wall inclined 10°, Rasht had the lowest UDI value, ranging from 27% to 51.9%, which reduced to between 17% and 42% at 40°. From the angle of − 40° to 10°, UDI increased slightly; values varied from 4.6% to 6.4% in all locations. From the angle of 10° to 40°, the data changed considerably, between 14.4% (Ardabil) and 11.6% (Bandar abbas). ASE was used to determine how the inclined wall affected the control of direct sunlight in certain places. The impact on the ASE decreased when the wall was inclined from − 30° to 40°. The angle of 40° had maximum control over direct sunlight in the interior space. In each category, Tehran had the highest value of ASE, and Bandar abbas had the lowest value. When the wall was inclined − 40°, the highest value of ASE was 56% (Tehran). The data ranged from 56% to 30% in this value, and the mean was 44%. This value was reduced between 20% and 7%, with a mean of 12% when wall was inclined 40°. Also, in Bandar Abbas, at − 40°, the ASE ranged between 49% and 26%, being the lowest value of ASE. At 40°, Bandar Abbas had the lowest value of ASE, which ranged from 7% to 2%, and the mean was 5%. By rotating the wall in a positive direction, ASE was reduced in all the investigated cities, and the mean decreased between 30% and 32% in all cases. When the wall rotated from − 40° to − 20°, the sDA value increased between 2% and 5%, but from − 20° to 40°, it decreased between 17% and 21% in all locations. The sDA changed at the same ratio in all cases. When the wall is inclined from − 20° to − 10°, all cases had the highest value of sDA; in other words, rotating the wall in the negative direction caused an increase in UDI. Generally, the value of sDA was the highest in Tehran and the lowest in Rasht. Lastly, to check the quality of the view outside, all four cities had the same data, and the best value was related to the angle of − 20°. The view outside decreased as the positive inclination increased.

Fig. 10 shows the effect of the inclined wall on energy consumption. In general, EUI was reduced by rotating the wall in a positive direction, but the reduction percentage is not equal in different locations. The cases that had the highest EUI were Bandar abbas (hot semi-arid), Tehran (cold semi-arid), Rasht (moist mild-latitude), and Ardabil (cold semi-arid), respectively. EUI in Bandar abbas at − 40° ranged between 120 kWh/m^2y and 184 kWh/m^2y, at 40° reduced to between 114 kWh/m^2y and 122 kWh/m^2y. In Ardabil, at − 40°, the EUI ranged between 100 kWh/m^2y and 152 kWh/m^2y, and at 40° it reduced to between 85 kWh/m^2y and 93 kWh/m^2y. The ratio of reduction in EUI was 31.3% in

Table 4
Material properties.

Material Name	Roughness	Conductivity	Density	Specific heat	thickness
		W/mK	kg/m^3	J/kg-k	m
wall materials characteristics					
Mortar plaster	Rough	0.72	1760	840	0.025
cement mortar	Rough	0.72	1650	920	0.015
aerated concrete block	Rough	0.48	880	840	0.15
cement mortar	Rough	0.72	1650	840	0.015
1/2 IN gypsum	Smooth	0.16	784.9	830	0.0127
Exterior roof & Interior floor					
Roof Deck	Rough	0.140	530	840	0.19
Expanded polystyrene (standard) EPS	Rough	0.04	15	1400	0.0604
100 mm lightweight concrete	Rough	0.24	750	1000	0.15

Table 5
Base Model.

Simulation result Original Model	**UDI$_{300–2000}$** [%]	**sDA$_{300/50\%}$** [%]	**ASE$_{1000,250}$** [%]	**EUI** [kWh/m^2/yr]	**Cooling load** [kWh]	**Heating load** [kWh]	**Lighting load** [kWh]	**QV** [%]
Ardabil	57.8	61.3	40	104.3	628.1	0	1321.6	97.1
Bandar abbas	58	64.7	33	142.9	1569.6	0	1298.4	97.1
Rasht	51.1	60.5	38	109.2	678.4	0	1341.2	97.1
Tehran	59.9	68.9	42	112.3	818	0	1279.3	97.1

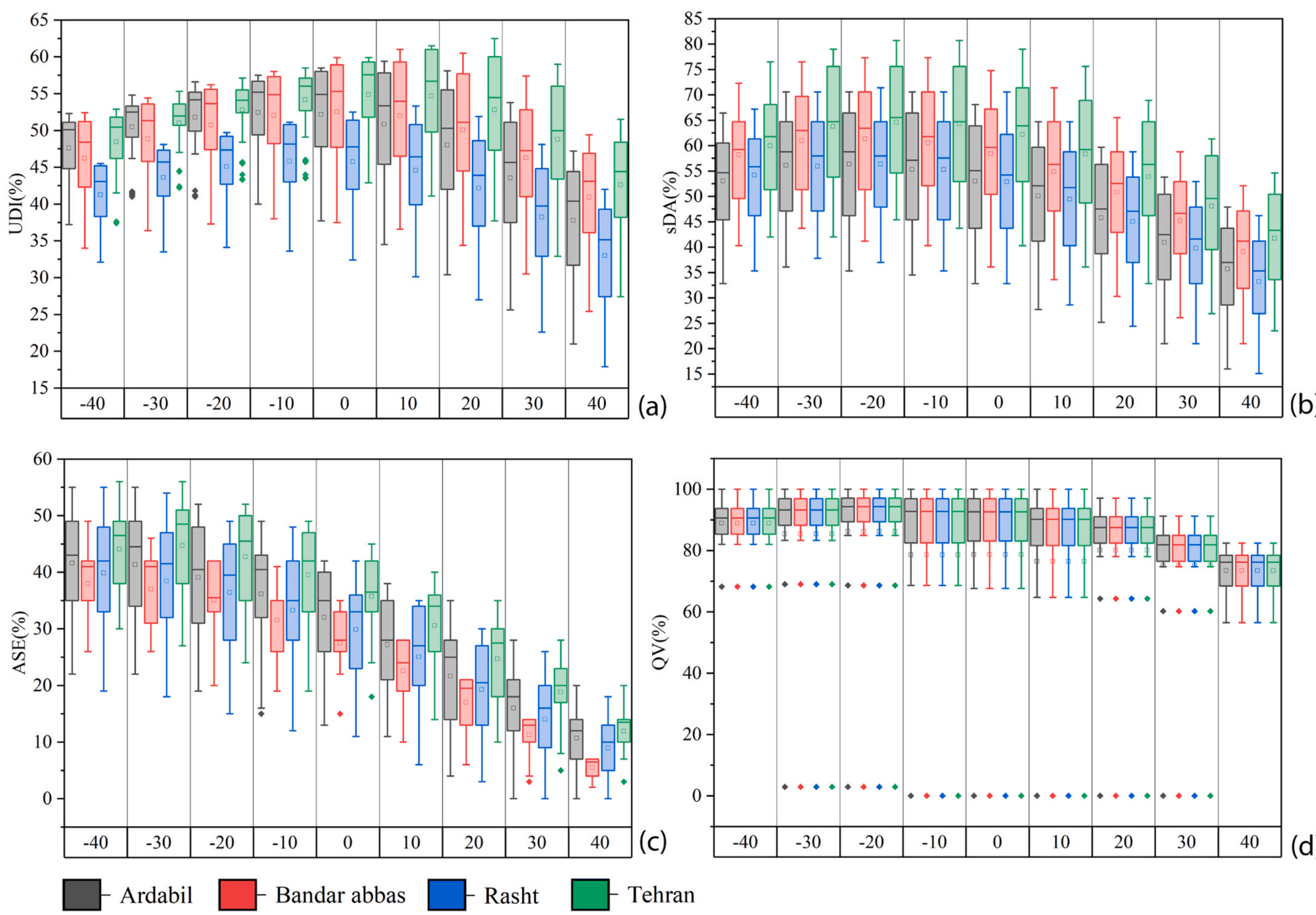


Fig. 9. Visual comfort results (a)UDI, b)sDA, c)ASE, and d)QV) based on rotating wall and locations.

Tehran, 27.5% in Ardabil, 21.6% in Rasht, and 19.1% in Bandar Abbas compared to the wall inclined − 40°. The value of heating energy was very low and negligible for Tehran, Bandar Abbas, and Rasht; only in Ardabil could the value of heating energy be investigated. In Ardabil, heating decreased when rotating the wall from − 40° to 0°. Moreover, the maximum heating load did not exceed 27 kWh. However, heating

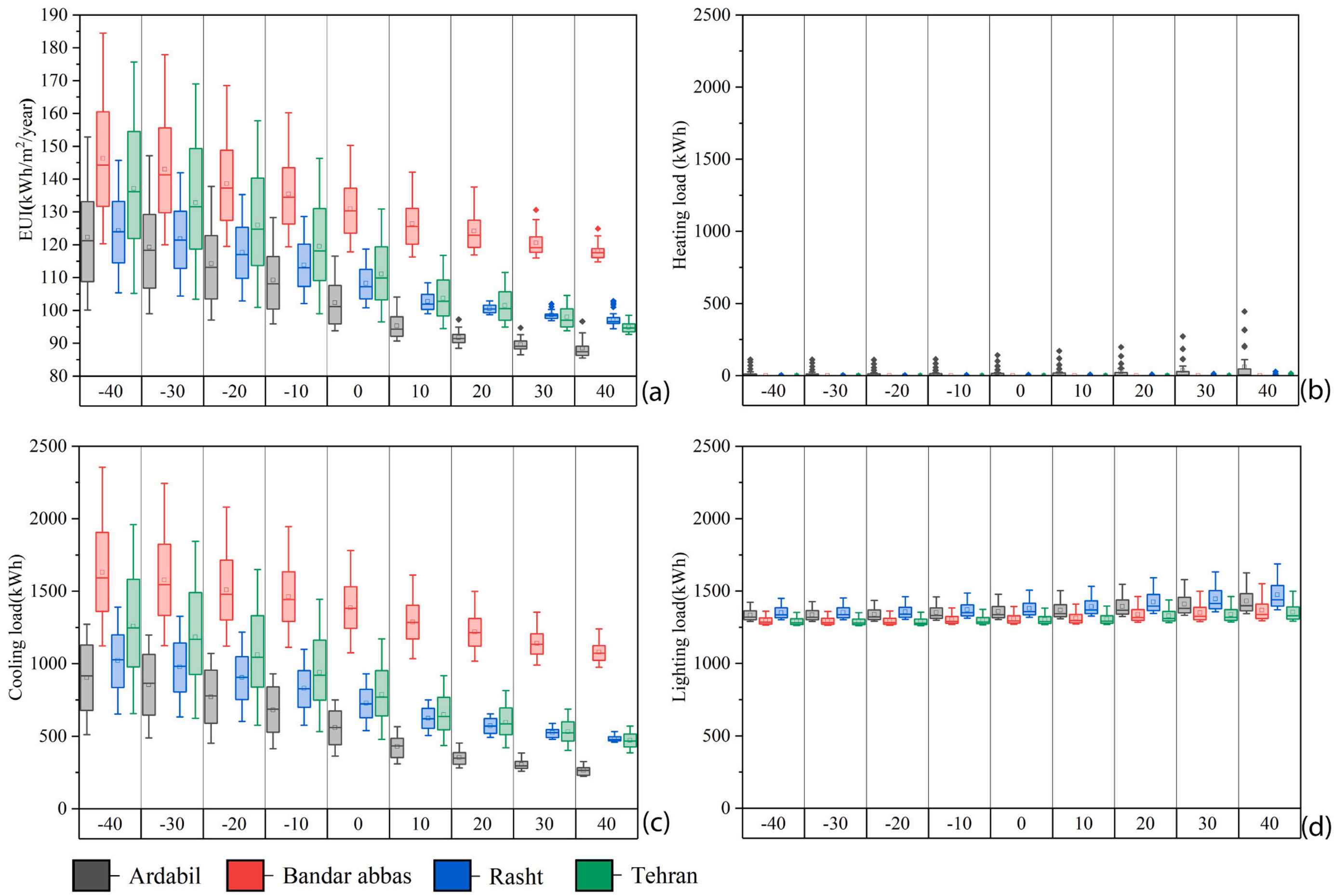


Fig. 10. Energy consumption results (a)EUI, b) Heating load, c) cooling load, and d) lighting load) based on rotating wall and locations.

increased from 0° to 40° with the highest value ranging from 0 kWh to 111 kWh. In this case, the average heating load was 59.3 kWh. Bandar abbas had the highest cooling load, ranging between 1122.5 kWh and 2355.3 kWh at − 40°, decreasing to between 975.6 kWh and 1240 kWh at 40°. Ardabil had the lowest cooling load, ranging between 510.1 kWh and 1272.5 kWh at − 40°, reduced from 222.5 kWh to 325 kWh at a 40°. The cooling load reduction was 70.7% in Ardabil, 62.6% in Tehran, 52.6% in Rasht, and 33.98% in Bandar abbas, compared to wall inclined − 40°. The lighting load increases by rotating the wall in a positive direction, with a ratio of increasing lighting load ranging between 4.6% (Tehran) and 8.2% (Rasht). The highest value of lighting load was Rasht, ranging from 1301 kWh to 1449 kWh with an average of 1351 kWh at − 40°. When the wall was inclined at 40°, it ranged between 1371 kWh and 1686 kWh with a mean of 1473 kWh. Tehran has the lowest lighting load, ranging from 1261 kWh to 1352 kWh with an average of 1290 kWh, which at 40° increased from 1291 kWh to 1499 kWh with a mean of 1354 kWh. In this section, the efficiency of the inclined wall was determined. According to the above results, it was found that the 40° is not effective, so the wall rotation range for optimization was chosen from − 30° to 30°.

4.3. Optimization

As mentioned before, the main objective of this research is to maximize occupants' visual comfort while minimizing energy demand. According to the literature review, facade geometry was evaluated to achieve the research objectives. The variables were investigated according to Table 2. For optimal performance in energy, daylight, and view, multi-objective optimization was performed. A multi-objective optimization method employs the genetic algorithm to define input variables and the objective function by minimizing and maximizing its threshold to discover evolutionary and parametric optimal solutions. The Non-Dominated Sorting Genetic Algorithm (NSGA-II) evaluated the variables with their assigned ranges to determine the most optimized options in terms of energy use intensity (EUI), quality of view (QV), useful daylight illuminance (UDI) in four Iranian cities: Ardabil, Bandar abbas, Rasht, and Tehran. In the optimization setting, generation size was 15, and the generation count was 100 for each city. Additionally, 1500 operations were performed for each case, and the Pareto front graphs were selected as optimal solutions. The three axes in Fig. 11 represent UDI (%), EUI (kWh/m^2 y), and QV (%). Also, the initial and final values of each axis and all possible solutions obtained during optimization were illustrated. Red dots present Patero optimal solution, and white dots show dominant solution. In the appendix, information about the Pareto solutions for Ardabil, Bandar abbas, Rasht, and Tehran was presented in Tables A1, A2, A3, and A4, respectively. Dominant and Pareto solutions were compared in the three-dimensional optimization.

Reducing EUI was chosen as one of the research objectives. As presented in Fig. 12, the EUI of the dominated solutions ranged from 86.5 kWh/m^2y to 104.5 kWh/m^2y for Ardabil, from 125.4 kWh/m^2y to 156.6 kWh/m^2y for Bandar abbas, from 96.9 kWh/m^2y to 110.4 kWh/m^2y for Rasht, from 93.8 kWh/m^2y to 116.8 kWh/m^2y for Tehran. Due to the difference in the cooling load, Bandar Abbas had higher energy consumption than other cities, and Ardabil had a lower energy consumption. The EUI of the Pareto optimal solutions in Ardabil ranged between 86.5 kWh/m^2y and 100.1 kWh/m^2y, between 125.4 kWh/m^2y and 143.6 kWh/m^2y for Bandar abbas, between 96.9 kWh/m^2y and 107.3 kWh/m^2y for Rasht, between 93.8 kWh/m^2y and 110.4 kWh/m^2y for

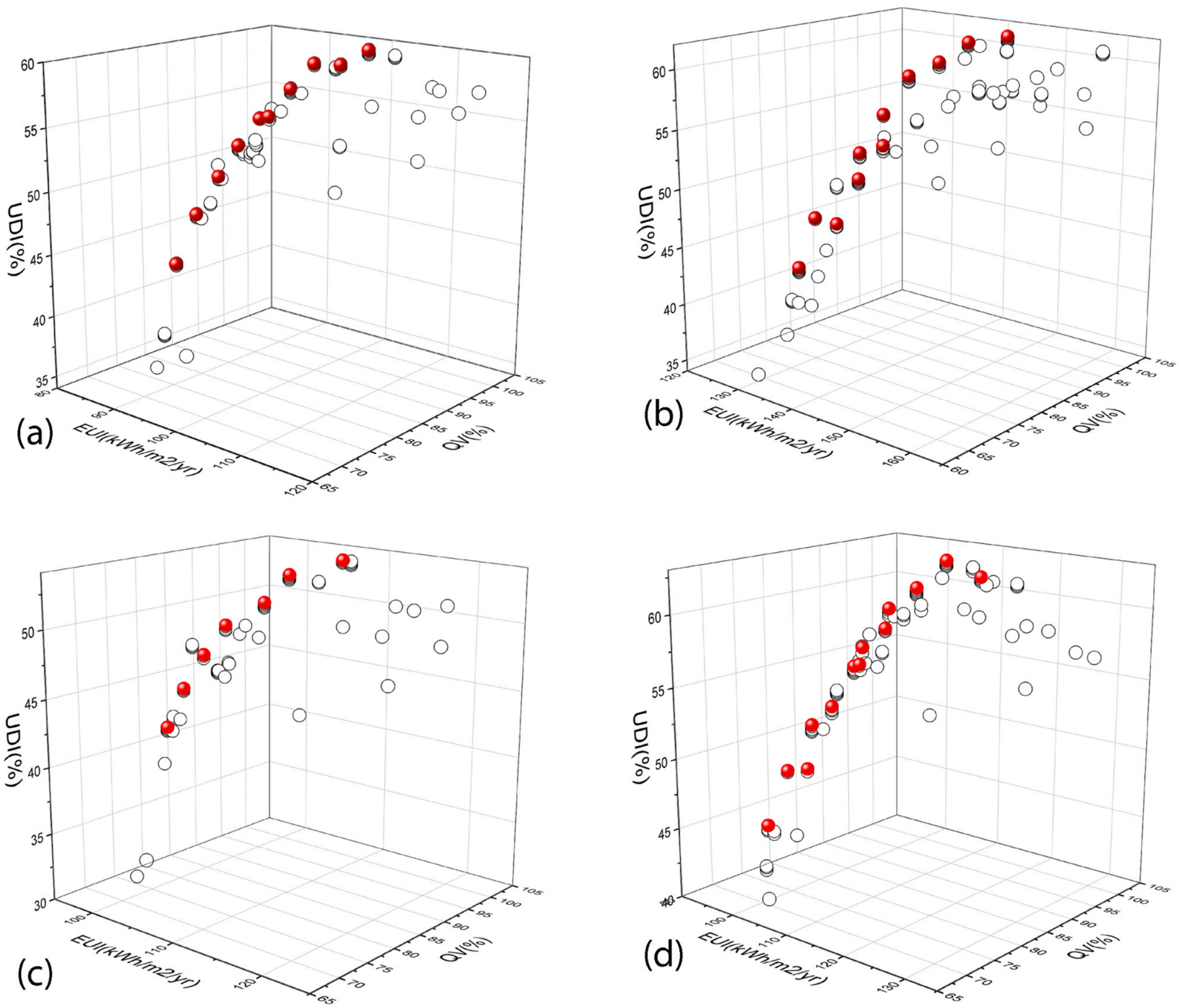


Fig. 11. Multi-objective optimization: a) Ardabil, b) Bandar abbas, c) Rasht, and d) Tehran.

Tehran. Comparing dominant and Pareto solutions for EUI demonstrated, the average was almost equal, but dominated solutions had some outliers upper bound. In optimal solutions, energy consumption was reduced compared to the original model, and the lowest EUI value for each location was achieved the wall inclined at 30°. However, the window-to-wall ratio and the glazing material differed in optimal conditions in different cities.

The dominated solutions' QV ranged from 68.6% to 100%. The mean of QV was 90.3% for Ardabil, 88.6% for Bandar abbas, 91% for Rasht, and 88.2% for Tehran. The main distribution interval for QV in the Pareto solutions was 79.4–100% for Ardabil, 76.5% – 100% for Bandar abbas, 82.4%– 100% for Rasht, and 76.5%– 100% for Tehran. The quality of view in all Pareto solutions was higher than 75%; therefore, according to the LEED v4 standards, all solutions provided appropriate access to outside. The maximum view quality in optimal solutions was for Rasht; it had a greater window-to-wall ratio for optimal solutions in humid subtropical climates. As shown in Fig. 10(a), the UDI of the dominated solutions ranged from 37.4% to 59.6% for Ardabil, from 34.4% to 61.2% for Bandar abbas, from 34.2% to 53.4% for Rasht, from 40.9% to 62.3% for Tehran. The UDI of the Pareto optimal solutions in Ardabil ranged from 43% to 59.6%, from 41.1% to 61 for Bandar abbas, from 41.4% to 53.4% for Rasht, and from 43.9% to 62.3% for Tehran. Compared to other cities, Rasht had the lowest UDI value. By examining the optimal solutions, it was concluded that UDI and QV conflict with EUI. In solutions with the highest UDI value, the window-to-wall ratio was between 50% and 60%. Moreover, the angle of the wall was between 10° and 20°.

4.4. Correlation analysis

As illustrated in Fig. 13, the Pearson correlation coefficient between variables was computed to provide a statistical overview of the dataset. The diagram's color and R values describe the magnitude and direction of the correlation. No strong correlation values ($R > 0.7$) were observed except for the window-to-wall ratio and the wall angle. The R values reveal the linear correlation between the variables. In the heat map diagram, colors present a relation between parameters; red indicates a positive effect (+1), and blue indicates a negative effect (−1). It was essential to observe that in-depth research was required to establish meaningful relationships between specific parameters. For example, the relationship between the heating load and any variable was unimportant because the R values reached a maximum of 0.55, and the window-to-wall ratio and the glazing material affected the amount of heating load. On the other hand, there was a deep relationship between the lighting load and the window-to-wall ratio. Increasing the window-to-wall ratio reduced the lighting load (R between 0.79 and 0.82).

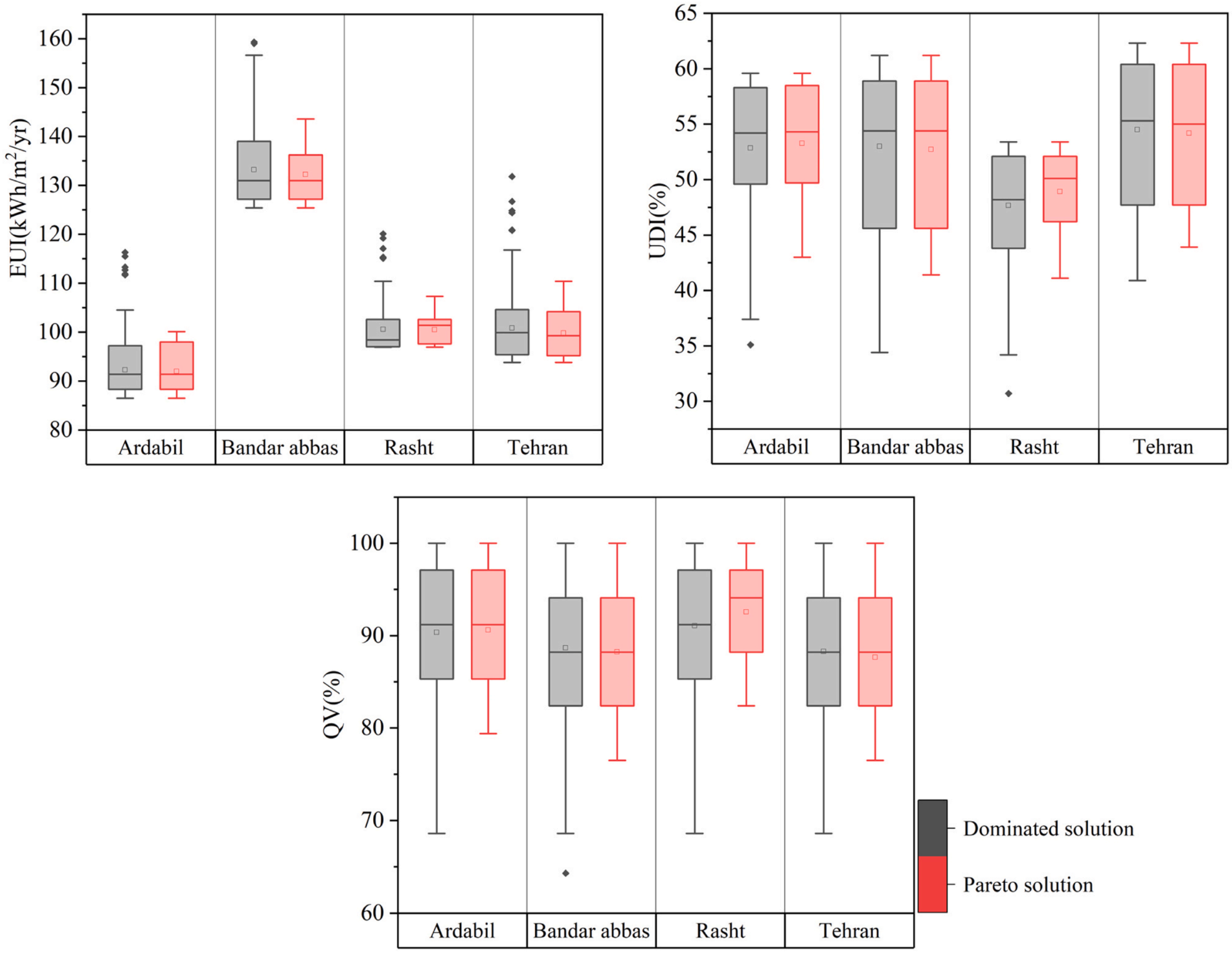


Fig. 12. Comparing pareto solutions and dominated solutions.

However, the relationship between the variables was not linear because despite the effect of the lighting load on the total energy consumption, with the increase in the window-to-wall ratio, the total energy increases despite the reduction of the lighting load. Different parameters were known with the investigations to control the visual comfort: to reduce the ASE, the wall angle (R between 0.67 and 0.83), and the window-to-wall ratio (R between 0.49 and 0.68). To increase sDA, the window-to-wall ratio (R between 0.85 and 0.88) and wall angle (R between 0.42 and 0.46) were important. To control EUI, the wall angle was the most critical factor (R between 0.59 and 0.78) and the window-to-wall ratio (R between 0.48 and 0.66). For the outside view, the window-to-wall ratio (R=0.64), window shape (R=0.21), and wall angle (R=0.11) were important.

5. Discussion

This article investigates the effect of facades' geometry on visual comfort and energy saving. Window-to-wall ratio, window type and glazing material were selected as variables. Additionally, the inclination of the south wall was investigated for self-shading. To ensure a thorough examination, four cities from different climates of Iran were selected: Ardabil (cold semi-arid), Bandar Abbas (hot semi-arid), Rasht (moist mild-latitude), and Tehran (cold semi-arid). For accurate comparison between selected climates, physical model's properties, except for thermostat set-points in Bandar abbas (hot semi-arid climate), have been considered the same. In previous sections, validation, optimization, and correlation analysis obtained an optimal self-shading recommendation for each climate region. In the first part, the effect of the inclined wall on visual comfort metrics (UDI, ASE, sDA), energy consumption (cooling, heating, lighting), and quality of view were investigated according to the LEED v4 standards. Analyzing the original model's EUI reveals that Bandar abbas has the highest value (136.4 kWh/m^2y), followed by 39.5% cooling and 35.5% lighting, and the remaining portion was related to electrical energy consumption, which has not been investigated in this study. This was the highest value of cooling energy consumption among all selected cases. The portion of cooling load and lighting load from the total annual energy consumption was different in each example, i.e., 23.6% cooling and 44.7% lighting in Tehran, 22.8% cooling and 46.2% lighting in Rasht, and the lowest cooling sector for Ardabil was 18.8% cooling and 48.8% lighting. So, lighting load has the most significant percentage of total annual energy consumption. By rotating the wall from -40° to 40°, the UDI decreases between 11.4% and 20.1%, which reduces adequate natural light but increases artificial lighting between 4.5% and 8.2%. However, a decrease in cooling load between 33% and 70.8% led to a decrease in EUI between 19.1% and 31.3%. The most significant reduction in cooling load related to Ardabil (70.8%) led to a 27.7% reduction in energy consumption.

The Pareto front solution reveals that the best rotating wall degree for the lowest energy consumption was 30°. All optimal solutions in four cities inclined wall between 10° and 30°. Although background studies claim that the window-to-wall ratio was a critical factor in energy use and glare (Bülow-Hübe, 1998; Mebarki et al., 2021), based on Fig. 13, this research results showed the impact of the positive inclination wall on saving energy and controlling solar heat gain. Although rotating wall

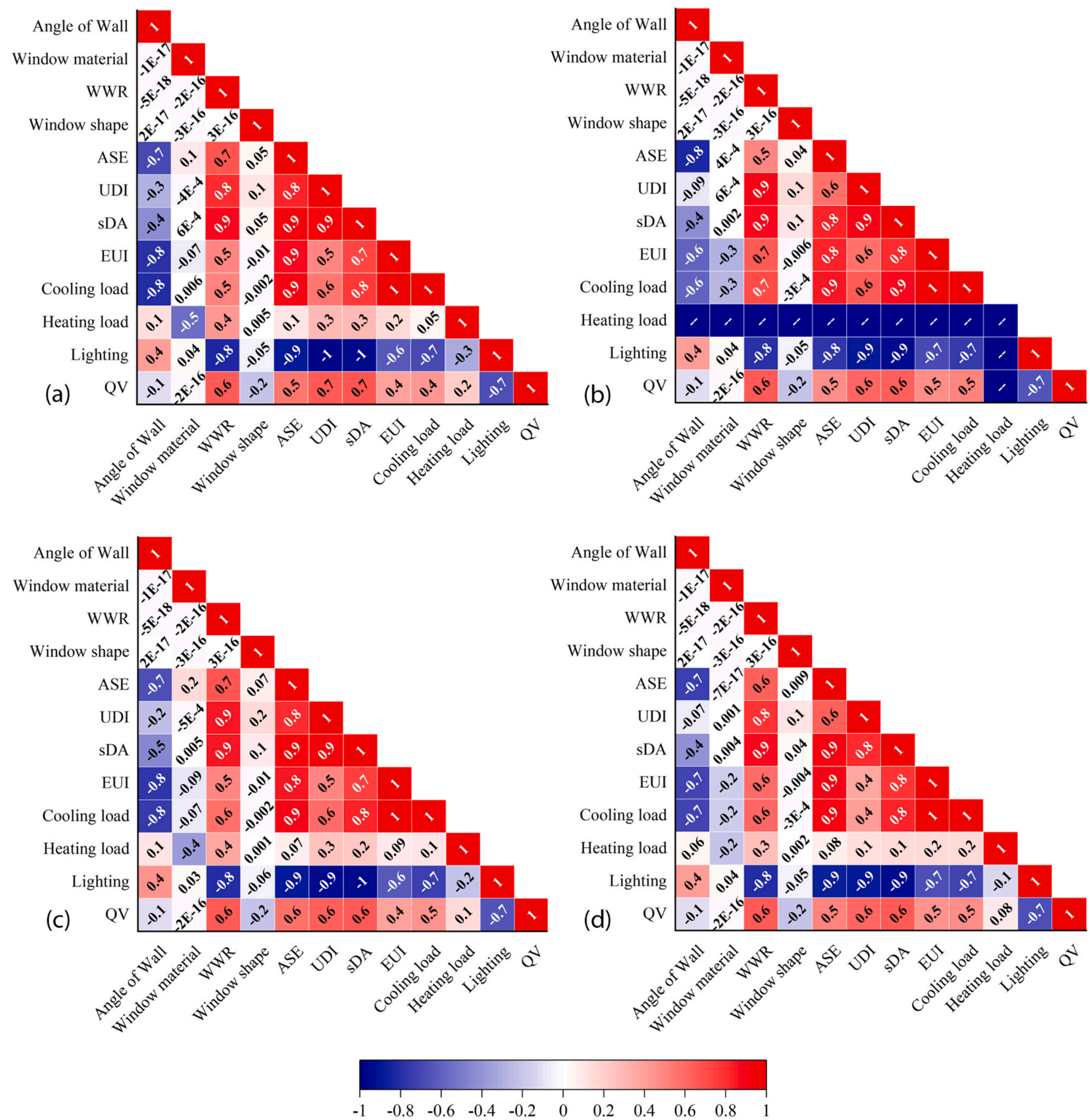


Fig. 13. Correlation parameters: a) Ardabil, b) Bandar abbas, c) Rasht, and d)Tehran.

in a positive direction increased lighting energy, optimal solution illustrated an inclined wall between 10° and 30°, because lighting increased between 1.7% and 4.5%, but cooling load decreased between 12.2% and 37.2%. Inclined wall control direct sunlight (ASE decreased by 12.5% and 16.1%), so optimal solutions have larger windows than the base model. In addition, the rotation of the wall in a positive direction increased heating load consumption in Ardabil and Rasht, which is much less than the saving in cooling. The optimal samples have generally reduced EUI between 7.8% and 12.5% compared to the original model. Tehran and Ardabil (cold semi-arid climate) had the highest reduction in energy consumption, which shows that this method was more effective in cold climates. However, it was also effective in other investigated climates (hot semi-arid and moist mild-latitude). Reducing cooling load was not the same as rotating the façade's wall in a positive direction in different cities. The most considerable reduction was in Ardabil (37.2%), Tehran (29.8%), Bandar Abbas (24.8%), and Rasht (12.2%), respectively. However, in all selected cities, the increase in lighting energy is low (between 1.3% and 2.5%).

Because the shape of the window only affects UDI and view to the outside, only the continuous horizontal in the center of the wall was selected as the optimal solution in all four cities. The optimal window-to-wall ratio in Tehran and Bandar abbas was 20%– 60%, Ardabil 30%– 60%, and Rasht 40%– 60%. The increase in the window-to-wall ratio compared to previous research (Mahdavinejad et al., 2012; Maleki and Dehghan, 2021; Bakmohammadi and Noorzai, 2020) was due to considering the quality of the view outside as the research objective in this research and inclined wall control direct sunlight. UDI for the optimal solution has decreased from 2.2% to 5.8% compared to the base model; Tehran has the highest value, and Rasht has the lowest value. Also, the view quality has decreased from 6.5% to 9.5%, but all the optimal solutions were above 75%, so the solution has access to view based on LEED v4 standards. In the investigation, ASE has decreased between 12.75% and 16.1% compared to the original model, and sDA has decreased between 6.6% and 12.5%. Fig. 13 shows the inclined wall's effect on ASE and sDA values. None of the optimal models were fulfilled in the LEED v4 visual comfort indicator. Therefore, the authors suggest the combination of self-shades with louvers to provide visual comfort. According to a previous study based on inclined wall self-shading, the optimum self-shading projection of 45° for Malaysia (Kandar et al., 2019) and 25° for the UK (Lavafpour and Sharples, 2015) could eliminate overheating risk. However, the relationship between the inclined wall and overheating preservation was proved.

The influence of all variables on the research outputs is shown in Fig. 13. The wall inclination has the greatest effect on ASE (R-value between −0.83 and −0.68). However, it caused a decrease in sDA (R-value between −0.46 and −0.42). The effect of the inclined wall on UDI was sensible in Ardabil (R= −0.28) and Rasht (R= −0.24), but in all cities reduces access to adequate daylight. The important finding was the influence of the inclination on controlling energy consumption, which can be seen significantly in all four cities (R-value between −0.59 and −0.78). Also, an impact on cooling load was proved in Ardabil (R= −0.8), Rasht (R= −0.76), Tehran (R= −0.7), and Bandar Abbas (R=−0.59), respectively. The effect of the wall angle on the energy use intensity in Ardabil, Rasht, and Tehran was higher than the window-to-wall ratio. This research's findings correct the previous study's conclusion (Bakmohammadi and Noorzai, 2020) that wall inclination and window-to-wall ratio were important for EUI and ASE. Although the relationship between type of window and measured outputs was shown to be effective only on UDI, examination of optimal models showed that horizontal windows located in the center of walls consume less energy than vertical windows. So, this article reconfirms the results of this study (Maleki and Dehghan, 2021). According to the previous study (Pilechiha et al., 2020b), by changing the parameters of the window, QV performance could be improved to more than 80% while maximizing daylight and saving energy. This article proved the relationship between window types and WWR with QV. However, rotating the wall in a positive direction decreased quality of view.

6. Conclusion

This study delves into the intricate relationship between facade geometry and its impact on visual comfort and energy efficiency. It examines window-to-wall ratio, window type, glazing material, and wall inclination. The research highlights that optimizing these variables is crucial for creating sustainable built environments. The study employs parametric design and multi-objective optimization to analyze the effect of facade geometry on mentioned objectives. First stage, the parameters of the facade were determined. Then, by comparing the rotating wall on visual comfort (UDI, sDA, and ASE), view out, and energy consumption (EUI, cooling load, heating load, and lighting load) in four Iranian cities (Ardabil, Bandar abbas, Rasht, and Tehran) the appropriate range was selected for optimization. Finally, by optimizing with the NSGA-II algorithm, the optimal solutions have been investigated. It determines optimal parameters for the facade and evaluates their performance in four Iranian cities.

The results challenge the conventional emphasis on window-to-wall ratio, revealing the significance of other factors. This research proved that wall inclination and window-to-wall ratio were important for EUI and ASE. Although the relationship between types of windows was shown to be effective only on UDI, examination of optimal models showed that horizontal windows located in the center of walls consume less energy than vertical windows. However, the window-to-wall ratio is the most important factor for UDI and lighting load. Notably, the study underscores the importance of tailoring design strategies to climate conditions. It also identifies key factors influencing heating load and emphasizes the need for detailed approach to optimizing heating systems. The research reveals a complex interplay between window-to-wall ratio and lighting load, emphasizing the need for a holistic approach to energy-efficient design.

Additionally, the study introduces innovative aspects to the discourse on facade design. It recommends inclined walls for improved visual comfort, daylighting, and energy savings. The rotating wall between 10° and 30° is optimal for various cases. The research demonstrates the effectiveness of this method, particularly in cold semi-arid climates, while still showing promise in other climates. The study provides a valuable framework for designing offices in similar climates and latitudes. Overall, the research highlights the importance of context-specific design strategies for achieving optimal energy efficiency, visual quality, and daylighting availability outcomes. It offers valuable insights for architects and designers to create sustainable and comfortable built environments tailored to specific regional conditions. The study acknowledges its limitations and suggests future research directions, including investigating different latitudes, climates, and glare control methods in combination with inclined walls.

CRediT authorship contribution statement

Conception and design of study: Mohammadjavad Mahdavinejad, Hassan Bazazzadeh, Fatemeh Mehrvarz. Acquisition of data: Tahereh Nasr, Somayeh Pourbagher, Hassan Bazazzadeh. Analysis and/or interpretation of data: Mohammadjavad Mahdavinejad, Fatemeh Mehrvarz, Hassan Bazazzadeh. Drafting the manuscript: Mohammadjavad Mahdavinejad, Hassan Bazazzadeh, Siamak Hoseinzadeh. Revising the manuscript critically for important intellectual content: Hassan Bazazzadeh, Umberto Berardi. Approval of the version of the manuscript to be published (the names of all authors must be listed). Mohammadjavad Mahdavinejad, Fatemeh Mehrvarz, Tahereh Nasr, Somayeh Pourbagher, Hassan Bazazzadeh.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that has been used is confidential.

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All persons who have made substantial contributions to the work reported in the manuscript (e.g., technical help, writing and editing assistance, general support), but who do not meet the criteria for authorship, are named in the Acknowledgements and have given us their written permission to be named. If we have not included an Acknowledgements, then that indicates that we have not received substantial contributions from non-authors.

Appendix

Table A1
Optimal solution of Ardabil.

Ardabil											
Wall inclination	WWR	Material	Window shape	EUI	Cooling load	Heating load	Lighting load	UDI	ASE	sDA	QV
30	30%	Single Clear	Continuous horizontal	86.5	264.8	31.8	1400.3	42.8	15	39.5	79.4
10	60%	Double Clear Air	Continuous horizontal	100.1	549.2	17.4	1311	59.3	35	63.9	100
30	40%	Single Clear	Continuous horizontal	87.2	271.5	65.5	1373	46.5	18	44.5	82.4
30	50%	Double Clear Air	Continuous horizontal	88.3	325.7	8.2	1360.7	49.4	21	48.7	85.3
20	50%	Double Clear Air	Continuous horizontal	92.5	406.7	11.5	1337.2	56.2	28	57.1	94.1
20	60%	Double Clear Air	Continuous horizontal	93.8	431.3	20.8	1327.6	57.9	34	58.8	97.1
10	50%	Double Clear Air	Continuous horizontal	98	510.7	10.2	1319	58.3	35	60.5	97.1
20	50%	Double Clear Air	Continuous horizontal	91.4	381.7	4.5	1349.7	54	28	52.1	91.2
30	50%	Double Clear Air	Continuous horizontal	89	340.3	16.5	1346.9	51.5	23	51.3	88.2
30	60%	Double Clear Air	Continuous horizontal	89.9	354.6	27.7	1336.5	53.5	27	53.8	91.2
20	50%	Double Clear Air	Continuous horizontal	91.4	381.7	4.5	1349.7	54	28	52.9	91.2
10	50%	Double Clear Air	Continuous horizontal	98	510.7	10.2	1319	58.3	35	60.5	97.1

Table A2
Optimal solution of Bandar abbas.

Bandar abbas											
Wall inclination	WWR	Material	Window shape	EUI	Cooling load	Heating load	Lighting load	UDI	ASE	sDA	QV
10	60%	Triple Clear	Continuous horizontal	131	1404.1	0	1273.8	61	28	69.7	100
30	20%	Triple Clear	Continuous horizontal	116	1034.4	0	1390.2	41.2	10	37.8	76.5
20	60%	Triple Clear	Continuous horizontal	127.5	1312.3	0	1288	60.3	21	64.7	97.1
20	50%	Triple Clear	Continuous horizontal	125	1263.9	0	1294.7	58.5	21	61.3	94.1
30	30%	Triple Clear	Continuous horizontal	116.5	1066	0	1348.6	45.4	12	45.4	79.4
20	20%	Triple Clear	Continuous horizontal	117.6	1076.9	0	1372.6	44.4	13	42	82.4
30	50%	Triple Clear	Continuous horizontal	119	1133.9	0	1310.2	50.9	14	52.9	85.3
10	30%	Triple Clear	Continuous horizontal	120.2	1170.9	0	1311.6	51.2	20	52.9	88.2
20	30%	Triple Clear	Continuous horizontal	118.8	1122.2	0	1337.3	48.3	19	47.9	85.3
30	60%	Triple Clear	Continuous horizontal	122.3	1206.1	0	1292.1	57.5	14	58.8	91.2
30	50%	Triple Clear	Continuous horizontal	120.6	1169.2	0	1299.7	54	14	55.5	88.2

Table A3
Optimal solution of Rasht.

Rasht											
Wall inclination	WWR	Material	Window shape	EUI	Cooling load	Heating load	Lighting load	UDI	ASE	sDA	QV
10	60%	Double Clear Air	Continuous horizontal	107.3	739.4	0	1329.8	53.3	35	63.9	100
30	40%	Single Clear	Continuous horizontal	96.9	513.5	0	1406.2	40.9	14	43.7	82.4
20	50%	Single Clear	Continuous horizontal	101.4	621.2	3.5	1356.1	49.7	26	56.3	94.1
30	60%	Single Clear	Continuous horizontal	98.4	558.9	13	1356.1	48	20	52.9	91.2
20	60%	Single Clear	Continuous horizontal	102.6	647.1	8.5	1345.1	52.1	27	58.8	97.1
30	40%	Single Clear	Continuous horizontal	97	528.1	1.5	1384.2	43.7	15	46.2	85.3
30	50%	Single Clear	Continuous horizontal	97.6	543.2	5.2	1368.2	46	19	51.3	88.2
30	60%	Single Clear	Continuous horizontal	98.4	558.9	13	1356.1	48	20	53.8	91.2
20	60%	Single Clear	Continuous horizontal	102.6	647.1	8.5	1345.1	51.9	27	58.8	97.1

Table A4
Optimal solution of Tehran.

Tehran											
Wall inclination	WWR	Material	Window shape	EUI	Cooling load	Heating load	Lighting load	UDI	ASE	sDA	QV
10	60%	Triple Clear	Continuous horizontal	110.4	789.7	0	1271.3	60.9	40	72.3	100
30	20%	Triple Clear	Continuous horizontal	93.8	430	0	1374.6	43.5	17	39.5	76.5
20	60%	Triple Clear	Continuous horizontal	106.8	717.1	0	1284.2	61.8	34	68.9	97.1
30	30%	Triple Clear	Continuous horizontal	94.6	467.7	0	1338.7	47.5	19	47.1	79.4
20	30%	Triple Clear	Continuous horizontal	97	510.1	0	1328.6	51.7	26	51.3	85.3
30	40%	Triple Clear	Continuous horizontal	96.2	506.9	0	1318.2	50.8	20	51.3	82.4
20	20%	Triple Clear	Continuous horizontal	95.2	460.6	0	1360.1	47	18	46.2	82.4
30	60%	Triple Clear	Continuous horizontal	101.9	626	0	1288.8	58.4	27	62.2	91.2
10	40%	Triple Clear	Continuous horizontal	101.2	605.2	0	1292.1	57.2	35	60.5	91.2
20	50%	Triple Clear	Continuous horizontal	104.2	664.9	0	1290.6	60.3	30	64.7	94.1
10	30%	Triple Clear	Continuous horizontal	98.3	544.5	0	1306.1	54.2	28	54.6	88.2
20	40%	Triple Clear	Continuous horizontal	99.3	561.2	0	1310.6	55.2	27	56.3	88.2
30	50%	Triple Clear	Continuous horizontal	99.9	586.5	0	1295.7	56.1	25	58.8	88.2

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