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Article

Retrofitting vernacular screens in contemporary facades in hot and dry regions: A climate control study using energy and CFD simulations

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ABSTRACT

This research examines the perforated geometric screens (jaali, also called mashrabiya) extensively used in Islamic and Indo-Islamic architecture. Historically, these elements have been used not only for aesthetic purposes but also as passive design strategies to regulate indoor temperature through natural ventilation and shading. This study hypothesizes that the principles of traditional jaali can be reinterpreted and integrated into contemporary facade design to improve thermal comfort, particularly in hot and dry climates. To test this hypothesis, the research used a conceptual case study of the Kilis Resource and Community Center (KRCC) in Türkiye. The study assessed internal airflow patterns and thermal conditions using energy modeling and Computational Fluid Dynamics (CFD) simulations via the IESVE software. The analysis was done during the cooling period, with two representative summer days: May 3rd and July 15th. Results showed that all investigated ventilation scenarios with jaali-integrated facades had lower indoor temperatures throughout the day. However, the presence of open windows was crucial to maintain indoor temperatures below outdoor levels, allowing air movement. The findings suggest that using jaalis in hot climates should be encouraged, as it lowered temperatures by up to 2°C during the cooling season with the help of natural ventilation.

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INTRODUCTION

Recent studies underscore the urgent need to address global warming and its environmental consequences (IPCC, 2022; Mofolasayo, 2022; Santos et al., 2022). Achieving sustainable development requires both mitigation to address the root causes of climate change and adaptation to minimize its impacts (Tol, 2005). The construction sector contributes nearly 39% of global energy-related CO_2 emissions- 28% from building operations and 11% from materials production and construction activities- and accounts for approximately 40% of annual global energy consumption, largely due to heating and cooling demands (Fumo, 2014; He et al., 2019; Simonen et al., 2017; Song et al., 2021; UN report, 2020; UNEP, 2009). To reduce operational energy use, research increasingly emphasizes passive design strategies such as natural ventilation, which can lower emissions and improve thermal comfort (Liu et al., 2023; Song

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et al., 2021). Unlike energy-intensive mechanical systems, natural ventilation leverages outdoor airflows and pressure differences, though its effectiveness depends on local wind patterns, climate, building orientation, form, and façade design (Ohba & Lun, 2010).

Vernacular Screens and Contemporary Facades

In response to the growing demand for sustainable and energy-efficient building designs, researchers have explored various retrofit strategies to improve the performance of existing building stock. The International Energy Agency (IEA) estimates that 20% of all buildings must be retrofitted with energy efficiency measures by 2030 to reach a net-zero emission goal by 2050 (Song et al., 2021). These retrofits aim to improve passive climate control within buildings, thereby reducing the reliance on active systems such as air conditioning (Liu et al., 2023).

One widely studied approach is the integration of vernacular screens into contemporary facades (Aflaki et al., 2015; Sarihi et al., 2021). Vernacular screens, also known as 'jaalis' or 'mashrabiyas', are traditional sun shading devices used in Islamic architecture for centuries to regulate heat gain and enhance ventilation (Du et al., 2019) when providing privacy (Figure 1). Historically, these screens were constructed from locally sourced materials such as stone, clay, wood, bamboo, or metal, tailored to the regional climate. Strategically positioned on exterior walls, their intricate geometric patterns not only enhanced the aesthetics of buildings but also reduced interior heat gain by blocking direct sunlight while allowing airflow (Du et al., 2019; Elzeyadi & Batool, 2017).

Natural ventilation occurs due to pressure differences created by wind acting on building surfaces and by temperature variations between indoor and outdoor air (El Semary et al., 2017). In Mughal architecture, controlled airflow and temperature regulation were achieved through building orientation, appropriately sized and proportioned openings, ventilated domes, and extensive use of jaali (Ali, 2013) (Figure 1b). The ventilated domes utilized the stack effect, whereby hot air inside the building rises and exits through dome openings, simultaneously inducing the airflow of cooler air from below.

Integrating vernacular screens into contemporary facades allows designers to combine traditional passive strategies with modern techniques, improving thermal performance and reducing the need for mechanical cooling. Sherif et. al (2010) showed in their research that lightweight screens with a 70-85% perforation ratio and 1:1 depth profile improved energy performance in residential buildings in hot-moderate climates, reducing solar heat gains, and enhancing thermal comfort (Sherif et al., 2012a). Originally developed for residential use, these screens are increasingly applied to diverse building typologies, including galleries and museums.

For instance, in contemporary exhibition design, traditional shading devices are reinterpreted to shape spatial atmosphere. Perforated wooden panels filter natural light,

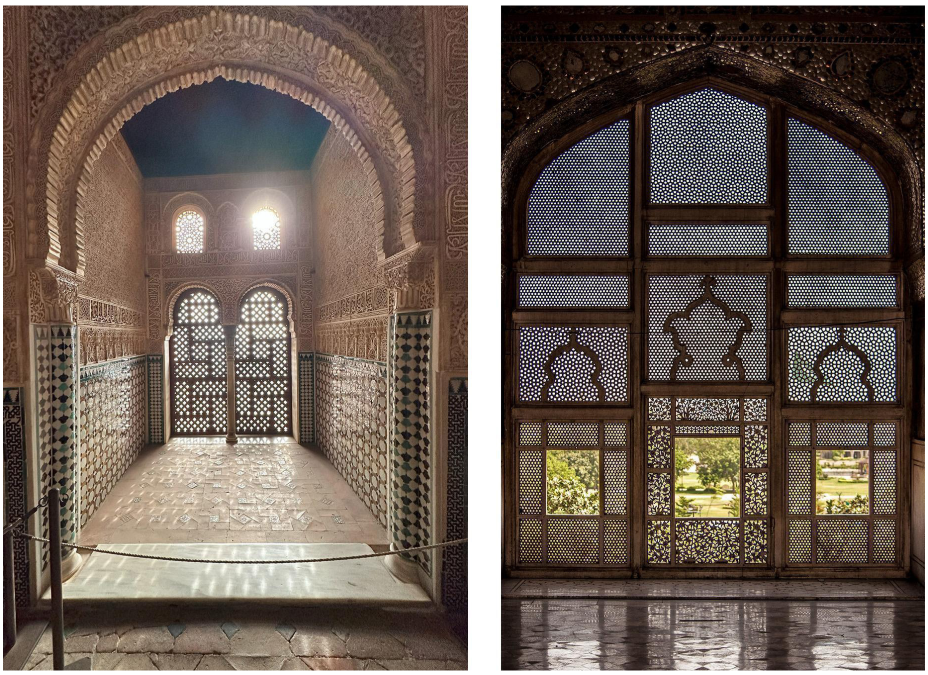

Figure 1. The use of Jaali screen in Islamic architecture, (Left) Alhambra Palace, Spain (Photo by Author, (Right) Lahore Fort, Pakistan.

casting patterned projections across floors and walls, moderating glare, reducing solar heat gain, and regulating the interior thermal environment. Simultaneously, the intricate perforations fragment daylight into shifting patterns, creating a dynamic visual experience that enhances visitor engagement (Figure 2). In museum contexts, this reinterpretation connects contemporary spaces to architectural traditions while enriching the atmosphere with distinct aesthetic qualities. For example, carved walnut screens by Ahmad Angawi in the British Library galleries filter light into exhibition areas, situating audiences within a dialogue between past and present (Jakeman, 2018).

These vernacular screens function on multiple levels: As climatic regulators, cultural expressions, and aesthetic elements that transform daylight into an ephemeral decorative feature within the interior environment. Previous research has shown that retrofitted screens can improve natural ventilation, shading, and daylighting, reducing reliance on mechanical cooling and artificial lighting (Du et al., 2019; El Semary et al., 2017; Elzeyadi & Batool, 2017). However, quantitative studies remain limited, particularly regarding optimal geometry, perforation ratios, and climate-specific design guidelines (Du et al., 2019). This study focuses on evaluating changes in interior climate performance resulting from retrofit designs that integrate *jaalis*.

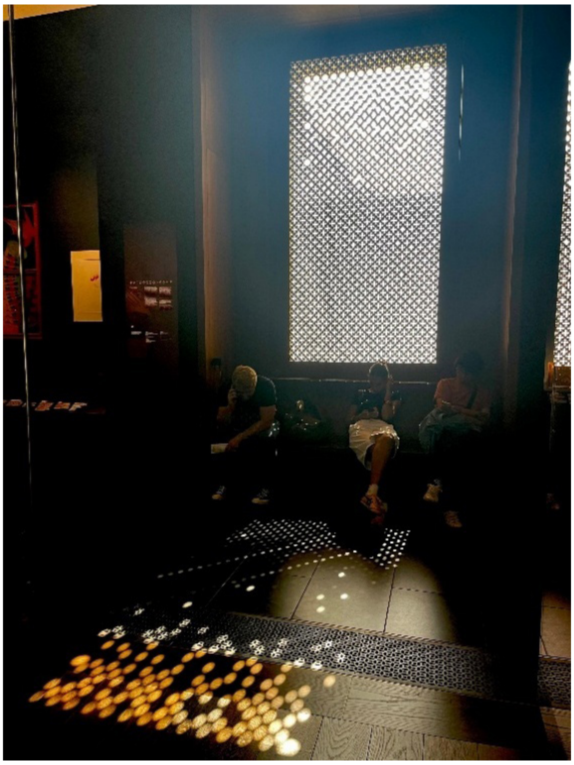

Figure 2. Jaali screen in the British Library, London. (Photo by Author).

Objectives of this Computational Study and Research Gap

Computational studies have shown that integrating vernacular screens can enhance buildings' thermal performance and energy efficiency (Ali, 2013; Dev et al., 2021; Sherif et al., 2012a). Such simulations typically account for factors including solar radiation, wind speed, and building materials, providing valuable insights into the potential benefits and limitations of retrofitting such elements. While prior research has modeled the efficiency of shading devices like louvers (Elzeyadi & Batool, 2018), there is still a gap in studies specifically assessing the impact of retrofitted vernacular screens on indoor climate using simulation tools (Taki & Kumari, 2023).

This computational study aims to investigate the potential of retrofitting vernacular screens (jaali) into modern facades for passive climate control. Specifically, it will assess how natural ventilation affects the thermal performance of a case study building equipped with retrofitted jaalis. Various ventilation scenarios, no ventilation, natural ventilation, and stack ventilation, are analyzed to assess their effectiveness in regulating indoor temperatures and enhancing occupant comfort. By focusing on the use of vernacular screens for passive climate control in contemporary facades, this study addresses an underexplored area in sustainable building design. Through simulation-based analysis, it provides evidence-based insights to inform energy-efficient and climate-responsive architectural strategies.

Literature Review

In contemporary residential design, architects and engineers face the dual challenge of ensuring occupant thermal comfort while reducing environmental impacts. Heating, ventilation, and air-conditioning (HVAC) systems are central to this effort, as their efficiency directly influences both energy demand and greenhouse gas emissions. With climate change, periods requiring mechanical cooling are lengthening, resulting in increased energy consumption in buildings. A more sustainable alternative lies in the passive cooling strategies offer a sustainable alternative, capable of reducing environmental impacts and operational costs (Sarna & Ferdyn-Grygierek, 2025). A recent study by Iskandar et al. (2025) emphasize the necessity of adaptive retrofit strategies, leveraging existing systems, the implementation of operational modifications, and the integration of shading devices to mitigate heat gain.

The challenge posed by climate change is evident not only in hot climatic zones but also in regions with historically heating-dominated temperate climates, which experience cold winters and mild to warm summers (Berger & Worlitschek, 2019; Parker, 2021). Studies of current and projected climate scenarios indicate that global warming will reduce heating demand while increasing cooling needs (Bay-Sahin et al., 2025; Rahif et al., 2022; Wilbanks et al., 2008). Beyond energy demand, climate change also affects renewable energy reliability (Rahman et al., 2025), and increases the risk of overheating, which negatively impacts occupant comfort, (Bay-Şahin & Elnimeiri, 2025; Lan et al., 2017), productivity (Hooyberghs et al., 2017), and health (Armstrong et al., 2011). However, research in Mediterranean climates remains scarce (Chkeir et al., 2024).

In these climates, passive cooling techniques for buildings can lower indoor temperatures in warm periods with minimal energy consumption. Geetha and Velraj (2012) classified these methods into three categories: Reducing internal heat gains, managing heat through thermal storage or night ventilation, and dissipating heat via natural ventilation (including evaporative, ground, or radiative cooling). (Geetha & Velraj, 2012). Fathy (2000) observed that traditional rural buildings in Pakistan achieved thermal comfort using passive design measures, including orientation, shading, and ventilation (Fathy, 2000). Similarly, a parametric study in Portugal showed that north-facing windows performed better thermally than northwest- or northeast-facing ones (Amaral et al., 2016).

In hot climates, window shading reduces cooling loads and energy consumption by mitigating solar heat gains. For instance, field measurements in a study of a courtyard situated in a hot and dry climate demonstrated that the covered outdoor sitting area and the shading screen significantly enhanced airflow and thermal performance of the courtyard (Mohamed, 2018). A computational study of a residential building in a desert climate evaluated various perforation percentages and depths. Results show that fixed, deep perforated solar screens on the west and south facades can achieve energy savings of up to 30% of total energy use (Sherif et al., 2012b).

Effectively bridging thermal comfort and natural ventilation requires understanding air flow dynamics, as air velocity is a key determinant of occupant comfort (Wu et al., 2021). Natural ventilation, driven by wind and buoyancy, is essential for improving indoor air quality and reducing cooling energy demand. Wind-driven cross ventilation and buoyancy-driven stack ventilation are the primary strategies for achieving passive airflow (Al-Shamkhee et al., 2022). Evaluating these strategies during the design stage is therefore critical. Building energy modeling has therefore become a common tool for evaluating design decisions early in the process and predicting performance in terms of energy use or natural ventilation (Du et al., 2019; I. M. K. Elzeyadi & Batool, 2017; Ghaddar et al., 2024).

Recent work has demonstrated how traditional sun-shading elements, such as Aegean venetian blinds, can be systematically evaluated through energy simulations to assess their impact on daylight balance and cooling loads, offering insights for adapting vernacular strategies to contemporary sustainable design (Cavka & Feruz, 2022). Another study in a similar climate used building simulations to show that the geometry and placement of residential jaali screens can effectively reduce solar heat gain on south- and west-facing openings. This reduction lowered cooling loads while also improving indoor daylight distribution, highlighting their value as passive design elements in a hot-dry climate (Prasad et al., 2022). Besides common use of energy simulations, computational Fluid Dynamics (CFD) analysis has emerged as a critical tool for understanding building airflow and heat transfer. By simulating thermal buoyancy, wind-driven forces, and data analysis, CFD enables designers to visualize and optimize natural ventilation and environmental performance (Ai & Mak, 2017; Zhai, 2006).

Simulation methods, widely used in industries like chemical and aerospace engineering, help model pressure, velocity, and temperature in fluid flow processes. They are often used to verify the accuracy of those models (Elshaw et al., 2018; Palmero-Marrero & Oliveira, 2010). CFD is useful to model the physics underpinning these systems, such as the effects of thermal buoyancy, wind-driven forces, and the psychrometric properties of incoming air for more precise environmental control (Cook et al., 2003; Yao & Dang, 2023). Today, CFD plays a growing role in the building design industry, helping optimize environmental performance for energy efficiency (IESVE, n.d.; Bay et al., 2022; Capeluto & Ochoa, 2014).

CFD analysis is mostly used to assess indoor environmental conditions influenced by solar gain and airflow (Almhafdy et al., 2015). Lau et al. (2016) modeled 20 shading device configurations using IESVE software for a high-rise office in Kuala Lumpur, finding 1.0%-3.4% annual cooling energy savings depending on device type and facade orientation. Elzeyadi and Batool (2017) used IESVE to evaluate jaalis with a 30% perforation ratio across three hot climate zones. Results showed superior thermal comfort in hot-arid climates compared to hot-humid ones.

CFD has also been applied in heritage buildings to optimize ventilation. Bay et al. (2022) used IESVE and real-world monitoring to assess ventilation strategies in a historic UNESCO-listed church in San Antonio, Texas. Their study showed reduced reliance on mechanical cooling in spring, supporting natural ventilation for occupant comfort. Similarly, (Elhassan, 2023) used CFD modeling to study a residential building in a hot, dry climate, demonstrating that natural ventilation effectively maintained comfort while lowering energy use.

Overall, literature indicates that passive cooling strategies, including shading devices and natural ventilation, are essential for energy-efficient design. CFD and building energy modeling provide powerful tools for evaluating these strategies quantitatively, yet gaps remain in climate-specific applications and the integration of vernacular design elements like *jaalis* into modern buildings.

METHODS

In this study, energy and CFD analysis were combined to evaluate the applicability and efficiency of jaalis in terms of passive cooling using IES VE software. This is a building simulation tool used to create the geometry and energy model of the case study building. After determining the boundary conditions of the building on the selected dates during the cooling season, the data were used for the CFD model. This includes temperatures of opaque and transparent surfaces, heat gains and losses, and airflow rates both outside and inside the building. CFD analysis was used to investigate heat transfer processes, buoyancy effects, and wind-driven ventilation through airflow patterns. The main steps of CFD analysis in IES VE are shown in Figure 3.

All simulations done during this research took into account the entire building. Each CFD analysis was done after overall energy analyses of the KRCC building for each ventilation scenario, since each scenario was tested with and without shading devices. Also, scenarios (i) no ventilation, (ii) cross ventilation, and (iii) stack ventilation have different open/close window configurations. Since the Apache energy simulation module automatically generates the boundary conditions for a selected day and time, the data for each scenario was exported into the CFD module. Then, the CFD model settings were prepared with exported boundary conditions from the result of energy analysis. The boundary conditions file contains various data about the external conditions, such as atmospheric data, atmospheric pressure, precipitation, and moisture content, and internal conditions, such as room air temperature, surface temperature, such as wall surface temperature, and room radiant temperature.

In the IES VE MicroFlo module, a grid was created with an aspect ratio under 12:1 to provide a high level of resolution, using the recommended number of grid cells. The default turbulence model of the software was kept as the k-e turbulence model to calculate the cell's turbulent viscosity (IESVE, n.d.). CFD graphs were generated for each scenario to visualize the data provided by the energy model. The method was used to investigate the most effective natural ventilation strategy and the effect of jaalis on cooling the interior environment in the dry Mediterranean climate. The overall process followed for this research is shown in Figure 4.

Retrofitting Vernacular Screens in Modern Structures in Kilis, Türkiye

The hypothetical case study building used for this research is an unbuilt design project in Kilis, Türkiye. After the recent earthquakes in the country on February 6, 2023, this building was planned to serve as a community and resource center, Kilis Resource and Community Center (KRCC), for the affected population of Syrian refugees in the earthquake region. Kilis is located in southern Türkiye, on the border with Syria, and it is known to host the most significant number of Syrian refugees in the country. Kilis is a small city of 147,919 inhabitants (TUIK Kurumsal, n.d.). However, the vulnerable refugee population in Kilis exceeds the local populace by a ratio of 70:30.

Kilis lies 660 meters above sea level. The summers are hot and dry with sunny and clear skies, while the winters are frigid and cloudy. The temperature typically changes from 0.5°C to 35°C. Also, during the hot season that lasts for 3.5 months between mid-June and mid-September, the average daily high temperature is above 30°C. The dry season lasts 5.5 months, from May to mid-October, while the wet season lasts 6.5 months. The outdoor temperature, relative humidity, and wind velocity data are shown in Figure 5. The prevailing wind direction is west in Kilis. The KRCC building's geometry was first generated in the ModelIt module within IES VE. Precise weather data and building parameters were defined to accurately simulate the real-world scenario in a virtual environment. A weather file of the location was obtained from IES VE. This research used a Typical Meteorological Year (TMY15) file for the necessary input for the simulation process. Multiple variables in this weather file were dry bulb temperature, solar altitude and azimuth, relative humidity, direct and diffuse radiation, wind speed, and wind direction, contributing to passive climate control in buildings and reducing the reliance on mechanical means of cooling and heating.

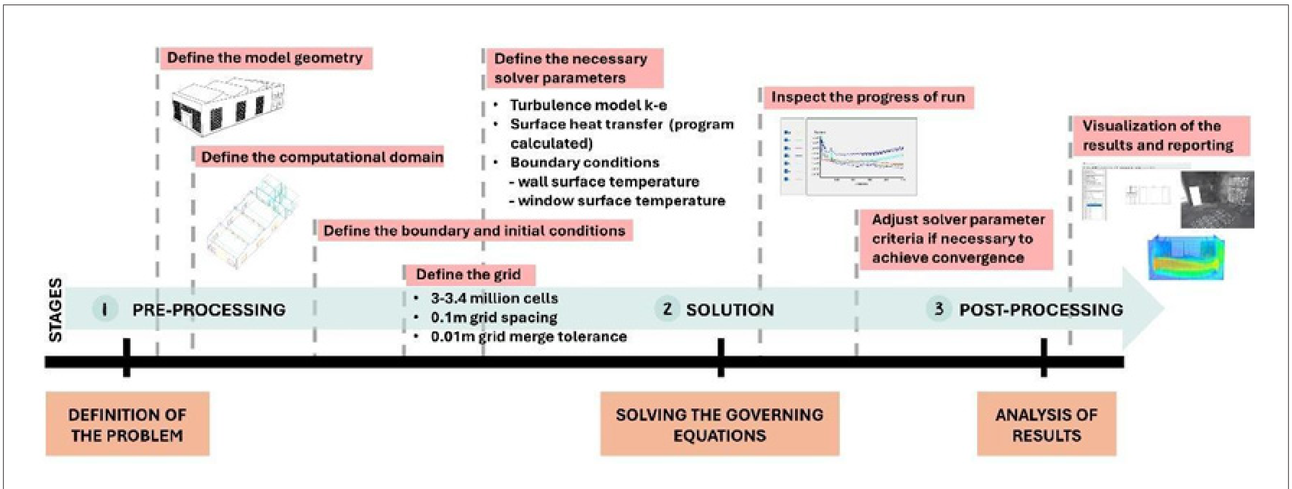

Figure 3. Main steps of CFD analysis.

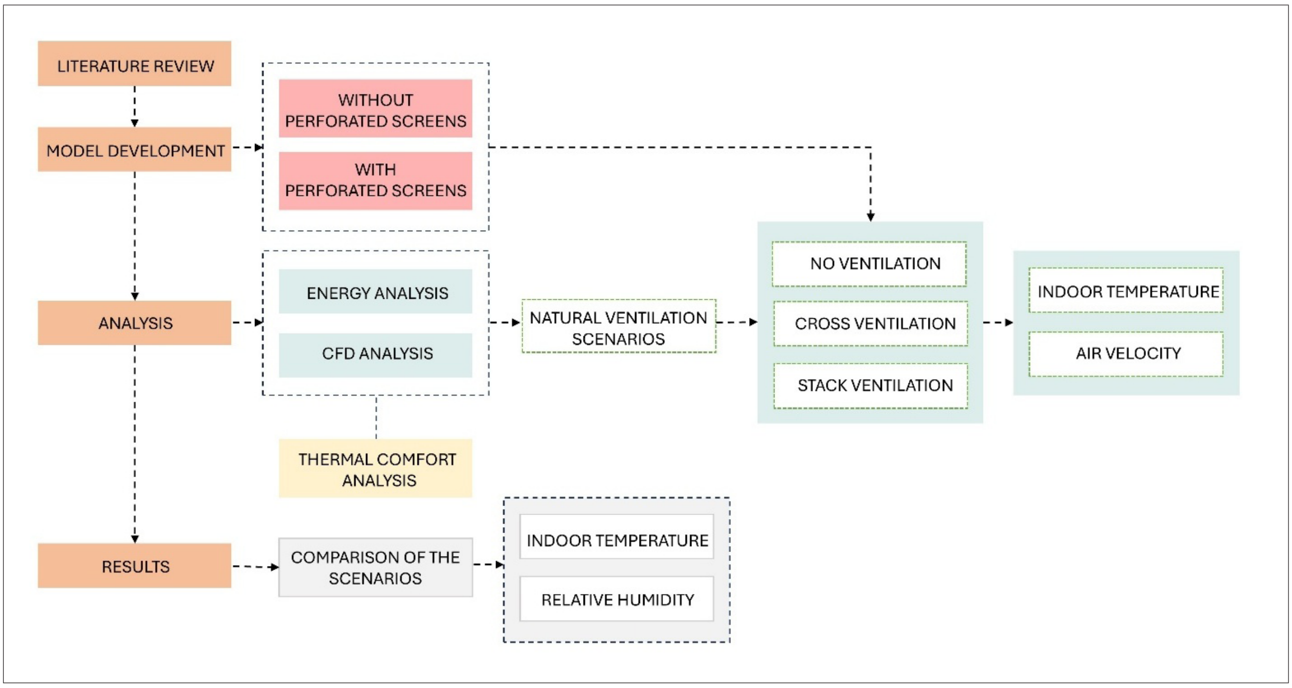

Figure 4. Applied methodology.

Case Study Building Design: KRCC

The structure was designed as a single-story building with a hall-like open office space in the south and a kitchen and bathrooms in the north. The form of the building was inspired by the metal container dwellings that have been used for housing the Syrian refugees in camps along the Türkiye-Syria border since 2011. Moreover, after the 2023 earthquake, they were used extensively in Türkiye to house the affected population in the same region, as shown in Figures 6a and 6b. The shape of the 8-meter by

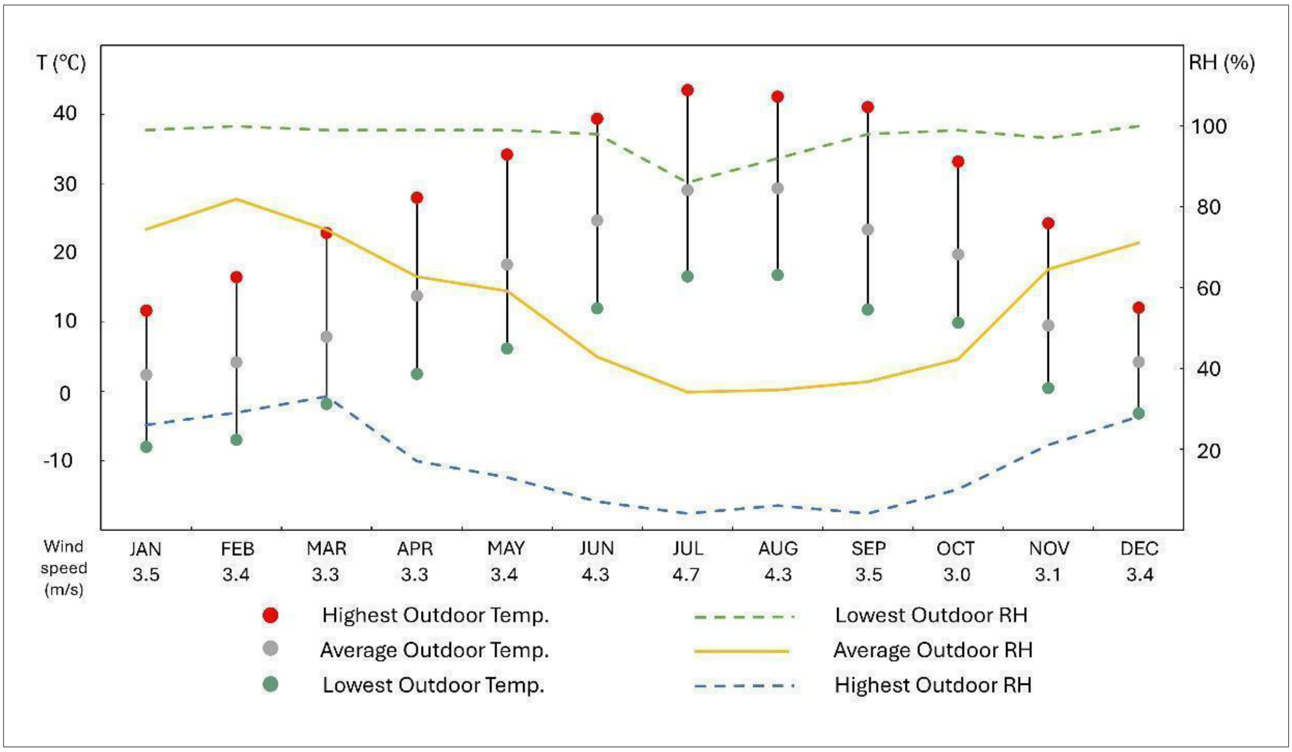

Figure 5. Outdoor temperature, relative humidity, and air velocity data for Kilis.

20-meter land parcel informed the rectangular building design shown in Figure 7.

The most problematic issues with these metal container dwellings are indoor air quality, temperature, and inefficient ventilation (Albadra et al., 2020; Wimalasena et al., 2021). During the cooling season, they become too hot, and in the winter, they become too cold because of their limited design characteristics. The KRCC building was designed as a rectangular enclosure to utilize the maximum land on the site with its long side along the north-south direction. Three triangular skylights were designed to run east-west on top of the 5.5-meter-tall building.

Window and *Jaali* Design: One essential feature of the building geometry was the window-to-wall ratio, which was determined as 21.4 % according to the ASHRAE criteria for this hot and dry climate. This value complies with the ASHRAE 90.1 standard, which recommends a WWR of less than 40% (ASHRAE, 2022). The other parameter is temperature, which affects the energy demand of buildings and the users' thermal comfort. Indoor temperatures need to be controlled, particularly in summer, when the effect of solar radiation is high. In the summer, outdoor temperatures reach more than 40°C in Kilis, making it hard to control indoor temperatures with large windows. Because of this extreme outdoor environment, the glazing designed for KRCC was kept small to minimize solar gain.

On the east, south, and west facades, side-hung operable windows were designed under the fixed horizontal windows for the main area, office, and kitchen space, as shown in Figure 7. The double-pane windows with metal frames were selected based on those commonly used by TOKI. The glass window panels can be opened towards the inside. However, the operable jaalis were designed to slide along a rail fixed on the outer side of the wall covering the window from the outside when closed (Figure 8). The bathrooms located on the northwest part of the structure had small bottom-hung windows for ventilation and natural light. To use buoyancy and bring natural light into the working space, three triangular skylights were added over the main working area, in the east-west direction. The premise for the skylights was to help the interior temperature drop by moving warm air from inside to outside through openings. The skylights provide extra daylight needed in the main hall since shading elements reduce the amount of light. The operable glazing areas were defined as 95% for side-hung windows and 30% for bottom-hung openings. Another parameter for this research was the proposed design of the shading screens, jaalis (Figure 9).

Construction Materials: When selecting construction materials for a project, it is essential to look at the local conditions, available and standard materials for affordability, and the selected materials' durability. This project took cues from the typical construction materials used in Türkiye by the governmental institution, the Mass Housing Administration (TOKI). TOKI has provided housing alternatives for the housing deficit in the country through social housing, disaster relief housing, and slum transformation projects. TOKI also builds public facilities like primary schools and neighborhood mosques (Bay, 2020). As shown in Figure 10, TOKI structures, primarily built using raft foundations, tunnel formwork, and high concrete strength, have proved durable and suitable for the region, as they withstood the two devastating 2023 earthquakes in Türkiye (Demirhan, n.d.). Thus, the KRCC building was also designed as a concrete structure.

The construction materials were selected for KRCC in the Apache module. As the typical construction material for durability and low maintenance, KRCC building walls were assumed to be made of average-weight precast concrete blocks. These blocks are formed before they are brought to the construction site. Shown in Figure 10, these

Figure 6. **a)** Container dwellings in refugee camps in Kilis, July 2022. **b)** Container dwellings shipped to Türkiye for post-earthquake emergency shelter use in the Kahramanmaraş region, April, 2023. (Photo by Authors).

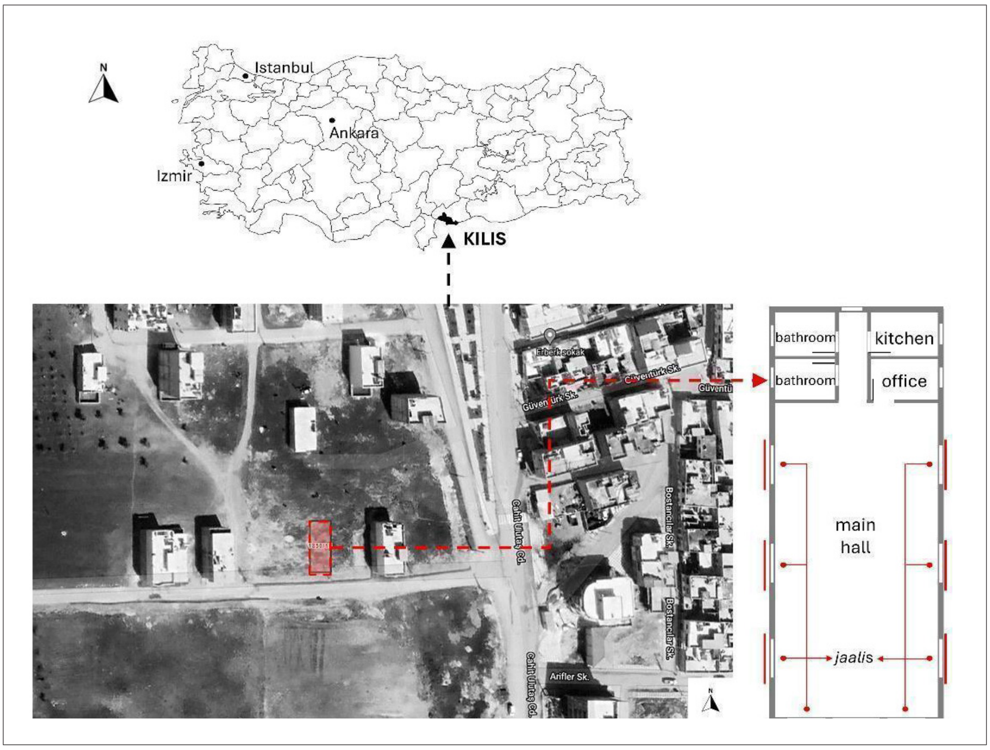

Figure 7. Proposed design of KRCC for the proposed site in Kilis. (Tapu ve Kadastro Genel Müdürlüğü, n.d.).

blocks have two hollow cavities, and they are 203 mm x 406 mm x 200 mm in size for the exterior walls and 152 mm x 406 mm x 200mm for partition walls. The materials selected for the KRCC building in the Apache module are shown in Table 1 along with the dimensions and specifications of the CFD model used in IES VE modules (ModelIt and MicroFlo). To evaluate different scenarios and understand the effect of water-resistant engineered

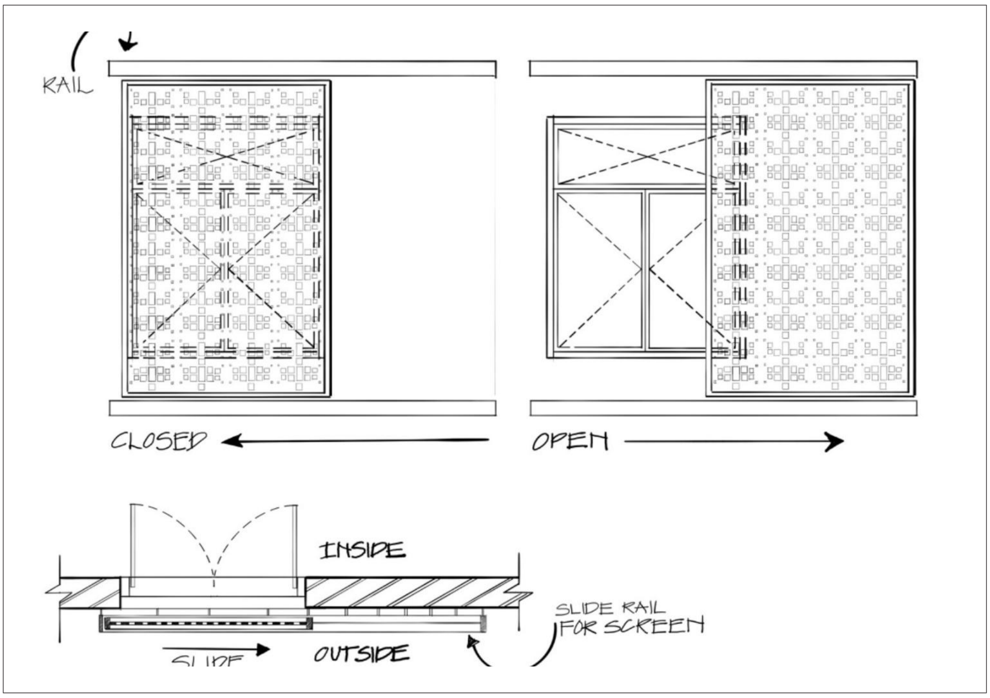

Figure 8. Operational detail of the proposed window design with jaalis for KRCC.

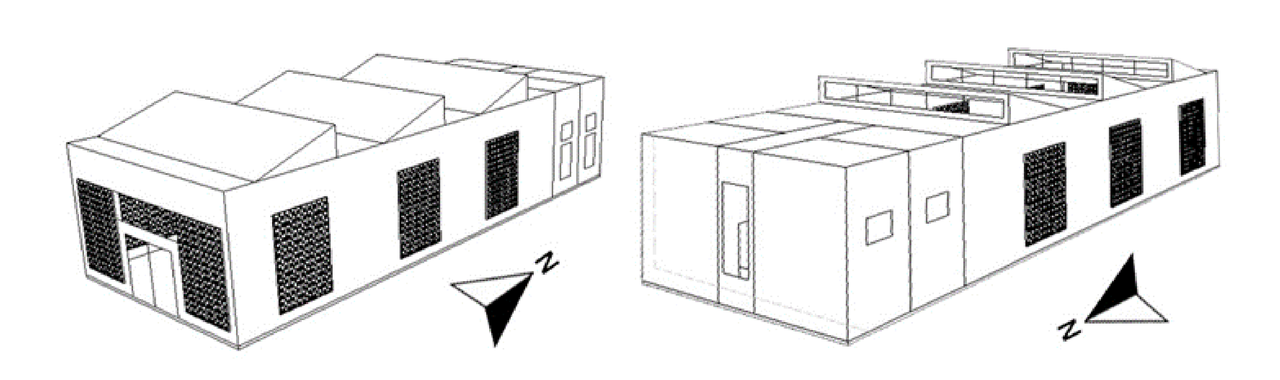

Figure 9. Proposed design with jaalis for KRCC.

wood shading screens on this structure, a 200 cm x 300 cm x 2.5 cm jaali screen was designed. The screen has two different sizes of square-shaped apertures or holes in the jaali pattern measuring 400 mm x 400 mm and 500 mm x 500 mm in size (Figure 11).

The jaali was modeled in IESVE ModelIt as water-resistant engineered wood with a thickness of 2.5 cm, as specified in the physical design. Standard thermal properties for engineered wood were assigned in the simulation. The surface color of the jaali was included indirectly by assigning a solar absorptance of 0.6, corresponding to the medium-brown color, which affects the heat gain through the screen. As shown in Figure 11, the jaali pattern included square apertures of 4 cm × 4 cm and 5 cm × 5 cm, resulting in an overall porosity of 20% (ratio 1:5). These geometrical parameters were directly incorporated in the numerical model by defining the window/shading fraction and the solar transmission through the openings, ensuring accurate representation of shading and daylight penetration.

Figure 10. Typical social housing project by TOKI in Gaziantep Türkiye.

Natural Ventilation Scenarios and Simulations

The KRCC building was tested in its free-floating state without considering any occupancy or any mechanical systems. Excluding any additional parameters such as internal loads, the study aimed to obtain a deep understanding of airflow patterns and thermal conditions. In order to determine the most appropriate passive cooling strategy, multiple natural ventilation scenarios were created, such as:

- No natural ventilation,
- Cross ventilation,
- Stack ventilation with all side and top openings.

In this study, we focused exclusively on internal CFD simulations, limiting the computational domain to the interior of the building rather than including the surrounding environment. Boundary conditions for airflow were generated from IESVE Apache simulation results using the VistaPro module and then exported to MicroFlo to analyze natural ventilation and passive cooling during the cooling season. Since MicroFlo does not have a built-in radiation model, radiation-related boundary conditions were derived automatically from the energy simulations. These included wind direction and speed, indoor and outdoor temperatures, atmospheric pressure, moisture content, as well as room air, radiant, and surface temperatures of walls and windows.

The simulations used a steady-state, three-dimensional convection–conduction model based on the finite volume meth-

Table 1. Building components used in IES VE Apache.

Building components	Material	Thickness (mm)	Conductivity (m^2K/W)
Walls*	Concrete block	200	1.6079
Partitions	Concrete block	100	0.0714
Roof	Concrete	203	1.1491
Ground floor	Concrete	380	4.3353
Windows	Double pane (metal frame)	24	0.4543

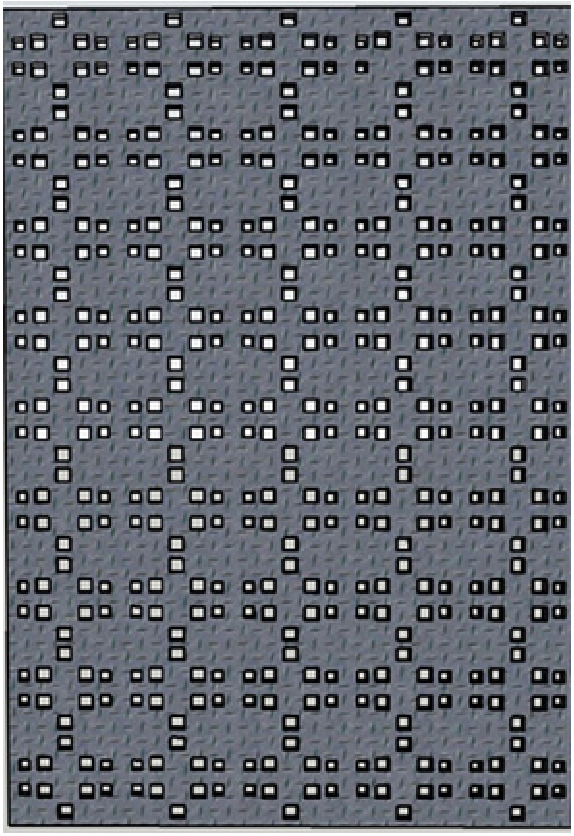

Figure 11. Proposed Jaali design for the KRCC building.

od, with the Standard k-ε turbulence model to represent turbulent airflow. The airflow in the model was aligned with the grid axes, and inlet and outlet performance was checked in MacroFlo to ensure the natural ventilation behavior was properly captured. To ensure the results were not influenced by the grid design, we performed a grid-independence study. The final mesh contained 3–3.4 million cells, providing enough detail to capture airflow patterns accurately without excessive computational cost. The mesh followed IESVE guidelines for grid spacing, cell aspect ratio (≤12:1), and grid line merge tolerance (≤0.1 m), with variable cell sizes to resolve critical areas more finely (Table 2). MicroFlo uses a structured, non-uniform Cartesian grid, which strikes a balance between accuracy and computational efficiency.

After modifying the openings based on each scenario, these models were organized into two sets. Energy and CFD simulations were run to analyze the efficiency of each. This step was repeated for two models; (i) KRCC model without jaalis (the perforated shading screens) and (ii) KRCC model with jaalis (the perforated shading screens on the main hall windows). In the first set of models, the geometry had no shading device, jaalis. In the second set, jaalis were added on the side-hung windows of the main hall on the east, south, and west facades. The vertical window brightening the corridor on the north and the triangular skylights above were used without jaalis. With the results of these simulations, indoor temperature, relative humidity, and air velocity graphs were created for two representative days of the spring and summer seasons: May 3 and July 15 at noon (Figure 12).

As shown in Table 3, the outdoor air temperature at midday was 21.4°C on May 3, rising to 32.2 °C on July 15. The external relative humidity levels at noon were 41% and 46% on May 3 and July 12, respectively. Wind speed was 3.2 m/s at noon on May 3 and 4.5 m/s on July 15. The wind direction was west during both times.

- Scenario 1 (S1): All windows were closed at all times to investigate the building without any ventilation. In this case, only air infiltration was considered. This scenario was used as a baseline model for comparison.
- Scenario 2 (S2): Cross ventilation was tested in this scenario, leaving only the east and west façade windows open. Other windows were fully closed at all times. Air infiltration was also considered.
- Scenario 3 (S3): All windows were open to allow natural ventilation and stack effect through the openings of the three triangular skylights on the top.

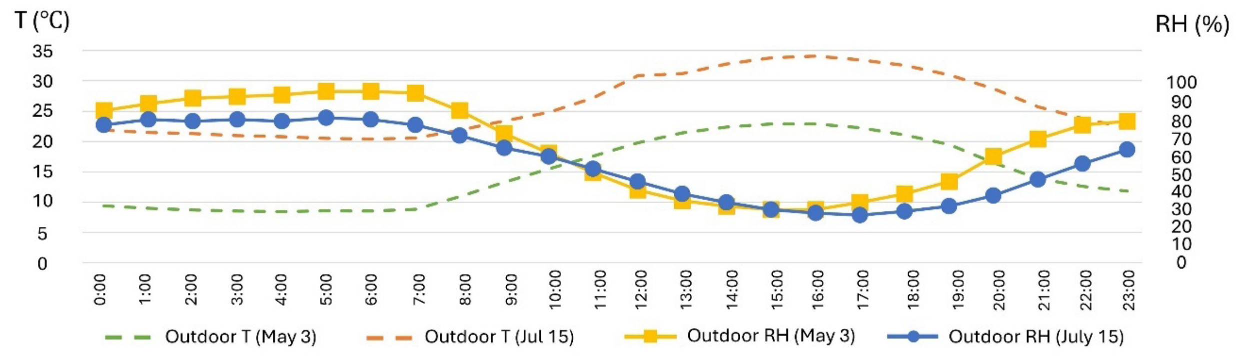

Figure 12. Outdoor conditions for selected representative days.

Table 2. Model dimensions and specifications of the CFD model (ModelIt and MicroFlo).

Building Specifications		IES VE CFD Model Specifications	
Floor surface area (m²)	160	Number of cells (million)	3.0-3.4
Volume (m³)	756	Max cell aspect ratio	<12:1
Ext wall area (m²)	285	Turbulence model	k-e
Ext opening area (m²)	61.24	Grid line merge tolerance (m)	0.01

Table 3. Airflow characteristics, indoor temperatures, relative humidity, and direct radiation.

Representative days for spring and summer	Time	Outdoor temperature (°C)	External relative humidity (%)	Velocity (m/s)	Direct radiation (W/m²)
3-May	12:00	21.4	41	3.2	883.000
15-Jul	12:00	32.2	46	4.5	960.000

Although all-natural ventilation scenarios only deal with open and closed window configurations with and without jaalis, the energy and CFD modeling took into account the entire building. Thus, the various temperature and velocity values were detected for each horizontal building section every 10 cm (Figure 13). The energy simulation also took into account the “unwanted” infiltration. Since the KRCC building was planned as a post-disaster structure and its construction materials were selected as typical ones used in the governmental institution TOKI, assumptions were made based on that. So, the KRCC building was considered leaky with a 2.032 l/ (s.m²) infiltration rate, combining the experience of past studies (Hanam et al., n.d.).

FINDINGS AND DISCUSSION

The indoor temperature and velocity graphs for each scenario were generated at a height of 1 meter above the floor (Figure 13). The slices on the X and Y axes were taken from this level for each scenario to show plans and sections, respectively. The false colors from blue to red represent the temperature range from coldest to warmest. Both graphs display the average values of temperature and velocity of the horizontal slice of the floor level on May 3 and July 15.

Scenario 1 – No Natural Ventilation

Scenario 1 was used as a baseline, with all windows closed. It was analyzed without any natural ventilation except infiltration via the building envelope. The results of this scenario for air temperature and airflow for May 3rd and July 15th are displayed in Figure 14. Since indoor temperatures reached 28°C and 42°C in May and July, respectively, different temperature range scales were used for this scenario (22°C-28°C for May and 36°C-42°C for July). In the cases without Jaalis, both in May and July, the temperature of the main hall was slightly higher than other spaces in the north part of the structure. Although indoor temperatures at noon dropped when perforated jaalis were added to the main hall windows, overall indoor temperatures were higher than the outdoor temperatures for both representative days.

In July, the office and bathroom 1 were cooler than other rooms, as seen in Figures 14e and g, due to their location in the northern part of the layout limited solar exposure and reduced heat accumulation. This indicates that spatial orientation has a stronger influence on indoor temperature distribution than infiltration alone. The addition of jaalis lowered indoor temperatures for each representative day by approximately 2°C by filtering direct solar radiation while still permitting some air leakage. However, since no significant air velocity was recorded, this cooling was limited to shading effects rather than active air exchange. Thus, without intentional ventilation, the building remains overheated compared to outdoor conditions, highlighting the inadequacy of infiltration-only strategies for maintaining thermal comfort.

Scenario 2 – Cross Ventilation

This scenario was analyzed with cross ventilation for prevailing winds in the west-east direction, achieved by opening windows on the west and east walls while keeping the skylight windows closed. As shown in the velocity graphs

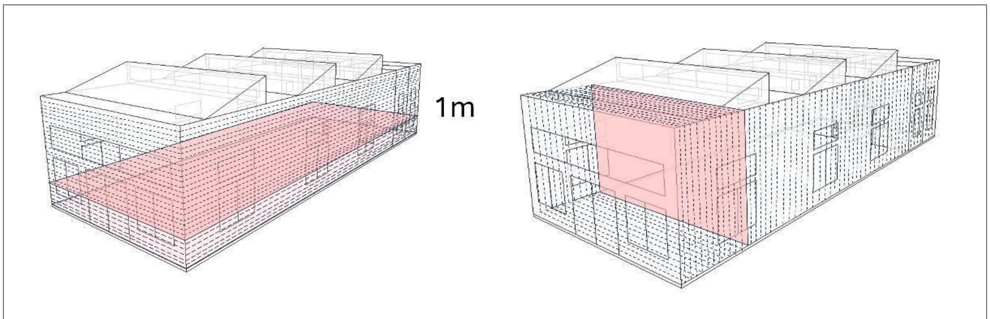

Figure 13. Horizontal and vertical slice positions for plans and sections.

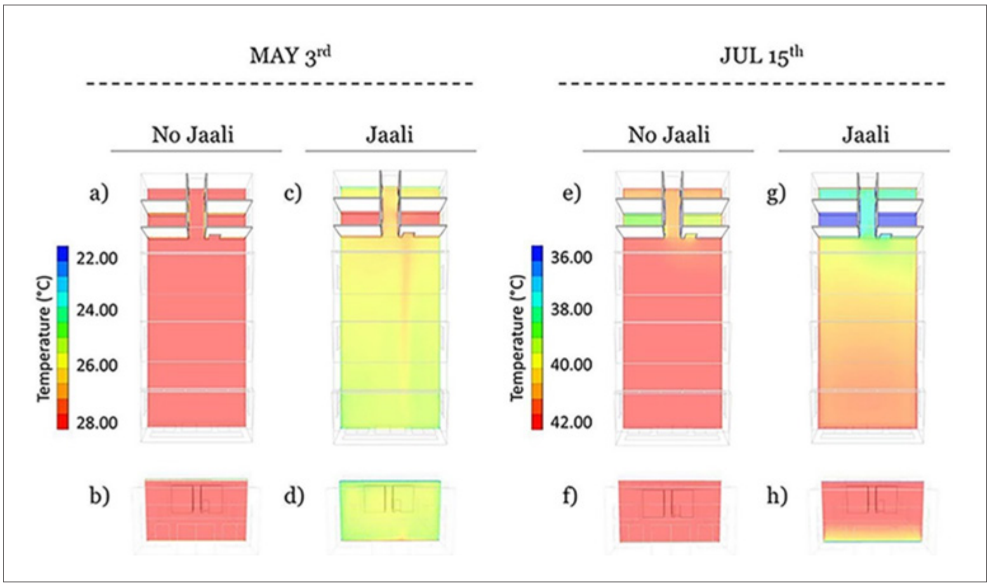

Figure 14. Air temperature distribution on the plan for Scenario 1.

in Figure 15, cross ventilation produced effective indoor airflows reaching 1.06 m/s in May and 1.3 m/s in July 15.

The higher velocities in July are directly related to stronger outdoor wind speeds, which increased the wind-driven pressure difference between the west and east façades. As a result, air entering from the west openings created a consistent airflow stream across the building. Overall, this mechanism not only reduces heat accumulation but also improves convective heat transfer from occupants' bodies, thus enhancing thermal comfort despite elevated indoor air temperatures.

The jaalis played a significant role. While they filtered solar radiation and reduced solar heat gain, they did not significantly obstruct air flow (15g and 15o). This indicated that the perforation ratio of the screens is adequate to balance shading and ventilation, making them an effective passive design element.

Moreover, thermal stratification was still evident in May with slightly higher temperatures in the west part of the building (Figure 15b). This effect can be attributed to solar exposure during the afternoon, which increased the surface temperature of west-facing walls. However, compared to Scenario 1, cross ventilation substantially improved air distribution, showing the importance of aligning openings with prevailing winds. Overall, cross ventilation harnessed wind-driven forces to generate sufficient air speeds for cooling. Although it did not always reduce indoor temperatures below outdoor levels, the increased air movement enhanced perceived comfort and prevented excessive heat in this climate.

Scenario 3 – Stack Ventilation

This scenario investigated the stack ventilation effect. To generate this scenario, all windows of the existing openings were fully open on each façade, including the bottom-hung skylight windows. In this method, hot and stagnant air in the space was forced to leave the building via the skylight windows because of temperature differences between indoor and outdoor air. Warm, buoyant indoor air rises and escapes through upper openings while cooler air is drawn in from lower openings.

Figure 16 shows the building sections. Figure 16b and 16g show that this mechanism is visible in May, where indoor hot air accumulated near the ceiling and was effectively vented through the skulight windows. Like in Scenario 2, the air movement was slower on May 3rd proportionally to the outdoor wind speed, as shown in Figure 16g and Figure 16h, reaching 0.95 m/s. On July 15th, the air movement failed to create a practical passive cooling effect since the outdoor temperatures were extremely high. Although the model with jaalis provided slightly cooler temperatures on the summer representative day, the resulting temperature was too high to reach a thermally comfortable environment for occupants. In May, the rooms with the warmest temperature in the building were those located in the northeast and northwest, while the main hall is about 2 degrees cooler, with and without jaalis. The cooler performance of the main hall highlights the effectiveness of stack-driven buoyancy when outdoor temperatures are moderate.

On the other hand, in July, the strategy failed to deliver thermal comfort. Despite the vertical airflow, the average temperature in the building is about 30°C. The reason lies in the small temperature gradient between indoor and outdoor air, since outdoor air was already extremely hot. The replacement air entering from the lower windows did not provide cooling. Instead, hot outdoor air simply replaced hot indoor air, limiting the usefulness of the stack effect. This demonstrates a key limitation of buoyancy-driven ventilation in hot summer climates.

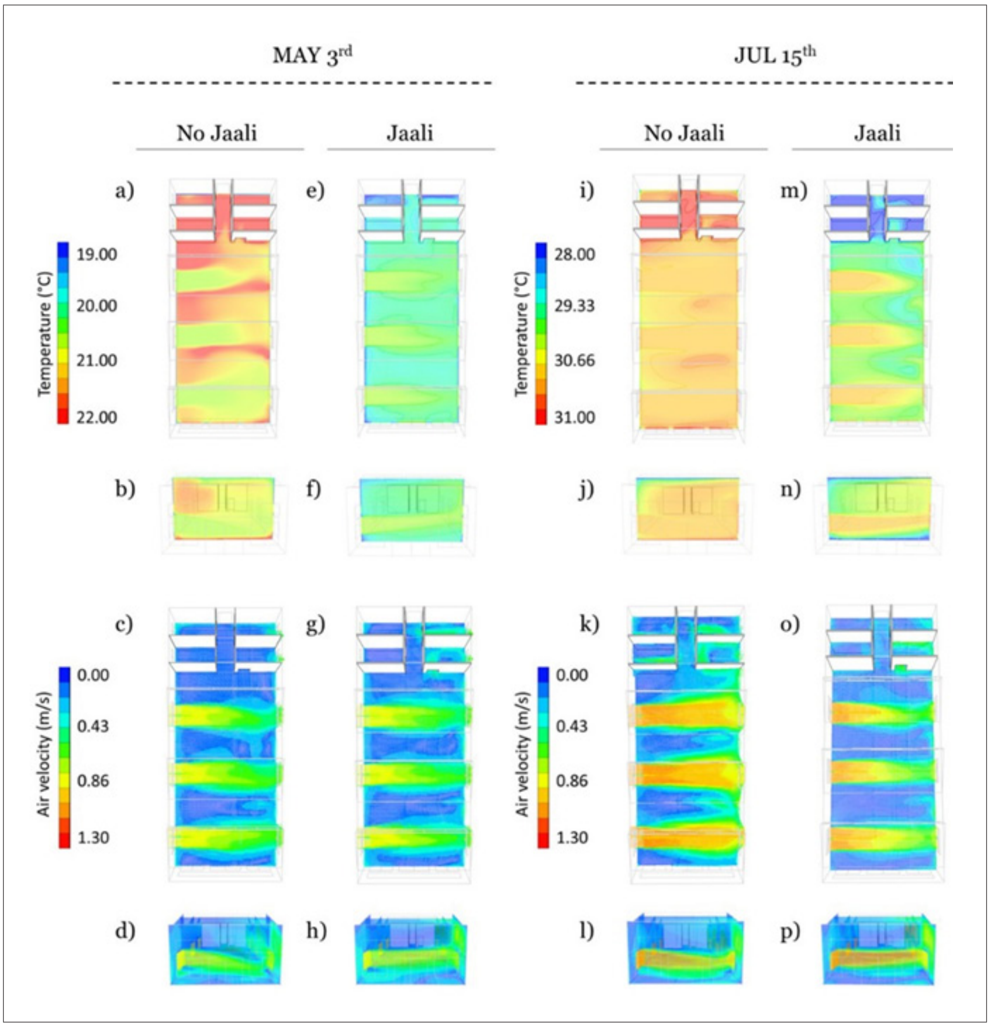

Figure 15. Air temperature and velocity distribution in the plan and East-West section for Scenario 2.

The jaalis offered slight mitigation by reducing solar gains through facade openings, resulting in lowering indoor temperatures. However, the shading effect alone was insufficient to offset the impact of high outdoor temperatures. Overall, stack ventilation was useful in May, where moderate outdoor temperatures allowed buoyancy forces to drive cooler air into the building and reduce indoor temperatures. In contrast, during peak summer, the strategy was ineffective because the outdoor air was too hot to contribute to cooling. This indicated that in climates with very high summer temperatures, stack ventilation must be combined with other strategies, like night cooling, evaporative cooling, to achieve thermal comfort.

Comparison of the Performance of Jaalis

Figures 17 and Figure 18 capture indoor hourly temperatures and relative humidity data comparing the three natural ventilation scenarios in spring and summer representative days (May 3 and July 15). The KRCC building simulation results without jaalis are presented in Figure 17, while Figure 18 shows the difference between scenarios with the use of these perforated shading screens. In Figure 18, the indoor temperatures of scenario 1, where all windows are closed, remain fairly constant without fluctuating hourly during both spring and summer representative days. On the other hand, there is an increase starting at 7am for other scenarios parallel to outdoor temperatures on both days. 4pm is the highest point for scenarios 2 and 3 indoor temperatures.

Similar to the indoor temperature graph, relative humidity trends are different for Scenario 1. Indoor relative humidity levels are constant and the lowest when windows are closed; however, in Scenarios 2 and 3, relative humidity levels change, corresponding to the increase and decrease in outdoor relative humidity during both representative days. The outdoor relative humidity level has a minimum value of 30% and reached a maximum of 97% on a spring representative day. Between 11pm and 1pm, outdoor rela-

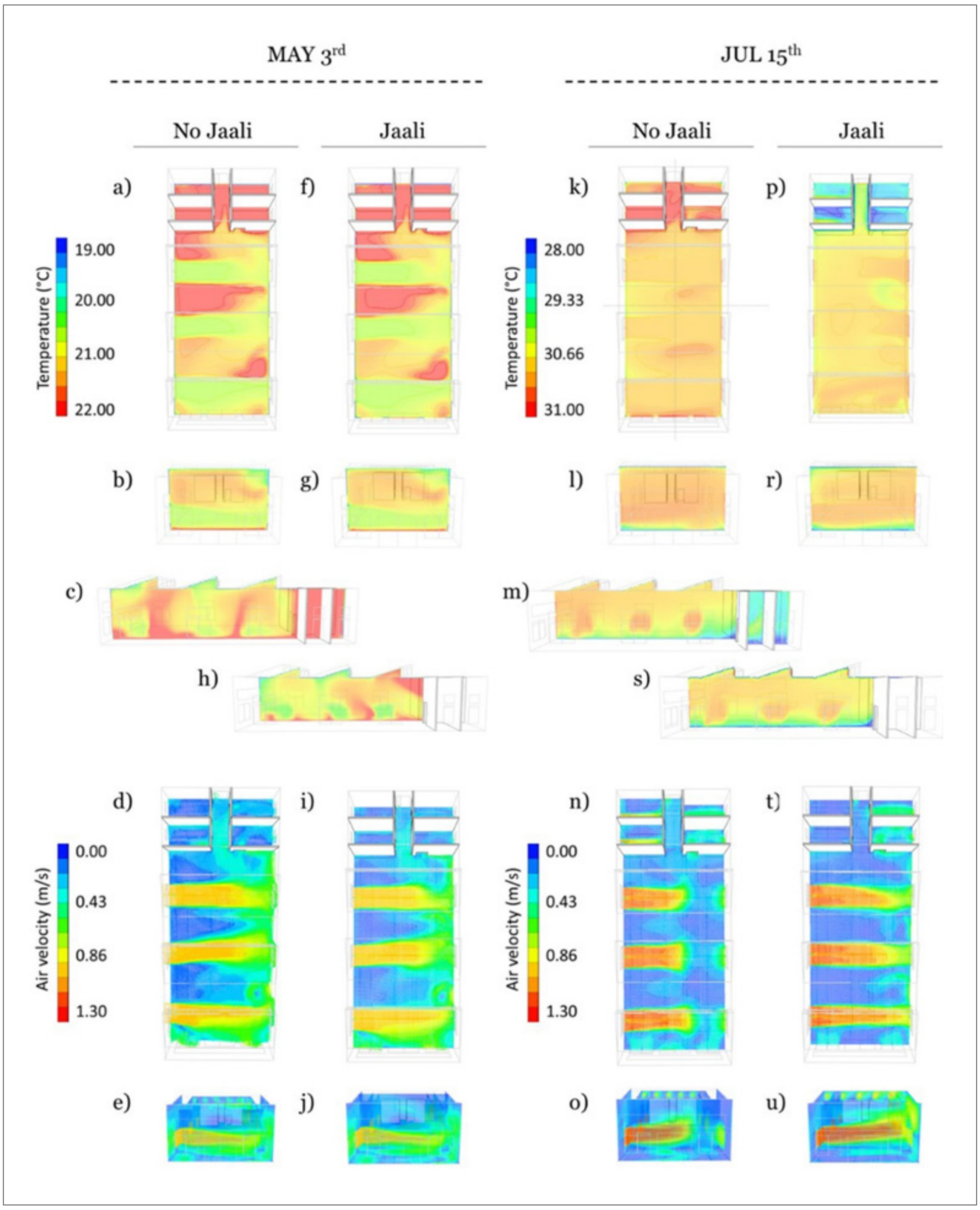

Figure 16. Air temperature and velocity distribution in plan and East-West section for Scenario 3.

tive humidity levels are higher than 80%. On July 15, the minimum value slightly drops to 27% while the maximum value is 82% at 5am.

Both Figures 17 and Figure 18 show that indoor temperatures fluctuate within a large range of ~10°C for all scenarios except scenario 1. All indoor temperature and relative humidity levels for scenarios 2 and 3 with or without jaalis follow the trend of outdoor temperature and humidity values. The most significant difference between the results of the models with jaalis and without jaalis is the indoor temperature values. Temperature diagrams in Figures 17 and Figure 18 depict that indoor temperatures decrease by about 2°C in the model with jaalis. As displayed in Figure 17, the highest indoor temperature is reached in the model without jaalis during Scenario 1 in summer. With the use of jaalis, this drops from 45°C to 43°C at 4 pm when the outdoor temperature on this representative summer day changes between 20.8 and 34.1°C.

Overall, the comparison demonstrates that jaalis consistently reduce indoor air temperatures by approximately 2°C, primarily by limiting direct solar gains while still permitting airflow. This effect is modest but significant when considered alongside the mechanisms of natural ventilation. In Scenario 1, where ventilation was absent, jaalis provided only partial relief, underscoring the limits of shading alone in overheated environments. In Scenarios 2 and 3, however, the combination

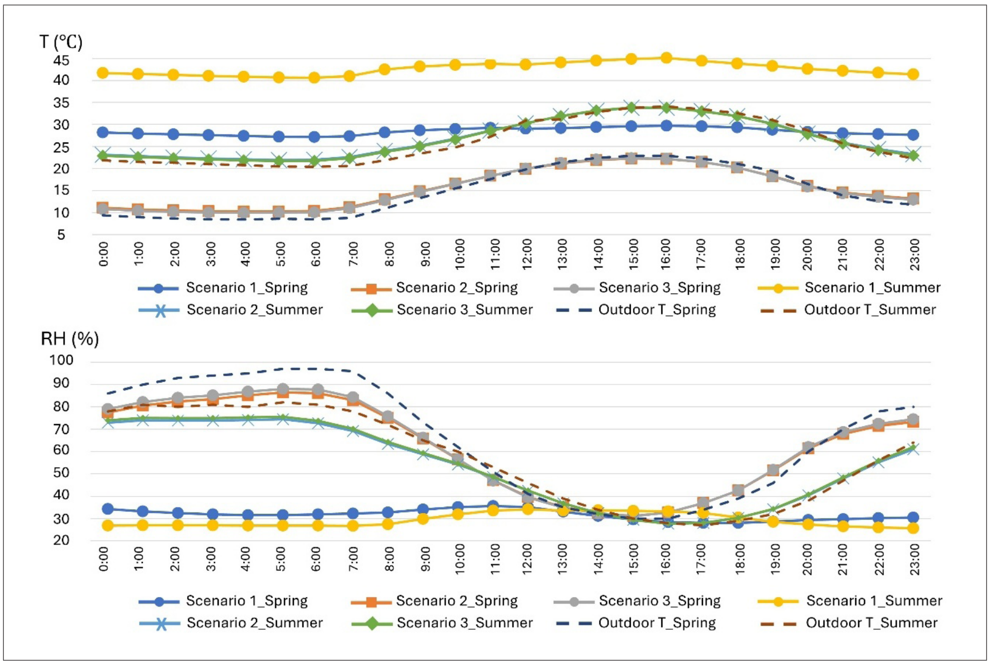

Figure 17. Comparison of the indoor temperature and relative humidity (without jaalis).

of jaalis with ventilation produced greater thermal stability. In cross ventilation, they complemented wind-driven cooling by reducing radiant loads without preventing airflow, while in stack ventilation, their benefit was more seasonal, effective only when outdoor temperatures were moderate. These findings highlight the synergistic role of jaalis since they are not a standalone solution. However, they enhance the performance of natural ventilation strategies by balancing the competing demands of shading and air movement. For hot climates like that of the KRCC building, this synergy is crucial: Cross ventilation with jaalis emerges as the most reliable passive strategy, while stack ventilation requires supplemental measures during peak summer to maintain occupant comfort.

Thermal Comfort Analysis

Thermal comfort is described as a "condition of mind that expresses satisfaction with the thermal environment (ANSI, n.b). Thermal comfort depends on environmental and per-

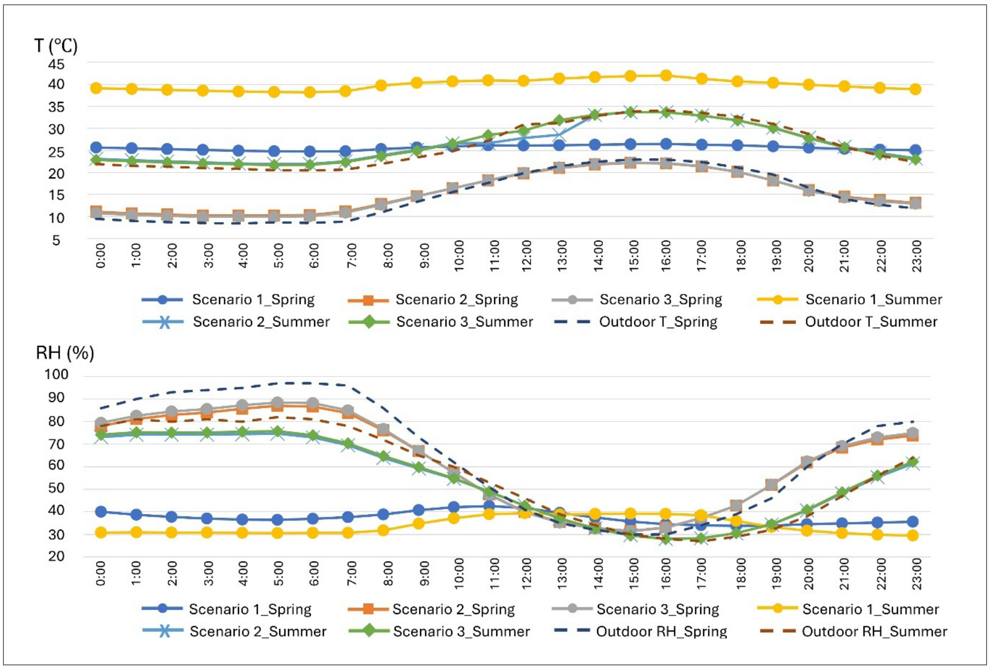

Figure 18. Comparison of the indoor temperature and relative humidity (with jaalis).

sonal variables such as temperature, relative humidity, airspeed, mean radiant temperature, clothing insulation, and metabolic rate. In this study, thermal comfort ranges on May 3 and July 15 were calculated using the Center of the Built Environment (CBE) Thermal Comfort Tool. This web-based tool was developed by UC Berkeley for thermal comfort calculations and visualizations (Tartarini et al., 2020) that complies with the ASHRAE55-2017 (ASHRAE, 2010, ISO 7730:2015, ISO 7730, 2005), EN 16798-1:2019, CEN, 2019) Standards. Multiple thermal comfort studies calculated PMV and PPD using the CBE tool (Hosseini et al., 2016; Iskandar et al., 2024; Rabeharivelo et al., 2022).

In order to evaluate if the selected natural ventilation strategies provide a thermally comfortable environment, thermal comfort zones for spring and summer representative days were generated using two variables: Air temperature (°C) and relative humidity (%). After the PMV method was selected, other parameters were entered, such as metabolic rate and clothing value. Since occupants were considered to have no local control on air velocity, it was fixed at 0.1 m/s for both representative days. Also, the metabolic rate was defined as 1.4 met. On May 3, the clothing level was 0.61 clo (trousers, long sleeve shirt) when the designated value was 0.5 clo as typical summer indoor clothing according to ASHRAE 55 (ASHRAE, 2017).

Figure 19 shows the thermal comfort zones on the selected representative days (May 3 and July 15), the hourly indoor environmental conditions of the natural ventilation scenarios, and outdoor environmental conditions. In addition, the percentage of hours within the thermal comfort zones on May 3 and July 15 is displayed in Table 4. A greater number of thermally comfortable hours was observed on the summer representative day compared to the spring representative day, where lower temperatures were recorded.

On May 3, the highest number of thermally comfortable hours indoors was seen in Scenario 1, closed windows with jaalis. Other scenarios and outdoor conditions had a similar trend, with percentages between 23% and 37 % within the thermal comfort zone. Without jaalis, cross ventilation (S2) was the second successful strategy, and no natural ventilation (S1) was the least effective approach during this spring representative day. With jaalis, stack ventilation (S3) increased comfort hours. During July 15, cross ventilation (S2) and stack ventilation (S3) provided thermal comfort. Both Scenario 2 and Scenario 3 had a higher number of thermally comfortable hours than outdoor environmental conditions. Similar to the spring representative day, the least effective approach was Scenario 1.

Overall, the thermal comfort analysis highlights that natural ventilation strategies perform differently depending on season and boundary conditions. On May 3, the presence of jaalis was decisive: While open-window strategies achieved only 23–37% of hours within the comfort zone, Scenario 1 with jaalis maintained 100% comfort, showing that a 2–3°C reduction in operative temperature was sufficient to shift conditions from slightly warm (PMV≈+1, PPD>25%) to fully acceptable (PMV≈0, PPD<10%). In contrast, on July 15, comfort could only be achieved when ventilation was introduced: Cross ventilation (S2) and stack ventilation (S3) provided 68–75% comfort hours, compared to 0% with closed windows. With jaalis, the share of comfort hours increased further, reaching 79% for cross ventilation, exceeding even outdoor comfort levels (58%). These results show that in hot-dry summer conditions, ventilation is indispensable for keeping PMV and PPD within acceptable limits, but jaalis consistently extend comfort hours by lowering radiant heat gains without impeding airflow. Taken together, the findings emphasize that while shading alone can deliver comfort

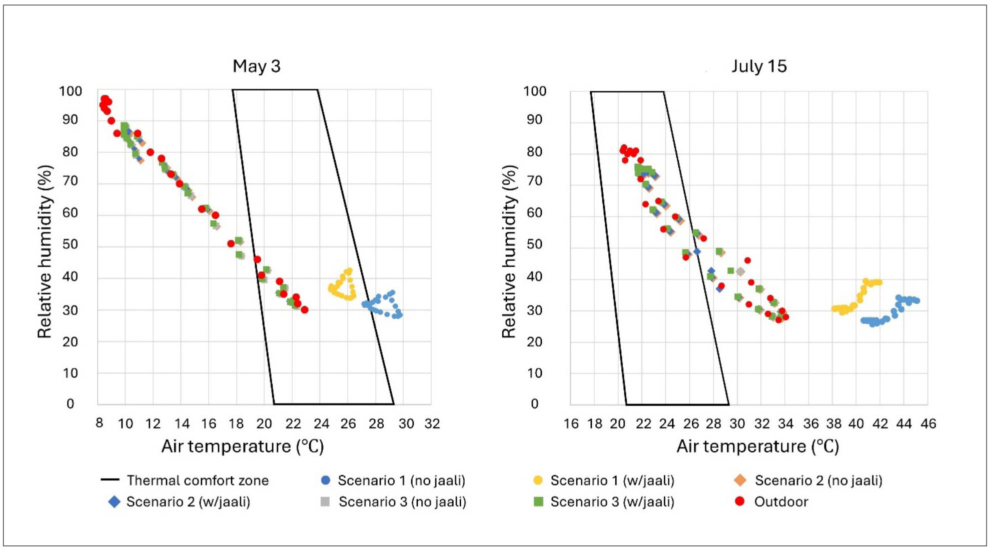

Figure 19. Thermal comfort analysis of ventilation scenarios and outdoor conditions on May 3 and July 15.

Table 4. Percentage of comfort hours in spring and summer representative days.

	Scenario 1 (no jaali)	Scenario 1 (w jaali)	Scenario 2 (no jaali)	Scenario 2 (w jaali)	Scenario 3 (no jaali)	Scenario 3 (w jaali)	Outdoor
May 3	23%	100%	37%	29%	33%	35%	33%
July 15	0%	0%	68%	79%	75%	66%	58%

during mild spring conditions, in hotter summer months, only the combination of shading and airflow can reliably maintain thermal comfort, confirming the seasonal adaptability of jaalis as an integrated passive design strategy.

CONCLUSION AND FUTURE DIRECTIONS

This study examined the effectiveness of natural ventilation strategies as passive cooling methods in a cooling-dominated, hot, and dry region. A conceptual building design for a resource and community center served as the case study. Three ventilation scenarios, no ventilation, cross ventilation, and stack ventilation, were tested both with and without jaalis installed on the main hall windows. Indoor environmental conditions were evaluated using energy simulations and Computational Fluid Dynamics (CFD) on two representative days: May 3rd (spring) and July 15th (summer).

The results showed that, on July 15th, outdoor temperatures ranged from 20.4°C to 34.1°C, while the midday indoor temperature in the baseline case (Scenario 1) reached 30.88°C. With natural ventilation, indoor temperatures slightly decreased to 29.28°C (Scenario 2) and 30.26°C (Scenario 3), and further dropped to 27.83°C and 29.48°C, respectively, when jaalis were added. On May 3rd, when outdoor temperatures were below 20°C, Scenario 1 still overheated to 29.21°C without jaalis, but dropped to 26.13°C with them. Overall, Scenario 1 was the least effective strategy, while Scenarios 2 and 3 reduced indoor temperatures by 1.5–2°C in exposed areas. Across all scenarios, jaalis consistently lowered temperatures by around 2°C, primarily by reducing solar gains without obstructing airflow.The study concludes that integrating jaalis into hot-climate buildings can enhance natural ventilation and extend the number of thermally comfortable hours. However, as the case study building has not yet been constructed, simulation results could not be validated against real-life measurements, representing a key limitation of this work.

Future research should investigate optimal porosity ratios, perforation patterns, and aperture sizes to maximize the cooling efficiency of jaalis. Additional studies could also explore (i) the interaction of jaalis with other passive cooling strategies, such as night flushing or evaporative cooling, and (ii) field validation of CFD models through post-occupancy monitoring once the building is constructed.

In conclusion, the findings demonstrate that the success of natural ventilation strategies in hot and dry climates depends on both the driving force of air movement (wind or buoyancy) and the control of solar heat gain. Scenario 1 confirmed that infiltration and shading alone cannot provide comfort in overheated spaces. Scenario 2 showed that aligning openings with prevailing winds delivers the most reliable cooling, while Scenario 3 revealed the seasonal limitations of stack-driven buoyancy when outdoor air is excessively hot. Across all scenarios, jaalis consistently enhanced performance by lowering radiant heat gains without significantly impeding airflow. Taken together, these results highlight that jaalis are most effective not as an isolated retrofit but as a synergistic element within a broader passive design strategy, where shading, ventilation, and climate-responsive operation are integrated to enhance resilience and comfort in extreme climates.

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