JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(5), 383–400
https://doi.org/10.12911/22998993/201997
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.02.05
Accepted: 2025.03.07
Published: 2025.03.16

Computational fluid dynamics – based assessment of thermal comfort parameters in residential buildings in Amman: Implications for indoor environmental quality

Mai Hathal Al-Zuriqat[1*], Bushra Obeidat[1]

[1] Department of Architecture, Jordan University of Science and Technology, Irbid, Jordan
* Corresponding author's e-mail: maialzuriqat@gmail.com

ABSTRACT

With the increasing reliance on indoor living, the design of residential environments has become essential for ensuring occupant comfort, health, and well-being. This study evaluates thermal comfort variables—air temperature and relative humidity (RH)—in apartment buildings in Amman, Jordan, using computational fluid dynamics (CFD) simulations to assess the impact of spatial design parameters on indoor environmental quality. The findings reveal thermal deficiencies in existing apartment layouts, where low indoor temperatures (16.6 °C) and excessive humidity (94.96%) compromise indoor comfort. The study examines how optimizing wall insulation (phenolic foam, R = 5.7, 8 cm) and window-to-wall ratio (40%) can improve indoor air conditions. While previous research suggests that temperature and humidity influence airborne virus viability, this study does not directly investigate pathogen survival. Instead, it provides a data-driven assessment of indoor thermal comfort, offering insights for future research, design improvements, and policy considerations to enhance residential indoor environments.

Keywords: thermal comfort, indoor air quality, apartment design, CFD simulation, humidity, temperature, Amman.

INTRODUCTION

The built environment is a fundamental determinant of health and well-being, practically within residential settings where individuals spend the majority of their lives. Among the various factors influencing indoor environmental quality, Thermal comfort—defined as the condition of mind expressing satisfaction with the surrounding thermal environment— stands out as a cornerstone of occupant comfort and a critical factor influencing public health outcomes. This state is influenced by several factors, including air temperature, humidity, air velocity, and personal variables such as clothing and metabolic rate. Among these elements, indoor temperature and RH play a crucial role in thermal regulation and occupant well-being. Scientific literature suggests that these parameters may also influence airborne pathogen behaviour; however, this study does not directly measure virus survival but rather assesses the thermal conditions that could potentially impact indoor air quality. With the increasing recognition of indoor environmental quality as a key determinant of health, particularly following the COVID-19 pandemic, understanding and managing these factors has become a scientific and practical priority.

Historically, airborne diseases have been among the primary drivers of devastating pandemics, leading to the loss of millions of lives (Rubino and Choi, 2017). The transmission of infectious diseases, particularly those caused by airborne viruses such as influenza and SARS-CoV-2, has posed significant global challenges throughout history (Koley and Dhole, 2021). The emergence of COVID-19 has further underscored the critical importance of indoor environmental quality (IEQ), particularly in high-density residential environments. Due to their unpredictable behaviour, airborne viruses extend their impact far beyond the immediate health crisis, placing substantial strain on economies, healthcare systems, and daily life worldwide (McKibbin and Fernando, 2023). Lessons gleaned from the management of past pandemics are informing and reshaping strategies for future disease prevention and mitigation. In response to these challenges, a growing focus on optimizing built environments has emerged within architectural and engineering disciplines. Architects and designers are critically reevaluating spatial configurations and the functional dynamics of indoor spaces, with a primary focus on enhancing indoor air quality and thermal comfort (Megahed and Ghoneim, 2021). As people spend 60–90% of their time indoor, optimizing the indoor environment has become essential for improving quality of life and mitigating health risks (Al horr et al., 2016).

Airborne viruses primarily spread through respiratory droplets and aerosols, which can remain suspended in the air and present significant infection risks in enclosed spaces. Evidential investigations highlight the potential for efficient transmission of airborne viruses through respiratory droplets or aerosols. These particles travel through indoor airflows, and their behaviour is influenced by multiple environmental factors, including temperature and RH (Domingo and Rovira, 2020). While previous studies have explored the potential links between thermal comfort and airborne virus viability, this study does not directly assess pathogen survival but rather evaluates indoor thermal conditions within apartment units. Temperature and RH directly affect indoor environmental stability, altering air moisture levels and air circulation, which in turn may influence respiratory droplet behaviour. Temperature affects thermal stability and comfort, while RH modulates the evaporation rate of respiratory droplets, impacting their suspension time in the air. Low RH has been associated with faster droplet evaporation, leading to smaller, more persistent aerosols, whereas high RH promotes faster droplet settling but may contribute to surface contamination risks and microbial growth (Noti et al., 2013; Yang and Marr, 2011). The complex interplay between temperature, humidity, and aerosol behaviour underscores the importance of maintaining stable indoor thermal conditions for improved indoor quality and occupant well-being.

The role of proper thermal conditions in supporting indoor environmental quality is widely recognized.(Molina and Yaguana, 2018; Mu and Kang, 2022). This principle applies across various settings, including healthcare facilities, educational institutions, office buildings, as well as residential spaces such as single-family homes and apartment complexes (Lin et al., 2023; Shajahan et al., 2019; Wolkoff et al., 2021). The World Health Organization (WHO) emphasizes the importance of maintaining balanced indoor temperature and RH, particularly during colder months, as low indoor air temperature is combined with inadequate ventilation (Moriyama et al., 2020). However, achieving and sustaining optimal thermal in residential settings remain challenging, especially in scenarios involving high-occupancy or space-limited environments (Goutte et al., 2020).

Multi-floor apartment buildings have become the dominant building typology in Jordan since the 1990s, exemplifying such challenges (Al-Betawi et al., 2020). During the first quarter of 2012 alone, approximately 82% of the total approved construction permits in Jordan were designated for apartment building projects (Ababsa, 2019). High-density living environments, such as apartment buildings, are associated with challenges in maintaining indoor air quality and thermal stability due to factors such as shared amenities, high occupant density, and outdated HVAC systems (Lai et al., 2020) (Zhang et al., 2020). The recent pandemic of COVID-19, has highlighted the vulnerabilities of apartment buildings, demonstrating the need to reassess and improve indoor conditions (Colin, 2020). In Jordan, over 7.000 apartment building were placed under quarantine protocols following the detection of a single COVID-19 case in each building (Roya News, 2020), demonstrating the urgent need to improve indoor environmental quality in such settings.

Jordan's Mediterranean climate, characterized by hot, arid summers and cool, wet winters, presents unique challenges for maintaining optimal indoor environmental conditions (optimal indoor temperature and RH stability). Residential buildings in Amman, particularly apartment complexes, often lack adequate thermal insulation and rely on outdated heating, ventilation, and air conditioning (HVAC) systems. These deficiencies contribute to significant fluctuations in indoor temperature and humidity levels, compromising both occupant comfort and health. During winter, heating systems frequently reduce indoor humidity to levels that exacerbate respiratory issues and increase the risk of viral transmission. Conversely, during summer, cooling systems may fail to maintain adequate humidity, further impacting thermal comfort and indoor air quality. These challenges highlighted the need to reassess apartment building design to improve resilience against airborne infections (Alqarni et al., 2024; Nair et al., 2022). Retrofitting apartment buildings in Amman provides an opportunity to optimize indoor thermal conditions by enhancing insulation, integrating advanced HVAC systems, and utilizing energy-efficient materials. For instance, improved insulation reduces heat loss during winter, minimizing reliance on energy-intensive heating systems and maintaining stable indoor temperatures with adequate humidity.

Study purpose and scope

This study evaluates thermal comfort parameters—temperature and RH within apartment units in Amman, Jordan, comparing them to established benchmarks for IEQ. These benchmarks suggest that maintaining recommended temperature and RH levels can minimize airborne virus viability, this study contextualizes its findings within these standards. However, it does not conduct direct experimental validation of pathogen survival. Instead, the results provide insights into how spatial design modifications influence thermal regulation in residential environments, supporting future design improvements and policy recommendations.

This study incorporates CFD simulations evaluate temperature and RH distribution in residential units and how specific spatial design parameters, such as wall insulation and window-to-wall ratio (WWR), influence indoor thermal conditions. The findings are compared to recommended benchmarks that have been associated in existing literature with improved occupant well-being and reduced airborne pathogen viability. While previous studies have explored thermal comfort and indoor environmental quality, this research takes a context-specific approach, focusing on Amman's unique climatic conditions and architectural characteristics and their influence on indoor thermal regulation.

Beyond theoretical analysis, the research provides practical recommendations for enhancing thermal comfort through architectural design modifications, retrofitting strategies, and regulatory improvements. As urbanization continues to reshape Amman's built environment, ensuring effective thermal management in apartment units is essential for creating resilient, health-conscious residential spaces. By linking architectural design with public health objectives, this study offers evidence-based insights to support sustainable and climate-responsive housing policies.

MATERIALS AND METHODOLOGY

This study aimed to investigate thermal comfort variables within apartment units, with a focus on air temperature and RH, and their implications for the survival and persistence of airborne pathogens. The research was conducted through a computational modelling and simulation techniques to analyse and optimize indoor environmental conditions.

Study area description

The study was conducted in Amman, the capital of Jordan, which lies within the arid subtropical steppe climate zone (31°96′N latitude and 35°93′E longitude). Amman's climate is influenced by its geographic location, topography, and proximity to surrounding bodies of water, resulting in distinct seasonal variations. The winter season in Amman, spanning from December to February, is marked by cool to cold weather, with daytime temperatures ranging between 10–15 °C (50–59 °F) and an average of 13 °C. This season is the wettest, with occasional snowfall in the highlands of Amman. In contrast, the summer season, from June to September, is characterized by clear skies, low humidity levels, and average daytime temperatures between 30–35 °C (86–95 °F), with occasional peaks exceeding 36°C. Prevailing westerly winds during winter months have an average annual speed of approximately 3.4 m/s.

Amman was selected as the primary focus of this study due to its prominence as Jordan's demographic and economic centre, as well as its high density of apartment buildings. The city recorded the highest number of apartment building lockdowns during the COVID-19 pandemic, providing comprehensive data on the challenges associated with airborne pathogen viability in high-density residential settings. The simulation study focused on the winter season, spanning from December 21st to March 21st (Fig. 1), a period critical for the survival and persistence of airborne pathogens due to environmental conditions such as low indoor air temperatures, elevated RH, and increased indoor activities. These factors contribute to a higher risk of airborne pathogen

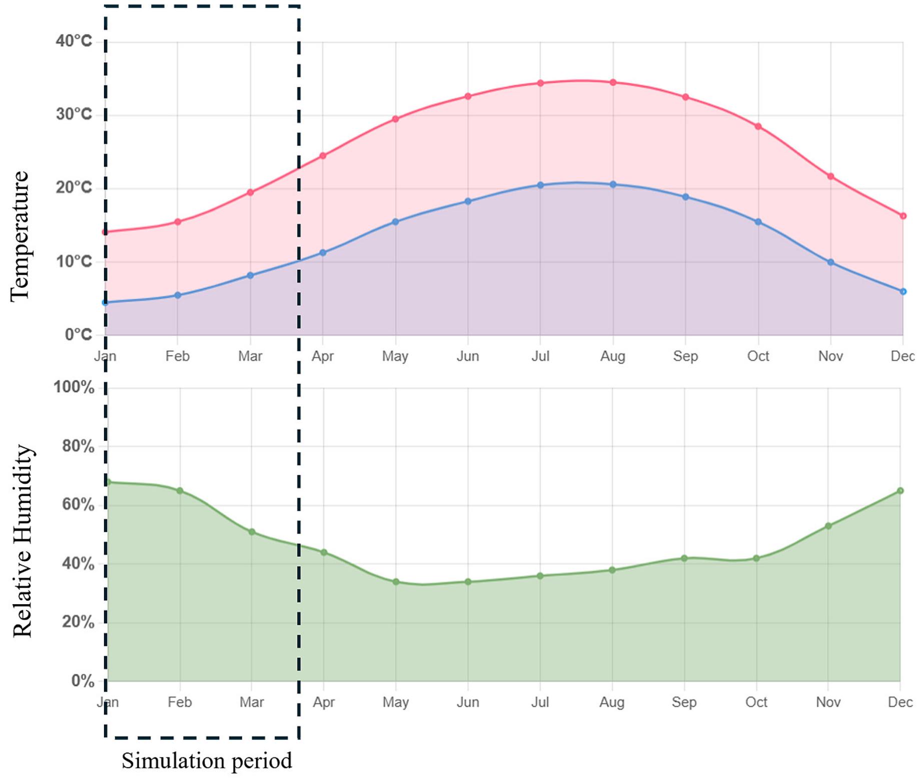

Figure 1. Weather data for Amman: temperature and Humidity during the simulation year (Amman Weather & Climate, n.d.)

viability, making this season particularly relevant for investigating thermal comfort and its impact on public health.

Research framework and simulation setup

The research began with the identification of a base case building, representative of typical apartment floor layouts in Amman. Data collection was conducted using government resources and previous studies to develop a detailed 3D model for computational fluid dynamics simulations. The simulations were performed using DesignBuilder v6 software. Numerous studies have validated the accuracy and reliability of DesignBuilder software, including comparisons with empirical data obtained from field measurements conducted on existing buildings (Alghamdi et al., 2023; Daemei et al., 2016; Eisabegloo et al., 2016; Elshafei et al., 2017). DesignBuilder is an intuitive and robust software platform equipped with advanced CFD capabilities, enabling the simulation of airflow patterns, ventilation dynamics, and contaminant dispersion within buildings (Strachan et al., 2008).

The CFD simulation framework incorporated geographic location parameters, along with configurations of turbulence models, boundary conditions, and solver settings to ensure accuracy and reliability in the results. The initial phase of the CFD analysis assessed the base case apartment design, quantifying key parameters such as air temperature and RH. The analysis focused on achieving compliance with prescribed thermal comfort standards and reducing the risk of airborne pathogen viability. Key findings were used to develop actionable recommendations for architectural design modifications. Subsequently, proposed architectural modifications aimed at enhancing thermal comfort were modeled and evaluated through CFD simulations. Figure 2 illustrates the methodological framework employed in this study. The framework integrates data collection, model development, simulation, and analysis to provide a comprehensive understanding of thermal comfort dynamics in apartment units.

Identification of the base case layout

The identification of the base-case architectural forms and typologies commonly observed throughout Amman was based on data from the Jordan Department of Statics (DoS), with the latest of which was published in 2017 (J.D.o Statics, 2017). According to the Department of Statistics

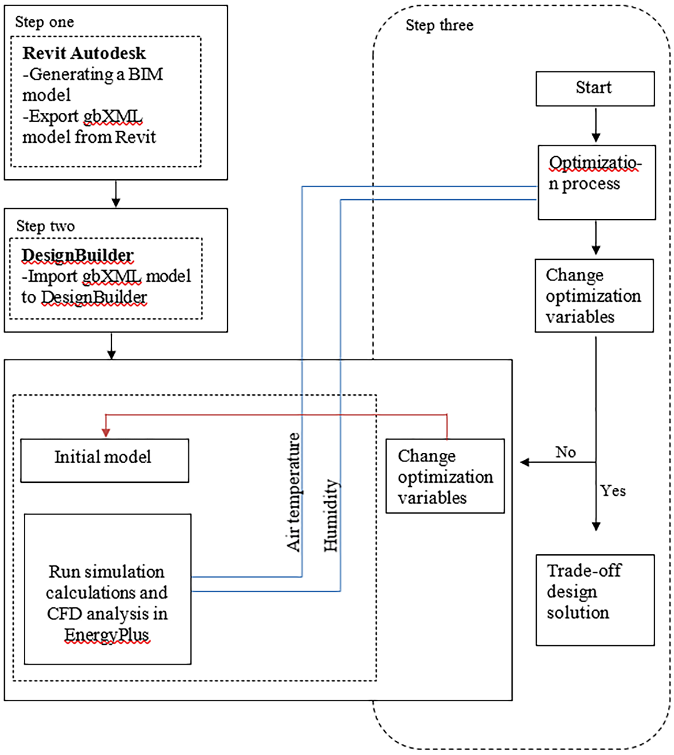

Figure 2. Simulation and CFD analysis framework

in Jordan, multi-story apartment buildings consist of varying numbers of apartments per floor. These multifamily buildings are typically designed with 1, 2, 3, or 4 apartments per floor, as illustrated in Figure 3. Four-story apartment buildings with two units per floor and unit sizes ranging from 120 to 150 square meters are the most prevalent (J.D.o Statics, 2017). This architectural configuration is a highly preferred choice among real estate clients within the urban context of Amman, Jordan.

The configuration of the apartment units was based on a survey of floor plan layouts of buildings with two apartment units per floor to determine the typical spatial layout of apartments. This process was published in Obeidat and Al-Zuriqat (2023). The analysis revealed that the typical spatial layout of apartments in Amman follows a linear configuration, with semi-public zones near the entrance and private zones positioned toward the rear. The entrance itself is designed as a separate space (Fig. 4). Particular attention was given to detailing the composition of interior and exterior wall layers, as well as the design of openings, including their material properties, thermal performance, and spatial arrangement. The base-case configuration was finalized in alignment with the Jordanian National Building Code, ensuring accuracy and realism (Eisabegloo et al., 2016).

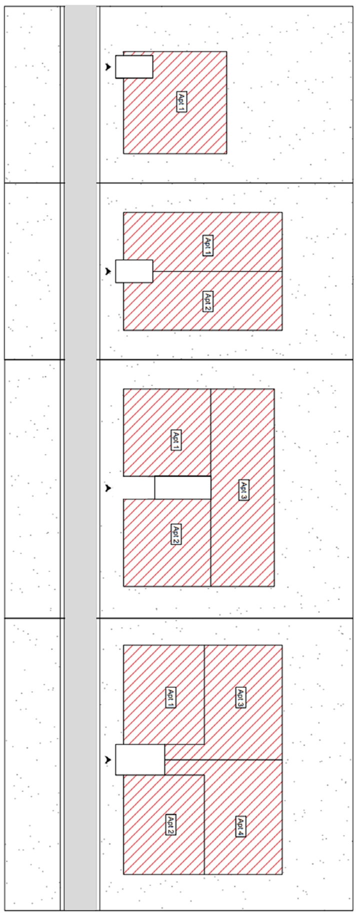

Figure 3. Number of apartments per floor of existing designs

In conclusion, the study building is a multi-story structure consisting of four levels, featuring two apartments per floor, each with a floor area of 148 m² (refer to Fig. 5). The apartments are interconnected both vertically and horizontally by a stairwell measuring 2.85 × 4.96 × 13 m. Exterior walls and openings serve as the primary pathways for thermal energy transfer into and out of the apartment unit. The openings comply with the minimum requirements of the Jordanian Building Code, with a WWR of 25% and manually operable double-glass windows. The composition of the exterior walls also adheres to the guidelines outlined in the same code manual. However, studies indicate that only 10–15% of apartment buildings in Amman meet the insulation standards mandated by the code, with smaller apartments having even lower compliance rates, often due to cost or lack of enforcement (Swiety and Alrefaee, 2024). Therefore, the base-case design was modelled to reflect prevailing design configurations, ensuring the representation of the

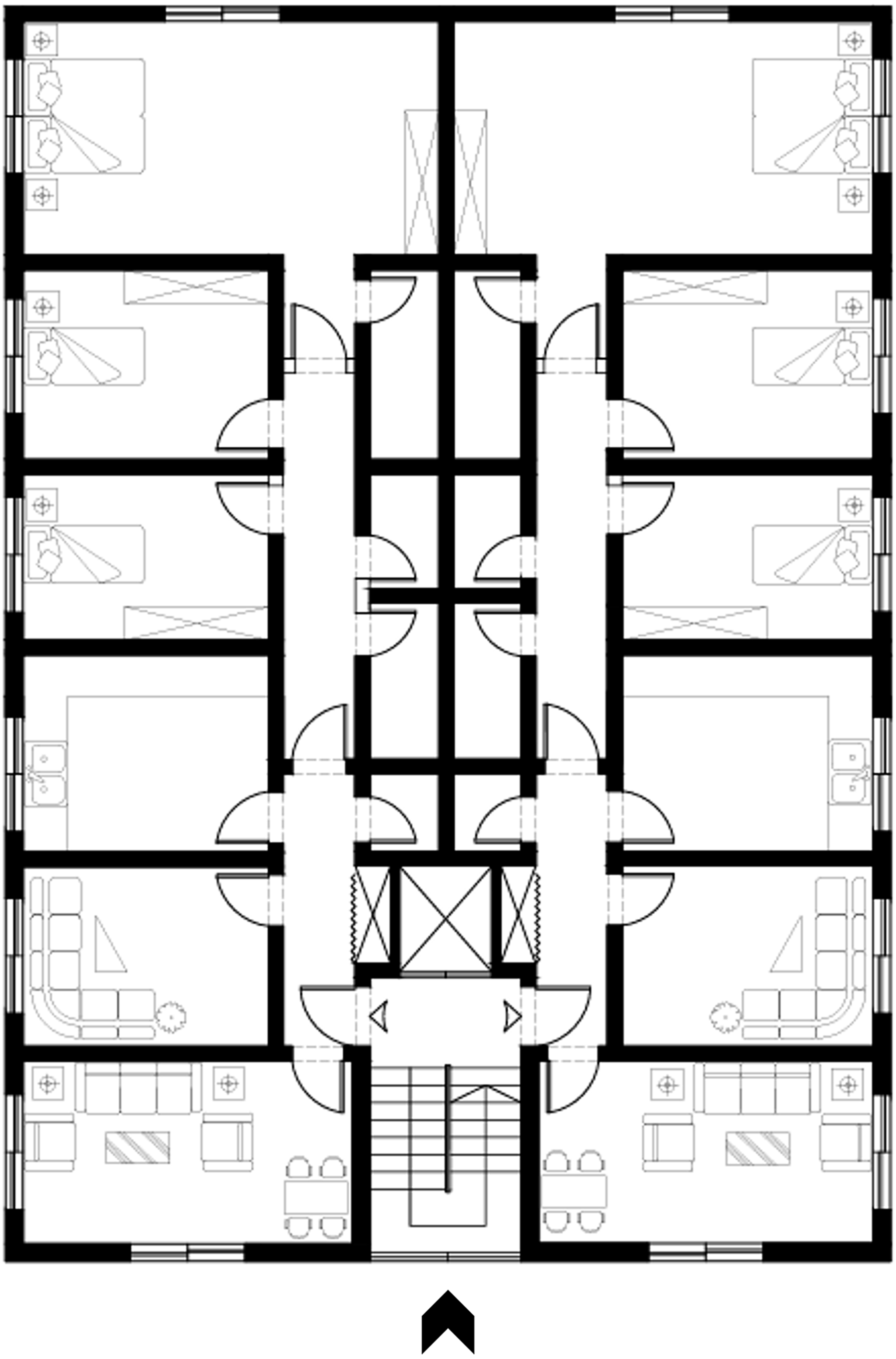

Figure 4. Typical spatial layout of apartment units in Amman

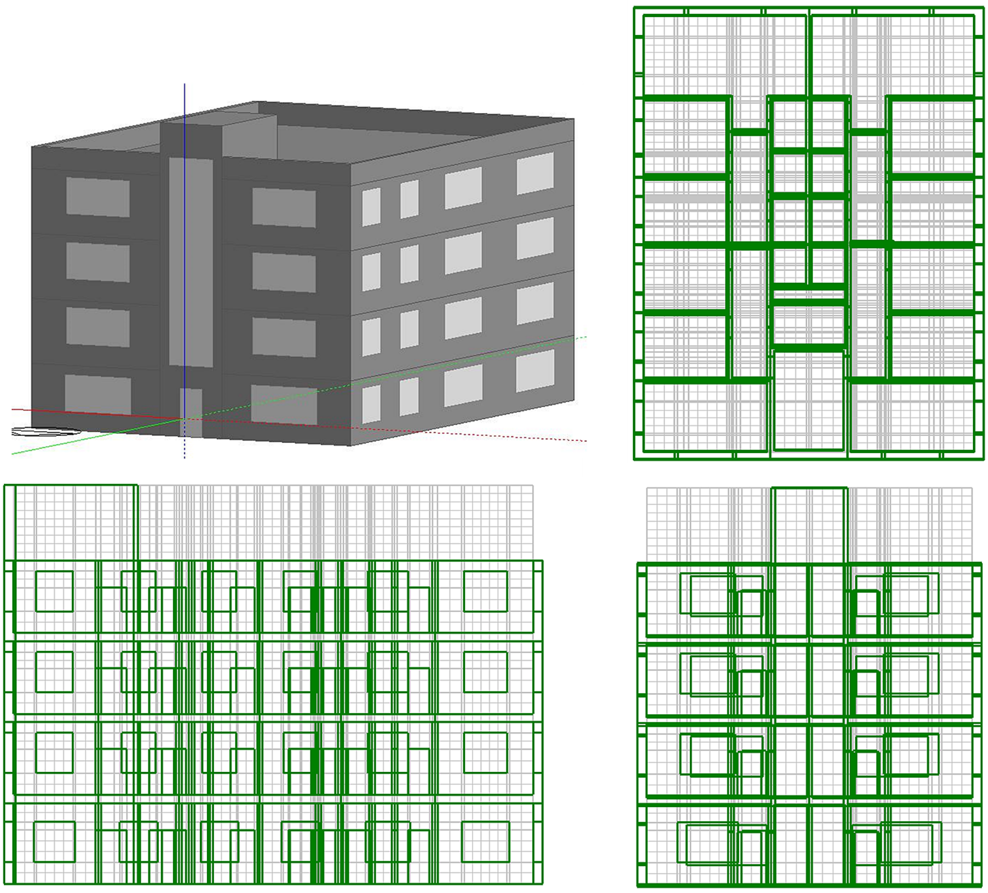

Figure 5. 2D and 3D representations of the building layout

Table 1. Construction specifications (construction specifications (as per the Jordanian National Building Code)

Element	Material	Thickness (cm)	U value (W/m² -K)
Exterior floor	Stone	5	0.79
	Concrete	18	
	Block	10	
	Plaster	2	
Internal partition	Plaster	2	1.90
	Block	10	
	Plaster	2	
Internal ceiling/floor	Tiles	3	1.20
	Mortar	3	
	Sand	7	
	Insulation	0.5	
	Reinforcement	25	
	Plaster	2	
Roof	Gravel	10	1.80
	Concrete	5	
	Insulation	0.5	
	Reinforcement	20	
	Plaster	2	
Windows	Aluminum frame	0.6	5.70
	Single glazing		

worst-case scenario. Table 1 provides a detailed summary of the construction specifications used in the CFD simulation, following the Jordanian National Building Code (Jordan National Building Codes 2020). The U-values and thickness listed for individual materials are adopted from the code's thermal performance requirements, ensuring that the simulation reflects realistic and standardized construction properties (Jordan National Building Codes 2020). The U-values and thickness listed for individual materials are adopted from the code's thermal performance requirements, ensuring that the simulation reflects realistic and standardized construction properties (Jordan National Building Codes, 2020). Additionally, Table 2 presents the building settings aligned with the typical activities of the population in Amman. These activity parameters serve as critical input data, involving building occupancy patterns, metabolic rate set points, and equipment usage profiles.

Computational fluid dynamics simulation

Turbulence model and convergence, boundary conditions, and solver settings

The CFD analysis of temperature and humidity in the base-case apartment was conducted using DesignBuilder. The k-ε turbulence model was employed due to its balance between computational efficiency and accuracy in predicting temperature and humidity distribution within the enclosed apartment spaces. The convergence criteria were set to ensure the stability of the simulation results, with residuals for continuity, momentum, energy, and turbulence parameters monitored and required to drop below 10^{-6} to confirm numerical stability.

Boundary conditions were defined based on Amman's climatic data, incorporating outdoor air temperature and RH during the winter season. The apartment's envelope, including walls, windows, and floors, was assigned material properties as per the Jordanian Building Code. Internal heat sources, such as occupant activities and electronic devices, were included to reflect real-world conditions. Ventilation rates were set according to standard air changes per hour (ACH) for residential buildings.

Table 2. Model settings and input data

Input Data	Value
Family size	6 members
Metabolic rate	0.8 met
Occupancy density	80 W/P
Lighting	5 W/m^2
Clothing	1.00
Appliances	0
Infiltration	Neglected value

For solver settings, a steady-state approach was initially applied to establish baseline conditions, followed by transient simulations to assess temporal variations in indoor air parameters. The SIMPLE algorithm was used for pressure-velocity coupling, while second-order upwind discretization schemes improved solution accuracy. Grid independence tests were performed to ensure mesh resolution did not influence the results, optimizing the balance between computational efficiency and accuracy.

To analyse indoor air temperature, the energy equation accounted for heat transfer and distribution. Simulation convergence was confirmed using two criteria:
- residual root mean square error (RMSE) below 1E−5, ensuring minimal discrepancy between iterations;
- stabilization of dependent variables, ensuring steady-state temperature values and energy balance within the model.

This approach enabled a precise assessment of how internal heat sources and external climatic conditions impact indoor air temperature and humidity.

Grid sensitivity analysis

The CFD model considered both external and internal boundary conditions to evaluate the relationship between thermal comfort and design parameters. External conditions included climate-based temperature and relative humidity data, while internal conditions were computed using EnergyPlus, accounting for factors such as opening design, occupancy effects, and material properties.

DesignBuilder's CFD module was used to simulate temperature (Tair) and (RH) as key indicators of indoor comfort. The following energy balance equation was applied:

$$Cp \cdot \rho \cdot V \cdot \frac{dTair}{dt} = \\ = \dot{Q}conv, solar + \dot{Q}conv, internal + \\ + \dot{Q}airflow + \dot{Q}HVAC \quad (1)$$

where: Cp – Specific heat capacity of air (J/kg·K), ρ – Density of air (kg/m³), V – Zone air volume (m³), $Tair$ – Indoor air temperature (°C), $\dot{Q}conv,solar$ – Convective heat transfer from solar radiation (W), $\dot{Q}conv,internal$ – Convective heat transfer from internal gains (W), $\dot{Q}airflow$ – Heat transfer due to ventilation and infiltration (W), $\dot{Q}HVAC$ – Heat supplied or removed by HVAC systems (W).

RH in DesignBuilder is defined as follows:

$$RH = \frac{Actual\ Water\ Vapor\ Pressure}{Saturation\ Water\ Vapor\ Pressure} \times 100\% \quad (2)$$

The calculated T_air and *RH* values were compared against established thermal comfort standards. ASHRAE Standard 55 ("Thermal Environmental Conditions for Human Occupancy") was used to determine acceptable indoor temperature ranges for residential settings, considering seasonal variations and occupant activity levels (ASHRAE, 2023). Although the standard does not specify explicit temperature ranges exclusively for residential settings, general recommendations can be considered. based on typical residential conditions with light clothing (0.5–0.7 clo during summer and 1.0–1.2 clo during winter) and sedentary activities (metabolic rate ≈ 1.0–1.2 met), Recommended values include (ASHRAE, 2023; Sehulster et al., 2003):

- winter: 20 °C to 23.5 °C (68 °F to 74 °F),
- summer: 23 °C to 26 °C (73.4 °F to 78.8 °F).

Maintaining appropriate indoor temperatures is crucial, as low air temperatures correlate with increased airborne virus viability due to physiological and environmental factors. Research suggests that RH between 40% and 60% effectively reduces the survival of airborne viruses, including influenza. The U.S. EPA recommends an RH range of 30% to 60%, while ASHRAE advises a maximum of 65% to prevent microbial growth and infection risks.

Optimization using DesignBuilder

DesignBuilder was used to optimize thermal comfort through simulations of multiple design scenarios. The software enabled an evaluation of:

- window-to-wall ratios (WWR),
- opening sizes and configurations,
- exterior wall insulation with varying U-values.

These parameters influence heat transfer, ventilation efficiency, and energy performance. By simulating different configurations, DesignBuilder provided insights into how modifications to fenestration and insulation can enhance indoor comfort, reduce energy consumption, and ensure compliance with standards aimed at minimizing the risk of airborne virus viability within indoor residential settings (Lian et al., 2024; Lowen et al., 2007; Zhang et al., 2020).

RESULTS

Simulation calculations and CFD analysis

Base case simulation analysis

The CFD analysis generated numerical data for air temperature and RH parameters. Daily calculations of air temperature and RH conducted throughout the simulated run period of the apartment unit (Figures 6 and 7). The figures state the maximum and minimum values recorded

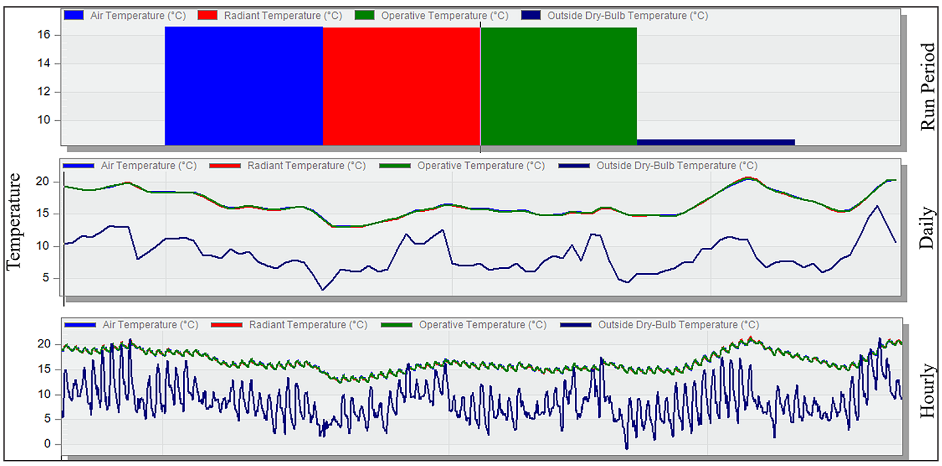

Figure 6. Indoor air temperature calculations of base case

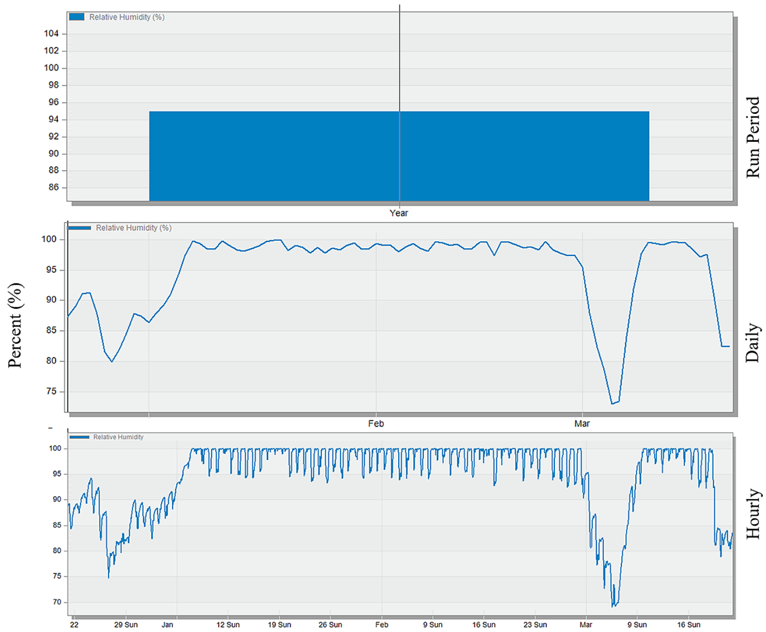

Figure 7. Relative humidity calculations of base case

throughout the simulation timeframe. On March 5, the space exhibited a maximum air temperature of 20.6 °C. whereas on January 20, a minimum indoor air temperature of 13 °C was registered. The RH data revealed that the space reached a maximum of 99.9% on January 18, reflecting elevated humidity levels, while the minimum RH of 73.% was observed on March 5.

Thermal dynamics through the apartment building

Continuous heat loss and gain occurs between the indoors of the apartment unit and the outdoor. CFD analysis, presented in Figure 8, provides valuable insights into the thermal dynamics within the apartment building. The analysis incorporated

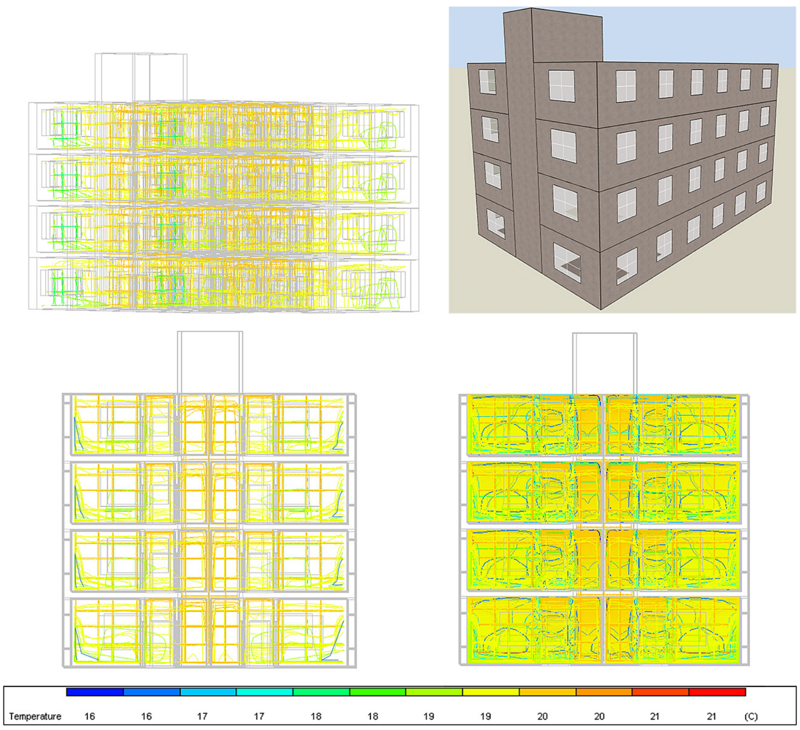

Figure 8. Indoor thermal CFD analysis

3D contour plots and sectional views to illustrate temperature distributions throughout the building. Notably, the results demonstrated that air temperature tends to be relatively lower in areas adjacent to the building's envelope, likely due to heat loss. Conversely, as the distance from the exterior walls increases, moving toward the interior spaces, the air temperature gradually becomes warmer. This gradient is attributed to the reduced influence of external thermal exchanges and the presence of internal heat sources, such as occupants, appliances, or solar heat gains through windows.

Heat loss/gain with the apartment unit

The CFD analysis conducted on the apartment unit revealed significant insights into heat loss dynamics and temperature distribution within the space (Fig. 9). The results demonstrated that lower temperatures were predominantly observed near the exterior walls. This phenomenon can be attributed to the lack of adequate thermal insulation in these walls, which facilitated higher rates of heat transfer to the outdoor environment. The thermal bridging effect, particularly at wall junctions and corners, further exacerbated the heat loss. Such findings highlight the critical role of exterior wall design in maintaining indoor thermal stability and minimizing energy consumption, emphasizing the need for improved insulation strategies. Conversely, the analysis indicated higher temperature regions near the window openings (Fig. 10), primarily due to solar heat gains. The direct exposure of these windows to sunlight allowed for significant heat ingress,

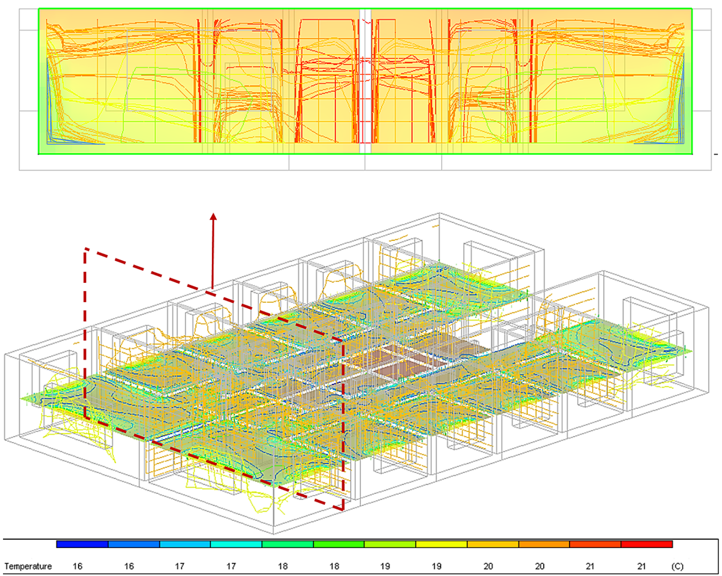

Figure 9. Thermal dynamics CFD analysis of base case

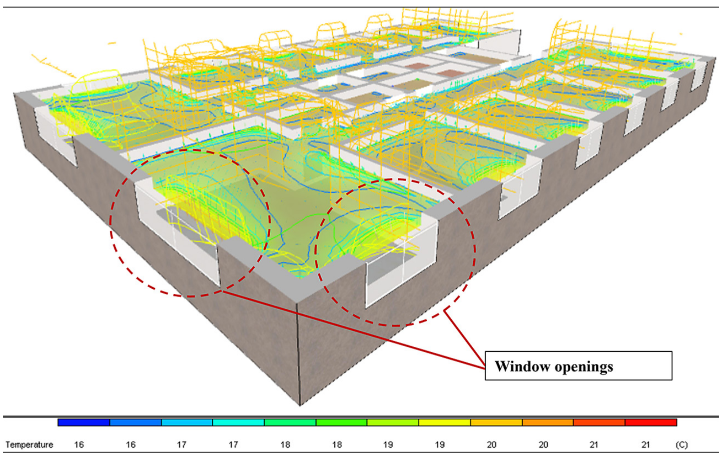

Figure 10. Thermal dynamics near window openings of base case

raising localized temperatures within the vicinity. This effect underscores the dual role of windows as both potential heat loss points and contributors to passive solar heating. The results advocate for optimizing window design through strategies such as double-glazing, low-emissivity coatings, and appropriate shading devices to balance solar heat gain and mitigate heat loss, thereby enhancing indoor thermal comfort and energy efficiency.

Thermal comfort enhancement strategies

The thermal comfort assessment conducted on the prevalent apartment unit design revealed inadequate indoor air temperature, falling below the recommended rates for safe and contamination-free environment. The average recorded air temperature through the simulation timeframe was 16.6 °C, while the recommended temperature ranging between 20–23.5 °C. This indicates poor thermal comfort which can lead to reduced immune system sufficiency, increase pathogens survival and higher energy consumption. Furthermore, the apartment unit exhibited values of RH significantly exceeding the recommended range for a healthy indoor environment. The RH was recorded at 95%, well above the advised range of 40–60%, which is considered optimal for maintaining indoor air quality and minimizing health risks. Such elevated humidity levels can promote the growth of mold and mildew, degrade building materials, and contribute to occupant discomfort. Furthermore, excessive RH may exacerbate respiratory conditions and create an environment conducive to the survival of airborne pathogens, underscoring the critical need for effective humidity control strategies. To improve thermal comfort and achieve acceptable air temperature and RH, enhancement strategies were followed. The focus of the strategy is centred on the design elements of the buildings envelop, as it plays a crucial role in heat loss/gain dynamics of the indoor space. The following simulations test the influence of exterior walls composition and WWRs. The aim was to evaluate the effectiveness of these strategies in enhancing the thermal comfort of the apartment unit.

Testing the application of different wall insulation materials

Table 3 represents the simulation calculations for multiple insulation materials with different R-values applied to the popular existing design of apartment units. Although the tested parameter measurement exhibited a noticeable difference, the application of expanded polystyrene (R-value = 2.64) resulted in an indoor air temperature of 18.9 °C, while extruded polystyrene (R-value = 3.32) improved the temperature to 19.7 °C. Polyurethane foam, with an R-value of 4.6, achieved an indoor air temperature of 20.6 °C. Notably, phenolic foam, offering the highest R-value of 5.7, resulted in an indoor air temperature of 21 °C, aligning with the targeted range recommended for infection control and a healthier indoor environment. These results emphasize the importance of selecting high-performance insulation materials to enhance thermal comfort, reduce energy consumption, and contribute to infection control in residential buildings.

The simulation analysis also evaluated the impact of different insulation materials with varying R-values on RH within the space, revealing a direct correlation between insulation performance and humidity regulation. Expanded polystyrene (R-value = 2.64) resulted in a relative humidity of 81.1%, indicating excessive moisture levels. Extruded polystyrene (R-value = 3.32) improved the RH to 77.3%, while polyurethane foam (R-value = 4.6) further reduced it to 71.5%. Phenolic foam, with the highest R-value of 5.7, achieved a RH of 658%, which approaches the recommended range of 30–65% for a healthier indoor environment and effective infection control. These findings highlight the dual benefits of high-performance insulation in enhancing both thermal comfort and indoor air quality, supporting the need for advanced materials to maintain optimal living conditions and mitigate airborne infection risks in residential spaces.

Testing the application of different WWRs

The simulation analysis investigated the impact of varying WWR on indoor air temperature and RH within the studied space. The base case applied the minimum recommended WWR of 25%, representing the most common configuration. To assess the effects of higher ratios, simulations tested values up to the maximum recommended WWR of 40%. The results demonstrated that a WWR of 30% resulted in an indoor air temperature of 17.1 °C and an RH of 92.9%. Increasing the WWR to 40% yielded slightly improved outcomes, with an air temperature of 17.9 °C and an RH of 85.6%. However, both scenarios produced conditions far from the recommended values for thermal comfort

Table 3. Comparison of different opening types for natural ventilation in apartment unit

Strategy		Simulation calculations	
		Air temperature (°C)	Relative humidity extruded (%)
Insulation material	Expanded polystyrene R-value = 2.64	18.9	81.1
	Extruded polystyrene R-value = 3.32	19.7	77.3
	Polyurethane foam R-value = 4.6	20.6	71.5
	Phenolic foam R-value = 5.7	21	658
WWR	30%	17.1	92.9
	40%	17.9	85.6

and healthy indoor environments, emphasizing the inadequacy of these configurations for maintaining optimal conditions for infection control.

Testing the application of integrated design parameters

The simulation analysis explored the combined application of phenolic foam insulation (R-value = 5.7) and a WWR of 40% to achieve optimal indoor thermal comfort and humidity regulation. This configuration yielded an indoor air temperature of 21.3 °C (Fig. 11) and a RH of 56.3% (Fig.12), both of which fall within the recommended ranges for a healthier indoor environment conducive to infection control. The high-performance phenolic foam effectively minimized heat loss through the building envelope, maintaining a stable and comfortable temperature, while the increased WWR maximized natural lighting, contributing to better moisture regulation (Fig. 13). These results highlight the synergy between advanced insulation materials

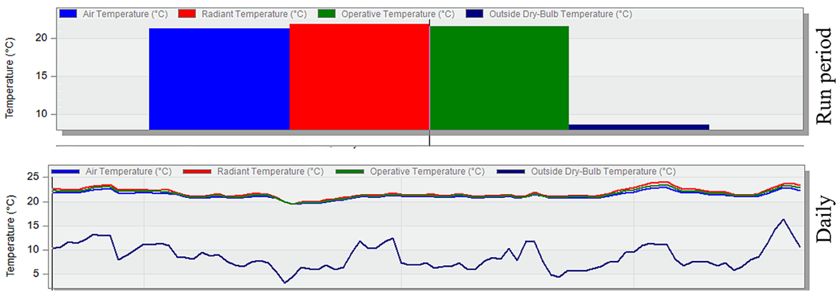

Figure 11. Air temperature simulation analysis of the application of integrated design parameters

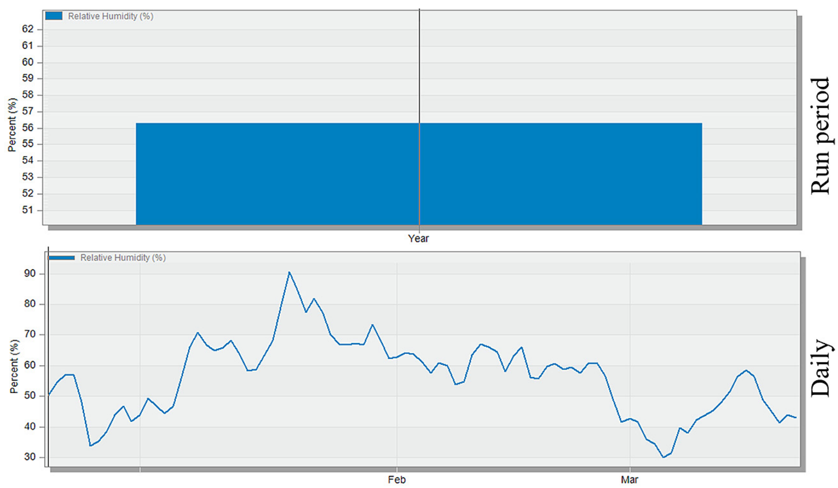

Figure 12. Relative humidity simulation analysis of the application of integrated designparameters

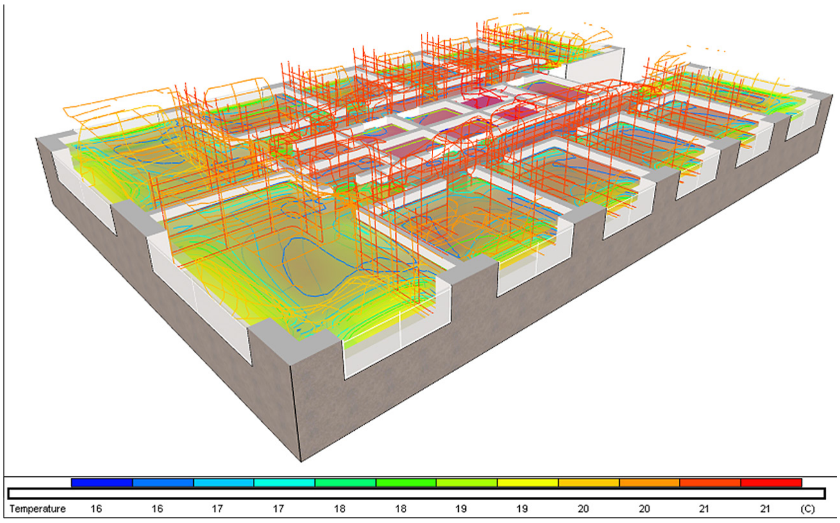

Figure 13. CFD analysis of the application of integrated design parameters

and optimized window design, demonstrating their combined potential to enhance indoor air quality, thermal comfort, and infection control in residential spaces. Such findings reinforce the importance of an integrated design approach to achieve sustainable and health-focused indoor environments.

DISCUSSION

This study examined the relationship between apartment unit design parameters and thermal comfort variables in the context of indoor environmental quality (IEQ) benchmarks within Amman's apartment buildings. The research focused on air temperature and RH by addressing the following key aspects:

The significance of design parameters for the survival of airborne viruses

The first objective of this study was to assess the impact of apartment design on thermal comfort and its alignment with recommended IEQ benchmarks that have been associated in previous research with reduced airborne virus. This study aimed to develop a better understanding of this phenomenon by referring to previous literature and structuring research variables accordingly. The importance of design parameters in shaping thermal comfort dynamics was emphasized, based on evidence from various scholars who have demonstrated the positive influence of spatial design on indoor temperature, humidity regulation, and overall occupant health (Alghamdi et al., 2022; Gaitov et al., 2021; Liu et al., 2023). Thermal comfort factors, specifically air temperature and relative humidity, are significantly influenced by design parameters (Thornton et al., 2022; Yin et al., 2023). The study identified two primary design parameters – wall insulation and opening area as key independent variables affecting indoor thermal conditions (D'Ambrosio Alfano et al., 2014).

The literature highlights that the COVID-19 pandemic exposed deficiencies in apartment building design, contributing to thermal instability that affects indoor air quality. The CFD simulation results reinforced these findings, demonstrating that existing apartment designs lead to poor indoor air temperature regulation and excessive humidity levels, deviating significantly from recommended IEQ standards. The CFD analysis revealed that indoor air temperature in the existing design was considerably lower than recommended levels, while RH levels significantly exceeded the acceptable range. The baseline simulation recorded an average indoor air temperature of 16.6 °C, compared to the recommended range of 20 °C to 23.5 °C. Additionally, RH levels averaged 95%, far exceeding the recommended range of 30% to 60%. These findings highlight critical thermal inefficiencies in apartment design and the need for strategic interventions to improve IEQ and occupant comfort.

Strategies for enhancing thermal comfort

The second objective of this study was to assess design-based interventions for improving thermal comfort in apartment units, specifically evaluating wall insulation and WWR through CFD simulations.

a) Impact of exterior wall insulation – the application of exterior wall insulation materials with varying R-values significantly influenced indoor air temperature, particularly when using an 8 cm insulation layer, as recommended by the Energy Efficient Building Code for Jordan. Among the tested materials, phenolic foam (R-value = 5.7 at 8 cm thickness) demonstrated the highest effectiveness, increasing indoor air temperature to 21 °C, aligning with recommended IEQ benchmarks. While phenolic foam effectively reduced RH from 95% to 65%, RH levels remained slightly outside the optimal range, indicating the need for complementary design modifications such as enhanced ventilation strategies to fully optimize indoor conditions.
b) Impact of window-to-wall ratio (WWR) – the size of openings (WWR) plays a critical role in apartment thermal performance. However, findings from this study indicate that modifying the WWR alone does not significantly improve thermal comfort. Applying a WWR of 40% (maximum recommended value) increased indoor air temperature only to 17.9 °C, which remains below the recommended range. Similarly, RH was only reduced to 85.6%, still exceeding acceptable thresholds. These results indicate that adjustments in WWR alone are insufficient to achieve optimal thermal conditions, and a more integrated design approach is required.
c) Optimized combination of insulation and WWR – the combined implementation of phenolic foam insulation (8 cm, R = 5.7) and a WWR of 40% demonstrated significant improvements in IEQ. The results showed an increase in indoor air temperature to 21.3 °C, bringing it within the recommended range, while RH was reduced to 56.3%, aligning with optimal levels. This highlights the synergistic effect of combining high-performance insulation and controlled window sizing to enhance both thermal comfort and overall indoor air quality.

Recommendations for future design and policy implementation

The third objective of this study was to provide recommendations for enhancing existing housing policies and building codes to support the design of contamination-free apartment units. The following measures are proposed:

- mandatory incorporation of high-performance insulation materials in apartment buildings to regulate indoor air temperature and minimize humidity fluctuations. Specific guidelines for insulation material selection should be included in building codes to ensure consistent indoor environmental quality across residential structures;
- encouraging an integrated approach to apartment design, accounting for the interaction between thermal insulation, window sizing, and ventilation systems. By promoting holistic design strategies in building codes, future apartment buildings can achieve healthier indoor environments, better comply with IEQ standards, and enhance occupant well-being.

CONCLUSIONS

This study highlights the critical role of spatial design parameters in influencing thermal comfort variables, specifically indoor air temperature and relative humidity, within apartment buildings. Through a simulation-based methodology utilizing CFD analysis, the research demonstrates the direct impact of design configurations on thermal comfort. The findings emphasize that achieving optimal thermal comfort requires an integrated approach, combining high-performance insulation materials with appropriate WWR. Testing the application of these strategies on the existing common apartment unit design resulted in an indoor air temperature (21.3 °C) and RH (56.3%) values that fall within set recommended values. While these strategies enhance indoor environmental quality, they also contribute to healthier living conditions by mitigating factors that sustain airborne pathogens.

This study provides actionable insights for improving current housing policies and building codes, advocating for design revisions in future apartment projects to prioritize thermal comfort and occupant health. The results serve as a foundation for further exploration into adaptive design solutions that balance energy efficiency, comfort, and public health objectives in residential environments.

While this study provides valuable insights into the relationship between thermal comfort parameters and airborne virus viability in apartment buildings in Amman, several limitations should be acknowledged. The research relies on CFD simulations, which, although effective in analysing airflow and thermal behaviour, depend on assumptions and input parameters that may not fully capture real-world complexities. Additionally, the study focuses on specific spatial design parameters, namely wall insulation and window-to-wall ratio, while other architectural factors such as ventilation strategies, material properties, and building orientation could further influence indoor environmental quality. Furthermore, occupant behaviour, including HVAC usage, window operation, and activity patterns, was not incorporated into the analysis, even though it significantly impacts thermal comfort conditions. Another limitation is the climate specificity, as the findings are based on Amman's environmental conditions, which may limit their direct applicability to other geographical regions with different thermal and humidity profiles. Future research should aim to expand the scope of design parameters, incorporate real-time occupant behaviour, and validate findings across different climatic contexts to enhance the generalizability and practical applicability of the results. Despite these limitations, this study establishes a scientific foundation for optimizing thermal comfort in residential buildings and informing design strategies that support occupant health and well-being.

REFERENCES

1. Ababsa, M. (2019). *Jordan National Urban Policy. Diagnostic Report*. https://shs.hal.science/halshs-04596420v1
2. Al-Betawi, Y. N., Al Nassar, F. H., Al Husban, A. A. & Al Husban, S. (2020). Transformations in the built form as a reflection of social change, the case of apartment buildings in Amman. *Open House International*, *45*, 143–171. https://doi.org/10.1108/OHI-04-2020-0005/FULL/XML
3. Al horr, Y., Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A. & Elsarrag, E. (2016). Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. *International Journal of Sustainable Built Environment*, *5*(1), 1–11. https://doi.org/10.1016/J.IJSBE.2016.03.006
4. Alghamdi, S., Tang, W., Kanjanabootra, S. & Alterman, D. (2022). Effect of architectural building design parameters on thermal comfort and energy consumption in higher education buildings. *Buildings*, *12*(3). https://doi.org/10.3390/BUILDINGS12030329
5. Alghamdi, S., Tang, W., Kanjanabootra, S. & Alterman, D. (2023). Optimal configuration of architectural building design parameters for higher educational buildings. *Energy Reports*, *10*, 1925–1942. https://doi.org/10.1016/J.EGYR.2023.08.066
6. Alqarni, Z., Rezgui, Y., Petri, I. & Ghoroghi, A. (2024). Viral infection transmission and indoor air quality: A systematic review. *The Science of the Total Environment*, *923*. https://doi.org/10.1016/J.SCITOTENV.2024.171308
7. *Amman Weather & Climate*. (n.d.). Retrieved February 11, 2025, from https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine,Amman,Jordan
8. ASHRAE. (2023). *Standard 55 – Thermal Environmental Conditions for Human Occupancy*. ASHRAE. https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy
9. Colin, S. (2020, 23. March). My Building Gave Me the Coronavirus. *Propmodo*. https://www.propmodo.com/my-building-gave-me-the-coronavirus-how-apartment-building-managers-can-help-prevent-the-spread-of-covid-19/
10. D'Ambrosio Alfano, F. R., Olesen, B. W., Palella, B. I. & Riccio, G. (2014). Thermal comfort: Design and assessment for energy saving. *Energy and Buildings*, *81*, 326–336. https://doi.org/10.1016/J.ENBUILD.2014.06.033
11. Daemei, A. B., Limaki, A. K. & Safari, H. (2016). Opening performance simulation in natural ventilation using design builder (Case Study: A Residential Home in Rasht). *Energy Procedia*, *100*, 412–422. https://doi.org/10.1016/J.EGYPRO.2016.10.196
12. Domingo, J. & Rovira, J. (2020). Effects of air pollutants on the transmission and severity of respiratory viral infections. *Environmental Research*, *187*, 109650. https://doi.org/10.1016/J.ENVRES.2020.109650
13. Eisabegloo, A., Haghshenas, M. & Borzoui, A. (2016). Comparing the results of thermal simulation of rasoulian house in Yazd by design builder software, with experimental data. *International Journal of Architectural Engineering & Urban Planning*, *26*(2), 121–130. https://doi.org/10.22068/IJAUP.26.2.121
14. Elshafei, G., Negm, A., Bady, M., Suzuki, M. & Ibrahim, M. G. (2017). Numerical and experimental investigations of the impacts of window parameters on indoor natural ventilation in a residential building. *Energy and Buildings*, *141*, 321–332. https://doi.org/10.1016/J.ENBUILD.2017.02.055
15. Gaitov, R., Tokbolat, S., Zhong, H. & Mustafa, M. (2021). Investigation of the impacts of design parameters on thermal performance of buildings in cold climate. *E3S Web of Conferences*, *246*. https://doi.org/10.1051/E3SCONF/202124607002
16. Goutte, S., Péran, T. & Porcher, T. (2020). The

role of economic structural factors in determining pandemic mortality rates: Evidence from the COVID-19 outbreak in France. *Research in International Business and Finance*, *54*, 101281. https://doi.org/10.1016/J.RIBAF.2020.101281
17. J.D.o Statics. (2017). *Jordan in Figures 2016*.
18. *Jordan National Building Codes*. (2020). https://www.scribd.com/document/503064438/JordanNationalBuildingCodes
19. Koley, T. & Dhole, M. (2021). *The COVID-19 Pandemic The Deadly Coronavirus Outbreak*. Routledge India. https://doi.org/10.4324/9781003095590
20. Lai, Y., Ridley, I. A. & Brimblecombe, P. (2020). Air Change in Low and High-Rise Apartments. *Urban Science*, *4*, 25. https://doi.org/10.3390/urbansci4020025
21. Lian, X., Huang, J., Li, H., Yan, W., Zhao, Y. & Wang, R. (2024). Cold waves accelerate the spread of infectious diseases. *Geophysical Research Letters*, *51*(15), e2024GL109405. https://doi.org/10.1029/2024GL109405
22. Lin, J. Z., Fang, Z., Zhang, S., Liu, J., Cheng, Y., Huan, C., Jendrossek, S. N., Jurk, L. A., Remmers, K., Cetin, Y. E., Sunder, W., Kriegel, M. & Gastmeier, P. (2023). The influence of ventilation measures on the airborne risk of infection in schools: A scoping review. *International Journal of Environmental Research and Public Health*, *20*(4), 3746. https://doi.org/10.3390/IJERPH20043746
23. Liu, Y., Luo, Z. & Grimmond, S. (2023). Impact of building envelope design parameters on diurnal building anthropogenic heat emission. *Building and Environment*, *234*, 110134. https://doi.org/10.1016/J.BUILDENV.2023.110134
24. Lowen, A. C., Mubareka, S., Steel, J. & Palese, P. (2007). Influenza virus transmission is dependent on relative humidity and temperature. *PLoS Pathogens*, *3*(10), 1470–1476. https://doi.org/10.1371/JOURNAL.PPAT.0030151
25. McKibbin, W. & Fernando, R. (2023). The global economic impacts of the COVID-19 pandemic. *Economic Modelling*, *129*, 106551. https://doi.org/10.1016/J.ECONMOD.2023.106551
26. Megahed, N. A. & Ghoneim, E. M. (2021). Indoor Air Quality: Rethinking rules of building design strategies in post-pandemic architecture. *Environmental Research*, *193*. https://doi.org/10.1016/J.ENVRES.2020.110471
27. Molina, F. Q. & Yaguana, D. B. (2018). Indoor environmental quality of urban residential buildings in Cuenca-Ecuador: Comfort standard. *Buildings*. https://doi.org/10.3390/buildings8070090
28. Moriyama, M., Hugentobler, W. J. & Iwasaki, A. (2020). Seasonality of respiratory viral infections. *Annual Review of Virology*, *7*(1), 83–101. https://doi.org/10.1146/ANNUREV-VIROLOGY-012420-022445
29. Mu, J. & Kang, J. (2022). Indoor environmental quality of residential elderly care facilities in Northeast China. *Frontiers in Public Health*, *10*, 1–23. https://doi.org/10.3389/fpubh.2022.860976
30. Nair, A. N., Anand, P., George, A. & Mondal, N. (2022). A review of strategies and their effectiveness in reducing indoor airborne transmission and improving indoor air quality. *Environmental Research*, *213*. https://doi.org/10.1016/j.envres.2022.113579
31. Noti, J. D., Blachere, F. M., McMillen, C. M., Lindsley, W. G., Kashon, M. L., Slaughter, D. R. & Beezhold, D. H. (2013). High humidity leads to loss of infectious influenza virus from simulated coughs. *PLOS ONE*, *8*(2), e57485. https://doi.org/10.1371/JOURNAL.PONE.0057485
32. Roya News. (2020). *Corona Weekly Report*. https://en.royanews.tv/
33. Rubino, I. & Choi, H. J. (2017). Respiratory protection against pandemic and epidemic diseases. *Trends in Biotechnology*, *35*(10), 907–910. https://doi.org/10.1016/J.TIBTECH.2017.06.005
34. Sehulster, L., Chinn, R. & Arduino, M. (2003). Guidelines for environmental infection control in health-care facilities. *Cdc.Gov*.
35. Shajahan, A., Culp, C. H. & Williamson, B. (2019). Effects of indoor environmental parameters related to building heating, ventilation, and air conditioning systems on patients' medical outcomes: A review of scientific research on hospital buildings. *Indoor Air*, *29*(2), 161. https://doi.org/10.1111/INA.12531
36. Strachan, P. A., Kokogiannakis, G. & Macdonald, I. A. (2008). History and development of validation with the ESP-r simulation program. *Building and Environment*, *43*(4), 601–609. https://doi.org/10.1016/J.BUILDENV.2006.06.025
37. Swiety, D. S. & Alrefaee, R. Q. (2024). Comprehensive Evaluation of Thermal Performance and Time-lag in Residential Apartments in Amman. *MATTER: International Journal of Science and Technology*, *10*, 75–95. https://doi.org/10.20319/MIJST.2024.10.7595
38. Thornton, G. M., Fleck, B. A., Dandnayak, D., Kroeker, E., Zhong, L. & Hartling, L. (2022). The impact of heating, ventilation and air conditioning (HVAC) design features on the transmission of viruses, including the 2019 novel coronavirus (COVID-19): A systematic review of humidity. *PLOS ONE*, *17*(10), e0275654. https://doi.org/10.1371/JOURNAL.PONE.0275654
39. Wolkoff, P., Azuma, K. & Carrer, P. (2021). Health, work performance, and risk of infection in office-like environments: The role of indoor temperature, air humidity, and ventilation. *International Journal*

of Hygiene and Environmental Health, *233*. https://doi.org/10.1016/J.IJHEH.2021.113709

40. Yang, W. & Marr, L. C. (2011). Dynamics of airborne influenza A viruses indoors and dependence on humidity. *PloS One*, *6*(6). https://doi.org/10.1371/JOURNAL.PONE.0021481
41. Yin, Y., Lai, M., Zhou, S., Chen, Z., Jiang, X., Wang, L., Li, Z. & Peng, Z. (2023). Effects and interaction of temperature and relative humidity on the trend of influenza prevalence: A multi-central study based on 30 provinces in mainland China from 2013 to 2018. *Infectious Disease Modelling*, *8*(3), 822–831. https://doi.org/10.1016/J.IDM.2023.07.005
42. Zhang, R., Li, Y., Zhang, A. L., Wang, Y. & Molina, M. J. (2020). Identifying airborne transmission as the dominant route for the spread of COVID-19. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(26), 14857–14863. https://doi.org/10.1073/PNAS.2009637117/SUPPL_FILE/PNAS.2009637117.SAPP.PDF