Condition Assessment of Building Thermal Leakage Using Infrared Thermal Imaging: A Case Study of a University in the UAE

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Abstract

Inefficient building envelopes are a major contributor to energy loss and discomfort in indoor environments. Traditional inspection methods often fail to detect hidden thermal pathways. There is limited comparative field evidence from hot-arid UAE campuses that links thermographic envelope diagnostics with occupant-reported comfort, thereby impeding precise retrofit decision-making. This study investigates heat loss in two university buildings in the UAE using infrared thermal imaging and occupant thermal comfort surveys. The selected buildings differ in age and construction standards, providing a comparative basis for evaluating insulation performance. To detect surface temperature fluctuations around windows and doors, infrared scans were performed with the Heating, Ventilation, and Air Conditioning (HVAC) system running continuously. Additionally, a survey was given to frequent users of both buildings to determine their comfort and usage behaviour. The results demonstrate that the newer building (ESB) had high insulation around windows and effective heat regulation at main entrances. However, emergency exits showed signs of leakage. On the other hand, the older building (EB2) has significant thermal leakage around doors and HVAC vents, indicating envelope deterioration. Survey responses confirmed discomfort in areas corresponding to leaking locations. Furthermore, to address these issues, the study recommends implementing real-time monitoring with thermal sensors, creating digital twins for virtual inspections, and integrating smart systems that respond to occupancy and temperature. These solutions aim to enhance building performance and support long-term energy efficiency goals.

Keywords

Infrared Thermal Imaging, Building Heat Loss, Comparative Condition Assessment, Thermal Performance Evaluation.

1. Introduction

Buildings consume a considerable part of the world's energy. Hence, their efficiency is an important component of global sustainability initiatives. About 30% of the world's final energy consumption and a comparable portion of carbon emissions related to energy use are caused by building operations (International Energy Agency (IEA), 2023). Indoor heating and cooling consume a large portion of this energy and significant heat loss can result from inefficient building envelopes. Heat can easily escape to the outside through thermal bridges and pathways created by air leaks and poorly insulated envelope components. For instance, windows are usually the weakest thermal link; if they are single-glazed or not properly sealed, they can account for around one-third of the overall heat loss in a typical home during the winter (Grablow). Similarly, gaps around doors or in foundations, as well as uninsulated walls or roofs, can all contribute to significant heat losses. In addition to increasing energy consumption and expenses, these thermal inefficiencies can lead to discomfort, such as cold drafts and uneven temperatures, and possible durability issues.

Using infrared thermography as the main diagnostic tool, this paper compares the heat loss in two buildings that were constructed according to different standards and at different times. An older existing building (EB2) and a contemporary energy-efficient building (ESB) are the subjects of the study. To find and compare patterns of heat loss between the two structures, infrared thermal scans are performed. To evaluate the relationship between variations in thermal performance and occupant comfort perceptions an occupant thermal comfort survey is also included. The results are intended to draw attention to the envelope's advantages and disadvantages for each building and stress the

value of combining technological diagnostics with human input when evaluating a building's performance. The study emphasizes the need for integrated approaches in sustainability assessments between technical and human-centric assessments for sustainable and high-performance buildings. Future research could build on these foundations to create standardized dual-assessment protocols and tools advancing the goal of sustainable, high-performance buildings.

With roots in the 19th century and major advancements in the 20th, infrared thermography has a lengthy history (Martin et al., 2022). Its fundamental idea is that every object releases thermal radiation in proportion to its temperature, which an infrared camera picks up and uses to calculate the temperature at each location in the scene. Additionally, it is employed to detect flaws in the thermal envelope, including air leakage pathways, thermal bridging, and inadequate insulation (Grey et al., 2021). Thermal bridges, air leakage sites and missing or damaged insulation are common issues found by IR (Tabet Aoul et al., 2021).

Infrared thermography (IRT) is a well-established non-destructive testing (NDT) technique used to produce detailed visual representations of a building's envelope condition (Kylili et al., 2014)(Plati et al., 2014). It is particularly valuable for retrofit planning, verifying construction quality, and assessing the effectiveness of insulation systems. When implemented correctly, IRT greatly enhances the detection of performance-related defects such as thermal bridging, air leakage, and missing or degraded insulation layers. The method relies on detecting infrared radiation emitted by objects with temperatures above absolute zero (−273.15 °C), following the principles of Planck's law (Plati et al., 2014). However, surface temperature readings captured by infrared cameras are not determined solely by the object's temperature. They are also influenced by several factors, including the material's emissivity (its ability to emit infrared energy), surface composition, surrounding temperature conditions, humidity levels, distance from the sensor, and the nature of the applied or ambient heat source (Büyüköztürk & Taşdemir, 2013).

For effective detection and reliable interpretation, it is essential to consider technical factors such as the spectral sensitivity, spatial and thermal resolution, temperature range, frame rate, and overall performance capabilities of the infrared camera (Bagavathiappan et al., 2013). Despite its strengths, IRT does have inherent limitations: it only detects surface temperatures, which may not fully reflect subsurface heat transfer under fluctuating conditions (Ibarra-Castanedo et al., 2013). Additionally, interpreting thermal images requires expertise in handling factors such as emissivity variation and misleading reflections. Since IRT is largely qualitative, translating thermographic visuals into meaningful quantitative heat loss estimates necessitates further analysis and modeling (Tabet Aoul et al., 2021).

Empirical studies using thermal imaging and other measurements have found that older buildings exhibit more thermal anomalies and higher heat loss rates than newer ones. (Tabet Aoul et al., 2021) conducted infrared thermography surveys on residential units of different ages in a hot climate, revealing common defect areas in both existing and under-construction homes. However, some newer units showed more thermal anomalies than older ones, attributed to workmanship and construction quality issues in the new builds. In addition, studies in building inspection demonstrated that thermal imaging can detect hidden thermal bridges, insulation flaws, and moisture accumulation, which are difficult to detect using visual examination, and thus emphasize the diagnostic precision offered by thermographic techniques. These realizations have made thermal imaging a cost-effective, accurate, and non-invasive tool in a variety of disciplines (Kylili et al., 2014).

2. Methodology

This study adopts a comparative experimental approach to assess thermal losses in two university campus buildings: the newer Engineering and Sciences Building (ESB) and the older Engineering Building 2 (EB2). Under steady-state Heating, Ventilation, and Air Conditioning (HVAC) conditions, infrared thermal imaging was conducted to capture thermal leakage variations at main entrances, side/emergency exits, and window assemblies. In parallel, an occupant comfort questionnaire was distributed via Google Forms to the university students, faculty, staff, and visitors who regularly use the ESB and EB2 buildings.

Integrating infrared thermography with occupant thermal comfort surveys provides a more holistic understanding of building performance. While thermography offers objective and quantifiable evidence of surface temperature variations and leakage zones, surveys capture subjective user experiences related to comfort and thermal satisfaction. By correlating these two datasets, the study bridges the gap between technical envelope diagnostics and human thermal perception, enabling a more accurate evaluation of how physical building conditions influence occupant comfort and energy efficiency. This dual-method approach enhances the reliability of the findings and supports data-driven recommendations for sustainable retrofit strategies. To clearly demonstrate the research workflow, Figure 1 presents the methodological flowchart summarizing the key stages of the study from site selection and thermal imaging to occupant survey analysis and the integration of both datasets for comparative evaluation.

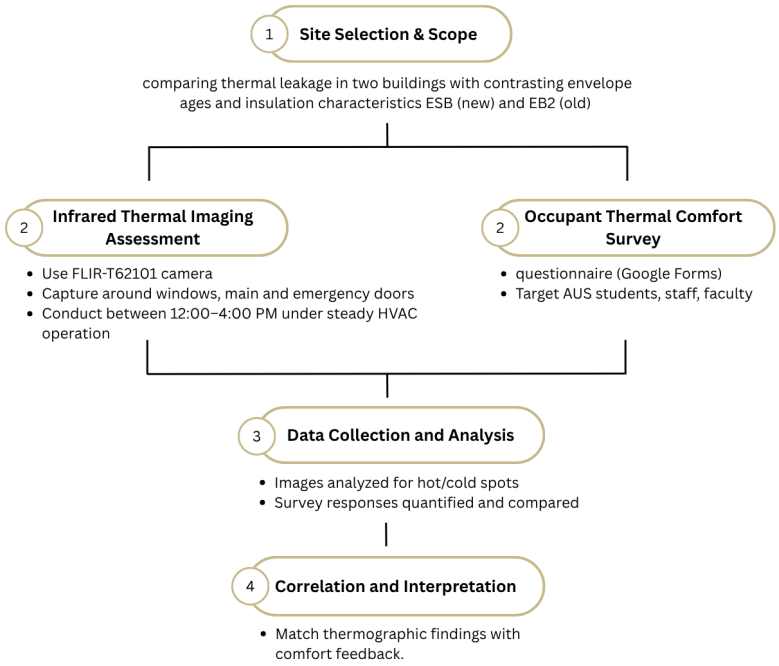

Fig. 1. Flowchart of Research Methodology.

2.1. Site Selection and Scope

Two buildings with differing construction ages and envelope characteristics were selected for the thermal assessment:

1. ESB – recently constructed, expected to have better insulation and sealing.
2. EB2 – an older building, potentially exhibiting more thermal leakage.

The primary parameters being assessed were thermal leakage through windows and doors, focusing on both the infiltration of hot outdoor air and the exfiltration of conditioned indoor air.

2.2. Infrared Thermal Imaging Assessment

Thermal imaging assessment was conducted using IR thermal camera Model: (FLIR-T62101) as shown in Figure 2, which detects the temperature variations on surfaces.

Fig. 2. IR thermal camera used for the assessment (FLIR-T62101).

The assessment followed a structured procedure and was conducted between 12:00 and 4:00 PM with the HVAC systems operating under normal conditions to maximize the thermal camera's sensitivity to indoor–outdoor heat variations and improve contrast. Infrared images were then captured around doors (main entrance and emergency/secondary doors) and windows, with at least three sampling points per building across different orientations, including glass surfaces such as facades directly exposed to the outdoors. A concurrent visual inspection documented gaps, cracks, and signs of poor insulation using standard photographs alongside the thermal images. For analysis, hot and cold spots were identified and compared across both buildings to evaluate thermal performance. To illustrate the detection method, Figure 3 contrasts a thermally intact door with a leaking door: the image on the left shows an even temperature distribution with no pronounced anomalies, whereas the image on the right exhibits concentrated on high-temperature zones (hot spots) near the frame (36.8 °C), confirming a localized thermal leakage.

Fig. 3. IR images comparing a door on the left showing no signs of thermal leakage vs a door on the right showing clear signs of thermal leakage .

2.3. Occupant Thermal Comfort Survey

An occupant thermal comfort survey was distributed via Google Forms to regular ESB and EB2 users, including students, instructors, staff, and guests. Respondents rated their overall thermal satisfaction on a five-point Likert scale and identified which portals (main entrance, and side/emergency exits) they used most frequently to determine whether the frequent operation of these doors influences the thermal leakage assessment.

3. Results

A total of 125 images were collected from two university buildings (ESB) and (EB2) as part of the condition assessment focused on identifying thermal leakage through windows and doors. The results presented here offer representative examples to illustrate the observed temperature variations and associated envelope performance. And a total of 42 responses were recorded from the survey (36 students, 4 faculty members, and 2 staff). The collected data were analyzed both qualitatively and quantitatively, and the findings will be discussed with respect to each survey question in the next section.

3.1 Infrared Thermographic Analysis of (ESB)

IR images of the ESB windows and facades depicted in Figure 4 show uniform temperature distribution with surface temperatures ranging from 21.8°C to 30.3°C around windows and 27.3°C to 35.1°C around the facades. These values suggest good insulation performance, with no significant evidence of thermal leakage. The absence of concentrated hot/cold spots around the frames and glazing supports emphasize intact thermal seals.

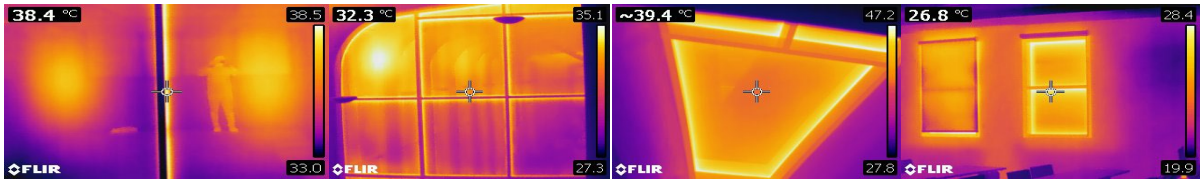

Fig. 4. IR Images capturing windows and facade of ESB building showing no sign of thermal leakage.

Moving on to the images of the emergency exit doors shown in Figure 5 from the indoor point of view, it shows uniform temperature distribution, with surface temperatures ranging from 25.4°C to 32.8°C. However, from the outdoor point of view, it shows clear thermal irregularities with temperatures ranging from 31.7°C to 52°C, having clear visible temperature gradient with cold spots around the door frames and thresholds. These visual abnormalities indicate the presence of thermal leakage, which upon further visual inspection, visible gaps were confirmed validating the infrared thermographic evidence. This indicates that this door leaks thermally towards the outside of the building, causing a waste of energy and putting more load on the HVAC system causing it to require more maintenance.

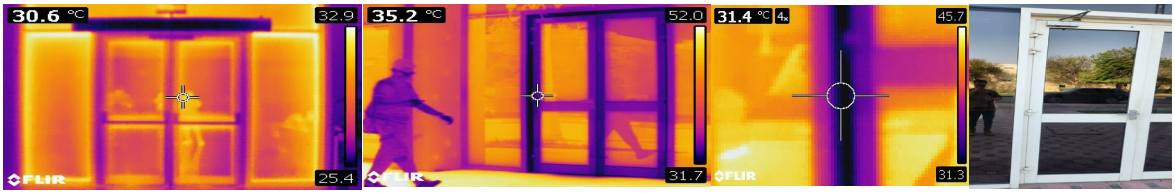

Fig. 5. IR and normal images capturing the emergency exit doors of ESB building showing signs of thermal leakage and upon physical and visual inspection leakage was confirmed.

Moreover, IR images of the ESB's main entrances in Figure 6 showcased an enhanced performance, as it showed temperatures ranging from 23.7 to 28.7C closing the temperature variation gap; this is attributed to the implementation of a two-door system. This configuration likely acts as a buffer zone, mitigating heat exchange between interior and exterior environments, thereby demonstrating a passive control measure to reduce thermal leakage.

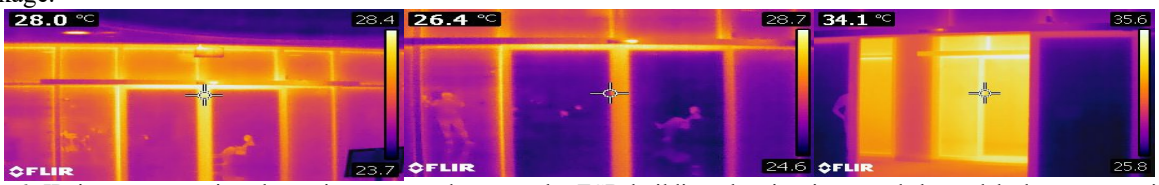

Fig. 6. IR images capturing the main entrance doors on the ESB building showing improved thermal leakage prevention by installing a two-door system.

3.2 Infrared Thermographic Analysis of (EB2)

IR images of the EB2 windows shown in Figure 7 highlight uniform distribution of temperatures between 31.4°C and 51.2°C. This gap in range is due to the sun orientation on the window hitting at an angle, as a result of which, some parts were shaded showing much lower temperatures. However, no concentrated hot/cold spots around the frames were identified, emphasizing no thermal leakage.

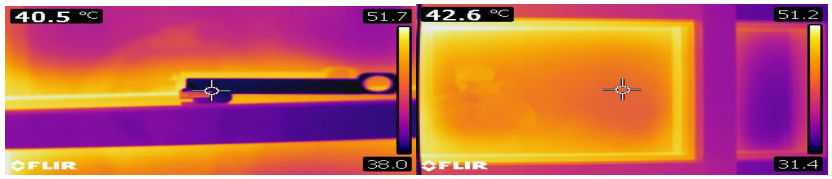

Fig. 7. IR Images capturing windows and facade of EB2 building showing no sign of thermal leakage.

However, the inspection of EB2's main entrance and emergency exit doors shown in Figure 8 revealed anomalies with high and low-temperature zones ranging from 26.4°C to 48°C. These thermal inconsistencies and cold/hotspots were observed from both the indoor and outdoor point of view, indicating that the doors leak thermally toward both the inside and outside. Upon further visual inspection degradation is observed in door thresholds and frame junctions of both main entrance and emergency exit doors . Unlike the ESB, where it was observed on the emergency exit doors only and it was leaking thermally towards the outside and not the inside, indicating that the EB2 building has more serious systemic envelope deterioration and wear-related sealant failure.

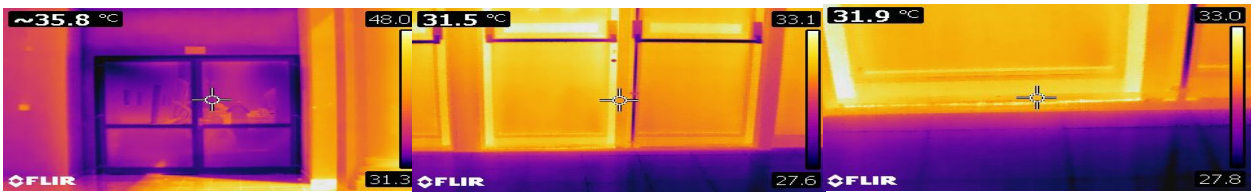

Fig. 8. IR images and normal images capturing the main entrance and emergency exit doors of EB2 building showing signs of thermal leakage and visual inspection confirmed leakage on several doors.

IR image analysis of HVAC ventilation grills within the EB2 dome shown in Figure 9 highlighted hotspots reaching up to 45.4°C, with the surrounding HVAC ventilation having significantly cooler temperatures as low as 12.4°C. This indicates that the HVAC ventilation grill on the dome is not working or disabled, which also suggests inefficiencies in duct insulation or leakage around diffuser perimeters, contributing to heat loss and reduced HVAC efficiency.

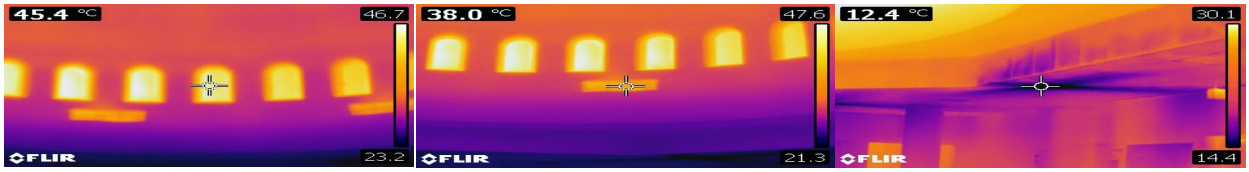

Fig. 9. IR images capturing the HVAC ventilation grills of EB2 building dome being disabled or not working allowing thermal leakage.

3.3 Occupant Thermal Comfort Survey

The first question as shown in Figure 10 (a) aims to understand the role of the respondents whether they were a student, faculty member, staff, or visitor. Knowing each person's role makes it possible to link their comfort ratings and door/window-use habits to the way they actually move through and use the building. The results indicate that a total of 42 responses were received, out of these, 85.7% came from students, 9.5% from faculty members, and 4.8% from staff, while no visitors took part in the survey. The second and third questions asked participants to indicate how often they use ESB (b) and EB2 (c). Capturing these visit frequencies is critical for linking each user's exposure and door/window interactions to their comfort ratings and infrared leakage measurements. as seen in Figure 10 (b) the results reveal that ESB experiences high intense building use, with 45.2% of respondents entering it several times a week and 38.1% daily, while only 9.5% use it once a week and 7.2% less frequently. In contrast, EB2 as seen in Figure 10 (c) indicates more occasional use with 38.1% of participants visiting rarely and 19.0% once a week, with just 9.5% coming daily and 21.4% several times a week suggesting that differences in traffic patterns and thus portal operation may help explain the thermal performance gaps observed between the two buildings.

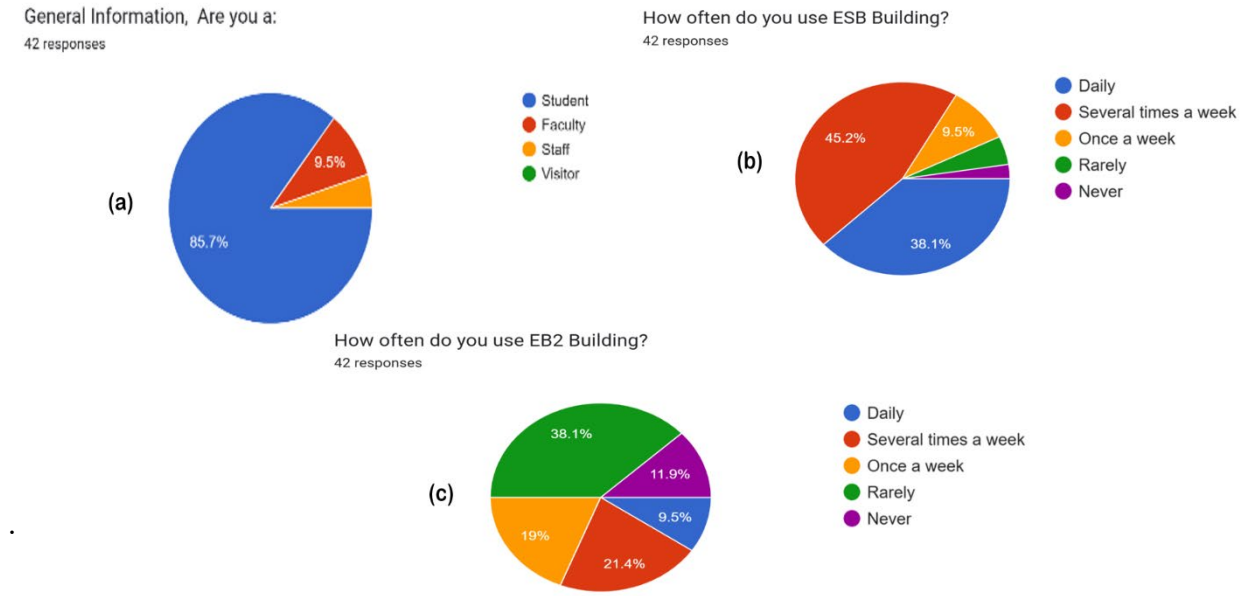

Fig. 10. Question 1-3 result summary

Furthermore, Figure 11 shows the fourth and fifth questions which asked participants to rate their overall indoor temperature comfort in ESB and EB2. Capturing these comfort perceptions is essential for understanding how users experience each building's thermal environment. The results show that ESB (a) comfort ratings were predominantly positive: 26.2% of respondents described the indoor temperature as "Very comfortable" and another 26.2% as "Somewhat comfortable," totaling 52.4%. In contrast, EB2 (b) had a higher proportion of indifferent replies with 21.4% of participants feeling "Neutral," 21.4% experiencing "Somewhat uncomfortable" conditions, and just 4.8% reporting feeling "Very uncomfortable." These differences suggest that occupants consider EB2 to be less thermally satisfying than ESB, a finding that aligns with the infrared leakage patterns observed.

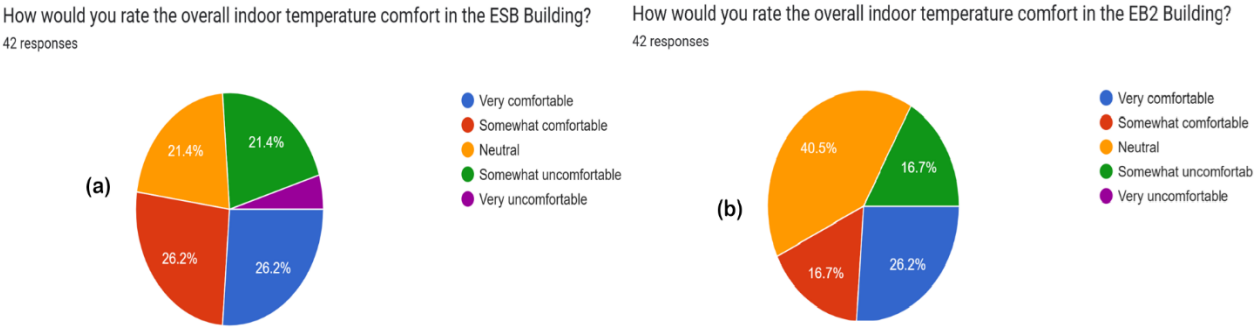

Fig. 11. Question 4&5 result summary

Moreover, Figure 12 (a) presents the results of question six focused on identifying if occupants had experienced any thermal discomfort near windows or doors in ESB and EB2, a key measure for linking thermographic leakage hotspots to real user complaints. The responses were evenly split: 50% of the 42 respondents reported feeling discomfort near these openings, while the other 50% did not. This precise balance indicates that, although half of the occupants notice draft-related issues at the building envelope, the other half remain unaffected, underscoring the need to align objective infrared findings with subjective comfort feedback. Furthermore, Figure 12 (b) presenting question seven asked participants which doors they used the most to enter or exit the facility. Understanding these preferences reveals which portals are used the most, and hence have the most opening cycles, which may contribute to heat loss. The findings show that 19% of respondents prefer the main entrance, 40.5% rely on side/emergency exits, and another 40.5% use all doors equally.

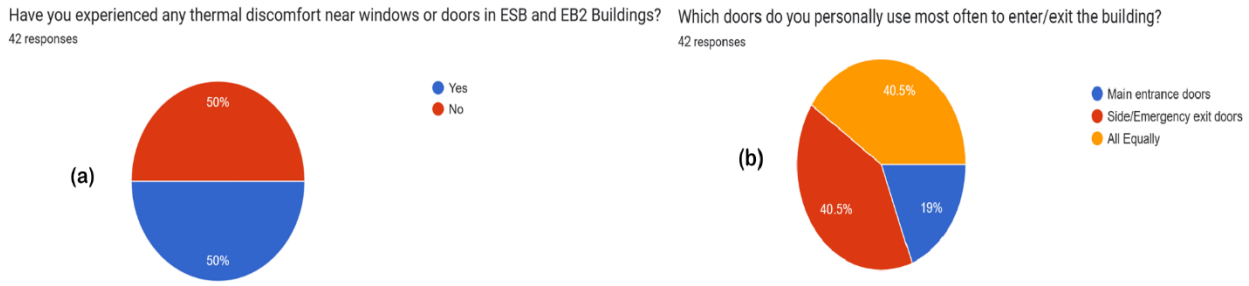

Fig. 12. Question 6&7 result summary

Figure 13 shows the reasons for the door choice, indicating that out of the eight responders who prefer the main entrance, the most important reason was easy access to parking (62.5%), followed by convenient access to classrooms and offices (50%), and being close to lifts (25%). Whereas, out of the 17 users who favor side or emergency exits, an even greater proportion (82.4%) highlighted parking convenience, with 58.8% preferring lift access and 35.3% mentioning shorter journeys to classes and offices. These patterns show that both exterior considerations, such as parking position, and internal circulation channels strongly influence door selection, determining how frequently different areas of the building envelope are used.

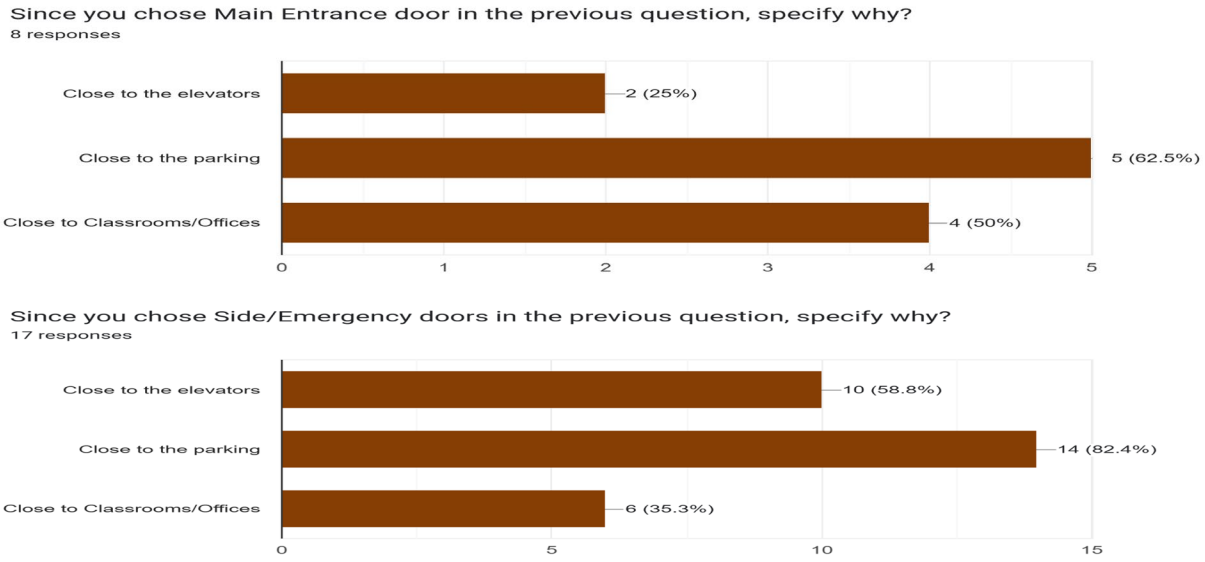

Fig. 13. Question 8&9 result summary

4. Thermography–Survey Correlation Discussion

When the infrared thermographic findings are combined with the occupant survey data, a clear pattern emerges: the architectural elements identified by thermal imaging as leakage locations are precisely those most used and complained about by occupants. In ESB, infrared scans revealed negligible window leakage and good two-door buffering at the main entry, but noticeable thermal flaws at the emergency escape door's locations that 40.5% of respondents reported using most frequently and where half of all participants acknowledged discomfort.

On the other hand, EB2's infrared analysis revealed widespread leakage at exit and main doors, as well as HVAC grille inefficiencies, and the survey reflects this deteriorated envelope: only 42.9% of users felt comfortable, compared to 52.4% in ESB, with a higher share reporting neutral or uncomfortable conditions. These results demonstrate that frequent door and window usage, driven by user patterns and preferences, magnify the envelope vulnerabilities revealed by thermography, having a direct impact on perceived indoor comfort in both buildings.

5. Conclusions and Recommendations

In conclusion, this comparative assessment successfully achieved its primary objective of evaluating and comparing the thermal leakage performance of two university buildings with different construction ages and envelope standards (ESB and EB2) using infrared thermography and occupant comfort surveys. Under steady-state HVAC conditions, the analysis revealed that fenestration components in both ESB and EB2 exhibited no significant thermal leakage, confirming effective glazing seals and insulation.

However, door assemblies presented contrasting performance: ESB's emergency exit doors showed localized thermal faults, likely due to frequent manual operation, while its main entrances, equipped with a double-door vestibule, maintained stable temperatures. In contrast, EB2 demonstrated widespread leakage at nearly all exit and main doors, along with HVAC grill inefficiencies in the dome, reflecting systemic envelope deterioration.

The integration of infrared data with occupant feedback confirmed that frequently used portals correspond to reported discomfort and lower comfort ratings, particularly in EB2, where only 42.9% of users reported comfort compared to 52.4% in ESB. These findings verify that the combined use of thermography and surveys effectively captured both technical and human-centered aspects of thermal performance, thereby fulfilling the research goal of establishing a dual-assessment approach to building envelope evaluation.

Accordingly, the following recommendations combine proven retrofit measures with innovative technologies to systematically mitigate thermal leakage and enhance indoor comfort:

• Implement IoT-enabled thermal sensors and drone-based infrared inspections that transmit real-time data onto a live dashboard for quick leak detection.

• Create a digital twin of each building envelope to enable virtual inspections using AR-guided seal checks and a scheduled retrofit timetable.

• Integrate AI-driven control systems that regulate ventilation and temperature based on real-time occupancy data and thermal feedback.

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