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A Low-Code Digital Twin Framework for IEQ-Guided Fabric-First Retrofit Decision-Making in Existing Buildings

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Abstract

Decarbonization of existing buildings is obstructed by the performance gap between intended and operational energy consumption. Smart energy management and monitoring of existing buildings through digital twins pose significant attributes towards decarbonization efforts. However, there is limited research that transforms digital twins' monitored performance into actionable retrofitting strategies. Hence, this research develops a framework that bridges the digital twin concept with standards-based IEQ analytics, guiding retrofit decision-making in existing buildings. The framework offers a low-code workflow that uses Autodesk Tandem to develop a digital twin integrating indoor environmental quality (IEQ) data, including thermal comfort and air quality. IEQ is monitored since inefficient management of its parameters often results in excessive HVAC demand, contributing to the performance gap. The framework structures IEQ parameter evaluations against benchmarks guided by ASHRAE to identify deviations indicative of operational inefficiencies in energy consumption. The digital twin model positions live IEQ tracking and analysis as diagnostic measures, leading to targeted fabric-oriented retrofit prioritization. The framework was tested on a case study in a hot arid climate, where its results indicate that the integration of digital twin-based IEQ analysis with building characteristics effectively identified the need for targeted envelope improvements, including high-performance glazing, external shading elements, and sound isolation, as key factors for eliminating overheating and high noise levels. Validating the proposed retrofits' effectiveness, energy simulations examines the whole building to find an 11.52% annual reduction in energy use intensity from 145.61 kWh/m^2·year to 128.84 kWh/m^2·year through shading elements and low-E films for glazing.

Keywords: digital twins; indoor environmental quality; energy efficiency; user comfort; fabric-first retrofits; data-driven decision-making; decarbonization

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1. Introduction

1.1. Rationale of the Study

Recent data from the International Energy Agency (IEA) in 2025 shows that buildings account for approximately one-third of global energy consumption [1]. Energy consumption, along with carbon dioxide emissions from building operations, positions the built environment in critical attention regarding decarbonization strategies and hinders a transition towards sustainable urban environments [2]. Concurrently, the architecture, engineering, and construction (AEC) industry is undergoing a digital transformation of building operations, with digital twin technology emerging as a pivotal medium that

empowers smart building management and real-time monitoring [3,4]. Digital twins are central to acquiring real-time data and its integration with virtual representation of physical assets, providing evidence-based analysis that assists in improving energy efficiency and operational optimization [5–8]. Poyyamozhi et al. (2024) indicated that a 30% reduction in energy consumption is possible through optimizing operational energy-intensive demands, such as thermal comfort, air quality, HVAC systems, and lighting [7,9]. Jradi et al. (2023) proposed a framework that focuses on retrofit strategies tied to digital twins monitoring data and analysis [10]. Through implementing the framework, the study highlighted projected reductions in energy consumption (≈15% on average, up to 60% for deep retrofits), CO_2 emissions (18–35%), and operational costs (up to 20%) [10]. This incorporation of sustainability and energy-oriented management for existing buildings aligns with United Nations Sustainable Development Goals (Goals 7 and 11) that mandate enhanced energy efficiency and resilient urban cities [11]. Furthermore, the implementation and development of digital twins in buildings can address crucial efforts toward decarbonizing the built environment [12,13].

Acting as performance optimization drivers, digital twins can address the performance gap resulting from the difference between predicted and measured operational energy consumption [14]. Operational energy performance deviates from intended forecasts due to inadequate integration of passive design strategies, poor construction methods, and poor material specifications [15]. Additionally, performance inadequacies result in building occupants experiencing uncomfortable indoor environmental quality in indoor spaces, which affects energy efficiency due to the reliance on mechanical systems to overcome IEQ shortcomings [16]. In contrast with traditional periodic IEQ assessments, digital twins provide structured data mapping and analysis of IEQ parameters, allowing continuous assessment of thermal comfort, CO_2 levels, and volatile organic compounds (VOCs), which are critical for maintaining a healthy indoor environment [16–19]. Using IEQ-based IoT sensors for digital twins can provide detailed insights into spatial and occupant dynamics of indoor environments, leading to the identification of rooms/zones in the building that require intervention [19,20]. Furthermore, an integrated framework for real-time monitoring of building energy use and IEQ highlights the importance of considering occupant behavior in retrofit strategies to optimize energy efficiency and enhance indoor environmental quality [20,21]. Jradi et al. (2023) shed light in their research on the importance of translating IEQ-sensed data into retrofitting solutions to reduce energy usage and cut costs [10]. Jradi et al. (2023) and Ullah et al. (2024), while testing their digital twin framework, highlighted the impact of continuous sensing of IEQ data to identify major building envelope inadequacies [10,22]. Thus, to address both the energy performance gap and occupant comfort, indoor environmental quality (IEQ) and retrofitting represent central variables within existing buildings' decarbonization strategies [2,15].

However, few studies have provided frameworks that translate monitored data into actionable retrofit decisions [23]. Systematic reviews indicate that while digital twins are frequently employed to enhance system efficiency, limited research has developed structured frameworks that translate monitored performance data into actionable retrofit decisions, particularly at the building envelope level. Existing studies often emphasize the technological aspects of data acquisition and visualization rather than the analytical contribution, which sets a foundation for guiding existing building retrofits. For instance, Lu et al. (2020) [24] aimed to establish a systematic and extensible digital twin architecture to enhance operation and maintenance (O&M) management at building and city scales. They developed a five-layer hierarchical architecture and implemented it through a digital twin demonstrator at the West Cambridge Campus, demonstrating effective data integration, querying, and decision support [24]. Hu and Assaad (2024) [25] aimed to propose

and validate a comprehensive BIM-enabled digital twin framework that autonomously monitors and visualizes indoor environmental conditions using robotic mobile sensing, SLAM-based 3D mapping, IoT sensors, and indoor positioning technology. They validated the framework, achieving effective spatial indoor air quality (IAQ) assessment and real-time BIM-based visualization, and recommended future research toward broader environmental applications, scalability to complex facilities, and enhanced integration with intelligent analytics and decision-support mechanisms [25]. Furthermore, Ullah et al. (2024) [22] developed a digital twin and performed iterative energy simulations to assess the impact of envelope upgrades, lighting reductions, and renewable integration. The authors demonstrated notable energy savings versus the baseline scenario through glazing upgrades, lighting power density reduction, and solar panel integration. The study recommended future research, including the incorporation of real-time building operational data, HVAC system control modeling, and AI-based predictive control to further retrofits, energy efficiency, and adaptive management [22].

While real-time digital twin applications have demonstrated accurate room-level IEQ mapping and thermal comfort prediction, the literature rarely connects these detections to structured fabric-first retrofit decision-making [10,21,23,26]. Several case studies have tested multiple data acquisition frameworks and focused on optimizing existing systems, such as HVAC systems [9,24,27,28]. Therefore, the gap is further significant when considering sustainable retrofit methodologies that adopt a fabric-first approach [13,15]. The significance lies in the need to create frameworks that utilize monitored data to optimize performance and achieve the lowest possible energy consumption.

1.2. Novelty and Contribution

This research aims to position digital twins as not just visual representations of buildings but analytical drivers for operational optimization in existing buildings through a structured low-code workflow that integrates real-time IEQ data analysis with standards-based evaluation to guide room-level retrofit decision-making. The framework leverages Autodesk Tandem to create a low-code, scalable implementation pathway that minimizes technical barriers while enabling systematic performance mapping. The novelty of this research lies in bridging three domains, which are digital twin performance optimization, standards-based IEQ analysis, and retrofit decision support [23]. Rather than focusing on mechanical system upgrades and optimization, the framework emphasizes envelope performance and fabric-first prioritization by embedding continuous IEQ assessment within a retrofit feedback loop to provide a practical pathway for reducing heating and cooling dependence throughout the operational lifecycle of existing buildings. Hence, it addresses the performance gap from an operational perspective and supports the broader ambition of achieving decarbonization of the built environment through informed, adaptive, and data-driven retrofitting practices.

2. Building Performance and Digital Twins

2.1. Digital Twins in Building Operations: IEQ–Energy Retrofits

The performance gap in building operations poses a barrier towards decarbonizing the built environment due to variations in the actual building envelope performance and occupant behavior that increase energy demand, resulting in higher operational costs and carbon emissions than those intended during the design phase [29–32]. To address this issue, Zheng et al. (2024) showed that actual building energy consumption can reach up to four times predicted levels, highlighting the importance of data-driven strategies, such as operational data analysis and retrofitting, to identify inefficiencies, understand occupant and building-related factors, and improve energy performance [23]. Addressing

the performance gap through data-driven approaches aligns with M. Grieves and J. Vickers' (2017) demonstration of the broad digital twin concept during the operation phase; a digital twin is central in real-time information gathering and analysis to continuously assess and improve systems and asset behavior [5,24,33,34]. Over the operation lifecycle, performance validation data and virtual simulations are used to support predictive maintenance and retrofit decision-making, aiming to holistically improve energy efficiency while satisfying occupant comfort [23,35,36]. Ageli & Chassiakos (2026) performed a scientometric and thematic review of 109 papers regarding IEQ–energy and digital twin research fields and found that the integration of IoT devices and BIM to optimize IEQ and energy performance has not been fully recognized, where research emphasizes monitoring and analytical capabilities but lacks complete feedback of sensed data, comprehensive representation of multiple IEQ parameters, and robust validation beyond short-term applications [37,38].

Concurrently, digital twins developed for evidence-based retrofitting to improve energy efficiency and IEQ are further unaddressed [10,22,39,40]. Various studies have reviewed current trends and research directions in the application of digital twins for building retrofitting; however, these reviews provide limited insight into practical frameworks or guidelines for applying digital twins to improve the energy efficiency [35,41,42]. Live operational data fills a gap of steady-state energy modeling, which poses a barrier in representing the actual dynamic behavior of building performance. For instance, Hamada et al. (2025) indicated that reducing the energy consumption of existing buildings can not be realized until existing operational conditions have been analyzed to generate suitable and efficient retrofits [43]. Hence, the incorporation of hourly dynamic simulations that assess conditions of a building on an hourly basis is crucial for holistic and efficient retrofits [44]. In the realm of digital twins, Tanase and Croitoru (2025) and Jradi et al. (2023) highlighted the importance of incorporating real-time monitoring of building data in existing building management to help a building's managers and owners make actionable performance optimization decisions [7,10].

Monitoring systems and associated programming of digital twins can be complex and costly when not installed during construction, highlighting the need for simple user-friendly frameworks for data collection and modeling in existing buildings [10]. Recent studies further emphasize hierarchical digital twin architectures within integrated energy systems, where they highlight that heterogeneous real-time data streams can be transformed into integrated virtual models and subsequently used for monitoring, optimization, and intelligent decision-making. Hence, along with virtual energy simulations that substantiate retrofits proposed based on IEQ analyses, the integration of actual energy meters of the building into the digital twin would provide significant value to the digital twin's role in detecting energy consumption [24,45]. In the realm of architectural buildings, a BIM-based approach of low-code platforms supports the configuration of digital twins, making them adaptable to changing requirements and environments [46]. Hence, low-code platforms allow the creation and operation of digital twins without extensive software engineering expertise, broadening stakeholder engagement [47,48]. Predefined components of low-code platforms simplify the process for non-technical users while allowing digital twins to integrate technologies, such as IoT, AI, and data analytics for enhanced building management and performance optimization [47,49].

2.2. Indoor Environmental Quality (IEQ) as a Driver of Operational Energy Demand

Indoor environmental quality describes the indoor state of a building that affects occupant health and comfort. The acceptability of IEQ is determined by several parameters, including thermal comfort, indoor air quality, lighting conditions, noise levels, and odor. As people spend almost 90% of their time inside buildings, it is essential to maintain good IEQ

to ensure a healthy, productive, and comfortable indoor environment [50]. Standards-based frameworks and certifications highlight the importance of understanding and assessing IEQ parameters to provide healthy and comfortable indoor spaces. For instance, ASHRAE, the American Society of Heating, Refrigerating and Air-Conditioning Engineers, provides IEQ benchmarks that target the general comfort of occupants [50,51]. In that sense, ASHRAE 62.1 and 62.2 define indoor air quality as air that is free from harmful contaminants and high percentages of carbon dioxide [52,53]. Thermal comfort is defined as the state of the mind that expresses satisfaction with the thermal environment. Since it is a subjective and individualistic response, ASHRAE standard 55 considers thermal comfort satisfactory when at least 80% of a space's occupants are satisfied [50,53]. The lighting condition is described as the visual comfort that is achieved by an adequate illuminance level and penetration of daylight, with respect to the space's functions and activities [54]. Noise level relates to occupant distraction and irritation resulting from excessive noise emitted from either machinery or noise transmitted through adjacent spaces and rooms [54,55]. Lastly, odor influences IEQ, as users' comfort and well-being is affected when they constantly experience unpleasant smells [50].

While (IEQ) is positioned within the social pillar of sustainability due to its direct impact on occupant health, comfort, and well-being, current building conditions, such as insulation, airtightness, and ventilation, create a cross-pillar connection with the environmental sustainability of buildings [39,53,56]. Thus, research has highlighted that meeting optimal thermal and light conditions is the most energy-intensive IEQ parameter, as it is highly affected by building conditions [38]. Awolesi et al. (2025) performed a systematic review of 99 studies and highlighted how indoor environmental quality is assessed alongside energy data, indicating that current research increasingly links IEQ assessments with energy performance in sustainability evaluations [38]. Highlighting the link of IEQ to energy consumption, Wang and Zheng (2020) identified IEQ as a major contributor to operational energy use in office buildings [39]. Additionally, Rus et al. (2025) further showed that summer overheating leads to increased cooling demand, highlighting that an indoor temperature reduction by 1 °C could lower emissions by approximately 1.17 kg CO_2e/m^2 [55]. Schroderus et al. (2025) showed that energy retrofits not only reduce energy use and emissions but also improve indoor environmental quality (thermal comfort, reduced drafts, better hygrothermal performance), illustrating a clear overlap between energy and IEQ outcomes [57]. In summary, Perera et al. (2025) demonstrated that IEQ parameters are complex in calibration, as they simultaneously address occupant comfort and energy consumption due to their high dependency on the existing building conditions and occupant behavior [53].

2.3. Fabric-First Retrofit

The fabric-first retrofit methodology in existing architecture refers to improving the building's envelope, including its walls, roof, floors, and windows, before considering energy efficiency measures tied to mechanical systems [58,59]. Tanase and Croitoru (2025), Mirzabeigi et al. (2024), and Rached and Anber (2022) highlighted the impact of existing building retrofits in reducing energy consumption and resisting climatic conditions through passive strategies, such as upgrading insulation and airtightness [7,20,60]. Hence, this approach is effective in achieving maximum environmental and social impact by prioritizing the reduction in energy demand [61]. Applying deep retrofits to existing buildings requires a detailed assessment of the pre-retrofit conditions, including simulations for energy consumption and thermal properties [62]. Santarsiero et al. (2024) performed a detailed energy audit evaluating actual energy consumption, building envelope characteristics, and heating and cooling systems to determine the building's energy performance and

highlighted potential energy savings through targeted retrofit measures [44]. The results of the fabric-first approach significantly reduce energy consumption by enhancing the thermal performance of the building envelope. For instance, upgrading insulation and glazing can lead to a 50% reduction in heating demand in existing buildings, preparing them for low-carbon heating systems [40]. Additionally, building retrofitting is a wide domain that is not limited to improving energy efficiency, as it also includes further economic, environmental, and social improvements [63,64]. Economically, retrofitted buildings acquire higher market values and are appealing to their owners. Environmentally, they include energy consumption alleviation and carbon emissions reduction [65]. The social benefits are tied to building occupant comfort, productivity, and health [65,66].

2.4. Post-Retrofit Performance Verification of Digital Twins

The integration of advanced technologies, including IoT sensors and BIM, supports post-retrofit analysis of existing buildings, where real-time monitoring of indoor comfort and energy performance is essential for validating retrofit efficiency and effectiveness [67]. In that sense, in addition to providing a pivotal role in informing retrofit decisions, an established digital twin allows post-retrofit analysis, leading to a closed loop centering on energy efficiency and IEQ diagnoses, retrofit recommendations, and post-retrofit tracking over the operational lifecycle [10,67,68]. Hence, post-retrofit monitoring plays an important role in refining retrofit strategies to continuously reduce greenhouse gas emissions in existing buildings, ensuring that energy-saving measures are effectively implemented and maintained over time [7,10,69]. For instance, a study on a government administrative complex in Riyadh, a city with a hot arid climate, demonstrated that post-retrofit monitoring confirmed energy savings of 31.7% in the first year, exceeding initial projections [70]. Meanwhile, in South Korea, monitoring of an envelope retrofit showed a 14.7% reduction in electricity consumption in the first year, highlighting the importance of empirical data in assessing retrofit effectiveness [71].

3. IEQ Digital Twin Framework

Building on the insights of the literature review, this research proposes a digital twin framework with the aim of deploying indoor environmental quality (IEQ) mapping as a data-based driver to overcome static and partial analyses of IEQ and guide retrofit decision-making. Within the framework structure, holistic IEQ parameters, including thermal comfort, air quality, lighting, and noise, are continuously monitored and assessed against benchmarks derived from IEQ evaluation standards, such as ASHRAE and CIBSE thresholds, to detect deviations that indicate occupant discomfort and operational inefficiencies. The framework highlights these deviations as diagnostic alerts that reveal underlying building envelope performance issues affecting its ability to resist outdoor climatic conditions, leading to high HVAC reliance. Therefore, this spatial and temporal monitoring process mapping of IEQ conditions allows the identification of inadequate performance patterns across building spaces and supports targeted retrofit prioritization. Within the framework, monitored performance data are translated through seasonal analyses, diagnostic patterns, and energy consumption simulations into a retrofit decision-making structure that aligns with fabric-first principles, where envelope-based interventions are prioritized to address the root causes of occupant discomfort and energy inefficiency before mechanical system upgrades are considered. As shown in Figure 1, the framework evaluates the effectiveness of implemented retrofitted measures through post-retrofit IEQ and performance analysis, creating an operational closed loop in which building performance is continuously assessed. Thus, through the proposed data-driven workflow, the framework positions digital twins

as decision-support systems capable of linking IEQ monitoring, performance verification, and retrofit prioritization [23,26].

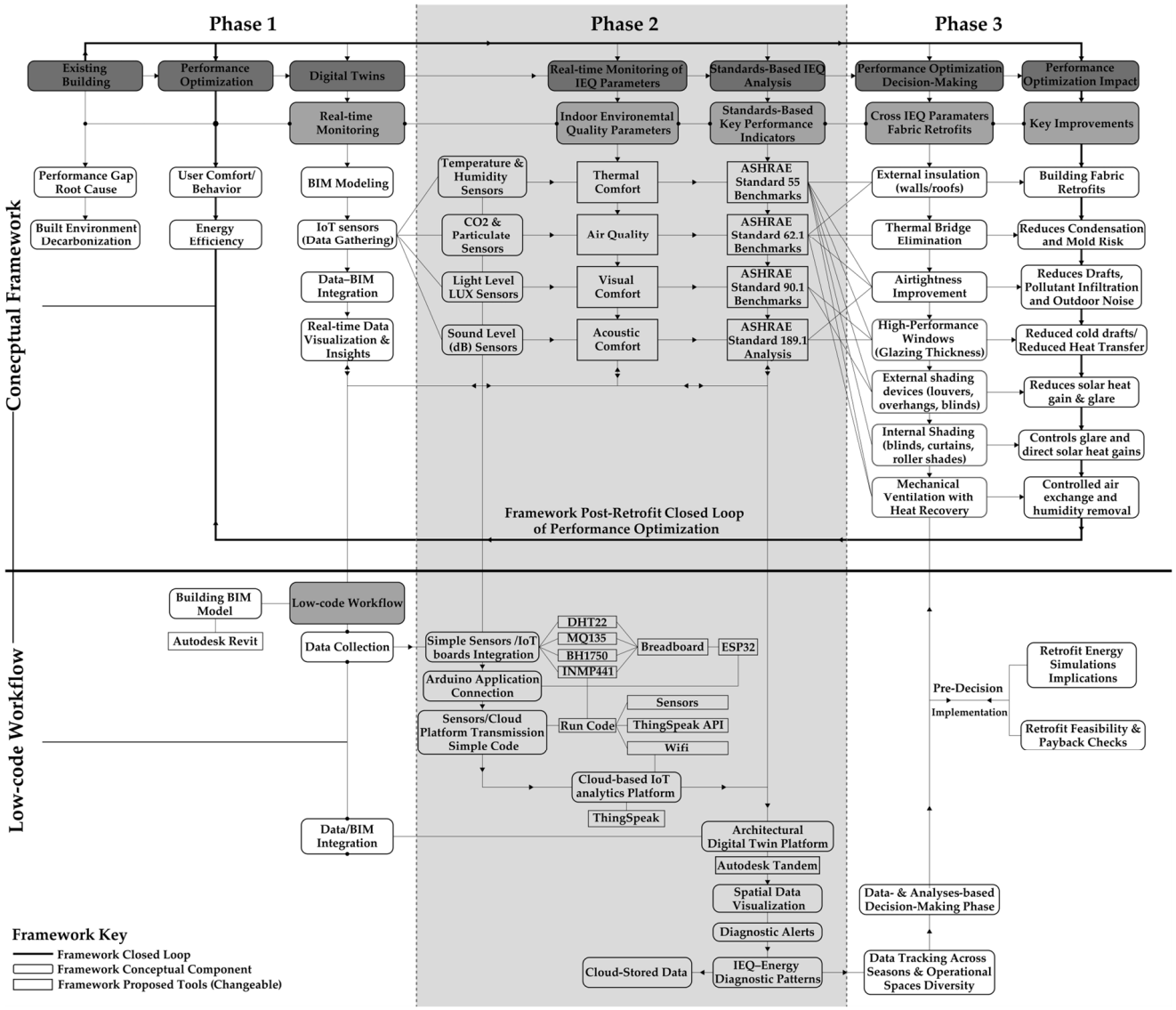


Figure 1. Framework of conceptual synthesis. The grey colors are used to visually highlight the three phases and to identify the hierarchal categorization of the framework.

4. Methodology

4.1. Framework Validation Overview

The validation process experiments with the framework synthesis on an office space that is located within an educational building on a university campus. The main aim is to test the low-code workflow that is user-friendly for architects to develop a digital twin using simple sensors, BIM models, and an architecture-oriented digital twin platform to assess IEQ, generate retrofit decisions to enhance occupant comfort, and reduce energy consumption. Consequently, the validation process encounters three main phases, which are ordered as digital twin model development, IEQ monitoring, and standards-based assessment, and retrofit decision-making. The first phase is to develop the digital twin through a simple data acquisition prototype that senses IEQ parameters, including thermal comfort, air quality, noise levels, and lighting exposure. In order to link the sensed data to the digital twin platform, simple coding takes place to deliver the sensed data to a

cloud-based IoT analytics platform, which is an intermediary between the two. Afterwards, acquired real-time data is visualized in BIM model of the office space through Autodesk Tandem, a cloud-based architectural platform that transforms BIM models into operational digital twins for buildings.

The second phase analyzes the monitored holistic IEQ parameters of the office to leverage the full potential of Autodesk Tandem's flexible capabilities in analyzing sensed data against set benchmarks. In that sense, the set benchmarks are derived from the corresponding ASHRAE standard of each IEQ parameter. This constant strategy of standards-based IEQ allows the digital twin to store IEQ off-benchmark alerts that highlight the need for performance optimizing interventions that simultaneously enhance occupant comfort and limit high HVAC and artificial lighting dependency. Additionally, assessment during different seasonal climatic conditions is considered to develop IEQ condition diagnostic patterns through different temporal off-benchmark alerts.

The third phase includes a decision-support layer that leverages the digital twin's findings as a guide for developing a data-driven retrofit strategy. As digital twins include spatial characteristics, building materials specifications, and real-time IEQ operating data, this synergy sheds light on various building spaces where different envelope conditions and characteristics need to be evaluated and upgraded. Additionally, this phase includes defining cross IEQ parameters and retrofitting passive strategies, where energy-oriented retrofits, such as glazing upgrades and shading devices, undergo energy simulations to identify their impact on energy consumption. Hence, this phase positions digital twins as tools for guiding building envelope retrofits to overcome increased reliance on HVAC and mechanical systems when mitigating outdoor climatic conditions.

4.2. Case Study Context Considerations

The selected case study, through which the framework is validated, is an office space within an educational building located on a university campus in the New Administrative Capital of Egypt, shown in Figure 2, and is characterized by a hot arid climate (as shown in Table 1) and operational patterns that rely heavily on HVAC cooling from mid-spring to mid-autumn. The building is predominantly covered with curtain wall facades, which intensify solar heat gains for all offices, classrooms, and studios. As a result, the characteristics of the building make managing indoor environmental quality (IEQ) critical for maintaining occupant comfort while reducing excessive cooling demand. The chosen rooms shown in Figure 3 are an office and a classroom on the same floor with different sizes, orientations, and occupancies. The office space (A2.510) has a southern orientation, is sized 4.5 × 4.7 SQM, and is occupied by four academics. The office, being on the highest floor, benefits from a 1 m cantilevered top of concrete that acts as a shading device along with vertical louvers shown in Figure 3a. The classroom (A2.508) has a northern orientation, is sized 11.6 × 10.5 SQM, and is usually occupied by 40 students and four academics. The classrooms have the same cantilevered top slab and vertical louvers shown in Figure 3a.

Table 1. Temperature ranges in Egypt across all seasons.

Season	Day Temperature Range	Night Temperature Range
Winter (December–February)	18–21 °C	9–12 °C
Spring (March–May)	23–32 °C	12–18 °C
Summer (June–September)	34–37 °C	21–26 °C
Autumn (October–November)	26–32 °C	16–20 °C

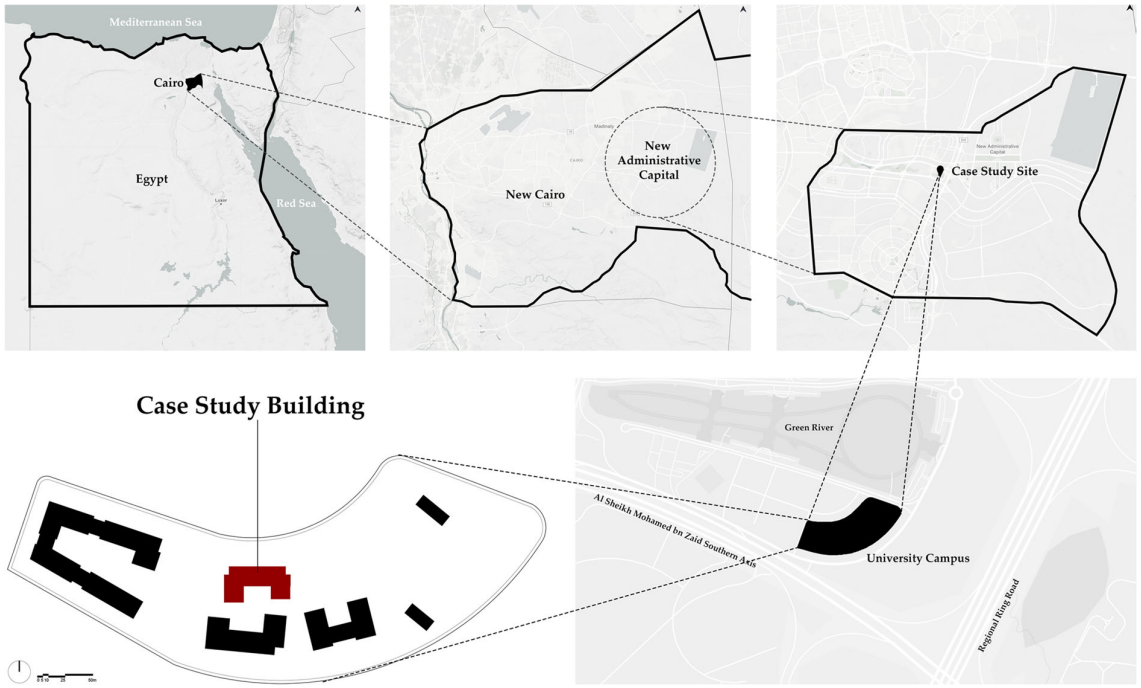


Figure 2. Context of Case Study (Basic maps by © Mapcreator, © OpenStreetMap, © AW3D30 (JAXA)).

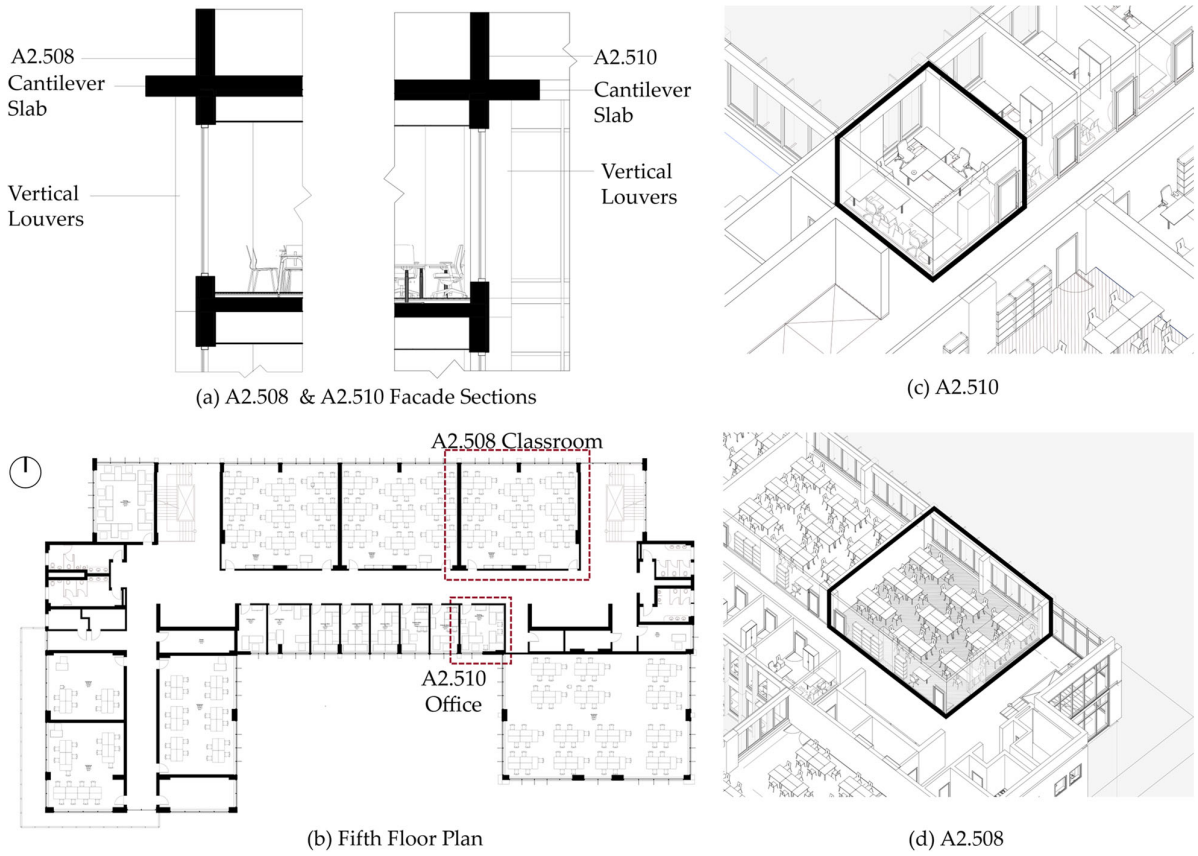


Figure 3. Case study with selected indoor spaces.

Case Study's Climate

According to the Köppen climate classification [72], Egypt has a hot desert climate that is characterized by minimal annual rainfall, high summer temperatures, and intense solar

radiation. Moreover, the climatic conditions imply low humidity and high evaporation rates. These conditions result in significant thermal stress and notable day and night temperature variations. These temperature variations, referred to as diurnal temperature swings, present opportunities for passive thermal regulation.

4.3. Phase 1: Digital Twin Development

The development of the digital twin in this study is based on a multi-layered model that connects multiple IEQ sensor data to an architectural digital twin platform, which is Autodesk Tandem. Autodesk Tandem, a cloud-based platform, equips a BIM model with sensor configurations as API-based data streams that receive real-time sensor data from external sources and integrate with the digital twin model for live monitoring and visualization. Therefore, the model includes interoperable synergy between hardware, software, and middleware in a low-code methodology in order to develop the digital twin. The development process includes six main phases through which real-time IEQ data are captured and displayed on a BIM model. Parts 2 to 6 of the first phase are replicated for each indoor space that is targeted for monitoring within the building.

4.3.1. BIM/Autodesk Tandem Preparation

The development of the digital twin begins with creating a BIM model of the building and spaces that are targeted for monitoring using Autodesk Revit. Then, the model is uploaded to Autodesk Tandem, where sensor connections are created and assigned to relevant sensing unit components within each space. This step creates the necessary API endpoints on Autodesk Tandem to receive real-time data and serves as a preparatory step for system integration.

4.3.2. Data Acquisition

An IEQ-sensing unit was developed to capture multiple environmental parameters within the physical space. The study uses ESP32 microcontrollers connected to temperature, humidity, air quality, sound, and light sensors to capture holistic IEQ insights. The ESP32 microcontroller, connected to a breadboard, integrates DHT22 for temperature and humidity measurement, MQ135 for air quality estimation, BH1750 for illuminance measurement, and INMP411 for sound level detection. The utilized sensors are pre-calibrated by their manufacturers and are ready to measure their corresponding IEQ parameters. However, the MQ135 sensor was calibrated using a clean-air reference measurement to determine the baseline sensor resistance (R_0). Then, the sensor resistance (R_s) was calculated from the measured analog voltage, and the ratio R_s/R_0 was determined. Following the methodology and sensitivity characteristics presented in the MQ135 datasheet, this ratio was used to estimate CO_2-equivalent concentration values expressed in parts per million (ppm), which are used as indicative estimates for trend monitoring rather than precise CO_2 measurements. Additionally, the INMP441 digital microphone is configured using the sensitivity characteristics provided in the manufacturer's datasheet. Audio samples acquired through the I^2S interface were processed to determine the signal amplitude using the root mean square (RMS) value. The measured amplitude was converted into estimated sound pressure levels (dB SPL) using the microphone sensitivity specification of approximately −26 dBFS at 94 dB SPL. Hence, this calibration derives indicative sound level measurements from the microphone.

4.3.3. Microcontroller Programming

The sensors are controlled and powered through an ESP32 microcontroller, which continuously reads real-time data of IEQ. The ESP32 is powered via a USB connection and is programmed using Arduino IDE to run a code that reads sensor data at 2.5 min

predefined intervals. Within this process, ChatGPT (GPT-5) was used as an AI-assisted development tool to support the generation of the base code that translates the data from the utilized sensors connected to the ESP32 microcontroller, where the generated code had been reviewed, tested and validated before deployment into the developed framework pipeline. Additionally, the necessary calibration of sensors took place according to their manual sheets; for example, the air quality sensor readings were calibrated using an empirical model to estimate CO_2-equivalent values. Then, the code utilizes the WiFi connectivity of ESP32 to transmit the collected data for logging and storage on a cloud-based IoT platform through HTTP GET requests authenticated via an API key.

4.3.4. Cloud Data Management

ThingSpeak is utilized as a cloud-based platform to store, organize, and visualize real-time sensor data. Each environmental parameter is assigned to a dedicated field within a ThingSpeak channel to ensure a structured data logging and real-time monitoring scheme. A separate channel is created and assigned for different spaces that are being monitored. This structure creates a middleware development that transmits the live monitored data to be visualized and analyzed on Autodesk Tandem.

4.3.5. Data/Digital Twin Integration

A Python-based middleware script, using python 3.13, was developed to allow data exchange between ThingSpeak, a cloud-based data logging platform, and Autodesk Tandem, a cloud-based digital twin platform. Reviewed, tested and validated before deployment, ChatGPT (GPT-5) was used to build the base script structure. The Python script was developed to automatically get IEQ sensor data from ThingSpeak and transfer it to Autodesk Tandem, enabling real-time synchronization between the physical environment and the digital twin model. The script provides real-time data processing and integration, where it operates continuously with a set time interval to retrieve the latest sensor data from ThingSpeak via its API and transmit it to Autodesk Tandem using authenticated HTTP requests. The script contains data streams from each tracked IEQ parameter that is predefined on Autodesk Tandem according to the previously defined BIM/digital twin preparatory phase. Thus, this middleware layer serves as a bridge between these independent platforms to ensure synchronized and seamless real-time data exchange.

4.3.6. Digital Twin Data Configuration

The incoming data streams in Autodesk Tandem are configured by mapping each received payload to its corresponding IEQ parameter using predefined JSON paths. This final phase ensures that the uploaded sensor values are correctly interpreted as real-time measurements for the IEQ variables, such as temperature and air quality. Additionally, timestamp fields are assigned to each parameter to preserve the temporal context of the data and enable accurate time-series visualization within the digital twin environment. This phase is important to ensure that the received data for the Tandem model are properly structured and identified as meaningful IEQ data. Additionally, external environmental data is integrated into the digital twin through a Python-based system to support a direct comparison between IEQ parameters and outdoor climate. Real-time outdoor weather data is obtained from a reliable API, such as Open-Meteo. Then, weather data, including temperature, humidity, and wind speed, is directly transferred to Autodesk Tandem. Lastly, as shown in Table 2, encoded values for weather conditions (sunny, cloudy, or overcast) and seasonal classification (winter, spring, summer, or autumn) are created to further contextualize the digital twin model.

Table 2. Digital twin's encoded values for weather conditions and seasonal variations.

Encoded Value	Weather Condition	Season
1	Clear	Winter
2	Cloudy/Partly Cloudy	Spring
3	Fog	Summer
4	Rain	Autumn

4.3.7. Data Flow and System Operation

The developed system demonstrates key characteristics essential for overcoming digital twin application challenges, including the ability to integrate heterogeneous platforms through effective interoperability. The architecture of the developed system adopts a modular workflow, which allows different parts comprising the digital twin, such as sensing units, data processing, and visualization layers, to operate independently while maintaining seamless system functionality. Additionally, the system offers a comprehensive workflow that allows smooth replication alongside scalability for future expansion through the integration of additional sensors, spaces, or functionalities.

In this research case study, as described in Table 3, the digital twin system operates through a continuous data pipeline that links the actual IEQ of a physical space with its digital representation. Sensor data is acquired by the ESP32 and transmitted via WiFi to a cloud-based platform for storage and management. The data is then transferred through a Python script, acting as a middleware layer, and delivered to Autodesk Tandem, where it is then integrated into the digital twin environment. Table 3 defines all the tools associated with the validation process and is ordered according to the sequence of the digital twin development.

Table 3. Digital twin's development tools.

Tools/Methods Categories	Tool	Task
Building Information Modeling	Autodesk Revit	Building Information Modeling (BIM) software, Autodesk Revit 2023, is used to create detailed digital models of buildings, including their design, structure, and MEP systems data.
Digital Twin Platform	Autodesk Tandem	A cloud-based digital twin platform, accessed in 2026, used to create and manage digital twins of buildings, helping track and maintain building data throughout its lifecycle.
IoT Sensors	DHT22	A sensor that measures temperature with ±0.5 °C accuracy and humidity with ±2–5% accuracy, manufactured by Aosong Electronics (ASAIR), Guangzhou, China.
	MQ-135	A gas sensor that detects air quality and harmful gases. It detects multiple gases, such as ammonia (NH_3), carbon dioxide (CO_2), benzene, and smoke, manufactured by Zhengzhou Winsen Electronics Technology Co., Ltd., Zhengzhou, China. When generating an estimated CO_2 concentration, it requires calibration to read a specific gas concentration.
	BH1750	A sensor that measures light intensity (lux) and can detect light levels from 0 to 65,535 lux, manufactured by ROHM Semiconductor, Kyoto, Japan.
	INMP441	A digital microphone sensor for capturing sound intensity, manufactured by InvenSense, San Jose, CA, USA (now part of TDK Corporation).

Table 3. *Cont.*

Tools/Methods Categories	Tool	Task
Microcontroller Programming	ESP32	A microcontroller with built-in WiFi and Bluetooth, manufactured by Espressif Systems, Shanghai, China.
	Breadboard	A board used to build and test electronic circuits without soldering.
	Arduino IDE	A software application, version 2.3.7, is used to write, edit, and upload code to microcontrollers, including Arduino boards and ESP32.
Cloud Data Management	ThingSpeak	An online cloud platform used to collect, store, and analyze data from IoT devices in real time, developed by MathWorks, Natick, MA, USA.
Data/Digital Twin Integration	Python	A programming language used to create software, automate tasks, and analyze data. The utilized Python version is 3.13 (64-bit).
Weather Data	Open-Meteo	An open-source weather data service that provides accurate forecasts, historical data, and climate information through simple API, developed by Open-Meteo, Zurich, Switzerland.

4.4. Phase 2: IEQ Standards-Based Evaluation and Monitoring

For the IEQ standards-based evaluation and monitoring, guidelines are identified from relevant standards for each IEQ parameter to assess acceptable comfort levels and thresholds. It is important to investigate adaptive IEQ standards and local studies. This methodology does not rely on universal thresholds; instead, it highlights comfort ranges that adapt to geographic and cultural context. This reflects adaptive guidelines that allow for climate and context-specific application. Thus, these benchmarks serve as indicators of whether indoor conditions are acceptable or if intervention is needed.

4.4.1. Thermal Comfort Evaluation and Threshold Definitions

This study evaluates indoor thermal conditions in office and classroom spaces using a real-time, data-driven approach based on the adaptive comfort framework as defined in both ASHRAE standard 55 and CIBSE TM52, which apply to naturally ventilated and free-running buildings [73,74]. Rather than applying fixed temperature thresholds, comfort limits are dynamically derived as functions of the outdoor running mean temperature of a context climate, along with individual clothing and psychological thermal sensation. Therefore, these interconnected variables lead to variations in an occupant's adaptation to the thermal environment. The adaptive comfort method is important because it reflects the dynamic relationship between occupants and their thermal environment, including behavioral, physiological, and psychological adaptation instead of assuming fixed comfort conditions. Although the case study building is equipped with HVAC, the analysis and data collection are processed without mechanical cooling to allow a standards-based application of the adaptive comfort model. Hence, the building is operated in a free-running mode to collect real-time indoor environmental data under passive conditions. This approach enables the assessment of thermal comfort using adaptive models while indicating the building's ability to resist outdoor climate conditions and reduce dependence on mechanical cooling [38,73,74].

In addition to the adaptive comfort model, the findings from a two-year local field study in Cairo conducted in a typical typology building are incorporated to refine the interpretation of comfort during active seasons of the university. The study used the adaptive comfort approach to investigate real occupant thermal comfort through two years in

multiple universities in naturally ventilated and mixed-mode buildings. Thermal comfort is evaluated by calculating the percentage of occupants who fall within an acceptable range of satisfaction, scaled by −1 to +1 on the thermal sensation scale. Then, the author highlighted measured temperatures at which a high percentage of occupants reported acceptable thermal sensations (slightly cool, neutral, slightly warm). Thus, thermal sensation questionnaires, along with actual measured temperature ranges, represent occupants who feel comfortable, and their proportion indicates the overall comfort level [26,75].

The data show that more than 50% of people felt "neutral" at indoor temperatures between 21 and 26 °C, and this range resembles the 80% satisfactory acceptable comfort range (ranging from slightly cool to slightly warm). After 27 °C, the level of comfort starts to decline. However, this represents the peak comfort zone rather than the full comfort range, as occupants still report acceptable conditions at higher temperatures, especially in naturally ventilated buildings [26,75].

This approach highlights the importance of climate-specific calibration in assessing building performance. The comfort thresholds are defined according to the active academic seasons, during which the university operates at full teaching capacity, reflecting the nature of the building typology [26,73,75].

The temperature data collection process is performed in accordance with ASHRAE standard 55, ensuring that temperature sensors have an accuracy of ±0.5 °C and humidity sensors ±5% relative humidity. Measurement locations are selected based on the standards' guidelines that define central room positions and areas expected to experience extreme thermal conditions. Additionally, the continuous monitoring of temperature and humidity values is required to be collected through intervals not exceeding 15 min over at least one month, according to the building automation system section [73].

Regarding the humidity factor, thresholds are derived in accordance with guidance from CIBSE Guide B2, which suggests an acceptable relative humidity range of approximately 40–70%. It identifies an upper limit of 60% relative humidity with air conditioning. Additionally, relative humidity of 30% or lower is acceptable for short periods of time [76]. Regarding the ASHRAE standard 62.1, it mentions that indoor humidity must not exceed a dew point temperature of 15 °C for spaces that are occupied and unoccupied zones at any time [77]. This can be interpreted in terms of thresholds that preserve an acceptable relative humidity of 15 °C at the dew point limit based on air temperature, ranging from 70% at 20 °C to below 40% at 30 °C [77].

4.4.2. Air Quality Evaluation and Threshold Definitions

Air quality is assessed in terms of carbon dioxide concentrations according to ASHRAE standard 62.1. This amount of CO_2 in an indoor space is an indicator of ventilation effectiveness and occupant acceptance of odorous bioeffluents (body odors). CO_2 concentrations of approximately 700 ppm above outdoor air levels indicate an outdoor air ventilation rate of about 7.5 L/s/person. At this concentration and air ventilation rate, the indoor air will feel comfortable for about 80% of people, since the ventilation effectively reduces human odors to a level that most visitors find acceptable. Since outdoor CO_2 levels are typically 300–500 ppm, indoor levels of about 1000–1200 ppm in spaces with sedentary occupants generally indicate that most visitors will find the air quality acceptable. It is important to address that CO_2 concentration is not the only indicator of the overall air quality, since it does not account for indoor pollutants, such as volatile organic compounds released from building materials and furniture [77–79].

Additionally, the standard defines maximum CO_2 limits according to indoor space function, area, outdoor air rate, and occupancy. These limits are identified by the standards

as maximum CO_2 above ambient, which refers to the allowable increase in indoor CO_2 concentration above outdoor levels [77].

4.4.3. Visual Comfort Evaluation and Threshold Definitions

Necessary lighting is evaluated by comparing measured illuminance levels with recommended values from the Illuminating Engineering Society (IES) according to the functions and activities that takes place in different rooms of a building. Additionally, ASHRAE 90.1 presents a guide that relates to operational aspects. It requires daylight-responsive lighting controls to ensure that artificial lighting is reduced or switched off when sufficient daylight is available [80]. Thus, the analysis of illuminance in different zones of a building supports considering both visual comfort and energy-efficient lighting performance [80–82]. The defined thresholds derived from IES are 500 lux for teaching spaces and 750 lux where drawings and detailed tasks take place. Regarding teaching staff offices, a 300–500 lux range is sufficient for computer-based activities, writing, and conducting meetings [81].

4.4.4. Acoustics Evaluation and Threshold Definitions

According to ANSI/ASA S12.60, background noise in an unoccupied classroom should not exceed 35 dB, mainly accounting for sounds from building systems and outside sources, and may reach 40 dB in high-noise locations [83]. This guideline supports a quiet environment that allows clear communication for teaching areas and focused work tasks in office spaces [83].

4.4.5. IEQ Thresholds Deviation and Exceedance Alerts

The identified IEQ thresholds, based on relevant standards for thermal comfort, indoor air quality, visual comfort, and acoustic conditions, are integrated into Autodesk Tandem through configured data streams. These thresholds are assigned to each IEQ parameter across the selected case study spaces. These thresholds are assigned to generate alerts if IEQ tracked values do not fall within the acceptable comfort levels for an assigned time limit. Thus, the platform then provides real-time heat mapping (plan and isometric view) and temporal graphs that illustrate the daily performance of each parameter.

4.5. Phase 3: Retrofit Decision-Support Workflow

4.5.1. IEQ Diagnostic Patterns Analysis

As the outdoor environment conditions are monitored alongside actual IEQ data, this synergy enables analyses and offers insights into how indoor spaces respond to external climate conditions. These climate conditions include weather data, conditions, and season classification ranges that directly affect the indoor environment. Furthermore, the building's orientation and massing response to the outdoor climate conditions provide different IEQ/outdoor climate correlation for each indoor space that is monitored [38]. This layer of real-time data integration supports comparative analysis between multiple spaces where it helps identify diagnostic patterns that can guide targeted improvements in indoor environmental performance. Thus, as shown in Table 4, IEQ deviations are analyzed by comparing measured performance against established comfort benchmarks, where discomfort measures are assessed in terms of frequency, duration, and spatial distribution [26,82,84–86]. To further validate the digital twin patterns, a psychrometric chart analysis of the baseline condition will be included to verify the findings related to the percentage of uncomfortable hours. The results are compared with the data identified by the digital twin model. Since data collection of IEQ takes place while the building is free running, free-running mode energy simulations are conducted to replicate the HVAC-off conditions during data collection to allow an independent assessment of time not meeting

the adaptive comfort model during occupied hours, providing additional verification of the digital twin results.

Table 4. Collective IEQ deviation patterns analyses against the literature's adapted variables [26,84,85].

Room/Zone	Building Characteristics		IEQ Parameter	Comfort Range	Monitored Pattern	Comfort Deviation Duration/Day	Frequency/Year (Seasonal Occurrence)
Monitored Room/Zone	Orientation		Temperature				
	Window-to-Floor Ratio (WFR)		Humidity				
	U-Value		CO_2 Concentration				
	R-Value		Light				
	Glazing Type		Sound				

4.5.2. Root Cause Diagnosis of IEQ/Energy Inefficiency

To diagnose the observed IEQ patterns that do not conform to the adapted standards benchmarks, a rule-based approach is used to identify underlying causes relevant to building's envelope and passive design features, as shown in Tables 5–8. The analysis of real-time IEQ data identifies relationships between indoor environmental conditions and physical characteristics of an existing building. For example, high indoor temperatures indicate insufficient shading and poor window performance [26,85,86].

Table 5. Overheating root cause analysis according to comfort deviation ranges with outer wall's U-value, R-value, and glazing type against adequate values for a hot arid climate (Cairo, Egypt).

Room/Zone	Season (Day Outdoor Temperature Range)	Shading Elements Sufficiency	Solar Heat Gain $Q = A \times SHGC \times (I_{direct} + I_{diffuse} + I_{reflected})$	Sun Altitude (Average/Season)	WFR	U-Value	R-Value	Glazing Type
Room	Winter (December–February) 18–21 °C							
	Spring (March–May) 23–32 °C							
	Summer (June–September) 34–37 °C							
	Autumn (October–November) 26–32 °C							

Table 6. High CO_2 concentration root cause analysis according to comfort deviation ranges.

Room/Zone	CO_2 Concentration	Air Change Rate	Occupancy Density	Window Opening/Ventilation Status
Room				

Table 7. Visual comfort noncompliance root cause analysis according to comfort deviation ranges.

Room/Zone	Optimal Lux	Measured Lux	WFR	Sky Condition/Season	Window Orientation	Obstruction
Room						

Table 8. Acoustic comfort noncompliance root cause analysis according to comfort deviation ranges.

Room/Zone	Function	Optimal Noise Range	Measured Noise Level	External Noise Source (Windows Opened)	Internal Noise Source	Envelope Insulation Quality
Room						

4.5.3. Building Fabric Retrofit Strategy

According to the IEQ diagnostic patterns, along with the grounded root causes, a fabric-first approach based on the principles of the Passive House Institute emphasizes optimizing the building envelope to reduce energy demand and improve IEQ [87]. A case study in Changsha, China, experiencing hot summers with significant cooling demands, similar to the research case study, found that retrofitting a building to the EnerPHit standard reduced heating energy demand by 90% and cooling energy demand by 73%, demonstrating significant energy and carbon savings in a hot climate [88]. As shown in Table 9, the building's fabric retrofitting approach considers implementing passive design features to the envelope to reduce direct reliance on mechanical systems as a solution for occupant discomfort. Hence, this retrofit strategy is effective in a hot arid climate, as it addresses the root cause of high energy demand and occupant discomfort [85,86].

Table 9. Retrofit approaches to achieve adequate IEQ and low energy consumption.

IEQ Issue	Building Retrofit Approaches
Overheating	Internal shading devices (blinds, curtains)
	Reflective films on glazing
	External shading systems (louvers, overhangs)
	Low-E/solar control glazing upgrade
	Building envelope insulation improvement (thermal bridge)
	Airtightness
Poor Ventilation	Room occupant ventilation control
	Window operation strategies/schedules
	Increase window area/openable ratio
	Incorporation of ventilation shafts or passive systems
Visual Comfort	Daylight-responsive lighting controls
	Increase window size (WFR)
	Light shelves implementation
Acoustics	Soft furniture
	Acoustic panels (internal)
	Space zoning (separating noisy areas)
	Improve wall sound absorption and isolation
	Airtightness
	Upgrade facade glazing

4.5.4. Decision-Support Framework

To support practical implementation, a staged approach adopting a phased evidence-based intervention is used, as illustrated in Table 10 [63,89]. Thus, the proposed retrofit strategies are categorized into immediate, short-term, and long-term interventions. Immediate interventions include simple occupant behavior to manually adjust and optimize internal blinds, windows, and lighting. Short-term interventions focus on low-cost and minimal actions that can be implemented without major alterations to the building's fabric. These minimal interventions include an occupant's behavioral and operational adjustments, control strategies, and internal shading. Conversely, long-term interventions include deep fabric upgrades, such as improved envelope insulation, glazing insulation, and external shading. These long-term interventions require higher investment and longer implementa-

tion time. Throughout the process of retrofit implementation, short-term approaches can be assessed by digital twins. This monitoring process after short-term retrofits is important to assess their effectiveness while deciding if implementing long-term retrofit approaches are necessary to further achieve maximum comfort levels and energy efficiency [23,89].

Table 10. Ranking the established retrofit approaches from Table 9 into immediate, short-term, and long-term to support the phased retrofit process [63,89].

IEQ Issue/Retrofit Approach	Immediate Decisions	Short-Term Decisions	Long-Term Decisions
Overheating	Window operation adjustment	Internal shading devices	low-E/solar control glazing upgrade
	Internal shading use	Reflective films on glazing	External shading systems
	HVAC usage	Automated HVAC control based on room occupancy and temperature	Building envelope insulation improvement (thermal bridge)
			Airtightness
Poor Ventilation	Room's occupants ventilation control	Window operation strategies/schedules	Increased window area/openable ratio
	HVAC usage		Incorporation of ventilation shafts or passive systems
Visual Comfort	Floor plan customization	Daylight-responsive lighting controls	Increased window size (WFR)
	Artificial lighting control		Light shelves implementation
Acoustics	Space zoning (separating noisy areas)	Acoustic panel installations (internal)	Improved wall sound absorption and isolation
		Soft furniture	Upgraded facade glazing

4.5.5. Retrofit Scenario Evaluation and Feasibility

The chosen retrofit decisions are simulated virtually to assess their effectiveness in overcoming the root cause of poor IEQ, and potential impact of improving multiple IEQ parameters on energy consumption and occupant comfort is observed [23,38]. This step validates that improving the envelope through targeted retrofits is feasible and effective when implemented [63]. Following energy consumption simulations, annual building energy consumption is then calculated using,

$$E_a = EUI \cdot A_f \cdot N, \quad (1)$$

where the simulated energy use intensity (EUI) is multiplied by the typical floor area (A_f) and the number of floors (N). The annual electricity cost is then calculated using,

$$Ca = E_a \cdot T \quad (2)$$

where T represents the applicable Egyptian electricity tariff. The performance of each retrofit scenario is evaluated against the baseline using the energy reduction percentage,

$$R_e\ (\%) = (EUI_b - EUI_r / EUI_b) \cdot 100, \quad (3)$$

where (EUI_b) resembles the baseline condition and (EUI_r) resembles the retrofit condition to determine annual energy reduction, while annual financial savings were calculated through,

$$S_c = C_{a\text{-}base} - C_{a\text{-}retrofit} \quad (4)$$
$$=(EUI_b \cdot A_f \cdot N \cdot T) - (EUI_r \cdot A_f \cdot N \cdot T),$$

allowing both energy and cost reductions to be quantified comparatively.

5. Results

5.1. System Architecture of the Sensing Unit Overview

The indoor environmental quality (IEQ) sensing unit was developed using an ESP32 as the central processing and communication platform, integrating multiple sensors to monitor key environmental parameters. These included DHT22 for temperature (°C) and relative humidity, MQ135 for estimated CO_2 concentration (ppm), BH1750 for measuring illuminance levels (lux), and INMP441 for estimated noise levels (dB). The implementation of the sensing unit incorporated multiple breadboards to facilitate flexible prototyping and reliable connectivity between components. Power distribution was organized through dedicated rails, including 3.3 V, 5 V, and grounded to the appropriate voltage supply of each sensor. Additionally, certain sensors, such as the BH1750 light sensor and the INMP441 microphone, were positioned directly on the breadboard facing upwards and remained unobstructed to ensure accurate environmental exposure and measurement reliability. As shown in Figure 4, all sensors share a common ground, while power distribution was managed using both 3.3 V and 5 V supply lines, depending on sensor requirements; subsequently, the sensors were connected using digital, analog, and I^2C communication protocols according to each sensor's manual sheet. Data acquisition was performed by the ESP32 at regular 2.5 min intervals, and the collected readings were transmitted via WiFi to ThingSpeak and then forwarded to the digital twin environment in Autodesk Tandem using a Python-based integration script. Through Python-based integration, this architecture facilitates automatic and seamless real-time transmission of data on IEQ conditions to the digital twin model. During system development, the INMP441 microphone, using the I^2S protocol that requires continuous data processing and consumes significant memory and CPU resources, caused the ESP32 to crash and reset, as it could not handle multiple sensor readings and WiFi operations simultaneously. Hence, a second ESP32 was dedicated to the INMP441 microphone.

5.2. Digital Twin Model

5.2.1. BIM—Live Data Integration and Analyses

As an architecture-based digital twin platform, the usage of Autodesk Tandem facilitated analysis of captured data alongside spatial visualization over the BIM model of the building, as shown in Figure 5a,b. A key feature of the digital twin model was the implementation of the standards-based IEQ framework that was developed through defining acceptable comfort thresholds for each monitored parameter. These thresholds established performance evaluation criteria for the digital twin model to continuously evaluate IEQ parameters and trigger alerts when deviations occurred. This capability allowed the digital twin to move beyond a monitor of IEQ into an active assessment tool; consequently, it aided in identifying underperforming conditions that were affecting each room in real time, as shown in Figure 3c.

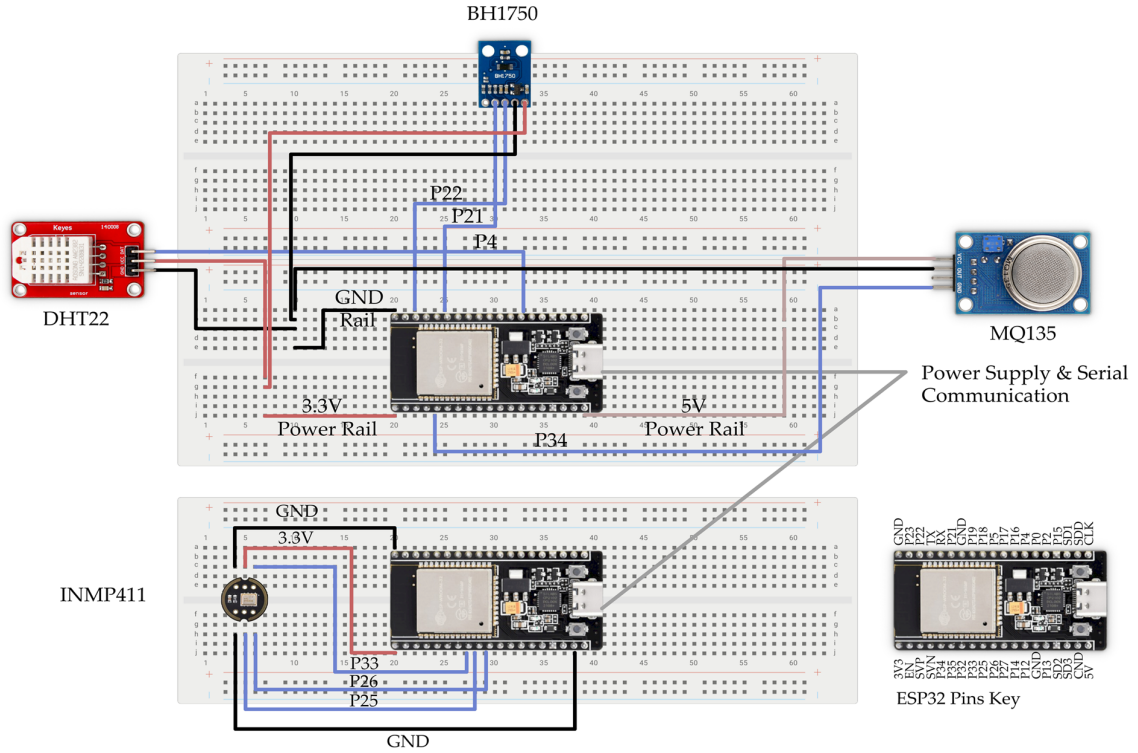
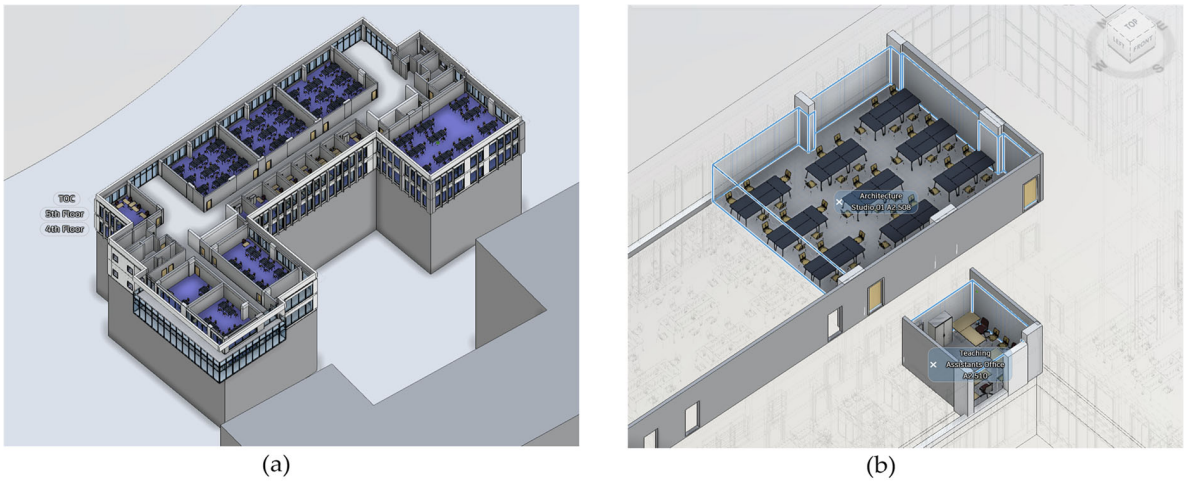


Figure 4. Sensing unit architecture.



	Name	Host	L	Rooms	Issues	Last Reading	Comfort Score	Last Comfort S...	Threshold	Threshold values
1	A2.508_Acoustics	Electrical_Sensors_...	Le...	Architecture Studio 01 A2.508	no data	last week		0	Noise Activity	● ≤ 0 ● ≥ 35 ● ≥ 50
2	A2.508_Air Quality	Electrical_Sensors_...	Le...	Architecture Studio 01 A2.508	no data	last week		470.81	ASHRAE CO2 PPM	● ≤ 0 ● ≥ 1101 ● ≥ 2000
3	A2.508_Humidity	Electrical_Sensors_...	Le...	Architecture Studio 01 A2.508	no data	last week		29.10	ASHRAE + CIBSE Humidity Comfort Range	● ≤ 20 ● ≤ 29 ● ≥ 61 ● ≥ 70
4	A2.508_Lighting	Electrical_Sensors_...	Le...	Architecture Studio 01 A2.508	no data	last week		253.33	IES Recommended Lighting (LUX)	● ≤ 250 ● ≤ 299 ● ≥ 501 ● ≥ 550
5	A2.508_Temperature	Electrical_Sensors_...	Le...	Architecture Studio 01 A2.508	no data	last week		25.60	ASHRAE-Based Temperature Range	● ≤ 19 ● ≤ 20 ● ≥ 25 ● ≥ 26
6	A2.510_Acoustics	Electrical_Sensors_...	Le...		no data	last week		0	Noise Activity	● ≤ 0 ● ≥ 600 ● ≥ 1000
7	A2.510_Air Quality	Electrical_Sensors_...	Le...		no data	last week		678.43	ASHRAE CO2 PPM	● ≤ 0 ● ≥ 1101 ● ≥ 2000
8	A2.510_Humidity	Electrical_Sensors_...	Le...		no data	last week		29.40	ASHRAE + CIBSE Humidity Comfort Range	● ≤ 20 ● ≤ 29 ● ≥ 61 ● ≥ 70
9	A2.510_Lighting	Electrical_Sensors_...	Le...		no data	last week		347.50	IES Recommended Lighting (LUX)	● ≤ 250 ● ≤ 299 ● ≥ 501 ● ≥ 550
10	A2.510_Temperature	Electrical_Sensors_...	Le...	Teaching Assistants Office A2.510	no data	last week		26.90	ASHRAE-Based Temperature Range	● ≤ 19 ● ≤ 20 ● ≥ 25 ● ≥ 26

Figure 5. (**a**) Autodesk Tandem digital twin; (**b**) monitored rooms; and (**c**) threshold definitions and live assessment.

In addition to analytical capabilities, the digital twin supported real-time spatial visualization of the IEQ parameters according to their comfort scores through live monitoring dashboards and heatmaps simultaneously. The captured data were visualized on charts

and tables that reflected their comfort scores, defined comfort ranges, and temporal information. Additionally, the live comfort scores were visualized as heatmaps that overlaid IEQ performance directly onto floor plans and 3D views of the building, as shown in Figure 6. This tool helps in illustrating spatial compliance with defined comfort thresholds across different zones while also spatially comparing between spaces under varying conditions.

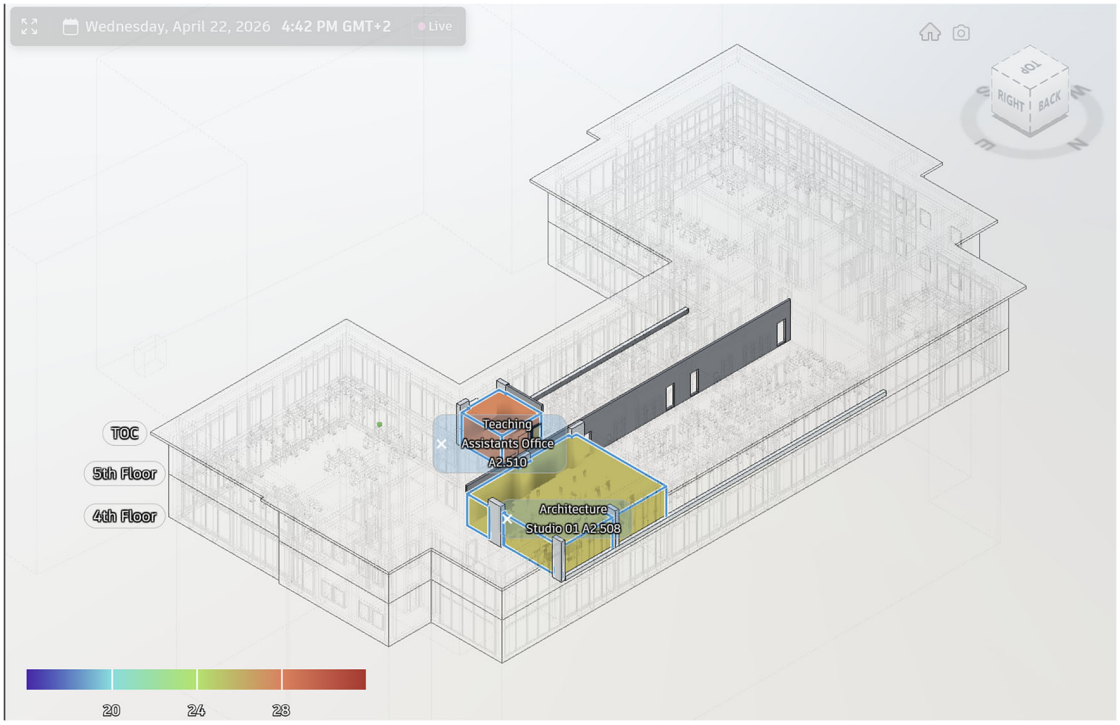


Figure 6. Live heatmap of monitored spaces illustrating live temperature variation based on the defined ASHRAE-guided acceptable comfort range.

5.2.2. Support of Framework Retrofit Decision-Making

The developed digital twin model collects real-time IEQ data from two distinct rooms, providing insights that aligns with the advantages of digital twins for optimizing performance and resource usage over time. These insights from two spaces with different sizes, orientations, and activities show a remarkable variation in the monitored IEQ parameters. Accordingly, this variation highlights the influence of spatial and operational factors on the environmental conditions of the digital twin. Additionally, as the digital twin noted, with an 25 °C of indoor temperature, occupant behavior emerged as an important factor that highlighted the need for cooling, which contradicted the acceptable thermal comfort range, as the monitored temperate was within this range. This inconsistency between measured performance and occupant behavior highlights the importance of integrating common occupant behaviors and habits into the performance evaluation of IEQ. Furthermore, live climate conditions data are streamed into the digital twin model in order to analyze IEQ performance and resilience to different seasonal conditions. These temporal datasets are stored as charts and tables to allow continuous tracking of IEQ parameters, correlating indoor conditions with live-streamed outdoor weather data over time. Inclusion of weather data led to valuable insights as variations in outdoor conditions, such as clear, overcast, or cloudy sky conditions, as well as solar radiation, directly influenced daylight availability and thermal behavior within the spaces, as shown in Figure 7.



Figure 7. Live and historical climate conditions stream. The light blue stepped line represents the true recorded/set weather condition values at each timestamp, while the blue line represents interpolated trend between those values.

The coexistence of real-time and historical data streams, as shown in Figures 8 and 9, creates a base of analysis that directly supports the study's structured decision-making phase. On the one hand, live data can support rapid short-term responsive interventions, such as adjusting HVAC operation, optimizing lighting control, or indoor shading in response to occupancy, and external climate conditions. On the other hand, historical data, as shown in Figures 8 and 9, support long-term targeted retrofit decisions through capturing recurring patterns and performance trends over various seasons across different zones, floors, and rooms of the building. Therefore, the resulting digital twin allows immediate operational optimization along with deep energy and comfort-oriented retrofits.

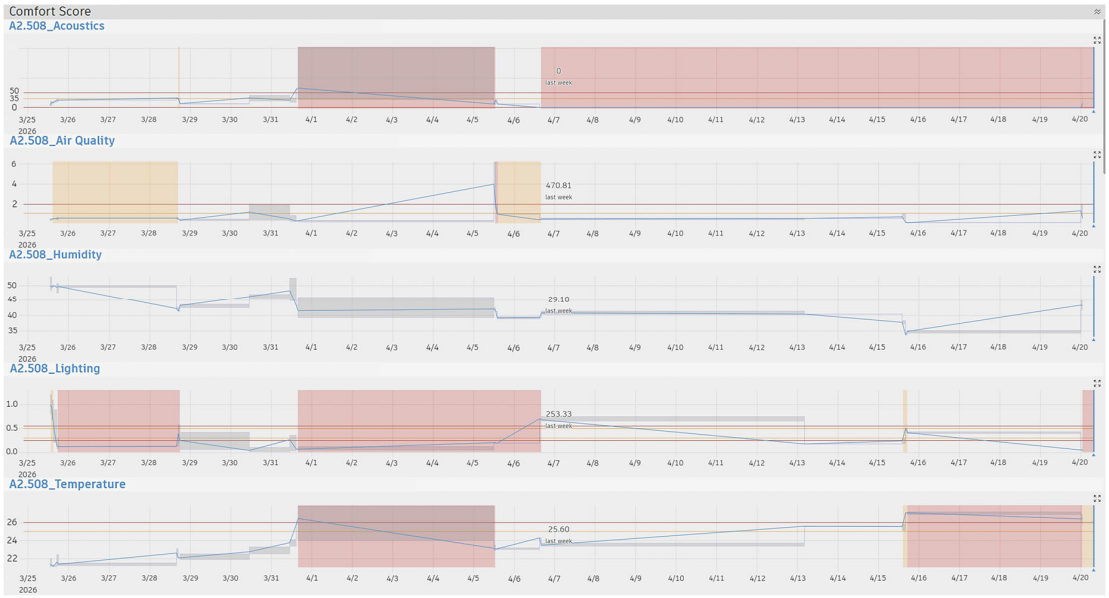


Figure 8. Historically analyzed IEQ against standards-based comfort thresholds in A2.508. Blue lines are mapped data, while colored yellow and red lines and fills, respectively, represent warnings and severe alerts of IEQ data deviations, defined in threshold values column in Figure 5c.



Figure 9. Historically analyzed IEQ against standards-based comfort thresholds in A2.510. Blue lines are mapped data, while colored yellow and red lines and fills, respectively, represent warnings and severe alerts of IEQ data deviations, defined in threshold values column in Figure 5c.

5.3. Digital Twin's Monitored IEQ Analysis and Diagnosis

IEQ data obtained through a digital twin facilitates comprehensive assessment by capturing real-time values and temporal patterns of IEQ conditions within the monitored rooms in relation to the building characteristics, orientation, and context. The analyses of the monitored IEQ data highlight several overlapping performance issues of IEQ parameters, which indicate the importance of a holistic assessment approach, along with relating to contextual weather conditions and seasonal variations. This approach paves the way for a holistic assessment that informs decision-making in the development of targeted retrofit strategies while simultaneously influencing multiple IEQ parameters.

5.3.1. Thermal Comfort

As shown in Figures 7 and 8, analyses of thermal comfort show that indoor temperature is highly affected by seasonal variations, including solar exposure and sun altitude, which pose different challenges for each room orientation. On the other hand, under all captured indoor conditions, relative humidity remained stable within the defined acceptable comfort range. During winter, indoor temperatures were generally within acceptable comfort ranges in both rooms; however, periods of direct solar radiation at lower solar altitudes led to overheating in the office, with temperatures rising to 25–26 °C. For several days during winter, several occupants of the office relied on mechanical cooling to alleviate the overheating effect. In contrast, the north-oriented classroom experienced issues of cold drafts during natural ventilation. Also, the temperature was almost identical to that of outdoors. The classroom experienced increased sensitivity to outdoor temperature transmission due to its curtain wall facade.

During transitional seasons, such as spring and autumn, moderate outdoor conditions (23–27 °C) with higher sun altitude, as well as with a 1 m cantilever in the roof level, resulted in reduced direct solar radiation on the fifth floor where the monitored rooms are located. This led to generally comfortable indoor environments in both spaces. However, outdoor temperature fluctuations, where outdoor temperature reached up to 32 °C, negatively impacted the office due to high solar gains and heat transfer through its large openings. This

resulted in the indoor temperature to average 26 °C, which passes the defined acceptable threshold at which a significant percentage of occupants begin to experience thermal discomfort and heavily rely on mechanical cooling. Regarding the classroom, it was mostly thermally stable, but it was still affected by heat transmission by the curtain wall during days that mark the peak range of seasonal outdoor temperature.

During data collection, the digital twin captured extreme weather conditions during April where the outdoor temperature reached 37 °C. This led to constant thermal discomfort in both rooms during the full working day, as the indoor temperature significantly drifted from the acceptable threshold range. The office space showed a strong heat gain, with its temperature ranging from 26 °C to 29.3 °C during the peak temperature of the day. Additionally, the classroom gained heat, where its temperature was 27 °C.

5.3.2. Air Quality (CO_2 Concentration)

Real-time monitoring of CO_2 levels shows that the concentrations remain stable and within the defined acceptable range as long as the rooms are naturally ventilated. Temporary increases in CO_2 levels occurred mainly at the beginning of occupancy after weekends or extended closures due to the accumulation of stale air when the building remains sealed. However, the concentration returns to optimal levels once windows are reopened. An important factor that highlights the interconnection of IEQ parameters is that natural ventilation increases heat gains from direct solar radiation and heat transfer, which negatively reduces thermal comfort, especially in the south-oriented office.

5.3.3. Visual Comfort

The results of the monitored lighting illuminance show that indoor daylight sufficiency depends on the relationship of the room's orientation, depth, and WFR. Adequate daylight levels (300–550 lux) are achieved between 10:00 a.m. and 4:00 p.m., then the illuminance level drops as it approaches late afternoon. Additionally, early mornings, late afternoons, and overcast conditions consistently fall below the required minimum, and the classroom significantly suffers during these conditions.

While both the office and the classroom had sufficient daylight starting from 10:00 a.m. till 4:00 p.m., the south-oriented office had slightly higher lux by approximately 50 lux, as shown in the table. However, the classroom, which is doubled in depth from that of the office, resulted in the center of the classroom (measuring point) being the furthest zone, where daylight illuminance matches IES standards and lux levels fail to reach the minimum 300 lux required for classroom use. This resulted from the orientation of the room, where the southern facade benefits from direct solar exposure, while the northern facade relies on diffuse daylight and is further limited by self-shading of the building mass.

Additionally, on a mostly cloudy day, the office space had 300 lux at 3:00 p.m. almost at the center of the room, indicating a daylight factor of 3%, which is adequate lighting, but the room could require additional lighting when illuminance drops to 250 and below. On the same day and at the same time, the classroom measured 230 lux in the center of the room, which accounts for 2.3%; however, as indicated by the daylight factor, this brightness of the room is not suitable for a classroom. The daylight factor in both rooms appeared adequate, while data proved through the classroom's monitoring process that its glazing provided the minimum illuminance, which did not fulfill the lighting needs of classrooms. These insights indicate that the office is resilient to different daylight conditions of the outdoor environment, while the classroom requires artificial lighting under several conditions.

5.3.4. Acoustics

Regarding the acoustics, both rooms were measured when empty of occupants to check the status of the noise level, of which both had acceptably quiet environments that

were suitable for teaching and working. However, increased noise from the outer corridor affects the focused nature of the room's function when the floor is fully operational, and all classrooms are occupied. This issue results from having more than 240 occupants per floor, where students transitioning through classrooms, lecture halls, and offices produce interrupting noises. This noise of students easily penetrates the classroom and office, suggesting a problem of weak noise isolation performance of the interior walls. Lastly, outdoor noise from the outdoor court, which is empty of vegetation and noise breakers, transmits the echoed noise of outdoor activities to the office when naturally ventilated.

5.4. Evidence-Based Retrofitting Support

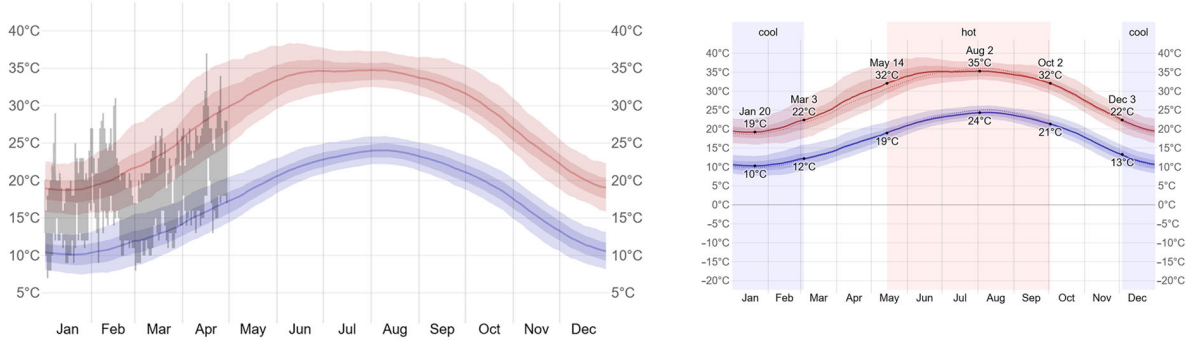
The insights that are derived from the monitored IEQ parameters are evaluated in terms of duration and frequency of occurrence for each room. The data, which were gathered during varying outdoor temperatures within a period of 10 weeks between February and April 2026, were used to project all IEQ deviation patterns across the entire year, as shown in Table 11. While weather conditions were monitored in real-time during IEQ monitoring in the digital twin model, the projection was guided by historical weather data from 2025 shown in Figure 10, along with seasonal temperature variations shown in Table 1 [38]. The projection of the retrofit proposal is further guided by the psychrometric chart in Climate Consultant, which maps the percentage of comfort conditions of a building's baseline scenario and the most effective passive design strategies to enlarge the comfort zone. Thus, the temperature ranges in Egypt shown in Table 1 and Figure 10, along with the psychrometric charts in Figures 11–14, serve for extrapolating to annual projections, as the IEQ data were gathered across significantly varying temperature ranges within the 10-week period of data collection. Accordingly, the collective analysis shown in Table 11 presents a holistic overview of the frequency and severity of IEQ deviation patterns and assists in identifying the root causes of IEQ parameters' noncompliance with standards-guided thresholds. Following the analysis of the data collected by the digital twin, retrofit strategies were proposed and then followed by energy performance simulations to validate energy consumption reduction, especially for retrofits that directly affect energy usage shown in Sections 5.4.6 and 5.4.7.

Table 11. Collective IEQ deviation patterns analysis.

Room/Zone	Building Characteristics		IEQ Parameters	Comfort Range	Deviated Monitored Pattern	Comfort Deviation Duration/Day	Frequency/Year (Seasonal Occurrence)
A2.508 (Classroom)	Orientation	North	Temperature	20–25 °C	26–27 °C	5–6 h 12:00–6:00 p.m.	May–October
	Window-to-Floor Ratio (WFR)	25%	Humidity	30–60%	-	-	-
	U-Value	2.01 W/m^2K	CO_2 Concentration	≤1100 ppm	1500 ppm	0.5–1 h	After long weekend
	R-Value	0.5 $m^2 \cdot K/W$	Light	300–500 lux	≤200 lux	4 h	Overcast outdoor conditions + deep room zones
	Glazing Type	Double-glazed U-Value 2 $W/m^2 \cdot K$	Sound	35–40 dB	50–65 dB	6 h 10:00 a.m.–4:00 p.m.	Academic year September–June

Table 11. *Cont.*

Room/Zone	Building Characteristics		IEQ Parameters	Comfort Range	Deviated Monitored Pattern	Comfort Deviation Duration/Day	Frequency/Year (Seasonal Occurrence)
A2.510 (Office)	Orientation	South	Temperature	20–25 °C	26 °C	6–8 h 10:00–6:00 p.m.	Mid-April–Mid-November
	Window-to-Floor Ratio (WFR)	39%	Humidity	30–60%	-	-	-
	U-Value	2.01 W/m^2K	CO_2 Concentration	≤1100 ppm	1200 ppm	0.5 h	After long weekend
	R-Value	0.5 $m^2 \cdot K/W$	Light	300–500 lux	250–280 lux	4 h	Overcast outdoor conditions
	Glazing Type	Double-glazed U-Value 2 $W/m^2 \cdot K$	Sound	35–40 dB	50–65 dB	6 h 10:00 a.m.–4:00 p.m.	Academic year September–June



(**a**) (**b**)

Figure 10. (**a**) Cairo temperature projections 2026: (**b**) Cairo temperature history, 2025; The daily range of reported temperatures are represented in gray bars. 24-h highs are represented through a red curve, while lows are represented through a blue curve © WeatherSpark.com.

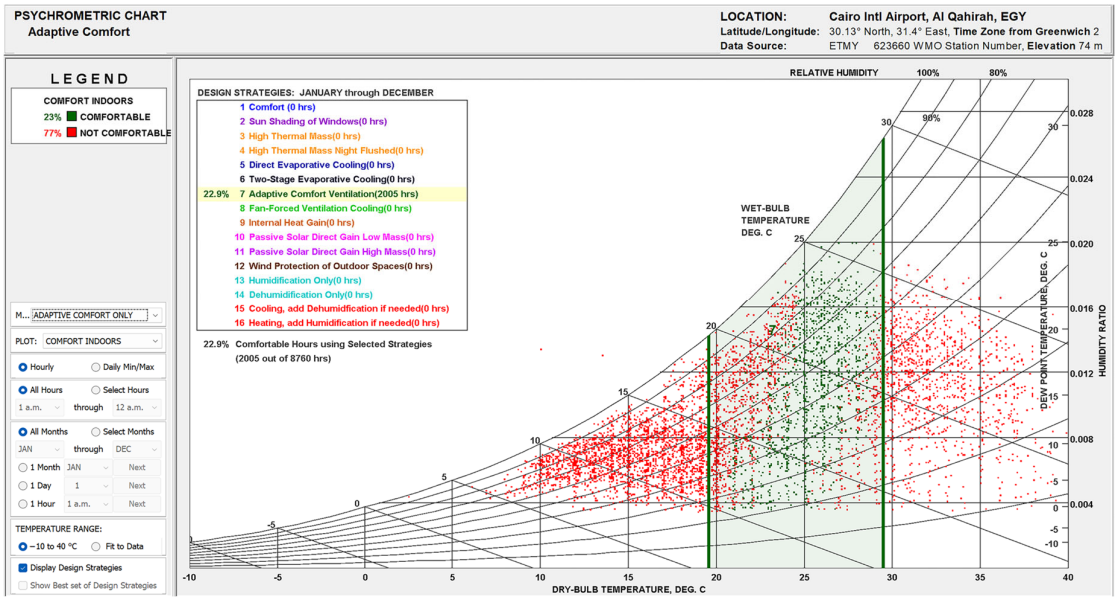


Figure 11. Psychrometric chart illustrating annual climatic conditions in Cairo within the adaptive comfort range, generated using Climate Consultant 6.0. The highlighted Strategy, 7, resembles existing scenario without passive iterations of design strategies, relying on natural ventilation.

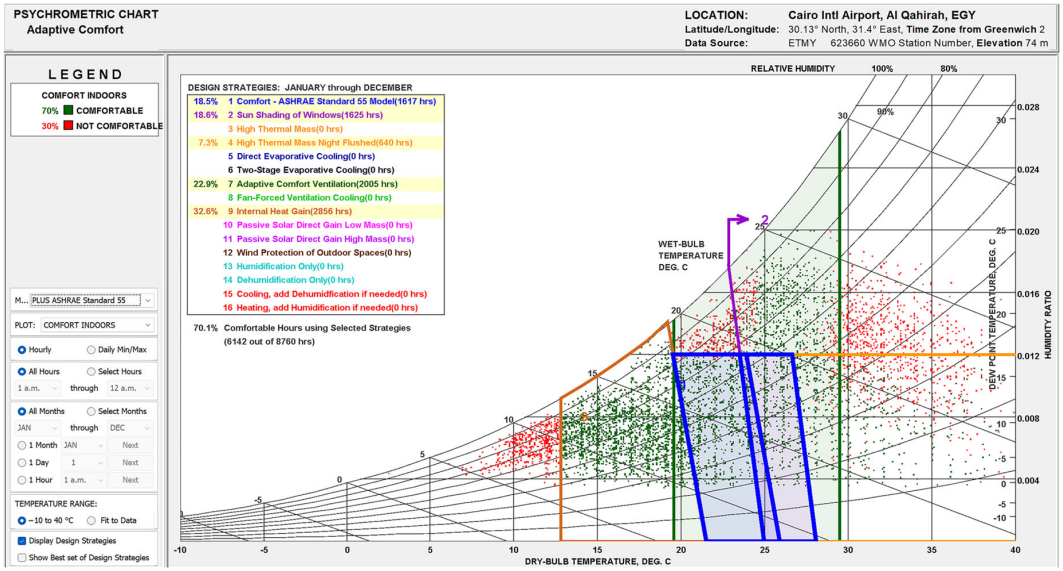


Figure 12. Psychrometric chart illustrating annual passive environmental design strategy impact in Cairo, generated using Climate Consultant 6.0. Strategies 2, 4 & 9, highlighted in yellow, are passive design strategies, where their text color indicates their impact on the psychrometric chart. Strategy 1 represents the percentage of annual hours that naturally meet the ASHRAE Standard 55 thermal comfort criteria.

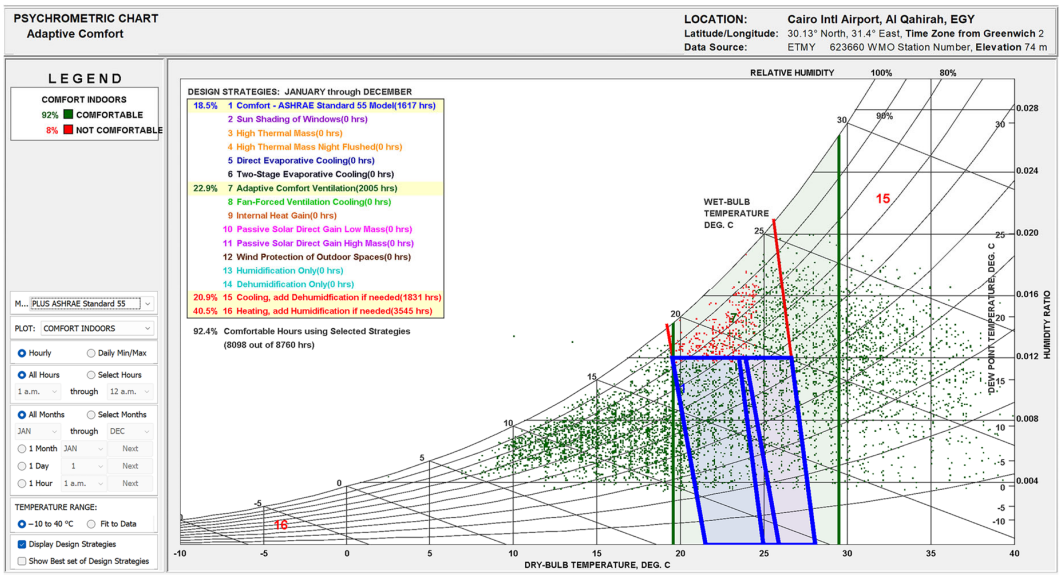


Figure 13. Psychrometric chart identifying annual heating and cooling demand zones in Cairo, generated using Climate Consultant 6.0. Strategies 15 and 16, highlighted in yellow, are cooling and heating strategies simulated without integration of passive design strategies, where their text color indicates their impact on the psychrometric chart.

5.4.1. Thermal Comfort Pre-Retrofit and Decision-Making Analysis

The thermal comfort findings of Tables 12 and 13 indicate the need for improved shading strategies for the office facade as well as improved thermal resistance for the outer envelope in terms of insulation and high-performance glazing. As shown in Table 12, the thermal data of both rooms acquired from the digital twin model 11 distinct days, highlighting strong variations across varying outdoor weather conditions. Accordingly, the collective IEQ analyses, along with live thermal data, indicate that the impact of decreasing U-value from 0.5 to 1.5 W/m^{2}K by implanting high-performance glazing can reduce heat

gains [86]. According to the UN-Habitat, in tropical regions, recommended U-values should be no higher than 1 W/m^2·K for walls, 0.85 W/m^2·K for roofs, and 5.00 W/m^2·K for windows. In hot humid and hot arid climates, these limits should ideally be reduced by at least 20%, particularly for air-conditioned buildings. Additionally, controlled ventilation is needed to maintain acceptable thermal comfort, as natural ventilation increased the solar gains of both rooms [90]. The office, oriented to the south, was prone to overheating for most of the year due to high solar heat gain through low-performance glazing. The rooftop cantilevered slab, shown in Figure 3a, acted as a shading device that resulted in the room A2.510 to have no direct sunlight in the south except in the winter season. Hence, the office experiences limited thermal comfort improvement in winter, early spring, and late autumn. In the north-oriented classroom, solar heat gains are relatively moderate and dominated by diffuse and reflected radiation, while direct solar impact is negligible. In room A2.508, the vertical louvers, as shown in Figure 3a, were effective in preventing direct sunlight penetration from sunrise and sunset periods. However, during harsh summer temperatures, the curtain wall performance did not resist heat transmittance.

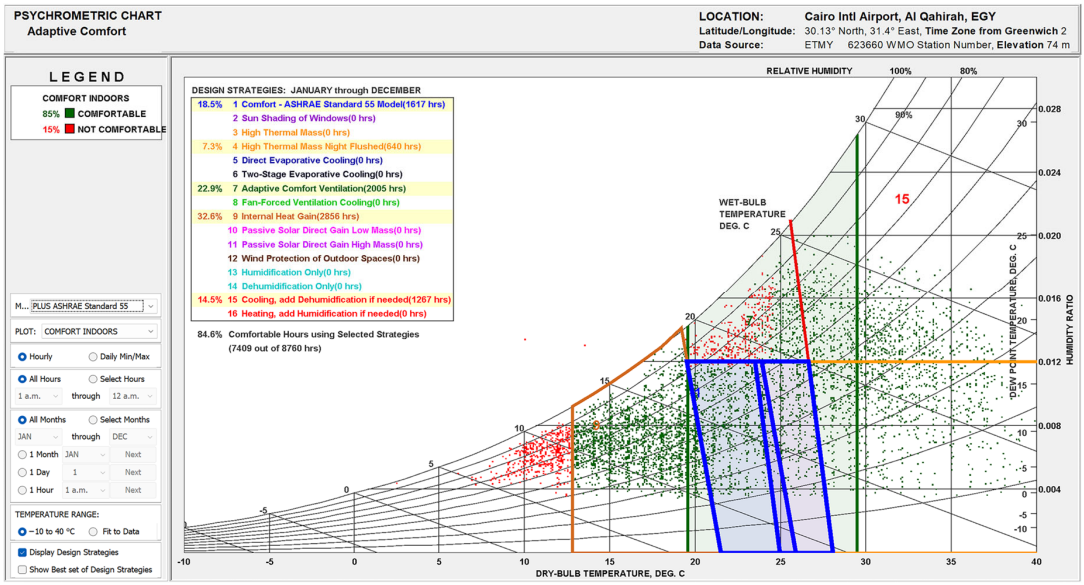


Figure 14. Psychrometric chart illustrating the annual applicability of passive environmental design strategies in conjunction with cooling requirements in Cairo, generated using Climate Consultant 6.0. The simulation shows passive design strategies, 4 and 9 along with the adaptive comfort, 7, integerated with mechanical cooling, strategy 15, where their text color indicates their impact on the psychrometric chart.

Table 12. Digital twin's monitored thermal data across A2.508 and A2.510.

Date	Weather Condition	Season	Outdoor Temperature (Maximum/Day)	Outdoor Humidity	A2.508 Indoors		A2.510 Indoors	
					Temperature (Average)	Humidity (Average)	Temperature (Average)	Humidity (Average)
23 April 2026	Clear	Spring	30 °C	67%	25 °C	29%	26.5 °C	29%
22 April 2026	Clear	Spring	30 °C	75%	25 °C	36%	26.5 °C	37%
16 April 2026	Clear	Spring	37 °C	37%	26.5 °C	37%	28 °C	35%
7 April 2026	Partly Cloudy	Spring	23 °C	31%	23.5 °C	41%	24 °C	43%
6 April 2026	Partly Cloudy	Spring	24 °C	27%	23 °C	41%	24 °C	36%
1 April 2026	Cloudy	Spring	27 °C	54%	24 °C	48%	24.5 °C	50%
31 March 2026	Clear	Spring	26 °C	29%	22.5 °C	46%	24.5 °C	43%
29 March 2026	Partly Cloudy	Spring	25 °C	43%	22.5 °C	42%	23.5 °C	48%
26 March 2026	Cloudy	Spring	20 °C	41%	21 °C	49%	22 °C	50%
10 February 2026	Clear	Winter	23 °C	33%	23.5 °C	-	25 °C	-
7 February 2026	Clear	Winter	29 °C	27%	23 °C	-	26.5 °C	-

Table 13. Overheating root cause analysis according to comfort deviation ranges with the outer wall's U-value, R-value, and glazing type against adequate values for a hot arid climate (Cairo, Egypt).

Room/Zone	Season (Day Outdoor Temperature Range)	Shading Elements Sufficiency	Solar Heat Gain $Q = A \times SHGC \times (I_{direct} + I_{diffuse} + I_{reflected})$	Sun Altitude (Maximum/Season)	WFR	U-Value	R-Value	Glazing Type
A2.508 (Classroom)	Winter (December–February) 18–21 °C	High	1.36 kW	36.5°	25%	Medium	Medium	Moderate
	Spring (March–May) 23–32 °C	High	1.81 kW	60°	25%	High	High	High
	Summer (June–September) 34–37 °C	High	2.26 kW	83.5°	25%	High	Medium	Medium
	Autumn (October–November) 26–32 °C	High	1.81 kW	60°	25%	High	High	High
A2.510 (Office)	Winter (December–February) 18–21 °C	Low	3.2 kW	36.5°	39%	Low	Low	Low
	Spring (March–May) 23–32 °C	High	3 kW	60°	39%	Low	Low	High
	Summer (June–September) 34–37 °C	Medium	2.05 kW	83.5°	39%	Low	Low	Low
	Autumn (October–November) 26–32 °C	High	3 kW	60°	39%	Low	Low	High

5.4.2. Air Quality Pre-Retrofit and Decision-Making Analysis

As shown in Table 14, the results of the measured air quality parameter showed that CO_2 concentrations remained within an acceptable limit of the defined threshold, highlighting the effectiveness of natural ventilation and fresh air flow. However, evaluation of indoor air quality requires measuring additional parameters, such as particulate matter and volatile organic compounds. During the data collection period between February and March, several days had poor climates characterized by windy and dusty outdoor conditions. These conditions affected the effectiveness of natural ventilation and required the use of air conditioning to supply pure fresh air. Thus, dust accumulation monitoring is crucial for periodic tracking of room deep cleaning patterns alongside external climate conditions [78].

Table 14. High CO_2 concentration root cause analysis according to different comfort deviation ranges.

Room/Zone	CO_2 Concentration	Air Change Rate	Occupancy	Window Opening/Ventilation Status
A2.508 (Classroom)	Optimal	High	44	Active
A2.510 (Office)	Optimal	High	4	Active

5.4.3. Visual Comfort Pre-Retrofit and Decision-Making Analysis

The visual comfort findings suggest that the window-to-wall ratio and daylight factor were efficient in the office. During sky overcast conditions, the illuminance of the space did not significantly drop. On the other hand, the classroom has good WFR, but its depth results in poor lighting conditions during clear conditions, as the illuminance intensity was measured further away from the center of the room. As shown in Table 15, the digital twin's monitored illuminance level shows that clear and partly cloudy weather conditions did not affect the room with the southern facade, while the room with the northern facade struggled to reach optimal levels due to its depth. Additionally, these design characteristics pose a strong challenge during overcast conditions where lux levels significantly drop, as

shown in Table 16. Finally, the results show a need for increasing natural light distribution in the classrooms with passive design interventions, such as lighting shelves along with automated lighting controls that are triggered by occupancy and poor lighting conditions to efficiently reduce artificial lighting usage [82].

Table 15. Digital twin's monitored illuminance levels across A2.508 and A2.510.

Date	Weather Condition	Season	A2.508 Average Range	A2.510 Average Range
23 April 2026	Clear	Spring	350–400	375–450
22 April 2026	Clear	Spring	350–400	375–450
16 April 2026	Clear	Spring	350–400	375–450
7 April 2026	Partly Cloudy	Spring	275–300	300–350
6 April 2026	Partly Cloudy	Spring	275–300	300–350

Table 16. Visual comfort noncompliance root cause analysis.

Room/Zone	Optimal Lux	Deviated Measured Lux	Window Orientation	Daylight Factor	WFR	Room Depth	Sky Condition/Season	Obstruction
A2.508 (Classroom)	300–500 lux	≤200 lux	North	2.3–2.5%	25%	10.5 m	Overcast	None
A2.510 (Office)	300–500 lux	250–280	South	3%	39%	4.5 m	Overcast	None

5.4.4. Acoustic Comfort Pre-Retrofit and Decision-Making Analysis

As shown in Table 17, the analyses of the acoustic comfort suggest that upgrading internal wall insulation is important, as the main source of distraction came from within the building. Outdoor noises are not frequent and can be considered negligible. Additionally, sound isolation of the air conditioning system is important, as the sound level reached 50 when it was on in both rooms.

Table 17. Acoustic comfort monitored noise against noncompliance root cause analysis.

Room/Zone	Function	Optimal Noise Range	Measured Noise Level	Outdoor Noise Source Impact	Internal Noise Impact (Corridors)	Envelope Sound Isolation Quality	Internal Wall Sound Isolation Quality
A2.508 (Classroom)	Teaching	35–40 dB	45–60 dB	45–50 dB	60 dB	Medium	Low
A2.510 (Office)	Research Work	35–40 dB	60 dB	45–50 dB	60 dB	Medium	Low

5.4.5. Retrofit Decision-Making Support and Validation

The derived insights from analysis of the digital twin data provided a critical basis for IEQ, where multiple parameters simultaneously deviated from standards-based comfort thresholds, leading to further poor energy efficiency during academic year operations. Analyses allowed real-time evidence of annual frequency and durations of poor IEQ to inform on where occupants mostly rely on mechanical systems and artificial lighting, transforming into a comprehensive IEQ issues comparison across the monitored rooms, as shown in Table 18. Based on these insights, Tables 19 and 20 show retrofit strategies categorized into immediate, short-term, and long-term interventions, which support a phased decision-making approach. While immediate retrofit decisions are taking place, the proposed short-term and long-term retrofit strategies are evaluated through a two-stage

validation process. The first stage includes retrofitting strategies' virtual assessment using building energy performance modeling and simulations to estimate their impact on IEQ and energy demand. During this stage, retrofit strategies are further evaluated in terms of cost and feasibility to prioritize low-cost and minimally invasive decisions during building operation. The proposed retrofits' extrapolation logic and validation are supported through virtual simulations, including the Cairo Adaptive Comfort Psychrometric Chart and energy simulation, highlighting the impact of energy-related retrofits on energy consumption reduction.

Table 18. IEQ issue root cause and the recommended retrofits for each monitored room.

Room	IEQ Issue	IEQ Issue Root Cause	Recommended Retrofits
A2.508 (Classroom)	Overheating	Window-to-Wall Ratio + Thermal Resistance of Envelope	Automated HVAC Control + Envelope Insulation
	Sound Isolation	Inadequate Acoustic Separation	Acoustic Panels Installation
	Adequate Natural Daylight	Room Depth (10 m)	Daylight-Responsive Lighting Controls + Light Shelves Installation
A2.510 (Office)	Overheating	Room Orientation Considerations + Window-to-Wall Ratio + Thermal Resistance of Envelope	Automated HVAC Control + Envelope Insulation Upgrade + Horizontal Louvers Installation
	Sound Isolation	Inadequate Acoustic Separation	Acoustic Panels Installation

Table 19. Short-term targeted retrofit proposals.

Room	Retrofit Strategies	Thermal Comfort (Overheating Elimination)	Air Quality and Ventilation (Fresh Air Supply)	Visual Comfort (Sufficient Daylight & Glare Reduction)	Acoustic Comfort
A2.508 (Classroom)	Automated HVAC control based on room occupancy and temperature	●	●		-
	Window operation strategies/schedules	-	●		-
	Daylight-responsive lighting controls			●	
	Acoustic panels installations				●
A2.510 (Office)	Internal shading devices (blinds, curtains)	●		-	
	Reflective films on glazing	●			
	Automated HVAC control based on room occupancy and temperature	●	●		
	Window operation strategies/schedules	-	●		
	Acoustic panels installations				●

Direct effect: ●; negative impact: -.

Table 20. Long-term targeted retrofit proposals.

Room	Retrofit Strategies	Thermal Comfort (Overheating Elimination)	Air quality and Ventilation (Fresh Air Supply)	Visual Comfort (Sufficient Daylight & Glare Reduction)	Acoustic Comfort
A2.508 (Classroom)	Low-E/solar control glazing upgrade	●			○
	Light shelves implementation			●	
	Incorporation of ventilation shafts or passive systems	○	●		
	Improve wall sound absorption and isolation				●
A2.510 (Office)	Horizontal louvers	●		○	○
	Low-E/solar control glazing upgrade	●			
	Incorporation of ventilation shafts or passive systems	○	●		
	Improve wall sound absorption and isolation				●

Direct effect: ●; indirect effect: ○.

The second stage of validation was real-world validation of the retrofit strategy before implementation decision-making. This stage capitalizes on the existing digital twin model to reassess IEQ conditions post-intervention. This criterion allows critical evaluation of retrofit performance, determination of IEQ improvements, and reduction in mechanical system utilization. This validation process includes prototypes of targeted retrofits across multiple building spaces with varying orientations, floor levels, and geometric characteristics. Furthermore, to enhance the effectiveness of this step, future integration of retrofit generation within the digital twin environment is essential, linking IEQ performance with occupancy patterns and enabling the incorporation of energy consumption data to estimate potential resource savings. This approach allows for the observation of spatial variability in performance and provides practical insights into the effectiveness of each strategy. Lastly, it supports immediate, short-term, and long-term retrofits during decision-making to prioritize efficient and high-performance retrofits.

5.4.6. Retrofit Impact Virtual Simulation A: Psychrometric Chart Simulations

To strengthen the validation of the digital twin findings, a psychrometric chart analysis of the baseline condition is included to verify the prevalence of overheating and the percentage of uncomfortable hours. These results are compared with the overheating durations reported by the digital twin model in Table 11. The psychrometric analysis for Cairo indicates that its climate experiences high temperature fluctuations across seasons. As shown in Figure 11, the baseline scenario, adopting the adaptive comfort model from ASHRAE standard 55, shows that only 23 percent of the year is perceived as comfortable. Multiple psychrometric chart simulations shown in Figures 12–14 reveal that Cairo's climate achieves a high percentage of comfort hours through a responsive building envelope that moderates heat transfer, limits unwanted solar gains, preserves useful internal heat, and integrates natural ventilation. Figure 12 shows that the implementation of passive

strategies, including shading devices, high thermal mass, and preserving internal heat gains, provide 70% comfortable hours annually, while the usage of mechanical cooling during severe summer periods can achieve 85% comfort hours annually. In contrast, dependence on only mechanical cooling and heating achieves similar comfort hours of 92%. These psychrometric charts facilitate extrapolating the digital twin's data, collected over 10 weeks, identified that 3532 h may experience overheating throughout, which can be eliminated through shading elements, enhancing the envelope's insulation, and minimal mechanical cooling, as indicated in Figure 14. Hence, the contribution of passive internal and solar heat gains indicates the need for a responsive building envelope that moderates heat transfer between indoors and outdoors, reducing unwanted summer heat gain while retaining beneficial heat during cooler periods. Furthermore, the digital twin's data that captured winter temperatures aligns with the data charts, where the building preserved its internal temperature during winter and required no heating. This correlation reinforces the proposed retrofits to further enhance the thermal resistance and direct solar radiation reduction, especially for severe summer heat.

5.4.7. Retrofits Impact Virtual Simulation B: Energy Simulations

Free-running and actual-operation energy simulations are conducted using the building's material properties, occupancy schedules, and operational characteristics. The free-running scenario replicates the HVAC-off conditions during data collection. This allows an independent evaluation of time not meeting the adaptive comfort model during occupied hours and provides additional verification of the digital twin collective analysis in Table 11. The study employed multiple annual energy simulations to evaluate the thermal and energy performance of the proposed retrofit strategies and identify the most effective envelope interventions for reducing cooling demand. Simulation inputs, as shown in Figure 15, reflected the building's actual operational conditions, including occupancy, clothing assumptions, equipment loads, lighting schedules, and cooling schedules, based on the university's academic calendar, where the building operates at full capacity from September to early June. The analysis began with a baseline scenario representing the existing building characteristics, as established in Table 11, initially with only cooling to demonstrate the extent of thermal stress and the need for active cooling to maintain indoor comfort under outdoor climatic conditions, as shown in Figures 16 and 17. The simulation was conducted using the EnergyPlus engine with a weather file of Cairo set on ASHRAE Climate Zone 2B, corresponding to the hot arid climate of the case study's location. Several retrofit scenarios were then tested, with external shading elements and low-E glazing films demonstrating the most balanced performance, reducing the building EUI from 145.61 kWh/m^2·year in the baseline case to 128.84 kWh/m^2·year, achieving an overall energy reduction of 11.52%, as shown in Table 21 and Figure 17. Reflecting energy consumption with the performance gap, research has indicated a lack of energy performance requirements and optimization calculation methods in Egyptian code, where it is broad and misses requirements for energy consumption limits and losses; however, a case study in an educational building within a university campus in Cairo, Egypt, achieved a 50% EUI reduction through a combination of envelope-based retrofits and mechanical system upgrades, lowering EUI from 230 kWh/m^2·year in the baseline scenario to 106 kWh/m^2·year [91,92].

Table 21. Comparative energy simulations of energy-oriented retrofits implications.

Energy Simulation Scenario	Energy Use Intensity (EUI) (kWh/m^2·Year)	CO_2 (kgCO_2e/m^2·Year)	Reduction Percentage (%)	Cost Savings/Year (USD)
Baseline	145.61 kWh/m^2·year	58.24	0.00%	0
Baseline + Insulation	145.55 kWh/m^2·year	58.22	0.04%	$33
Baseline + Shading	138.32 kWh/m^2·year	55.33	5.01%	$3961
Baseline + Low-E Double Glazing SHGC = 0.35	125.19 kWh/m^2·year	50.08	14.02%	$11,113
Baseline + Low-E Double Glazing SHGC = 0.35 + Shading	122.31 kWh/m^2·year	48.92	16.00%	$12,681
Baseline + Low-E Double Glazing SHGC = 0.35 + Shading + Wall Insulation	123.21 kWh/m^2·year	49.28	15.38%	$12,191
Baseline + Shading + Wall Insulation	138 kWh/m^2·year	55.2	5.23%	$4135
Baseline + Low-E Double Glazing SHGC = 0.35 + Wall Insulation	125.51 kWh/m^2·year	50.2	13.80%	$10,939
Baseline + Low-E Films	132.79 kWh/m^2·year	53.12	8.80%	$6971
Baseline + Low-E Films + Shading	128.84 kWh/m^2·year	51.54	11.52%	$9122

Table adapted by the authors based on annual energy use simulation results generated using OpenStudio with the EnergyPlus engine OpenStudio®.

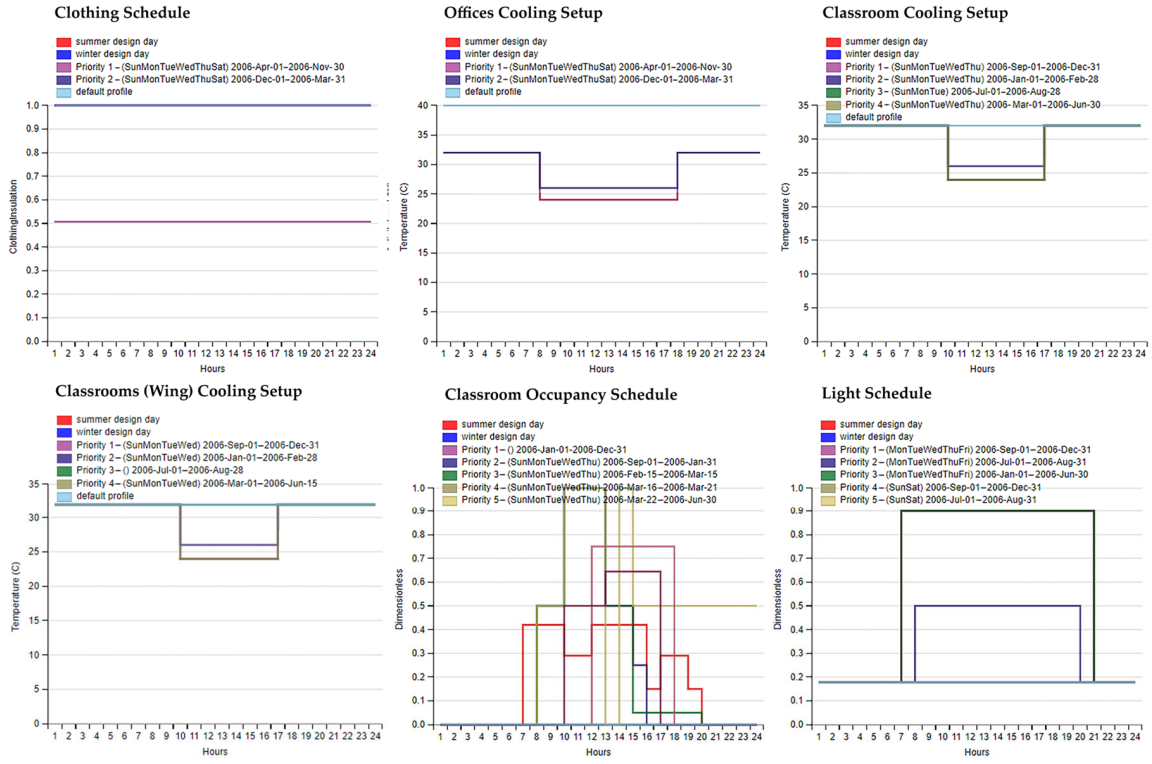
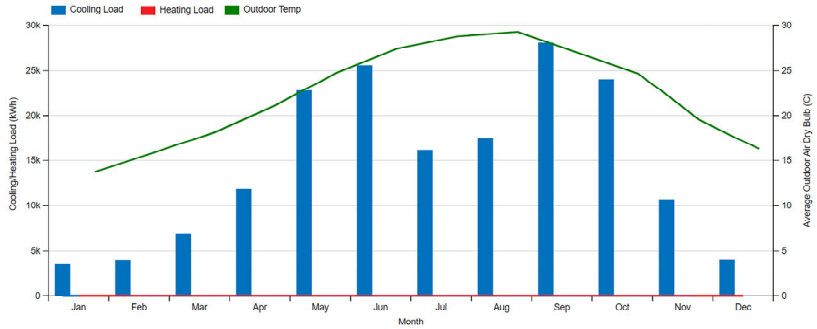


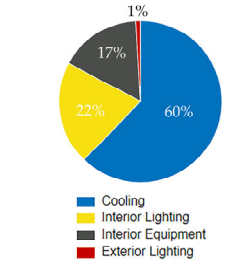
Figure 15. Energy simulations operational schedules samples; OpenStudio®.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Outdoor Air Dry Bulb (C)	13.7	15.9	18.2	21.1	24.8	27.4	28.8	29.2	27.0	24.7	19.6	16.3
Cooling Load (kWh)	3501.87	3982.89	6877.13	11,840.75	22,734.67	25,540.44	16,097.07	17,442.83	28,029.42	24,011.15	10,703.67	4027.68
Heating Load (kWh)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

End Use	Consumption (kWh)
Heating	0
Cooling	174,789
Interior Lighting	58,089
Exterior Lighting	2619
Interior Equipment	45,489
Exterior Equipment	0



(a)

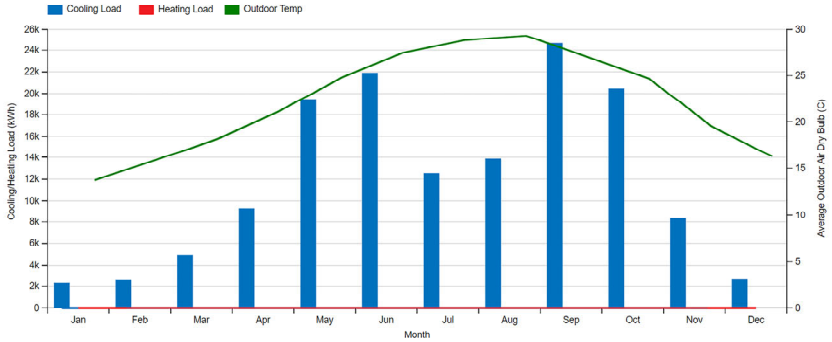


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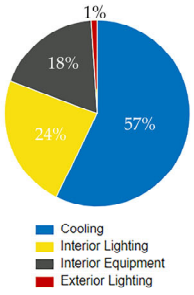
Figure 16. Energy simulation impact on energy use for the baseline scenario and actual operational conditions; (**a**) HVAC monthly load profile; (**b**) Annual end use table and statistics; OpenStudio®.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Outdoor Air Dry Bulb (C)	13.7	15.9	18.2	21.1	24.8	27.4	28.8	29.2	27.0	24.7	19.6	16.3
Cooling Load (kWh)	2264.96	2566.55	4890.58	9260.74	19,382.56	21,865.96	12,490.98	13,842.55	24,615.62	20,415.47	8303.76	2635.78
Heating Load (kWh)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

End Use	Consumption (kWh)
Heating	0
Cooling	142,536
Interior Lighting	58,089
Exterior Lighting	2619
Interior Equipment	45,489
Exterior Equipment	0



(a)



(b)

Figure 17. Energy simulation impact on energy use for the retrofitted scenario: baseline + low-e films + shading; (**a**) HVAC monthly load profile; (**b**) Annual end use table and statistics; OpenStudio®.

While the strategy adopting low-E double glazing and shading devices recorded the greatest energy reduction, its implementation was found to be less feasible due to a significantly longer payback period compared with low-E glazing films, which demonstrated a more practical payback duration of approximately 10–15 years according to materials cost and installation costs in the case study's local market. The payback is calculated according to Equations (5)–(8) based on the tariff rate of electricity in Egypt, accounting for the case study's typology, where the annual savings impact is noted in Table 21. This step validates that improving the envelope through targeted retrofits is feasible and effective when implemented [88]. Following energy consumption simulations, annual building energy consumption (E_a) is calculated to calculate the annual electricity cost (Ca), as given by Equations (5) and (6). The energy use intensity, noted in Table 21, along with annual energy consumption cost are used to find energy reduction percentage (R_e) and annual financial savings, as given in Equations (7) and (8).

$$E_a = 145.61 \times 1722 \times 6 \quad (5)$$

$$E_a = 1{,}504{,}046.52 \text{ kWh/year}$$

$$Ca = 1{,}504{,}046.52 \text{ kWh/year} \times 2.74 \quad (6)$$

$$Ca = \text{EGP } 4{,}121{,}087/\text{year} \equiv 79{,}100 \text{ USD}$$

$$R_e\ (\%) = (145.61 - 128.84/145.61) \times 100 \quad (7)$$

$$R_e\ (\%) = 11.52\%$$

$$S_c = (145.61 \times 1722 \times 6 \times 2.74) - (128.84 \times 1722 \times 6 \times 2.74) \quad (8)$$

$$S_c = \text{EGP } 474{,}105.64/\text{year} \equiv \text{USD } 9122/\text{Year}$$

Additionally, the comparative assessment of ASHRAE acceptability limits for adaptive comfort during occupied hours, serving as an indicator for retrofit effectiveness, shows a clear improvement in thermal comfort as interventions are introduced. Without any cooling or retrofits in the baseline (no cooling) scenario, and in the last floor shown in Table 22 the classrooms and offices in the last floor recorded the highest occupied–hour discomfort, reaching 2746.5 h and 2565 h where its roof received direct solar radiation, indicating severe overheating during most occupied periods, especially in south-oriented zones; on the other hand, in the middle floors, such as the fourth floor, highest occupied–hour discomfort reached 2375 h, as shown in Table 23. Adding cooling, which makes up the baseline of all simulations, significantly reduces discomfort across all zones. External shading provided additional improvement, particularly in south-, east-, and west-facing spaces. The strongest overall performance was achieved with shading combined with low-E glazing films, which consistently produced the lowest discomfort hours across most orientations. Through the energy simulation, retrofit strategies across the building zones proved to significantly lower discomfort hours by 10 to 80% per space from that of the baseline scenario, which includes cooling, as noted in simulation scenarios on the top and middle floors, shown in Tables 22 and 23. Overall, the adaptive comfort assessment based on ASHRAE 55 (80% acceptability) indicated that indoor conditions remained within acceptable limits for approximately 82% of occupied annual hours in the best-performing retrofit cases, while remaining discomfort was concentrated during peak warm periods. Hence, results confirm that overheating is the main thermal challenge; thus, combining solar shading with low-E films on existing glazing offers the most effective envelope retrofit strategy for improving adaptive comfort.

Table 22. Time not meeting the adaptive comfort model during occupied hours on the fifth floor.

Simulation Scenario	Baseline (No Cooling)		Baseline + Cooling		Baseline + Shading		Baseline + Shading + Low-E Glazing	
Room/Function/Orientation North: (N) South: (S) East: (E) West: (W)	ASHRAE55 90% Acceptability (Hours)	ASHRAE55 80% Acceptability (Hours)	ASHRAE55 90% Acceptability (Hours)	ASHRAE55 80% Acceptability (Hours)	ASHRAE55 90% Acceptability (Hours)	ASHRAE55 80% Acceptability (Hours)	ASHRAE55 90% Acceptability (Hours)	ASHRAE55 80% Acceptability (Hours)
A2.507 (1) CLG CLASSROOM (S + W)	2746.5	2746.5	1366.33	1059.83	1280.17	1013	1191	929.17
A2.507 (2) CLG CLASSROOM (S + E)	2746.5	2746.5	1284.33	987.44	1267.32	978.43	1129.17	756.33
A2.508 (1) CLG CLASSROOM (N)	2746.5	2746.5	834.17	542.67	/	/	825.5	496
A2.508 (2) CLG CLASSROOM (N)	2746.5	2746.5	837.67	545.83	/	/	824.5	496.67
A2.510 CLG OFFICE (S)	2565	2565	1005.67	841.67	928.5	815	848.83	806
A2.511 CLG OFFICE (S)	2565	2565	1131.33	910.17	1056.33	854.33	929.83	820.83
A2.512 (1) CLG CLASSROOM (N)	2746.5	2746.5	838.17	545.83	/	/	824.83	497.17

Table 22. *Cont.*

Simulation Scenario	Baseline (No Cooling)		Baseline + Cooling		Baseline + Shading		Baseline + Shading + Low-E Glazing	
Room/Function/Orientation North: (N) South: (S) East: (E) West: (W)	**ASHRAE55 90% Acceptability (Hours)**	**ASHRAE55 80% Acceptability (Hours)**	**ASHRAE55 90% Acceptability (Hours)**	**ASHRAE55 80% Acceptability (Hours)**	**ASHRAE55 90% Acceptability (Hours)**	**ASHRAE55 80% Acceptability (Hours)**	**ASHRAE55 90% Acceptability (Hours)**	**ASHRAE55 80% Acceptability (Hours)**
A2.512 (2) CLG CLASSROOM (N)	2746.5	2746.5	838.17	545.83	/	/	825.33	498.17
A2.513 CLG OFFICE (S)	2565	2565	1156.67	926.5	1079.83	868.17	948.17	826.5
A2.514 CLG OFFICE (S)	2565	2565	1200.5	950.17	1118.67	894.17	986.67	834.33
A2.515 CLG OFFICE (S)	2565	2565	1207.67	952.33	1124.83	897.83	994.33	835.83
A2.516 CLG OFFICE (S)	2565	2565	1203.33	950.83	1124.5	897.5	995.5	835
A2.517 (1) CLG CLASSROOM (N)	2746.5	2746.5	836.33	545.5	/	/	826.17	499.33
A2.517 (2) CLG CLASSROOM (N)	2746.5	2746.5	837.5	545.67	/	/	826.17	501.33
A2.518 CLG OFFICE (N + W)	2134	2134	1393.67	817.83	1125.17	602.17	1058.83	560.5
A2.519 CLG OFFICE (S)	2565	2565	1191.33	946	1101	879.83	966.5	827.17
A2.521 CLG OFFICE (S)	2565	2565	958.33	826.5	894.83	810.67	838	805.33
A2.526 (1) CLG CLASSROOM (E)	2746.5	2746.5	1262.83	972.5	1203.33	932.5	1141.17	866
A2.526 (2) CLG CLASSROOM (E)	2746.5	2746.5	1262.5	973.17	1218	942.17	1151.83	873.33

Table adapted by the authors based on annual energy use simulation results generated using OpenStudio with the EnergyPlus engine; OpenStudio®.

Table 23. Time not meeting the adaptive comfort model during occupied hours in fourth floor.

Simulation Scenario	Baseline (No Cooling)		Baseline + Cooling		Baseline + Shading		Baseline + Low-E Glazing + Shading	
Room/Function/Orientation North: (N) South: (S) East: (E) West: (W)	**ASHRAE55 90% Acceptability (Hours)**	**ASHRAE55 80% Acceptability (Hours)**	**ASHRAE55 90% Acceptability (Hours)**	**ASHRAE55 80% Acceptability (Hours)**	**ASHRAE55 90% Acceptability (Hours)**	**ASHRAE55 80% Acceptability (Hours)**	**ASHRAE55 90% Acceptability (Hours)**	**ASHRAE55 80% Acceptability (Hours)**
A2.407 (1) CLG CLASSROOM (S + W)	1909.33	1309.33	812	477.83	787	427.17	729.67	332.83
A2.407 (2) CLG CLASSROOM (S + E)	1909.33	1309.33	765	450.83	793	435.17	845.17	302.6
A2.408 (1) CLG CLASSROOM (N)	636.5	190.5	635	246.17	/	/	938.67	294.5
A2.408 (2) CLG CLASSROOM (N)	656	202.5	630.17	246	/	/	936.5	294.33
A2.410 CLG OFFICE (S)	1897.83	1586.67	781	386.33	752.5	271.83	856.17	73
A2.411 CLG OFFICE (S)	2028.83	1705.67	776.17	609	767.17	586.83	806.17	353.83
A2.412 (1) CLG CLASSROOM (N)	659.67	205.5	629.67	246	/	/	939.83	294.5
A2.412 (2) CLG CLASSROOM (N)	660	205.67	629.67	246.17	/	/	937.33	294
A2.413 CLG OFFICE (S)	2154.67	1831.67	789.33	637.83	783.67	629.5	808.17	429.67
A2.414 CLG OFFICE (S)	2362.67	2106.17	815.67	669	804.83	661.67		512.5
A2.415 CLG OFFICE (S)	2375.83	2134.17	817.17	672.67	806.5	665	819.83	520.17
A2.416 CLG OFFICE (S)	2344.17	2091	811.33	661.67	804.67	663.4	820.5	484.67
A2.417 (1) CLG CLASSROOM (N)	649	198.67	632	245.83	/	/	947.33	296.83
A2.417 (2) CLG CLASSROOM (N)	658.67	203.83	630	245.83	/	/	946.67	296.33
A2.418 CLG OFFICE (N + W)	1698.5	1370.17	1393.67	817.83	858.17	587.17	969.67	354.73
A2.419 CLG OFFICE (S)	2227.67	1956.5	788.17	606.83	757.67	551.33	809.5	319.67
A2.421 CLG OFFICE (S)	1598.5	1310.17	744.5	322.5	710	201.83	760.83	44.17

Table adapted by the authors based on annual energy use simulation results generated using OpenStudio with the EnergyPlus engine; OpenStudio®.

6. Discussion

6.1. Limitations

Due to time constraints, data were collected over a short period of time. However, this timeframe captured a range of significantly varying temperatures. When data were collected during a time when the outdoor temperature range fell under different seasons, as shown in Tables 12 and 13, this diversity of varying ranges provides a basis for generalizing the findings to other seasons. Ideally, a more comprehensive assessment would involve monitoring the full building continuously over an entire year to capture its performance across all seasons. Hence, continuous monitoring of IEQ for a full year will be conducted in future analysis to cover all seasonal variations. This holistic assessment will support a thorough and holistic evaluation and will be more effective in fully capturing the broader aim of the study's proposed framework.

The study's digital twin encompassed only two rooms on the same floor plan, which limits the generalization of the phase of generating retrofits to solve discomfort patterns in other rooms and orientations. Thus, the full building needs to be monitored by the digital twin to include spaces in all possible orientations and spatial distributions to assess how the IEQ results change across different zones, considering the mass articulation, facade design variation, and occupant activity. Additionally, due to collecting data during the academic year, less data were collected from the classroom as its HVAC was in constant use by its occupants; as the indoor temperature reached 24 °C and the outdoor temperature exceeded 25 °C, where monitoring the environmental condition of the case study required forcing the occupants to turn off cooling, this marked a behavioral discomfort pattern. Thus, creating digital twins for building spaces can identify IEQ and energy efficiency issues across spaces, floors, or zones, as well as be able to generate efficient, targeted, and phased retrofits.

Regarding IEQ data collection and monitoring, air quality assessment was limited to assessing carbon dioxide concentration, while a comprehensive assessment needs the inclusion of different air quality contributing parameters. Additionally, the developed digital twin model demonstrated good capabilities in integrating real-time IEQ data with BIM; however, there are hardware limitations that need to be highlighted. The accuracy of data collected depends on the quality and precision of the data collection sensors. In this sense, low-cost sensors, such as MQ135 and INMP441, require calibration to provide estimated and indicative measures rather than precise measurements. The INMP441 microphone was calibrated using the sensitivity specifications provided in the manufacturer's datasheet to convert raw audio samples into estimated sound pressure levels (dB). A limitation of this approach is that the sensor was not experimentally calibrated against a certified acoustic reference device. Consequently, the reported values should be considered indicative sound levels rather than precise acoustic measurements. Additionally, INMP441 and MQ135 needed high power, which was not implemented correctly overall. On many occasions, the MQ135 needed long preheating to generate a reliable output.

6.2. Architecture-Based Digital Twin Platforms

Architecture-based digital twin platforms, such as Autodesk Tandem, provide a practical low-code workflow that bridges BIM models with dynamic operational data through minimal coding for automated data transfer and synchronization. A key strength lies in the ability to simultaneously define comfort thresholds and performance criteria regarding multiple monitored parameters and/or systems of a building. For instance, in the case study, IEQ parameters are evaluated against predefined standards-guided comfort thresholds, live outdoor climate conditions, and their spatial distribution, from which real-time data streams are generated for specific building zones and occupancy patterns. The assessment is further supported by the integration of BIM model embedded building characteristics

data, including solar heat gain, U-values, and R-values, to allow deeper analysis of how design characteristics influence performance. Additionally, the automatic generation of heatmaps across floor plans and 3D views further supports real-time data visualization and comparison of multiple spaces under varying activity levels, building characteristics, and external climate conditions. Monitored data are continuously structured into graphs and tabled datasets differentiated by building zones and rooms, which synergize seamless tracking of historical and real-time performance, positioning digital twin platforms as powerful tools for data-driven building analysis and decision-making.

6.3. IEQ Real-Time Monitoring Implications

The findings of the case study support IEQ not only as a measure of occupant comfort but also as an indicator of energy demand, as the real-time monitoring process revealed increased reliance on cooling systems whenever IEQ parameters drifted from adequate comfort ranges in buildings lacking effective passive design strategies in hot arid climates. Analysis of the developed digital twin, which is applied across differently oriented spaces, revealed frequent overheating with long durations throughout different seasons of the year. Additionally, while indoor air quality remained within acceptable limits, as indicated by CO_2 concentrations, the reliance on natural ventilation through window operation introduced a different negative impact by increasing solar heat gain. These solar heat gains produced occupant discomfort during conditions when outdoor temperatures exceeded 25 °C. The visual comfort in the classroom, which has a deep floor plan, required the assistance of artificial lights; however, the building facade is entirely covered with a curtain wall. The utilization of the digital twin for assessing daylight sufficiency aligns with the Climate-Based Daylight Model (CBDM), introduced by Christoph Mardaljevic in 2006, which evaluates daylight using year-long and location-specific sun and sky data. This approach generates contextually rooted analysis and provides more accurate predictions of indoor lighting conditions than traditional methods like daylight factor, which rely on a fixed overcast sky assumption. Thus, insights of the daylight analyses could be effectively used to generate retrofits that maximize daylight to suit different functions while lowering reliance on artificial lighting. The cross-factor analyses show the interdependency across IEQ parameters, where targeted improvements in a single parameter may negatively impact other parameters. Therefore, monitoring all IEQ parameters provides an integrated approach for identifying intersecting IEQ factors, supporting passive design strategies that simultaneously address thermal, visual, air quality, and acoustic performance. For instance, the proposed light shelves, guided by the retrofitting phase based on the digital twin's diagnostic patterns, can work on maximizing daylight transmittance to the indoors while acting as a shading device to lessen direct solar radiation.

6.4. Digital Twin's Decision-Making Support

The findings of the study show that the developed digital twin model serves as an effective decision-support tool by enabling comparative analysis of IEQ performance across different building spaces while also considering critical factors such as orientation, massing, building characteristics, and climatic zone. Holistic comparison of IEQ parameters enables a deeper understanding of their interdependencies, supporting identification of passive design interventions that address multiple IEQ parameters simultaneously. Additionally, supporting the framework's proposed retrofits with energy consumption reduction and economic indicators strengthens its role as a comprehensive tool for guiding cost-effective and scalable retrofit strategies. In this sense, the digital twin model is perceived as a diagnostic tool as well as a smart decision-making tool that could allow the prediction of problems from its historical temporal data. This leads a building's stakeholders to

evaluate retrofit scenarios based not only on current performance but also on anticipated environmental conditions, space usage patterns, and IEQ deviation patterns.

In a broader context, data-driven building analysis through real-time monitoring plays a crucial role in decarbonization and sustainability, allowing optimization of building performance throughout the operational lifecycle. In this sense, recommended retrofits benefit from energy simulation models by validating their effectiveness. Furthermore, for future experimentation, low-cost prototypes of the recommended retrofits can be further implemented and tested in real life, such as in multiple rooms and in different parts of the building. This step highlights the digital twins' effectiveness in pre-retrofit and post-retrofit monitoring, assessment, and decision-making generation. Thus, the impact of digital twin technology on performance optimization not only aids in achieving energy efficiency but also supports the transition towards net-zero carbon emissions in the built environment.

6.5. Developed Framework Scalability and Replication

Due to its modular and phased structure, the proposed framework indicates strong potential for scalability and replication when assessing IEQ across different building typologies and climatic contexts. The digital twin development phase relies on easily accessible sensor technologies and BIM platforms. This allows the framework to be adapted to different buildings with varying levels of data availability and complexity, which can integrate any IEQ variable and collect data beyond IEQ parameters.

The modular design of the framework further highlights a flexible and structured data-driven hierarchy that can adopt different IEQ standards or regulations in the IEQ monitoring and assessment phase. This structure allows consistent application across different case study contexts while maintaining comparability of results. The generation of targeted retrofits follows a rule-based logic guided by standards that provide retrofitting criteria. This makes the IEQ-based diagnostic logic adaptable and transferable to other buildings by adjusting contextual variables, such as climate conditions, occupancy patterns, and building characteristics. In other words, the framework supports decision support for improving occupant comfort and energy efficiency not only within similar hot arid environments but also in broader contexts.

6.6. Future Recommendations

Future work can build on the study's findings by creating a full digital twin of a whole building to capture the full potential of digital twins' monitoring capabilities in performance optimization. Extending the deployment of the digital twin across multiple zones and buildings will further validate the system under different climatic and operational conditions on an annual basis. Hence, this would further improve the scalability and generalizability of the approach. Along with IEQ monitoring, the integration of energy consumption data with the digital twin is a crucial factor that supports efficient resource utilization in existing buildings. Additionally, the development of low-cost mockups of the desired retrofits for testing on the actual building in different spaces is a further validating step that can benefit from the existing digital twin model.

The utilized microcontroller (ESP32) was not able to handle simultaneous high-frequency tasks, which necessitated a distributed system architecture. Thus, the development of a system with further advanced microcontrollers and precise sensors would analyze IEQ in a more comprehensive manner and present true performance. Additionally, expanding the system to include additional environmental parameters, such as particulate matter (PM2.5), VOCs, or occupancy detection sensors, would provide a more comprehensive assessment of indoor environmental quality.

7. Conclusions

Being underexplored in hot arid climates, the digital twin's results show its impact in pre-retrofit and post-retrofit decision-making, which aligns with decarbonization efforts of the built environment. The development of a comprehensive IEQ–digital twin framework positions real-time monitoring as a decision-making tool that can guide retrofit strategies in hot arid climates. The aim of the research lies in the development of a framework that integrates digital twins, indoor environmental quality monitoring, and retrofit decision-making. Real-time monitoring identified significant performance gaps, including persistent overheating across different spaces and orientations for significant frequencies and durations, which contributed to increased reliance on mechanical cooling systems. Overheating signs were found through the digital twin, especially in the south-oriented monitored office, which was validated through energy simulations highlighting the same impact across all south- and west-oriented spaces. The findings of the digital twin highlighted the interdependency between IEQ parameters, where ventilation strategies, daylight penetration, and solar heat gains emerged as interconnected variables, requiring a balance in envelope design against climatic conditions to provide the building's occupants with adequate air quality, thermal comfort, natural ventilation, and visual comfort. The integration of IEQ monitoring with a rule-based diagnostic framework adapted from IEQ standards provided the identification of underlying causes of discomfort and linked them to targeted retrofit interventions, which were classified into strategies into immediate, short-term, and long-term measures.

The third phase of the framework benefited the digital twin's environmental insights, with energy simulations serving to identify causes of poor IEQ results, which lead to inefficient annual energy consumption. The results of the energy simulation, which were annually tested, provided evidence for long hours of overheating, aligning with the IEQ-focused digital twin's diagnostic patterns gathered during the academic year. The results of retrofits indicate that the combination of IEQ analysis with building characteristics and climate context supports identifying room-specific envelope upgrades, such as glazing performance, shading elements, and insulation. Amongst the proposed targeted retrofits, relevant to occupant comfort and energy consumption, are shading elements and low-E films for enhancing the solar heat gain coefficient and U-value of the building's glazing, accounting for approximately 70% of the window–wall ratio (WWR) across all facades. Consequently, the energy simulation for the retrofits, aiming to validate their impact on energy reduction, proved to lower the energy use intensity (EUI) from 145.61 kWh/m^2·year in the baseline case, which the case study building adopted, to 128.84 kWh/m^2·year, where it achieved an annual energy reduction of 11.52%. Accordingly, the developed framework establishes IEQ as an indicator of both occupant comfort and energy demand, offering scalable and data-driven decision-making.

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Abbreviations

The following abbreviations are used in this manuscript:

IEQ	Indoor Environmental Quality
IEA	International Energy Agency
AEC	Architecture, Engineering, and Construction
HVAC	Heating, Ventilation, and Air Conditioning
SDG	Sustainable Development Goals
VOC	Volatile Organic Compounds
IAQ	Indoor Air Quality
CO_2	Carbon Dioxide
PPM	Parts Per Million
IoT	Internet of Things
API	Application Programming Interface
BIM	Building Information Modeling
MEP	Mechanical, Electrical, and Plumbing
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CIBSE	Chartered Institution of Building Services Engineers
IES	Illuminating Engineering Society
EUI	Energy Use Intensity

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