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Article

# Low-Code Digital Twin Framework with Standards-Based IEQ Analytics: Generating Fabric-First Oriented Retrofit Decision-Making for Existing Buildings in Hot Arid Climate

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## Abstract

Decarbonization of existing buildings is obstructed by the performance gap between intended and operational energy consumption. The Operational carbon footprint emitted through achieving stable indoor environmental quality and user comfort highlights a significant contribution to the performance gap that hinders decarbonization. Smart energy management and real time monitoring (digital twins) of existing buildings pose significant attributes towards decarbonization efforts. However, there is limited research transforming real time monitored performance of existing buildings to actionable retrofitting strategies. Most digital twins research focus on data visualization and building management, lacking design optimization and decision making frameworks that respond to the monitored performance. Therefore, this research bridges the digital twin concept with standards-based IEQ analytics for generating 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, humidity, and air quality. In essence, IEQ is selected to be real time monitored, since inefficient management of these parameters often results in excessive HVAC demand, contributing significantly to the performance gap. The framework structure IEQ parameters continuous evaluation against performance benchmarks derived from ASHRAE standards to identify deviations indicative of operational inefficiencies. Unlike conventional retrofit planning based on periodic audits or predictive modelling, the proposed framework links live IEQ tracking and analysis, enabling efficient and effective retrofit interventions. Validating its effectiveness, the proposed workflow is tested through a case study on an office space in hot arid climate to generate retrofitting decisions. The case study tests the research proposition of combining low-code digital twin implementation with standards-based analytical logic to generate actionable retrofit guidance. The results indicates 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.

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

## 1. Introduction

### 1.1. Rationale of the Study

Recent data from the international energy agency (IEA) 2025 shows that buildings account for approximately one third of global energy consumption [1]. This amount of energy consumption along with carbon dioxide emissions of buildings' operation positions the built environment in critical attention with regard to decarbonization strategies and hinders a transition towards sustainable urban environments [2]. Concurrently, the architecture, engineering and construction (AEC) industry is encountering a digital transformation of building operations with digital twins technology emerging as a pivotal medium that empower smart building management and real time monitoring [3,4]. Digital twins (DT) are central about acquiring real time data and its integration with virtual representation of physical assets [5]. In essence, the importance of a building digital twin is realized by its ability to provide continuous real time monitoring and evidence-based analysis to improve energy efficiency and operational optimization throughout the operational phase of a building [6–8]. Poyyamozi et al., (2024) indicated that a 30% reduction of energy reduction 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 projections of reductions in energy consumption ( $\approx 15\%$  on average, up to 60% for deep retrofits), CO<sub>2</sub> emissions (18–35%), and operational costs (up to 20%) [10]. Such incorporation of sustainability and energy-oriented management for existing buildings align 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 address crucial efforts toward decarbonizing the building environment [12,13].

Acting as performance optimization drivers in existing buildings, digital twins can address the performance gap resulting from the difference between predicted and measured operational energy consumption [14]. Operational performance deviates from intended forecasts due to inadequate integration of passive design strategies, poor construction methods and poor materials specifications [15]. Additionally, performance inadequacies result in building occupants to experience uncomfortable indoor environmental quality in indoor spaces, which affect energy efficiency due to reliance on mechanical systems to overcome IEQ shortcomings [16]. In contrast with traditional periodic IEQ assessments, Digital twins provide continuous and structured data mapping and analysis, which pave the way for overcoming the performance gap in existing buildings [16–18]. Real-time monitoring of IEQ parameters allows for the continuous assessment of temperature, humidity, CO<sub>2</sub> levels, and volatile organic compounds (VOCs), which are critical for maintaining a healthy indoor environment [18,19]. Using IEQ based IoT sensors provides detailed insights into the spatial and occupants dynamics of indoor environments, leading to verification of building rooms/zones 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 his 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 highlighted while testing their digital twins frameworks the impact of continuous sensing of IEQ data to identify major building envelope inadequacy [10,22]. Thus, to address both energy performance gap and occupant comfort, indoor environmental quality (IEQ) represents a central variable within buildings' decarbonization strategies [2,15].

While digital twins can address the performance gap through real-time monitoring and analysis of multiple factors, including IEQ, current digital twins frameworks focus on the data acquisition layer of digital twins. Few research 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) aimed to establish a systematic and extensible digital twin architecture to enhance operation and maintenance (O&M) management at building and city scales [24]. They developed a five-layer hierarchical architecture and implemented it through a DT demonstrator at the West Cambridge Campus, demonstrating effective data integration, querying, and decision support [24]. The study highlights the need for further framework research that allow a digital twin to adopt advanced data interoperability, scalability, and deeper integration of intelligent analytics and user interaction [24].

Hu and Assaad (2024) 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 technologies [25]. They developed and experimentally validated the framework in multiple indoor scenarios, achieving effective spatial indoor air quality (IAQ) assessment and real-time BIM-based visualization [25]. The results demonstrated reliable spatial IAQ detection, effective real-time visualization within BIM, and high indoor positioning accuracy 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) aimed to enhance sustainability of a public building in the city of Milan by constructing a digital twin and performing iterative energy simulations to assess the impact of envelope upgrades, lighting reductions, and renewable integration [22]. 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, Detailed HVAC and 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 tested multiple data acquisition frameworks and focused on existing systems optimization, 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 a need to create frameworks that utilize monitored data to optimize performance and achieve lowest possible energy consumption. Such methodology and workflow align with IEQ and deep energy retrofit literature, which is central about envelope-based improvements regarding air tightness, thermal bridging and insulation [20,29]. Additionally, multiple building certification and sustainable design standards, such as passive house institute and Association for Environment Conscious Building (AECB), require envelope related retrofits rather than mechanical systems upgrades to optimize building performance [29]. Thus, developing a digital twin framework focusing on performance optimization that achieves improved IEQ and significant energy reductions mandate fabric-first retrofit decision-making before optimizing heating and cooling systems [10,20,23,30].

### 1.2. Novelty and Contribution

This research aims to position digital twins not only as visual twins of buildings but also as analytical drivers for operational optimization in existing buildings. By capitalizing on real-time monitoring capabilities, the study proposes a structured low-code workflow that integrates IEQ data analysis with standards-based evaluation to guide retrofit decision-making at room level. The framework leverages Autodesk Tandem to create a scalable implementation pathway that minimizes technical barriers while enabling systematic performance mapping. Rather than focusing mechanical

systems upgrades and optimization, the framework highlights the importance of shifting toward envelope performance and fabric-first prioritization.

The novelty of this research lies in bridging three domains: digital twin performance optimization, standards-based IEQ analysis, and retrofit decision support [23]. It establishes a methodological workflow that transforms real-time monitored data into actionable retrofit strategies that aim to reduce reliance on mechanical systems, enhance energy efficiency and maintain occupant comfort. By embedding continuous IEQ assessment within a retrofit feedback loop, the study contributes 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 & Digital Twins

### 2.1. Building Performance Gap and Decarbonization Implications in Hot Arid Climate

Tackling the building performance gap is crucial for enhancing the sustainability and climate resilience of the built environment, improving operational efficiency and reducing carbon emissions [31,32]. Building operation performance gap pose several challenges that obstruct the decarbonization efforts of the built environment. Across different climates and settings, the gap is multifaceted due to different variables of the building envelope and occupants' behaviors that affect energy consumption. For example, poor building envelope resistance to external climate conditions leads to increased energy consumption, particularly for cooling, which is a major energy demand in hot arid climates that increases operational costs and contributes to higher carbon emissions [33,34]. In hot arid climates, the gap emerges through multiple envelope and mechanical factors, such as poor construction practices, poor insulation and glazing and inefficient HVAC systems. Zheng et al. 2024 shows that the actual energy consumption of buildings can consume up to four times the energy initially predicted [35]. To improve building energy performance, real building data analysis and building retrofitting are data driven strategies that aim to overcome performance gap by detecting the root cause of energy inefficiency to generate energy optimizing solutions [34,36]. Wang et al., 2023 demonstrated the role of buildings' real operational data analysis in identifying energy consumption deviations from efficient and sustainable measures. Furthermore, data driven tracking is crucial for understanding the role of occupant behavior, building condition and indoor environment in the performance gap [34]. Tanase and Croitoru, 2025, Mirzabeigi et al, 2024) and Rached & Anber, 2022 highlighted the impact of existing buildings retrofitting in reducing energy consumption and resisting climatic conditions through passive strategies, such as upgrading insulation, HVAC and airtightness. in the realm of air quality [7,20,36]. 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 buildings management to help building's architects, managers and owners to decide actionable performance optimization decisions [7,10]

### 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 its occupants' 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 stay almost 90% of their time inside buildings, it is essential to maintain good IEQ to ensure a healthy, productive and comfortable indoor environment [37]. Standard based frameworks and certifications highlight the importance of understanding and assessing IEQ parameters to provide healthy and comfortable indoor spaces. For instance, ASHRAE, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, provide IEQ benchmarks that target general comfort of occupants [37,38]. In that sense, ASHRAE 62.1 & 62.2 defines indoor air quality as air that is free from harmful contaminants and high percentages of carbon dioxide [39,40]. Thermal comfort is defined as the state

of the mind which expresses satisfaction with the thermal sensation. Since it is a subjective and individualistic response, ASHRAE Standard 55 considers thermal comfort satisfactory when at least 80% of a space occupant are satisfied [37,40]. The lighting condition is described as the visual comfort that is achieved by adequate illuminance level and penetration of daylight, respecting the space function and activities [41]. Noise level relates to occupants' distraction and irritation that results from excessive noise emitted from either machinery and noise transmitted through adjacent spaces and rooms [41,42]. Lastly, Odor influences IEQ as users constantly experiencing unpleasant smells affect their comfort and wellbeing [37].

While (IEQ) is positioned within the social pillar of sustainability due to its direct impact on occupant health, comfort, and wellbeing, present building conditions, such as insulation, airtightness, and ventilation create cross-pillar connection with environmental sustainability of buildings [40,43,44]. Thus, research highlights that meeting optimal thermal and light conditions is the most energy intensive IEQ parameters, which are highly affected by building conditions [45]. Awolesi et al. (2025) performed a systematic review of 99 studies highlighting how indoor environmental quality is assessed alongside energy data, indicating that current research increasingly links IEQ assessments with energy performance in sustainability evaluations [45]. Lizhen et al. identify IEQ as a major contributor to operational energy use in office buildings [43]. Rus et al. further showed that summer overheating leads to increased cooling demand, highlighting that indoor temperature reduction by 1°C could lower emissions by approximately 1.17 kg CO<sub>2</sub>e/m<sup>2</sup> [42]. Schroderus et al. (2025) shows 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 [46]. Perera et al. (2025) demonstrates that IEQ parameters are complex in calibration as they simultaneously address occupant comfort and energy consumption due their high dependency on existing building conditions in addition to occupants' behavior with the building system [40].

### 2.3. Fabric First Retrofit

The fabric first retrofit methodology in existing architecture refers to improving the building's envelope, including walls, roof, floors, and windows before considering other energy efficiency measures related to mechanical systems [47]. This approach is effective in achieving maximum environmental and social impact by prioritizing the reduction of energy demand [48]. Additionally referred to as Deep Renovation, the methodology captures the full economic energy efficiency potential of improvement works for a building's outer shell to achieve enhanced energy performance in existing buildings [49]. Applying deep retrofits to existing buildings require detailed assessment of the pre retrofit conditions, including simulations for energy consumption and thermal properties [50]. The fabric first approach significantly reduces 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 older buildings, preparing them for low-carbon heating systems like heat pumps [51]. Additionally, (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 [52]. The analysis identified significant thermal inefficiencies and outdated systems, highlighting considerable potential for energy savings through targeted retrofit measures [52].

Thus, not only limited to improved energy efficiency, building retrofit is a wide domain that includes further economic, environmental and social improvements [53,54]. Economically, retrofitted buildings acquire higher market value and are appealing to their owners [55]. Environmentally, include energy consumption alleviation and carbon emissions reduction[55]. The social benefits are tied to building occupant comfort, productivity and health [55,56]. Jo & Wang et al. 2024 developed a rating tool and tested it on 52 retrofit systems to provide an overview of areas of focus and areas that are under investigated [55]. The result showed that most sustainable building retrofit methodologies are driven by strong environmental and social performance indicators [55]. Therefore,

the benefits of each pillar intertwine [29,30,55,56]. For instance, enhanced IEQ is perceived as a social benefit of existing building retrofit [46,56].

#### 2.4. Digital Twins: Performance Optimization Through IEQ-Energy Retrofits

As per M. Grieves and J. Vickers et al, (2017) demonstration of the broad digital twins' concept during operation phase, a digital twin is cored around real time information gathering and analysis to continuously assess and improve systems behavior [57]. In the AEC industry, a digital twin refers to the integration of an existing building real time data with a digital model, which receives data through sensors, meters and operational systems [5,24,58]. Over the operation life cycle, performance validation data and virtual simulations are used to support predictive maintenance and retrofit decision making, aiming to holistically improve energy efficiency while satisfying occupants satisfaction [23,59,60]. The implementation of digital twins in existing buildings unleash retrofitting and renovations opportunities relevant to identification of inefficiencies of energy usages, indoor environmental quality and mechanical systems aligning with achieving sustainability targets of SDG11 by ensuring resource efficiency and resilience in urban cities, [11,14,18,61]. Ageli & Chasiakos (2026) performed a scientometric and thematic review of 109 papers regarding IEQ-energy and digital twins research field and finds that despite significant progress in IoT-enabled sensing, predictive analytics, and the growing adoption of digital twin implementations, many existing approaches still exhibit limitations. Research often emphasizes monitoring and analytical capabilities while lacking complete feedback of sensed data, comprehensive representation of multiple IEQ parameters, and robust validation beyond short-term applications [62]. Various research 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 and carbon performance of existing buildings [59,61,63]. Additionally, Awolesi et al. (2025) refers that the integration of IoT devices and BIM to optimize IEQ and energy performance is not fully recognized [45].

Concurrently, the potentials of digital twins fills multiple research gaps related to evidence-based retrofitting that targets energy efficiency and enhanced indoor environmental quality are furtherly unaddressed [10,22,43,51]. For instance, Hamada et al. (2025) indicated that reducing energy consumption of existing buildings can not be realized until existing operational conditions are analyzed to generate suitable and efficient retrofits and renovation [64]. While Santarsiero et al. (2024) assesses energy, social and structural conditions for retrofitting social housing, a key limitation of this study is the reliance on steady-state energy modeling, which may not fully represent the dynamic behavior of the building performance. The study recommended incorporating hourly dynamic simulations, once supported by the software that assess conditions of a building over hourly frequency, to enable further optimized retrofit solutions [52]. Awolesi et al. (2025) demonstrates that although simulation-based approaches support proactive and scenario-driven IEQ assessment, their application is often fragmented, relying on single IEQ parameter analyses and steady-state assumptions. Therefore, the study sheds light on the importance of shifting towards holistic real-time analytics of all IEQ parameters altogether to realize full potential IEQ proactive analysis [45].

Therefore, future research recommendations in the realm of IEQ and retrofitting shed light on digital twins' and continuous monitoring role in performance optimization, encouraging development of holistic digital twins frameworks that realize the full potential of IEQ parameters analysis [23,25,45,62]. Since there is limited research that combines digital twins, IEQ and retrofit of building fabric to improve energy efficiency, such frameworks are encouraged where the synergy bridges several gaps and is expected to achieve significant energy reductions in retrofitted buildings [10,22]. (As mentioned in the introduction) In that sense a digital twin, holistically mapping operational IEQ parameters, becomes an ongoing simulation tool that facilitates building management and decision making towards targeted retrofits, leading to improved IEQ, energy efficiency and occupants' comfort [43].

While digital twins offer significant contributions in enhancing the performance of existing buildings with IoT sensors and smart meters, monitoring and data collection systems are complex and costly to use during operation when not installed. The complexity of digital twins' associated technologies and programming urge the need to create digital twin frameworks that rely on simple user-friendly approaches for data collection and modeling for existing buildings [10]. Low-code platforms allow domain experts to create and operate digital twins without needing extensive software engineering expertise, thus broadening the user base and enabling more stakeholders to engage with digital twin concept [65,66]. The visual application development tools and predefined components of low-code platforms simplify the development process, making it more accessible to non-technical users without the need of manual coding techniques [65]. The BIM-based approach of low-code platforms supports the configuration and reconfiguration of digital twins, making them adaptable to changing requirements and environments [67]. Digital twins integrated with low-code platforms can leverage complementary technologies such as IoT, AI, and data analytics to enhance building management and performance optimization [68].

### 2.5. Post-Retrofit Performance Verification

The integration of advanced technologies, including IoT sensors and BIM can enhance post-retrofit analysis of an existing building. For instance, Real-time monitoring provides valuable data on indoor comfort and energy performance, which is essential for validating the efficiency and effectiveness of retrofits [69]. These systems can guide energy optimization by learning from performance data, thus forming a closed-loop system, which continuously incorporates lifecycle optimization to minimize overall energy consumption [70]. In that sense, not only providing a pivotal role informing retrofit decisions, a digital twin, facilitating real-time monitoring of building performance by integrating IoT sensors and data analytics, allow post retrofit analysis, leading to a closed loop of energy efficiency and IEQ diagnosis, retrofit and post retrofit tracking [10,69,70]. Hence, post-retrofit monitoring plays an important role in reducing greenhouse gas emissions in existing buildings by ensuring that energy-saving measures are effectively implemented and maintained over time [7,10]. Through digital twins' empirical data and insights of operational performance, this process involves the continuous evaluation of building performance to verify energy consumption reductions and performance optimization and refine retrofit strategies [71]. For instance, a study on a government administrative complex in Riyadh demonstrated that post-retrofit monitoring confirmed energy savings of 31.7% in the first year, exceeding initial projections [72]. 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 [73].

## 3. IEQ Digital Twin Framework

Building on the insights of the literature review, this research proposes a digital twins framework with the aim of deploying indoor environmental quality (IEQ) mapping as a data-based driver for retrofit decision making. The framework responds to literature-extracted need for data driven approaches that overcome static and partial analyses of IEQ by integrating real time operational with standards-based evaluation of indoor environmental conditions. Within this structure, IEQ parameters, including thermal comfort, air quality, humidity and lighting, are continuously monitored and assessed against benchmarks derived from IEQ evaluation standards, such as ASHRAE and CIBSE thresholds in order to detect deviations that indicate occupant discomfort and operational inefficiencies. Then, 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 allow the identification of inadequate performance patterns across building spaces and support targeted retrofit prioritization. Additionally, IEQ assessment against standard-based benchmarks trigger a holistic overview of IEQ off-benchmark and benchmark complying conditions across different spaces, which direct decision

makers towards optimized performance that achieves occupant comfort and energy consumption reduction. Within the framework, these monitored performance data are translated through seasonal analyses and diagnostic patterns to retrofit decision making structure aligning 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, this continuously monitoring and analyzing framework of IEQ evaluates the effectiveness of implemented retrofit measures through post-retrofit IEQ and performance analysis, creating an operational closed loop in which building performance is continuously assessed over time. Through this data-driven workflow, the proposed framework positions digital twins as decision-support systems capable of linking IEQ monitoring, retrofit prioritization, and performance verification within a unified operational strategy with a broader aim of overcoming buildings' performance gap and advancing decarbonization of existing buildings [23,26].

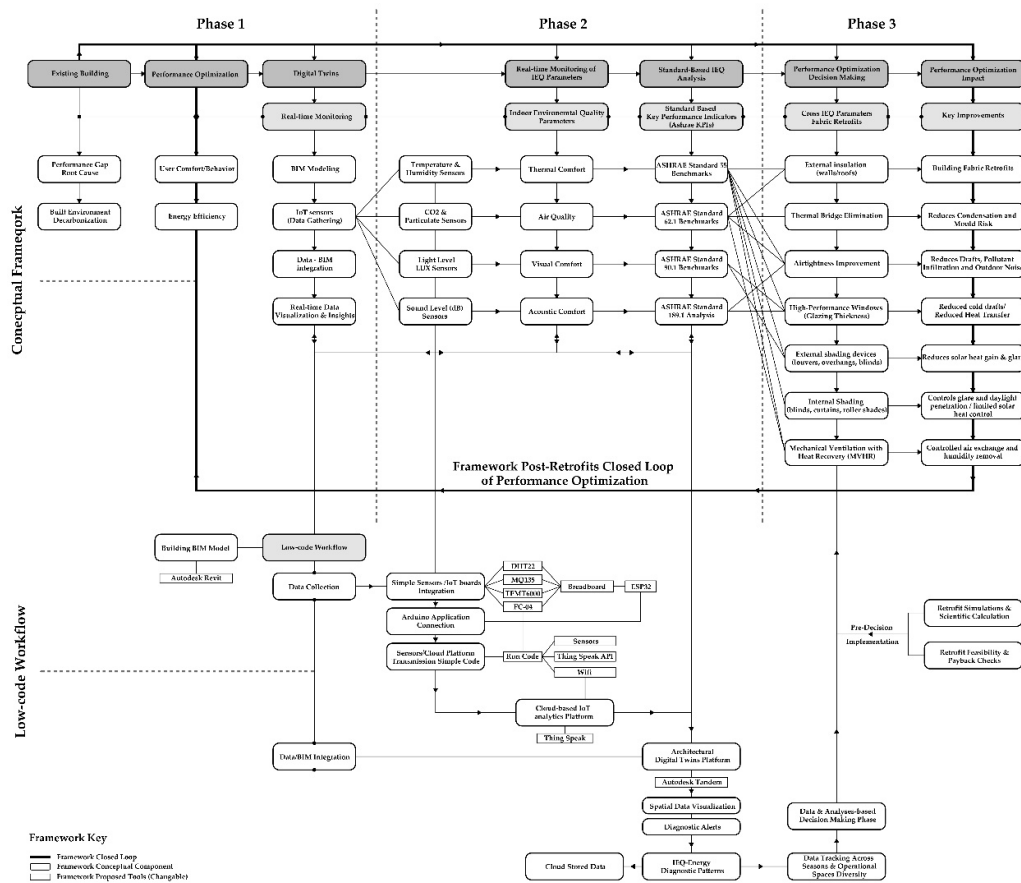


Figure 1. Framework Conceptual Synthesis.

## 4. Methodology

### 4.1. Framework Validation Overview

The validation process experiments the framework synthesis on an office space that is located within an educational building on a university campus. The main aim is testing the low code workflow that is user friendly for architects to develop a digital twin using simple sensors, BIM models and architecture-oriented digital twins platform to assess IEQ and generate retrofit decisions to enhance occupants' comfort and reduce energy consumption. Consequently, the validation process encounters three main phases, which are ordered as digital twin model development, IEQ

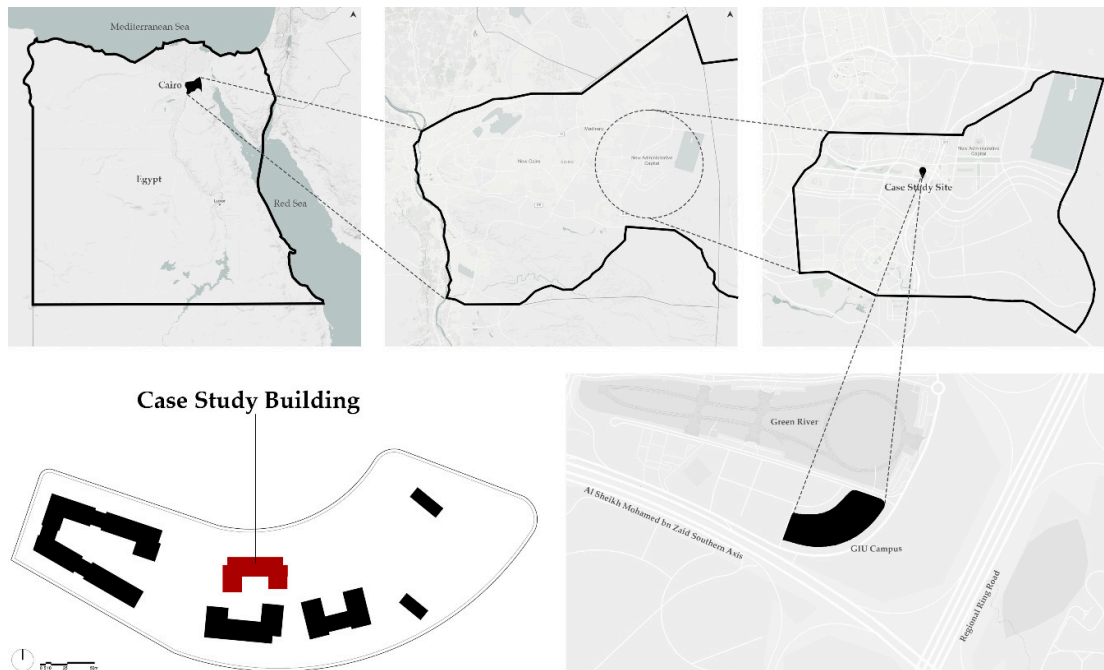
monitoring and standard-based assessment, and retrofit decision making. The first phase is to develop the digital twin through a simple data acquisition prototype that senses IEQ parameters, including Temperature, humidity, air quality, noise levels and lighting exposure. In order to link the sensed data to the digital twins platform, simple coding takes place to deliver the sensed data to a cloud-based IoT analytics platform, which is an intermediary in order to link the sensed data to the digital twin platform. Afterwards, acquired real time data is visualized on the office space BIM model of the office 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 state of the office to leverage the full potentials of Autodesk Tandem flexible capabilities in analyzing sensed data against set benchmarks. In that sense, the set benchmarks are derived from the respective ASHRAE standard of each IEQ Parameter. This constant strategy of IEQ Standard-based allows the digital twin to store IEQ off-benchmark alerts that highlight the need of performance optimizing interventions that simultaneously enhance occupants 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.

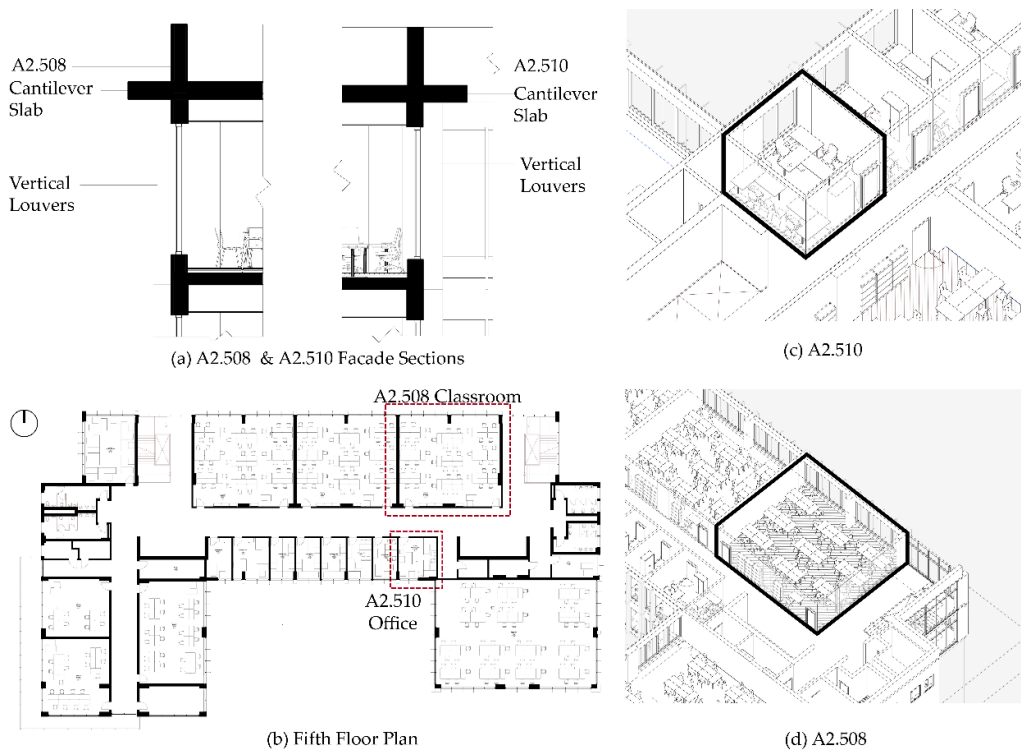
The third phase includes a decision support layer that leverages digital twin's findings as guide developing a data driven retrofit strategy. As digital twins include spatial characteristics, building's materials specifications and real time IEQ operating data, this synergy sheds light on various building's spaces where different envelope conditions and characteristics are necessary to get evaluated and upgraded. Additionally, this phase includes defining cross IEQ parameters and retrofits passive strategies, where improved thermal bridge, air tightness, shading, insulation that improves overall IEQ. This phase positions digital twins as a tool guiding building envelope retrofits to overcome increased reliance on HVAC and mechanical systems to mitigate 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, which 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 a 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 room and classroom in one floor with different size, orientation and occupancy. The office space (A2.510) has south orientation and is sized 4.5x4.7 SQM, and it is occupied by 4 academics. The office, being the highest floor benefit from 1-meter cantilevered top of concrete that acts as a shading device along with vertical louvers shown in Figure 3. The classroom (A2.508) has north orientation and is sized 11.6x10.5 SQM, and it is usually occupied by 40 students and 4 academics. The classrooms has the same cantilevered top slab and vertical louvers shown in figure. Therefore, it is crucial to monitor IEQ performance across varying climatic temperature ranges in order to detect diagnostic patterns of compliance and deficiency. The resulting data can inform retrofit interventions aiming to achieve optimal occupant comfort and energy efficiency across seasonal fluctuations.



**Figure 2.** Context and Case Study Building Location (Basic maps by © Mapcreator © OpenStreetMap).



**Figure 3.** Case Study Building and Indoor Spaces.

### Case Study's Climate

According to Köppen climate classification [74], 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. Those conditions result in significant thermal stress and notable day and night temperature variations. Those

temperature variations, referred to as diurnal temperature swings, present opportunities for passive thermal regulation.

**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

#### 4.3. Phase 1: Digital Twin Development

The development of the digital twin in this study is based a multi-layered model that connects multiple IEQ sensor data to an architectural digital twins platform, which is Autodesk Tandem. Autodesk Tandem, a cloud-based platform, equips a BIM model with sensor configurations which are API-based data streams that receive real-time sensor data from external sources and integrate it into the digital twin model for live monitoring and visualization. Therefore, the model includes interoperable synergy amongst hardware, software, and middleware in low-code methodology in order to develop the digital twin. The development process includes six main phases through which real time IEQ data are being captured and displayed on a BIM model. Development phases 2 to 6 replicate respectively for each indoor space that is targeted for monitoring within the building. Table x defines all the tools associated with the validation process ordered respectively according to six phases of the digital twin development.

##### 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 on Autodesk Tandem the necessary API endpoints 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 that connect to temperature, humidity, air quality, sound and light sensors to capture holistic IEQ insights. The ESP32 microcontroller, connected to a bread board, integrates DHT22 for temperature and humidity measurement, the MQ135 for air quality estimation, the BH1750 for illuminance measurement, and the KY-037 for sound level detection.

##### 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 minutes predefined intervals. Additionally, necessary calibration of sensors took place according to their manual sheets; for instance, the air quality sensor readings are calibrated using an empirical model to estimate CO<sub>2</sub>-equivalent values. The sound sensor is also calibrated according to multiple noise levels deviation to generate a reliable noise level detection scheme. Then, the code enables WiFi connectivity of ESP32 to transmit the collected data for logging and storage to 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 is developed to allow data exchange between ThingSpeak (Data logging cloud-based Platform) and Autodesk Tandem (Cloud-Based digital twins platform). The script operates continuously with a set timely interval that retrieves latest sensor data from ThingSpeak via its API and transmits it to Autodesk Tandem streams 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 a bridge between 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 sensors' values are correctly interpreted as real-time measurements for the IEQ variables such as temperature, humidity 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 are directly transferred to Autodesk Tandem streams. 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 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 that include the ability to integrate heterogeneous platforms through effective interoperability. The architecture of the developed system is adopting a modular workflow which allows different parts that compose the digital twin, such as sensing unit, data processing, and visualization layers, to operate independently while maintaining seamless system functionality. Additionally, the system offers a comprehensive workflow that allows smooth replication in addition to 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 twins 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 that acts as a middleware layer to deliver to Autodesk Tandem, where it is integrated into the digital twin environment.

**Table 3.** Digital twin's development tools.

Tools/Methods Categories	Tool	Task
Building Information Modeling	Autodesk Revit	Building Information Modeling (BIM) software used to create detailed digital models of buildings, including their design, structure, and MEP systems data.
Digital Twins Platform	Autodesk Tandem	A cloud-based tool 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 and humidity with $\pm 0.5^{\circ}\text{C}$ accuracy and humidity with $\pm 2-5\%$ accuracy.
	MQ-135	A gas sensor that detects air quality and harmful gases. It detects multiple gases, such as ammonia ( $\text{NH}_3$ ), carbon dioxide ( $\text{CO}_2$ ), benzene, and smoke. Generating estimated $\text{CO}_2$ 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 65535 lx.
	INMP441	A digital microphone sensor for capturing sound Intensity.
Microcontroller Programming	ESP32	Microcontroller with built-in WiFi and Bluetooth.
	Bread Board	A board used to build and test electronic circuits without soldering.
	Arduino IDE	A software application 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.
Data/Digital Twin Integration	Python	A programming language used to create software, automate tasks, and analyze data.
Weather Data	Open-Meteo	open-source weather data service that provides accurate forecasts, historical data, and climate information through simple APIs

#### 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 whether indoor conditions are acceptable or if intervention is needed.

##### 4.4.1. Temperature Evaluation and Thresholds Definition

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 are applicable to naturally ventilated and free-running buildings. 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, those interconnected variables lead to variations in occupants' 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 rather than 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 standard 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 [75–77].

In addition to the adaptive comfort model, findings from a two year local field study in Cairo that were conducted in a typical typology building are incorporated to refine the interpretation of comfort during active seasons of a university. The study used the adaptive comfort approach to investigate real occupants' 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 acceptable vote ranges satisfaction scale of  $-1$  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 [26,78].

The data shows that more than 50% of people felt “neutral” at indoor temperatures between 21–26 °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 [26,78].

This combined approach aims to incorporate evaluation thresholds that combine theoretical acceptability (as defined by adaptive standards) and occupant satisfaction (as indicated by local field study). 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 [26,75,78].

Temperature data collection process is performed in conformance with ASHRAE Standard 55, ensuring that temperature sensors have an accuracy of  $\pm 0.5^{\circ}\text{C}$  and humidity sensors  $\pm 5\%$  relative humidity. Measurement locations are selected based on the standard's guidelines that define central room positions and areas expected to experience extreme thermal conditions. Additionally, the continuous monitoring temperature and humidity values are required to be collected through intervals not exceeding 15 minutes over at least one month according to the building automation system section [75].

#### 4.4.2. Humidity Evaluation and Thresholds Definition

Humidity thresholds are derived in accordance with guidance from CIBSE Guide B2, which suggest 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 [79]. 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. This can be interpreted in terms of thresholds that preserves acceptable relative humidity of 15°C dew point limit based on air temperature-ranges from 70% at 20°C to below 40% at 30°C [80].

#### 4.4.3. Air Quality Evaluation and Thresholds Definition

Air Quality is assessed in terms of carbon dioxide concentrations according to ASHRAE standard 62.1. This amount of CO<sub>2</sub> in an indoor space as an indicator of ventilation effectiveness and occupants' acceptance of odorous bioeffluents (body odors). CO<sub>2</sub> 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 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<sub>2</sub> 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<sub>2</sub> 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 [80–82].

Additionally, the standard defines Maximum CO<sub>2</sub> limits according to indoor space function, area, outdoor air rate and occupancy. Those limits are identified by the standard as maximum CO<sub>2</sub> above ambient, which refers to the allowable increase in indoor CO<sub>2</sub> concentration above outdoor levels [80].

#### 4.4.4. Visual Comfort Evaluation and Thresholds Definition

The needed lighting is evaluated by comparing measured illuminance levels with recommended values from the Illuminating Engineering Society (IES) according to the function and activity that takes place in different rooms of a building. Additionally, ASHRAE 90.1 presents a guide related to operational aspects. It requires daylight-responsive lighting controls to ensure that artificial lighting is reduced or switched off when sufficient daylight is available [83]. Thus, the analysis illuminance in different zones of a building supports considering both visual comfort and energy-efficient lighting performance [83–85].

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, 300–500 lux range is sufficient for computer-based activities, writing and conducting meetings [84].

#### 4.4.5. Acoustics Evaluation and Thresholds Definition

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. This guideline supports a quiet environment that allows clear communication for teaching areas and focused work tasks in office spaces [86].

#### 4.4.6. 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. Those 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 being monitored alongside with actual IEQ data, this synergy allows analyses and gives insights on how indoor spaces respond to external climate conditions. Those climate conditions include weather data, condition and season classification ranges

that directly affect the indoor environment. Furthermore, the building's orientation and massing response to the outdoor climate condition provide different IEQ/Outdoor climate correlation for each indoor space that is monitored [77]. 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, with discomfort measures are assessed in terms of frequency, duration, and spatial distribution [26,85,87–89]. Additionally, occupants whom are frequently experiencing discomfort can lead to decreased productivity, health issues, and overall well-being; this relationship directly impacts energy consumptions [87].

**Table 4.** Collective IEQ deviation patterns analyses against literature adapted variables [26,88,89].

Room/Zone	Building Characteristics		Comfort Frequency/Year		
			IEQ Parameter	Comfort Monitored Range	Deviation Duration/day Occurrence
Monitored Room/Zone	Orientation		Temperature		
	Window to Floor Ratio (WFR)		Humidity		
	U-Value		CO2 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 related to the building's fabric and passive design features, as shown in Tables 5–8. The analysis identifies through real time IEQ data relationships between indoor environmental conditions and physical characteristics of an existing building. For example, high indoor temperatures and direct solar radiation are indications of insufficient shading and poor windows performance [26,88,89].

**Table 5.** Overheating root cause analysis according to comfort deviation ranges with rated 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 $Q=A \times SHGC \times (I_{direct} + I_{diffuse} + I_{reflect})$	Sun Altitude (Average / Season)	WF R	U-Valu e	R-Valu e	Glazin g Type

September) 34–37 °C Autumn (October- November) 26–32 °C
--

**Table 6.** High CO<sub>2</sub> concentration root cause analysis according to comfort deviation ranges.

Room/Zone	CO <sub>2</sub> 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.** Acoustical 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 principles of Passive House Institute, which emphasize optimizing the building envelope for reducing energy demand and improving IEQ [29]. As shown in Table 9, building's fabric retrofitting approach considers implementing passive design features to the envelope to reduce direct reliance on mechanical systems as a solution for occupants' discomfort. Hence, this retrofit strategy is effective in hot arid climate as it addresses the root cause of high energy demand and occupants' discomfort [88,89].

**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's occupants 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 façade glazing

#### 4.5.4. Retrofit Scenario Evaluation and Feasibility

The chosen retrofit decision(s) is/are simulated virtually in order to assess its effectiveness in overcoming the root cause of poor IEQ. Additionally, potential impact on improving multiple IEQ parameters simultaneously and their relation to improving energy consumption and occupants' comfort [35,77]. This step validates that improving the envelope through targeted retrofits are feasible and effective when implemented [90].

#### 4.5.5. Decision-Support Framework

To support practical implementation, a staged approach that adopts phased, evidence-based intervention is used as illustrated in Table 10 [90,91]. Thus, the proposed retrofit strategies are then categorized into immediate, short-term and long-term interventions. Immediate interventions include simple occupant behavior to manually adjust internal blinds, windows operation and lighting operation optimization. Short-term interventions focus on low-cost and minimal actions that can be implemented without major alterations to building fabric. Those minimal interventions include occupants' behavioral and operational adjustments, control strategies, and internal shading. On the contrary, long-term interventions include deep fabric upgrades, such as improved envelope insulation, glazing insulation and external shading. Those long-term interventions require higher investment and longer implementation time. Throughout the process of retrofit implementation, the short-term approaches can be assessed by the digital twins. This monitoring process of post short-term retrofits is important to assess their effectiveness while deciding the need of implementing long term retrofit approaches to further achieve maximum comfort levels and energy efficiency [35,91].

**Table 10.** Ranking the established retrofit approach in table x into immediate, short-term and long-term to support phased retrofit upgrades [90,91].

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

## 5. Results

### 5.1. System Architecture of 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<sub>2</sub> 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 3.3V, 5V, and ground to appropriate voltage supply to 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 3.3V and 5V supply lines depending on sensor requirements; subsequently, the sensors were connected using digital, analog, and I<sup>2</sup>C communication protocols according to each sensor manual sheet.

Data acquisition was performed by the ESP32 at regular 2.5 minutes 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 transmittance of IEQ conditions' data to the digital twin model.

During system development, the INMP441 microphone, using the I<sup>2</sup>S protocol that requires continuous data processing and consumes significant memory and CPU resources, caused esp32 to crash and reset as it could not handle multiple sensors readings and Wi-Fi operations simultaneously. Hence, a second ESP32 dedicated to the INMP441 microphone.

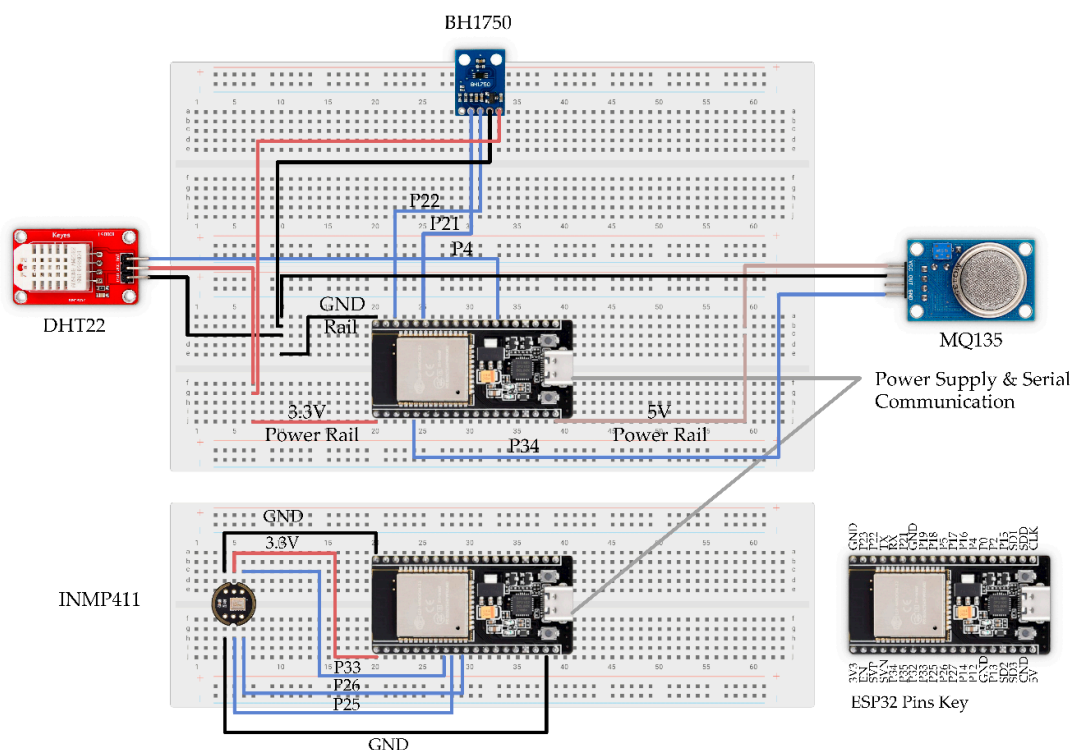
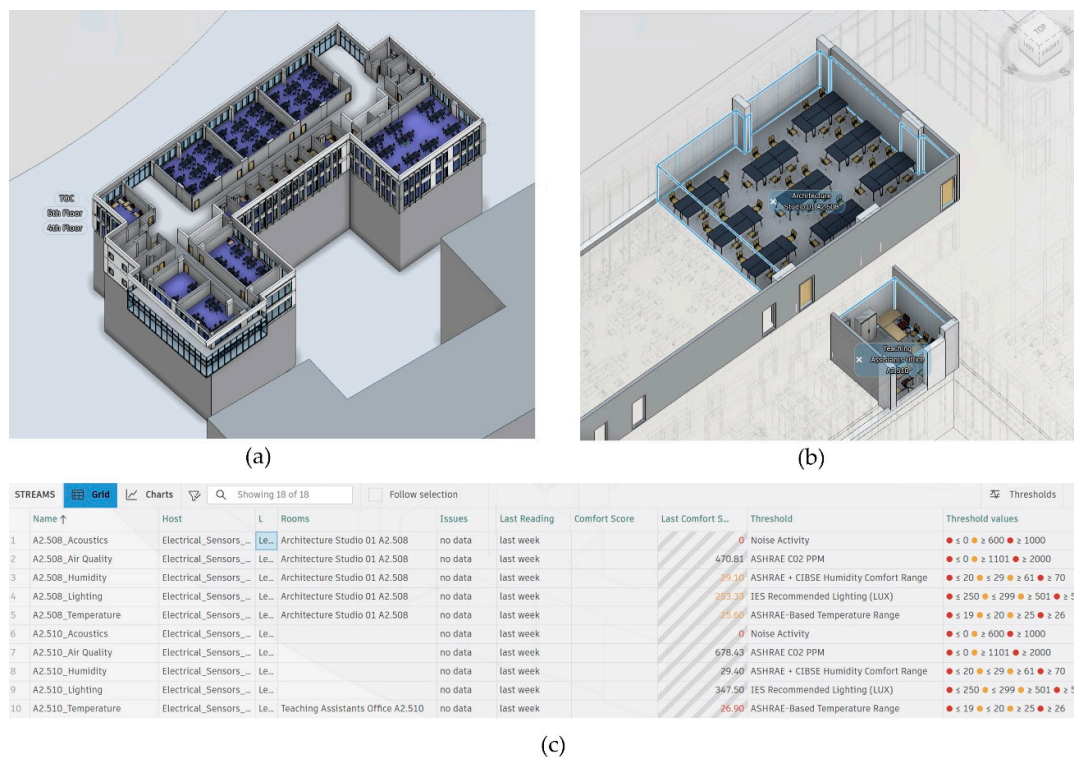


Figure 4. Sensing unit architecture.

## 5.2. Digital Twin Model

### 5.2.1. BIM - Live Data Integration and Analyses

Being an architectural based digital twins platform, the usage of Autodesk Tandem facilitated analysis of captured data along with its spatial visualization over the BIM model of the building as shown in Figure 5(a) and 5(b). A key feature of the digital twin model was the implementation of the developed standards-based IEQ framework 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 monitoring of IEQ into an active assessment tool; consequently, it aided identifying underperforming conditions that affect each room in real time as shown in Figure 3(c).



**Figure 5.** (a) Autodesk Tandem digital twin model; (b) Real-time monitored rooms; (c) Thresholds definition and live assessment.

In addition to analytical capabilities, the digital twin supported real-time spatial visualization of the IEQ parameters according to their comfort score through live monitoring dashboards and heat maps simultaneously. The captured data are visualized on charts and tables that reflect their comfort score, defined comfort range and temporal information. Additionally, the live comfort score is visualized as heat maps that overlay 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.** Monitored Spaces' live heat map illustrating live temperature variation based on the defined ASHRAE guided acceptable comfort range.

### 5.2.2. Support of Framework Retrofits Decision Making

The developed digital twin model collects real-time IEQ data for two distinct rooms, which provides insights and aligns with the advantages of digital twins for optimizing performance and resource usage over time. Insights from two spaces with different size, orientation and activity show a remarkable variation in the monitored IEQ parameters. Accordingly, this variation highlights the influence of spatial and operational factors on environmental conditions results of the digital twin. Additionally, as the digital twin noted 25°C of indoor temperature, Occupants' behavior emerged as an important factor that highlighted the need for cooling, which contradicted that the monitored temperature falls within acceptable thermal comfort range. This inconsistency between measured performance and occupant behavior highlights the importance of integrating occupant common behavior and habits into 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 seasons' conditions. Those 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 resulted in valuable insights as variations in outdoor conditions, such as sky condition (clear, overcast or cloudy) and solar radiation directly influenced daylight availability and thermal behavior within the spaces (as shown in figure).

The coexistence of real-time and historical data streams, shown in Figure 7, creates the base of analysis that directly supports the study's structured decision-making phase. On 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, shown in Figure 8, supports long-term targeted retrofit decisions through capturing recurring patterns and performance trends over seasonal variations 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.

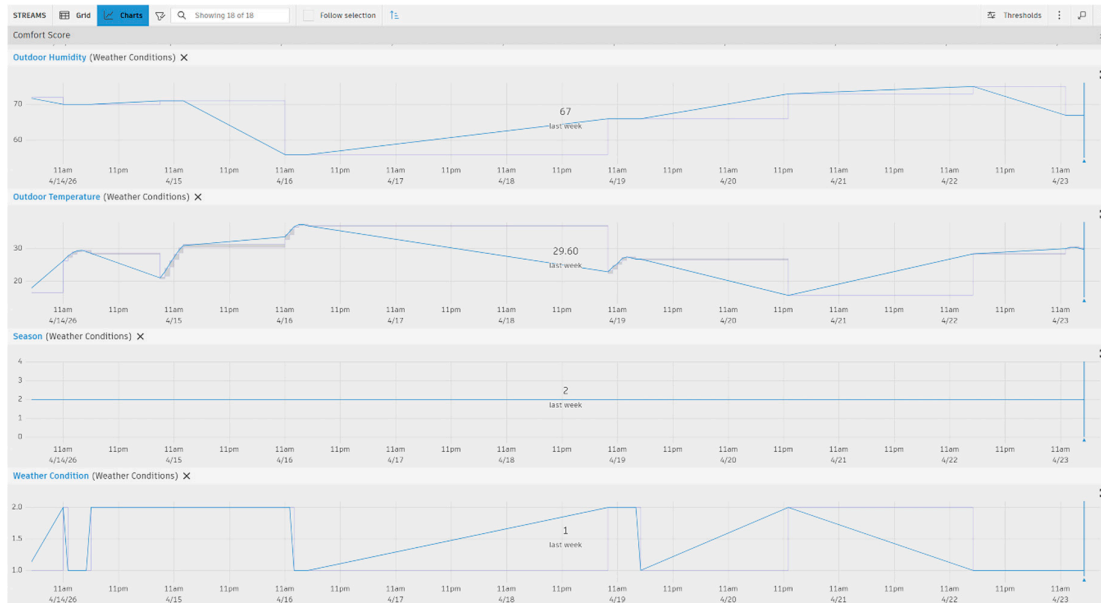


Figure 7. Live and historical climate conditions stream.



Figure 8. Historically analyzed IEQ against Standards-based comfort thresholds in A2.508.

### 5.3. Digital Twin's Monitored IEQ Analysis and Diagnosis

Capturing IEQ data through a digital twin facilitates a 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 highlights several overlapping performance issues of IEQ parameters, which indicate the importance for a holistic assessment approach along with relating to contextual weather conditions and seasonal variations. This approach paves the way for holistic assessment that informs decision-making towards development of targeted retrofit strategies that can simultaneously influence 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 and within the defined acceptable comfort range as shown in table x. 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. At 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 the outdoors. The classroom experienced increased sensitivity to outdoor temperature transmission due to its curtain wall facade.

During transitional seasons (spring and autumn), moderate outdoor conditions (23–27°C) along with higher sun altitude along with a 1-meter 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 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 peak range of seasonal outdoor temperature.

During data collection, the digital twin captured extreme weather conditions during April at which 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 peak temperature of the day. Additionally, the classroom gained heat where its temperature was 27°C.

### 5.3.2. Air Quality (CO<sub>2</sub> concentration)

Real-time monitoring of CO<sub>2</sub> 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<sub>2</sub> levels occur 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 day light sufficiency depends on the relationship of room's orientation, depth and WFR. Adequate daylight levels (300–550 lux) are achieved between 10:00 AM till 4:00 PM 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 those conditions.

While both the office and the classroom had sufficient daylight starting 10:00 AM till 4:00 PM, the south orientated office had slightly higher lux by approximately 50 lux as shown in table. However, the classroom which is doubled in depth from that of the office resulted that the center of the classroom (measuring point) is the furthest zone where daylight illuminance matches IES standards, where lux levels fail to reach the minimum 300 lux required for classroom use. This resulted from the orientation of the room where the south facade benefits from direct solar exposure,

while the north 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 PM at almost the center of the room indicating a daylight factor of 3% which is adequate lighting adequately lit, 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 the daylight factor formula indicates an adequate daylight factor; however, this brightness of the room does not suit a classroom. The daylight factor in both rooms appears adequate; however, data proved through the classroom's monitoring process that its glazing provide the minimum illuminance, which does not fulfil lighting needs of classrooms. Those insights indicate that the office is resilient to different daylight conditions of 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 occupant to check the status of noise level, which both had acceptable quiet environments that suit teaching and working environments. However, increased noises from the outer corridor affect the focused nature of the room's function when the floor is fully operational and all classrooms are occupied. This issue results due to 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 and suggests a problem of weak noise isolation performance of interior walls. Lastly, outdoor noise from the outdoor court, which is empty from vegetation and noise breakers, transmits 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 per each room. The data, which gathered during varying outdoor temperatures, are used to project all IEQ deviation patterns across the entire year as shown in Table 11. This projection is guided by historical weather data of 2025 shown in Figure 9(a) and 9(b) along with seasonal temperature variations shown earlier Table 1 and constant working conditions of the monitored rooms [77]. Hence, the collective analysis assists in identifying the root causes of IEQ parameters' noncompliance with standards guided thresholds.



Figure 9. Historically analyzed IEQ against Standards-based comfort thresholds in A2.510.

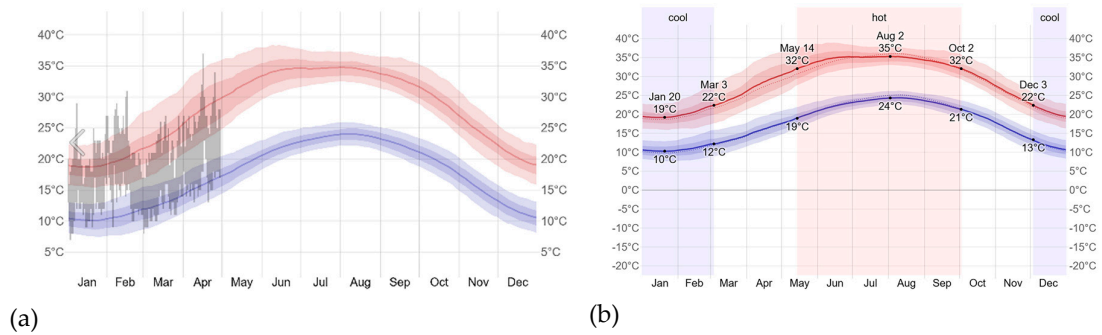


Figure 10. Cairo Temperature projections 2026 (a) Cairo Temperature History 2025 (b) © WeatherSpark.com.

Table 11. Collective IEQ deviation patterns analyses.

Room/Zone	Building Characteristics		IEQ Parameter	Comfort Range	Deviated Monitored	Comfort Deviation Duration/day	Frequency/Year (Seasonal Occurrence)
A2.508 (Classroom)	Orientation	North	Temperature	20-25 °C	26-27 °C	5-6 hours 12:00-6:00 Pm	May-October
	Window to Floor Ratio (WFR)	25%	Humidity	30-60 %	-	-	-
	U-Value	2.01W/m <sup>2</sup> K	CO <sub>2</sub> Concentration	≤1100ppm	1500 ppm	0.5-1 hour	After long weekend
	R-Value	0.5 m <sup>2</sup> ·K/W	Light	300-500 lux	≤200 lux	4 hours	Overcast outdoor conditions + deep room zones
	Glazing Type	Double glazed U-Value 2 W/m <sup>2</sup> ·K	Sound	35-40 dB	50-65 dB	6 hours 10:00am-4:00 Pm	Academic year September-June
A2.510 (Office)	Orientation	South	Temperature	20-25 °C	26 °C	6-8 hours 10:00-6:00 Pm	Mid-April –Mid November
	Window to Floor Ratio (WFR)	39%	Humidity	30-60 %	-	-	-
	U-Value	2.01W/m <sup>2</sup> K	CO <sub>2</sub> Concentration	≤1100ppm	1200 ppm	0.5 hour	After long weekend
	R-Value	0.5 m <sup>2</sup> ·K/W	Light	300-500 lux	250-280 lux	4 hours	Overcast outdoor conditions
	Glazing Type	Double glazed U-Value 2 W/m <sup>2</sup> ·K	Sound	35-40 dB	50-65 dB	6 hours 10:00am-4:00 Pm	Academic year September-June

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

The thermal comfort findings of Table 12 and 13 indicate the need for improved shading strategies in the office façade along with 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 for 11 distinct days highlight Strong variations across varying outdoor weather conditions. Accordingly, the collective IEQ analysis along with live thermal data indicate that the impact of decreasing U-value to 0.5 to 1.5 W/m<sup>2</sup>K by implanting high performance glazing can reduce heat gains [89]. According to the UN Habitat, in tropical regions, recommended U-values should be no higher than 1 W/m<sup>2</sup>·K for walls, 0.85 W/m<sup>2</sup>·K for roofs, and 5.00 W/m<sup>2</sup>·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 naturally ventilation increases the solar gains of both rooms [92]. The office, oriented south, is prone to overheating for most of the year due to high solar heat gain through low-performance glazing. The roof top cantilevered slab shown in Figure 3(a) acted as a shading device that resulted in having room A2.510 in the south to have no direct sun light except in the winter season. Hence, the office experiences limited thermal comfort improvement in winter, early spring and late autumn. In the classroom oriented north, 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 shown in Figure 3(a) is effective in preventing sun rise and sun set periods direct sunlight penetration. However, during harsh summer temperatures, the curtain wall performance does not resist heat transmittance.

**Table 12.** Digital twin's monitored thermal data across A2.508 & 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)
23/4/2026	Clear	Spring	30 °C	67 %	25 °C	29 %	26.5 °C	29 %
22/4/2026	Clear	Spring	30 °C	75 %	25 °C	36 %	26.5 °C	37 %
16/4/2026	Clear	Spring	37 °C	37 %	26.5 °C	37 %	28 °C	35 %
7/4/2026	Partly Cloudy	Spring	23 °C	31 %	23.5 °C	41 %	24 °C	43 %
	Partly Cloudy	Spring	24 °C	27 %	23 °C	41 %	24 °C	36 %
1/4/2026	Cloudy	Spring	27 °C	54 %	24 °C	48 %	24.5 °C	50 %
31/3/2026	Clear	Spring	26 °C	29 %	22.5 °C	46 %	24.5 °C	43 %
29/3/2026	Partly Cloudy	Spring	25 °C	43 %	22.5 °C	42 %	23.5 °C	48 %
	Cloudy	Spring	20 °C	41 %	21 °C	49 %	22 °C	50 %
10/2/2026	Clear	Winter	23 °C	33 %	23.5 °C	-	25 °C	-
7/2/2026	Clear	Winter	29 °C	27 %	23°C	-	26.5 °C	-

**Table 13.** Overheating root cause analysis according to comfort deviation ranges with rated 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)	WF R Value	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-	High	1.81 kW	60°	25%	High	High	High

	May) 23–32 °C							
	Summer (June- September) 34–37 °C	High	2.26 kW	83.5°	25%	High	Mediu m	Mediu m
	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 & Decision-Making Analysis

As shown in Table 14, the results of the measured air quality parameter showed that CO<sub>2</sub> concentrations remained with 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 in February and March, several days had poor climate characterized by windy and dusty outdoor conditions. This condition affected the effectiveness of natural ventilation and required the usage of air conditioning to supply pure fresh air. Thus, dust accumulation monitoring is crucial for periodic tracking of rooms' deep cleaning patterns along with external climate conditions [82].

**Table 14.** High CO<sub>2</sub> concentration root cause analysis according to different comfort deviation ranges.

Room/Zone	CO <sub>2</sub> 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 & Decision-Making Analysis

The visual comfort findings suggest that the window to wall ratio and daylight factor is efficient in the office. During sky overcast conditions, the illuminance of the space does not significantly drop. On the other hand, the classroom has good WFR, but its deep depth results in poor lighting conditions during clear conditions as the illuminance intensity is measured further that the center of room. As shown in Table 15, the digital twin's monitored illuminance level show that clear and partly cloudy

weather condition does not affect the room in south façade, while the room in north façade struggles to reach optimal levels due to its deep depth. Additionally, these design characteristic 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 [85].

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

Date	Weather Condition	Season	A2.508 average range	A2.510 average range
23/4/2026	Clear	Spring	350-400	375-450
22/4/2026	Clear	Spring	350-400	375-450
16/4/2026	Clear	Spring	350-400	375-450
7/4/2026	Partly Cloudy	Spring	275-300	300-350
6/4/2026	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%	10.5m	Overcast	None
A2.510 (Office)	300-500 lux	250-280	South	3%	39%	4.5m	Overcast	None

#### 5.4.4. Acoustical Comfort Pre-Retrofit & Decision-Making Analysis

As shown in Table 17, the analyses of the acoustical comfort suggest that upgrading internal wall insulation is important as the main source of distraction comes 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 reaches 50 when it is on in both rooms.

**Table 17.** Acoustical comfort monitored noise against noncompliance root cause analysis.

Room/ZoneFunction	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	45-60dB	45-50 dB	60 dB	Medium	Low
A2.510 (Office) Research work	35-40 dB	60 dB	45-50 dB	60 dB	Medium	Low

#### 5.5.5. Decision-Making Support

The derived insights from analysis of the digital twin data provided critical basis for IEQ where multiple parameters simultaneously deviated from standards-based comfort thresholds, leading further poor energy efficiency during academic year operation. Analyses allowed real-time informed evidence of annual frequency and durations of poor IEQ that shed light where occupants mostly rely on mechanical systems and artificial lighting. Based on these insights, Tables 18 and 19 show retrofit strategies categories into immediate, short-term, and long-term intervention, 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 simulation to estimate their impact on IEQ and energy demand. During this stage, each retrofit strategy is further evaluated in terms of cost and feasibility to prioritize of low-cost and minimally invasive decisions during building operation.

The second stage is real-world validation of the retrofit strategy prior to implementation decision making. This stage capitalizes on the existing digital twin model to retrack IEQ conditions post-intervention. This criterion allows critical evaluation of retrofit performance and determines IEQ improvement and reduction in mechanical systems utilization. This validation process includes prototypes of targeted retrofits across multiple building's 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 of immediate, short-term, and long-term retrofits blend of categories during decision-making to prioritize efficient and high-performance retrofits.

**Table 18.** Short-term targeted retrofits proposal.

Room	Retrofit Strategies	Thermal Comfort (overheating elimination)	Air quality and ventilation (Fresh air supply)	Visual comfort (sufficient daylight & glare reduction)	Acoustical 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: ● Indirect effect: ○ Negative impact: -.

**Table 19.** Long-term targeted retrofits proposal.

Room	Retrofit Strategies	Thermal Comfort (overheating elimination)	Air quality and ventilation (Fresh air supply)	Visual comfort (sufficient daylight & glare reduction)	Acoustical comfort
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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: ○ Negative impact: -.

## 6. Discussion

### 6.1. Architecture-based Digital Twins Platforms

Architecture based digital twins platforms, such as Autodesk Tandem, demonstrate an effective workflow that effectively bridges BIM models and dynamic operational data. Those platforms present a practical solution for developing low-code digital twins in architectural applications, since they require minimal coding to automate the transfer and synchronization of sensed data. Preserving BIM geometries and semantic building information, those platforms prove to be effective in transforming traditional BIM models into dynamic and data-driven environments as they continuously synchronize real-time sensor data. 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 and live outdoor environment conditions. Thereby, this workflow supports data-driven assessment of environmental quality and building resistance performance to outdoor conditions in its hot arid context.

In the case study, the platform provides data oriented spatial assessment by linking live data streams to specific building zones through which indoor environmental conditions are assessed in relation to spatial distribution of rooms and occupancy patterns. The assessment is further supported by 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 heat maps across floor plans and 3D views further support real time data visualization and comparison of multiple spaces under varying activity levels, building characteristics and external climate conditions. The monitored data are continuously structured into multiple graphs and tabled datasets according to different building zones to allow seamless tracking of both historical and real-time performance. Thus, the combination of integration, visualization, and historic data accessibility makes architecture based digital twins platforms a powerful tool that can support low code workflows to develop performance-driven building analysis and decision-making.

### 6.2. IEQ Real-Time Monitoring Implications

The findings of the case study support the role of IEQ as not only a measure of occupant comfort but also as an indicator of energy demand. This relationship is identified through increased reliance on cooling systems when IEQ parameters drift from adequate comfort ranges. Real-time monitoring of IEQ provides a robust basis for evaluating occupant dependence on mechanical systems in buildings that lack 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<sub>2</sub> concentrations, the reliance on natural ventilation through window operation introduced a different negative impact by increasing solar heat gain. Those solar heat gains posed occupant discomfort during conditions when outdoor temperatures exceeded 25°C. The visual comfort in the classroom which has a deep floor plan required 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 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 in the building could effectively be 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 of all IEQ parameters poses an integrated approach towards identifying cross IEQ intersecting factors. Furthermore, it supports the development of passive design strategies that simultaneously address thermal, visual, air quality and acoustical performance. For instance, the proposed light shelves, guided by the retrofitting phase that is based on the developed digital twin's diagnostic patterns, can work on maximizing day light transmittance to the indoors while acting as a shading device to lessen direct solar radiation.

### 6.3. Digital Twin's Decision-Making Support

The findings of the study shows that the developed digital twin model serves as an effective decision-support tool as it allows comparative analysis of IEQ performance across different spaces in a building. This comparative analysis considers critical factors that affect IEQ, including building's orientation, massing, characteristics and climatic zone. Additionally, a holistic comparison of IEQ parameters altogether accounts for in depth realization of their interdependencies that lead to occupant discomfort and energy consumption. As a result, this supports identification of passive design interventions that address multiple IEQ parameters simultaneously. Additionally, future work expanding the framework to include energy consumption data and economic indicators would strengthen its role as a comprehensive tool for guiding cost-effective and scalable retrofit strategies.

In that sense, the digital twin model is perceived as a diagnostic tool and a smart decision-making tool that could also allow prediction of problems from its historical temporal data. This leads a building's stakeholders to evaluate retrofit scenarios not only based on current performance but also anticipated environmental conditions, space usage patterns and IEQ deviation patterns.

In a broader context, data-driven analysis of buildings using real-time monitoring plays a crucial role in decarbonization and sustainable practices. This is manifested by its capability to foster data-driven optimization of a building's performance across its whole operational lifecycle. In that sense, recommended retrofits can be simulated using revit to validate their effectiveness. Furthermore, low cost prototypes of the recommended retrofits can be further implemented and test it in real life in multiple rooms 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 twins 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.

#### 6.4. Developed Framework Scalability and Replication

Due to its modular and phased structure, the proposed framework indicates strong potential for scalability and replication for 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 that can integrate any IEQ variable and can 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 IEQ benchmarks and case studies' 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 transferrable 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 occupants' comfort and energy efficiency not only within similar hot arid environments but also in broader contexts.

#### 6.5. Limitations

Due to time constraints, data was collected over a short period of time. However, this timeframe captured a range of significantly varying temperatures. When data are collected during a time where the outdoor temperature range falls under different seasons as shown in Tables 12 and 13, this diversity of varying ranges provided a basis for generalizing the findings to other seasons. Ideally, a more comprehensive assessment would involve monitoring the building continuously over an entire year to capture its performance across all seasons. This holistic assessment will support a thorough and holistic evaluation and will be more effective to fully capture the broader aim of the study's proposed framework.

The study's digital twin encompassed only two rooms in 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 distribution to assess how the IEQ results change across different zones, considering the mass articulation, facade design variation and occupants' activity. Additionally, due to collecting data during the academic year, less data was collected for the classroom as it constantly had HVAC on by its occupants as the temperature reached 24 °C, which marked a behavioral discomfort pattern. Thus, creating a digital twin for building space to identify IEQ and energy efficiency issues by spaces, floors or zones and identify to 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 data collecting sensors. In that sense, Low cost sensors, such as the MQ135 and INMP441 required calibration to provide estimated and indicative measures rather than precise measurements.

The utilized sensors showed strong reliability and stability. However, Inmp441 and MQ135 needed high power, which was not handled correctly altogether. During many occasions, the MQ135 needed long preheating durations to be able to generate reliable output.

### 6.6. Future Recommendations

Future work that can build on the study and its findings by creating a full digital twin of a whole building to capture the full potentials 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. This further would improve scalability and generalizability of the approach. Along with IEQ monitoring, the integration of energy consumption data into the digital twin is a crucial factor that supports efficient resource utilization in an existing building. Regarding the framework's phase 3, the generated retrofit decisions are preliminary and manually generated based on direct assessment from the digital twin. However, the full integration of the framework's through delving into evaluating simulations and feasibility study is an important measure prior to implementation decision-making. Additionally, the development of low cost mockups for the desired retrofits and testing them 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) is not able to handle simultaneous high frequency tasks, which necessitated a distributed system architecture. Thus, the development of the system with further advanced microcontrollers and precise sensors would make the analyses of IEQ reliable and an accurate representation of the real 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

The development of a comprehensive IEQ-digital twin framework positions real time monitoring as a decision-making tool guiding 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. The findings highlighted the interdependency among IEQ parameters, where ventilation strategies, daylight penetration and solar heat gains emerged as interconnected variables that requires 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. Being underexplored in hot arid climates, the digital twin's results show its impact in pre-retrofit and post-retrofit decision-making, which aligns decarbonization efforts of the built environment.

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. The results further indicated that the combination of IEQ analysis with building characteristics and context's climate supports identifying room-specific envelope upgrades, such as glazing performance, shading elements, and insulation. Furthermore, the classification of retrofit strategies into immediate, short-term, and long-term measures provided a structured and practical approach that prioritizes low-cost and efficient solutions to support long-term IEQ and energy performance enhancement. Accordingly, the developed framework establishes IEQ as both an indicator of occupant comfort and an indicator for energy demand to offer a 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 & construction
HVAC	Heating, ventilation, and air conditioning
SDG	Sustainable Development Goals
VOC	Volatile organic compounds
IAQ	Indoor air quality
CO <sub>2</sub>	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

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