Building occupant comfort monitoring through Digital Twins using plug-and-play IoT sensors

by

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Surveillance du confort des occupants du bâtiment via des jumeaux numériques utilisant des capteurs IoT plug-and-play

Pezhman SHARAFDIN

RÉSUMÉ

Les bâtiments consomment globalement environ 40 % de l'énergie totale, principalement destinée aux systèmes de chauffage et de refroidissement pour le maintien du confort thermique. Cependant, l'évaluation en temps réel du confort thermique est souvent peu pratique en raison de la complexité des modèles nécessitant la mesure ou l'estimation de diverses variables environnementales et personnelles.

Il existe plusieurs études axées sur les modèles conceptuels et la mise en œuvre du jumeau numérique (DT) en architecture, ingénierie, construction et gestion des installations (AEC-FM). Les DT, malgré leur potentiel de visualisation et d'analyse en temps réel des données du bâtiment, n'ont pas été utilisés de manière adéquate pour la surveillance du confort en temps réel.

Cette recherche vise à combler cette lacune et propose une solution pour mettre en œuvre un système DT pour la surveillance du confort en temps réel de l'environnement bâti. La solution améliore le confort des occupants en permettant aux gestionnaires des installations de surveiller les niveaux de confort. Dans l'étude de cas, un système DT est mis en œuvre pour évaluer l'applicabilité de la solution proposée.

Le système mis en œuvre intègre un réseau de capteurs Internet des objets (IoT) plug-and-play avec la modélisation des informations du bâtiment (BIM) pour créer un DT, qui fonctionne comme un outil de surveillance du confort en temps réel des occupants. Le réseau plug-and-play de capteurs IoT collecte des données sur les variables environnementales. Les données collectées sont automatiquement mappées dans les pièces correspondantes dans le système DT. De plus, un tableau de bord de surveillance du confort en temps réel est conçu et intégré à l'interface utilisateur de DT, fournissant un aperçu en temps réel des niveaux de confort de chaque pièce, permettant aux gestionnaires des installations de prendre des mesures en réponse aux conditions du bâtiment.

Mots-clés: IoT, jumeau numérique, BIM, capteurs plug-and-play, capteurs environnementaux, suivi du confort, phase d'exploitation et de maintenance

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ABSTRACT

Buildings globally consume approximately 40% of total energy, primarily directed towards heating and cooling systems for thermal comfort maintenance. However, real-time assessment of thermal comfort is often impractical due to the complexities of models requiring measurement or estimation of various environmental and personal variables.

There are several studies focusing on conceptual models and implementation of Digital twin (DT) in Architecture, Engineering, Construction, and Facility Management (AEC-FM). DTs, despite their potential for real-time visualization and analysis of building data, have not been adequately employed for real-time comfort monitoring.

This research aims to address this gap and proposes a solution to implement a DT system for real-time comfort monitoring of the built environment. The solution enhances occupants' comfort by enabling facility managers to monitor comfort levels. In the case study, a DT system is implemented to assess the applicability of the proposed solution.

The implemented system integrates a plug-and-play Internet of Things (IoT) sensor network with Building Information Modeling (BIM) to create a DT, which functions as a tool for real-time comfort monitoring of occupants. The plug-and-play network of IoT sensors collects data on environmental variables. The collected data is automatically mapped into corresponding rooms in the DT system. Moreover, a real-time comfort monitoring dashboard is designed and integrated into DT's user interface, providing real-time insight into the comfort levels of each room, enabling facility managers to take action in response to the building's conditions.

Keywords: IoT, digital twin, BIM, plug-and-play sensors, environmental sensors, comfort monitoring, operation and maintenance phase

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LIST OF ABREVIATIONS

ÉTS	École de Technologie Supérieure
DT	Digital Twin
IoT	Internet of Things
BIM	Building Information Modeling
BAS	Building Automation System
O&M	Operations and Maintenance
API	Application Programming Interface
DSRM	Design Science Research Methodology
TSI	Time Series Insight
HVAC	Heating, Ventilation, and Air Conditioning
BMS	Building Management System
FM	Facility Management
BLE	Bluetooth Low Energy
GATT	Generic Attribute Profile
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
IQA	Indoor air quality
PMV	Predicted Mean Vote
IEQ	Indoor Environmental Quality
PPM	Parts Per Million
PPD	Predicted Percentage Dissatisfied

INTRODUCTION

Buildings consume almost 40% of the world's total energy (International Energy Agency (IEA) 2019:201), with a significant portion attributed to heating and cooling systems for maintaining thermal comfort (International Energy Agency (IEA) 2020). Additionally, people spend more than 80% of their time indoors (Zhao, Sun, and Ding 2004), where various factors, such as thermal, visual, acoustic, and air quality comfort can significantly impact their well-being (Halhoul Merabet et al. 2021). However, real-time and continuous assessment of thermal comfort is often not practically feasible since most thermal comfort models require the measurement or estimation of various environmental and personal factors (Pavlin et al. 2017).

Although Digital Twins (DTs) have great potential for delivering detailed and user-friendly visualizations of building monitoring's data, they have received little attention in the context of thermal comfort (Shahinmoghadam, Natephra, and Motamedi 2021). Thus, there is a need to investigate the application of DTs for real-time monitoring of comfort in built environments to improve occupant comfort while potentially reducing energy consumption.

The primary goal of this research is to investigate a solution to enable building operators to monitor the comfort level of occupants for various types of built environments (e.g., as residential, and commercial buildings) in real-time. The proposed solution encompasses a software/hardware architecture and an implemented system as a proof of concept in a real-world case study. The solution includes a plug-and-play network of Internet of things (IoT) sensors and a DT platform for the visualization of comfort levels. The proposed solution is based on the integration of Building Information Modeling (BIM) and IoT data sources to create a DT of the build asset.

The plug-and-play network of IoT sensors collects data on environmental variables, such as temperature, humidity, air quality, and sound level. These sensors' data are automatically mapped into related rooms on a DT platform, providing real-time insight on the comfort level of each room. The developed solution aims to offer a practical and innovative approach for real-time comfort monitoring identifying areas that require attention by facility managers to maintain the comfort levels of the building, which potentially leads to optimizing energy consumption while maintaining occupant comfort.

0.1 Research Questions

The overall research question of the thesis is: "How can a digital twin solution be employed for real-time comfort monitoring of built environments through the integration of BIM and IoT?"

The main research question can be broken down into the following more specific questions:

- What environmental variables contribute to the comfort of occupants in built environments, and how can they be measured using IoT sensors?
- How can an IoT sensor network be designed to be plug-and-play, and what are the key design considerations for achieving this feature?
- What is the best fitting method to calculate the comfort level of each room in real-time?
- How can a digital twin platform visualize the indicators of comfort level and provide real-time insights for facility managers?

These research questions seek to explore the utilization of a DT platform to monitor the comfort of occupants within built environments in real-time, leveraging the synergy between BIM and IoT technologies. This investigation is divided into four specific queries.

Firstly, it examines the key environmental variables, such as temperature, humidity, and air quality, that affect occupant comfort and how IoT sensors can be deployed to measure these factors. Secondly, the research delves into the architectural design of an IoT sensor network that supports easy integration or 'plug-and-play' functionality, focusing on the critical design elements required to achieve this capability. Thirdly, it assesses the most effective methods for real-time comfort level monitoring in each area. Lastly, the research investigates how a DT platform can represent comfort level indicators visually, thereby providing facility managers with instant, actionable insights to maintain or enhance occupant comfort within the built environment.

0.2 Research Objectives

The main objective of this research is to investigate a solution for real-time monitoring of building comfort. Following the proposed solution, a web-based DT system for thermal monitoring will be designed, developed, and assessed. The system includes the development of a data acquisition layer using IoT sensors for the measurement of environmental variables. The collected data will then be integrated with the BIM model to create DT for comfort monitoring.

More specifically, the research objectives are to:

1. Conduct a literature review to synthesize state-of-the-art applications of DTs for comfort monitoring and to identify key variables that influence occupant comfort in built environments.
2. Design and implement a plug-and-play network of IoT sensors that can be easily installed and used in various built environments.
3. Integrate the IoT sensor network with a digital twin platform for real-time data monitoring and analysis.
4. Identify a method of visualization to provide insights into the comfort of a built environment in real-time.
5. Validate the applicability and effectiveness of the proposed solution through a case study implementation.

0.3 Delimitation

The proposed solution is intended for the operational phase of buildings, excluding the construction and design phases. Regarding the sensors used in the case study implementation, as the focus of the research is to provide a software/hardware architecture and demonstrate the proof of concept through a case study, their precision and accuracy may not be optimal for industrial implementation.

The communication protocol selected for this study is Bluetooth Low Energy (BLE); other wireless technologies are not considered. Additionally, the research assumes that the rooms have already been defined in a BIM model, and the study will not focus on the process of designing or developing the BIM model.

In terms of thermal comfort analysis, a variety of methods are available. The primary aim of this research is not to develop new methods for assessing comfort or to validate the efficiency of existing ones. Instead, it focuses on the integration of sensor data into the DT to monitor thermal comfort using existing methods. With this goal, the research selects a thermal comfort analysis method that is most compatible with the experimental setup being used, including the type of space (i.e., air-conditioned office space) and the types of sensors. Lastly, for the thermal comfort analysis, it is assumed that the building uses an HVAC system and that the rooms being monitored are not subjected to solar radiation.

0.4 Research Contributions

By addressing the research questions outlined above, this study aims to make contributions to the advancement of knowledge and practice in the following areas:

- The research contributes to the development of a plug-and-play network of IoT sensors that can be easily installed in various built environments to measure environmental variables in real-time.

- The proposed software/hardware architecture for the automatic integration of plug-and-play IoT sensors with the BIM model, including an automated method of mapping sensors to the related rooms for the purpose of real-time monitoring and analysis of sensor data, contributes to the existing body of research on DT for built environments.

This architecture facilitates the creation of DTs implemented for comfort monitoring, addressing the gap in existing literature and practices.

- The research results contribute to the body of knowledge on comfort monitoring solutions by providing a DT-based solution for real-time monitoring of each room in a building. This can potentially help building owners and operators better identify areas where energy savings can be achieved while maintaining occupant comfort.

- The research contributes to the academic literature on smart building management, IoT sensor networks, and DT platforms by providing new insights into how these technologies can be used to develop a comfort monitoring system for buildings.

CHAPTER 1

LITERATURE REVIEW

This chapter delves into the relevant literature, with a focus on the key concepts of the research including building comfort, IoT, BIM, and DT in built environments. The review provides definitions, state-of-the-art research and implementation, challenges, and limitations of each concept, which helps to establish a solid background foundation for the proposed solution.

1.1 Comfort in built environments

Individuals typically spend 65% of their time at home and 85-90% of their time in indoor environments (Ganesh et al. 2021). Based on variables, such as age and the type of work being undertaken, this proportion may increase considerably (Brasche and Bischof 2005). Insufficient indoor comfort can lead to occupants' dissatisfaction and to decrease their productivity and performance. Additionally, it can give rise to other problems, such as dryness, health, and Sick Body Syndrome (SBS) (Budaiwi 2007). Hence, the implementation of a monitoring system to assess the internal environment can be very helpful and beneficial to ensure that buildings remain in comfort condition (Kang, Lin, and Zhang 2018). Along with the growth of cities, people are using more energy every day. It is anticipated that over time, the demand for energy will rise dramatically. Almost 70% of all the energy used in the world goes to keeping the inside of buildings comfortable (US Energy Information Administration 2012). Therefore, it is important to preserve a balance between the energy demands of the building and the indoor environmental quality. The level of comfort experienced by occupants has a significant impact on both their well-being and the amount of energy consumed. The combination of acoustics, visual, indoor air quality (IAQ), and thermal conditions are among the physiological and psychological variables that are studied under the terms comfort and Indoor Environmental Quality (IEQ) (d'Ambrosio Alfano et al. 2014).

Occupants may perceive comfort differently even when experiencing the same IEQ conditions. It is due to the fact that comfort is a combination of several parameters, even individuals who are in the same geographical region at the same time and age might have different perceptions of comfort (Standard and EN15251 2007). Consequently, the development of a monitoring system that comprehensively considers the varying parameters affecting thermal comfort is crucial. This system should be capable of accommodating the diverse comfort needs of individuals, thereby ensuring that buildings not only function efficiently but also enhance the health and holistic well-being of their occupants.

1.1.1 Acoustic comfort

Acoustic comfort means keeping occupants from being bothered by unwanted noise (Ganesh et al. 2021). The concept can be defined as "a state of satisfaction with acoustic conditions" (Vardaxis, Bard, and Persson Waye 2017). Acoustic comfort is indeed a crucial factor that contributes to providing an acceptable indoor environment for occupants. It is the study of various factors that affect sound quality and aims to reduce noise levels, thereby minimizing discomfort and promoting a more comfortable environment. The level of comfort experienced is influenced by both the environment's physical characteristics and the sound's attributes (Andargie, Touchie, and O'Brien 2019). Numerous researchers have attempted to establish a correlation between the impacts of acoustic comfort on overall comfort and IEQ. Fanger et al. (1977) conducted an experiment to observe the impact of background noise on the comfort levels of the occupants. The author reported that a combination of 40 dBA background noise and 85 dBA white noise did not have a significant impact on the comfort levels of the occupants. Pellerin and Candas (2003) have conducted several studies to categorize the impact of sound on IEQ. There are two primary methods for quantifying sound intensity. Sound pressure level (SPL) for both short and long durations, as well as frequency of sound. Their study revealed that the presence of ambient noise did not significantly influence the occupants' perception of comfort for an initial period of 30 minutes. However, another study by Yang et al. (2018) shows that when ambient noise persisted for over 120 minutes, a notable effect was observed.

Frontczak and Wargocki (2011) introduced thermal and acoustic comfort as the most crucial variables in occupants' comfort. In the meantime, HVAC equipment has been suggested as one of the most significant variables that can be manipulated when considering thermal-acoustic trade-offs (Chen et al. 2019). Clausen et al. (1993) suggested that the 3.9 dB noise change induces the same effect as changing 1 °C in the operative temperature. This synergy between thermal and acoustic has been recommended to be seen and worked on in high-performance buildings (Ferrara et al. 2021). Yang et al. (2019) conducted experiments with bubbles, fans, music, and water sounds at intensities of 45, 55, 65, and 75 dBA and reported that "acoustic comfort rises in thermoneutrality, thermal comfort increases with a decrease in the noise level at 500 lx, and visual comfort increases with a decrease in the noise level at thermoneutrality". Lai et al. (2009) found that once noise levels exceed 70 dBA, noise acceptability decreases significantly. On the other hand, Jeon et al. (2010) observed a substantially lower threshold. They reported 80% dissatisfaction with drainage and airborne noise levels of 42 and 43 dBA, respectively.

Furthermore, the acoustic comfort of an occupant is influenced by additional parameters, such as acoustic insulation, absorption, and echo duration (Cowan 1993). It has been found through experimentation that there is a direct link between worker performance and acoustic comfort (Landström et al. 1995). Several causes of acoustic discomfort have been identified, including airborne noise, outdoor noise, noise from the neighboring room, noise from the workplace, and noise from local services. The level of discomfort experienced by an individual may vary depending on the strength and frequency of the sound (Veitch et al. 2002). Hence, it is important to consider all the above-mentioned factors when designing a workplace or building. Strategies for noise cancellation, such as electronic sound masking techniques, utilizing tile roofs, and acoustic panels have been proposed (Loewen and Suedfeld 1992). However, it should be noted that these methods of noise cancellation may only work for a short period, as the long-term effects can lead to severe headaches and discomfort. Studies that used sound pressure levels to evaluate acoustic comfort suffer from a significant limitation. Acoustic comfort encompasses more than just the volume of sound; it is influenced by a combination of factors, including the frequency of the noise, which can have a significant impact on how sound is perceived and experienced. The human ear's sensitivity to noise varies with frequency (Burns 1973). Consequently, the strength and noise level of two noise sources with the same sound pressure level but different frequencies are perceived differently. The A-weighted sound pressure level is a more suitable method to measure how loud a sound is to the human ear, but it has been shown to decrease the effects of low-frequency sounds, especially those with a frequency below 100 Hz (Waye 2011). It also reduces the effects of pressure levels that are higher than 60 dB (McMinn 2013). As a result, it is inappropriate for occupants to be exposed to low-frequency noise sources such as HVAC systems and vehicles.

1.1.2 Visual comfort

Visual comfort is defined as "a subjective condition of visual well-being induced by the visual environment" (Standard and EN15251 2007). According to literature, indoor visual comfort is influenced by six main parameters, which include glare, outside view, daylight, lighting level, lighting uniformity, and privacy (Andargie et al. 2019). A study conducted by Katafygiotou et al. (2015), concluded that visual comfort is essential for the productivity and well-being of indoor building occupants, regardless of the type of activity. The authors investigated the effect of lighting on eyes and general health of occupants after working in low light conditions, based on their age, gender, climatic conditions, and type of their task. The study found that working in low light conditions resulted in poor quality sleep at night and severe post-work damage. Bakmohammadi et al. (2020) proposed a framework that utilizes daylight to optimize visual comfort in classrooms while minimizing energy consumption. Wymelenberg et al. (2014) recommended an optimal window glazing ratio to maximize the utilization of natural light while maintaining visual comfort and energy efficiency at an optimal level. Kwong (2020) highlighted that in the modeling of modern green buildings, visual comfort is given equal importance as energy efficiency and natural light utilization. Therefore, it is crucial to focus on lighting and ensure that visual comfort in enclosed buildings meets the desired standards. In addition, studies show that occupants are satisfied with lower-than-recommended light intensity levels in areas such as the bedroom and family room (Holton 2012). According to the findings of Lai et al. (2009), while the acceptability of illumination levels improves from 10 lux to 50 lux, their acceptance level remains constant after 50 lux, implying that levels as low as 50 lux are appropriate for the occupants.

1.1.3 Air quality comfort

Studies have shown that indoor air pollution is one of the top five environmental risks to public health. In a recent survey conducted in the US (Sun et al. 2019), it was found that 76% of occupants would feel more comfortable entering buildings where IEQ is monitored and known. Thermal comfort and IAQ are two of the most important factors that impact occupant comfort and productivity (Wu et al. 2020). IAQ refers to several factors, such as drafts, blocked air, dry air, humid air, odor, and the concentration of pollutants in indoor air. The concentration of pollutants and dust particles can cause various health problems, such as respiratory issues, eye irritation, and the spread of infections and viruses (Bluyssen et al. 2016). Ventilation systems play an essential role in IAQ and occupant comfort in the interior environment. They remove pollutants from the air and dilute their concentration to appropriate levels (Chenari, Carrilho, and da Silva 2016).

Several studies reveal that indoor air quality has a significant impact on occupant comfort, health, and productivity, indicating the need for further research (Andargie et al. 2019). Wei et al. (2019) reviewed the current state of the art in IAQ prediction using statistical models, such as partial least squares, generalized linear models, and Bayesian hierarchical models. Many studies have looked at occupants' comfort with IAQ without attempting to understand the reasons for the varying levels of satisfaction, but only a few have concentrated on the specific factors or parameters related to IAQ (Andargie et al. 2019).

The measurement of carbon dioxide (CO_2) concentration holds significance in assessing IAQ and is frequently employed as an indicator for ventilation rates (Fisk 2017). The concentrations of CO_2 serve as an indicator of the acceptability of IAQ, the adequacy of air exchange, and the sufficiency of fresh air supply in buildings (Apte, Fisk, and Daisey 2000). The levels of CO_2 within indoor environments can often exceed those found outside, with concentrations normally falling within the range of 350 to 2500 parts per million (ppm) (Seppänen, Fisk, and Mendell 1999). However, there are instances where CO_2 levels indoors can reach as high as 4000-4500 ppm or even beyond these values (Shaughnessy et al. 2006). Symptoms associated with SBS resulting from heightened levels of CO_2 encompass headache, fatigue, ocular irritation symptoms, neurophysiological symptoms, as well as upper and lower respiratory tract symptoms (Ma et al. 2021).

The study conducted by Földváry et al. (2017) discovered that air exchange rates are positively correlated with the acceptability of IAQ. This correlation was established through the measurement of CO_2 concentrations. Similarly, Strøm-Tejsen et al. (2016) found an inverse relationship between indoor CO_2 levels and occupant satisfaction. However, some studies found that there is no match between reported IAQ satisfaction levels and measured CO_2 levels, which could be due to the behavioral and physical activity of occupants (Leivo et al., 2016; Rojas et al., 2016). Additionally, other IAQ indicators were used to assess the relationship with occupant satisfaction. Du et al. (Du et al. 2015) found that higher levels of $PM_{2.5}$, PM_{10}, formaldehyde, NO_2, radon, fungi, and relative humidity in residences led to occupants' dissatisfaction with IAQ. Moreover, Földváry et al. (2017) reported that IAQ acceptance levels have an inverse relation with formaldehyde and total volatile organic compounds (TVOC) levels.

Aside from the aforementioned IAQ indicators, occupants' satisfaction with IAQ is affected by several other factors. According to studies that relied on subjective reporting for causes of dissatisfaction with IAQ, odor, stuffy air, and dust affect IAQ satisfaction levels (Xue, Mak, and Ai 2016). Perceived control, which refers to the occupants' ability to personally adjust environmental factors within a space, also influences the occupants' satisfaction with IAQ. Brown and Gorgolewski (2014) reported that occupants with higher perceived control have higher perceived IAQ. Chan et al. (2008) found a negative correlation between temperature levels and IAQ satisfaction. Similarly, Gou et al. (2018) found that satisfaction with IAQ has a positive relationship with thermal comfort and air velocity. It may be because occupants can easily sense discomfort when both IAQ and thermal conditions are outside the comfort range.

1.1.4 Thermal comfort

Indoor thermal comfort is an important aspect that determines the satisfaction of individuals with their living environment. It is defined as "that condition of mind that expresses satisfaction with the thermal environment" (Zahid, Elmansoury, and Yaagoubi 2021). Since people spend most of their time indoors, the thermal environmental conditions have a significant impact on their well-being, performance, and overall satisfaction with the built environment (Zhang, de Dear, and Hancock 2019). To determine the thermal comfort level, numerous thermal comfort indices have been developed since the 1960s. Many studies have characterized the range of acceptable temperatures for optimal thermal comfort and predicted temperatures where thermal neutrality would occur. The neutral temperature, which is the temperature at which occupants feel neither warm nor cold, is a crucial parameter in determining the thermal comfort level (Mui and Wong 2007). In a study conducted by De Dear et al. (1998), it was suggested that neutral temperatures are influenced by indoor conditions and tend to align with the mean indoor temperatures due to occupants' adaptations. However, the findings from a literature survey indicate that the outdoor temperature may have a more significant impact. For example, Wang et al. (2011) found neutral temperatures were higher during the heating season compared to before the heating season, despite similar indoor temperatures during both periods.

The most commonly used thermal comfort indices are the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) indices (Fanger 1970), which have been adopted by several international standards, such as ISO 7730 and ASHRAE 55. The PMV, as defined by Fanger (1970), predicts the average thermal sensation votes of a large group of people. While the ASHRAE 55 standard recommends a seven-point scale for thermal sensation, ranging from +3 (hot) to -3 (cold) (ANSI/ASHRAE 2017:55). Three factors influence thermal comfort inside buildings. Measurable environmental factors, including air temperature (°C), air velocity (m/s), mean radiant temperature (°C), and relative humidity (%), personal factors, such as metabolic rate (met) and level of clothing insulation (clo), and psychological factors, such as color, texture, sound, light, and aroma influence thermal comfort. However, measurable environmental and personal factors are more commonly used to describe thermal comfort conditions in the literature (Grondzik and Kwok 2015).

The PMV index is used in ISO 7740 Standard. It takes into account four physical variables, including air temperature, air velocity, mean radiant temperature, and relative humidity, as well as two personal variables, clothing insulation, and activity level of the occupant. The PMV equation (1.1) is used to calculate the thermal sensation votes of a large group of people (Valinejadshoubi et al. 2020):

$$PVM = (0.303 \times e^{(-0.06M)} + 0.028) \times \{M - W - 3.05 \times 10^{(-3)} [5733 - 6.99 \times (M - W) - \rho_a] - 0.42 \times (M - W - 58.15) - 1.7 \times 10^{(-5)} \times M(5867 - \rho_a) - 0.0014 \times M(34 - t_a) - 3.96 \times 10^{(-8)} \times f_{cl} \times [(t_{cl} + 273)^4 - (t_r + 273)^4] - f_{cl} \times h_c \times (t_{cl} - t_a)\} \quad (1.1)$$

Where:

M is Metabolic rate $\left(\frac{W}{m^2}\right)$

W is the mechanical power $\left(\frac{W}{m^2}\right)$, zero for activities such as writing

t_a is indoor air temperature °C

t_r is mean radiant temperature °C

ρ_a is partial pressure of water vapor (Pa)

h_c is convection heat transfer coefficient $\left(\frac{W}{m^2K}\right)$

t_{cl} is clothing surface temperature °C is related to the cloth that the person wear.

f_{cl} is clothing surface area factor

i_{cl} is clothing insulation (m2 K/W)

V_{ar} is relative air velocity $\left(\frac{m}{s}\right)$

1.2 Internet of Things (IoT) in built environments

1.2.1 Definition and principles of IoT

IoT can be defined as a network of interconnected physical devices, such as sensors, mobile devices, and Radio Frequency Identification (RFID) devices, which collects real-time data (Pan 2021). Each device is equipped with sensors, network connectivity modules, and processing units, enabling them to communicate with each other to offer a range of smart services to end-users (Asghari, Rahmani, and Javadi 2019).

IoT has fundamentally changed the way we view and interact with everyday objects. With its ability to connect people and objects, IoT has brought about a level of interconnection that was previously unimagined, thereby disrupting traditional ways of carrying out tasks and processes (Gubbi et al. 2013).

BLE is a technology designed for wireless data communication over short distances. It is highly cost-effective and energy-efficient, making it a critical component of IoT applications that require low power consumption and bandwidth over short distances (Perri, Cuomo, and Locatelli 2022). Generic Attribute Profile (GATT) is a part of the BLE protocol that defines the way data is organized and accessed on a BLE device. In GATT, data is organized hierarchically in the form of services, which are collections of characteristics. A characteristic contains a value and may have additional information such as descriptors (Hirsch et al. 2023). Figure 1.1 shows the data structure hierarchically in GATT.

During the initial connection between two devices, a discovery phase of services, characteristics, and descriptors is required for GATT to operate. This discovery phase is essential for establishing the connection between BLE devices. However, if not optimized, this discovery step can take a few seconds, leading to delays for the end-user (T'Jonck et al. 2021).

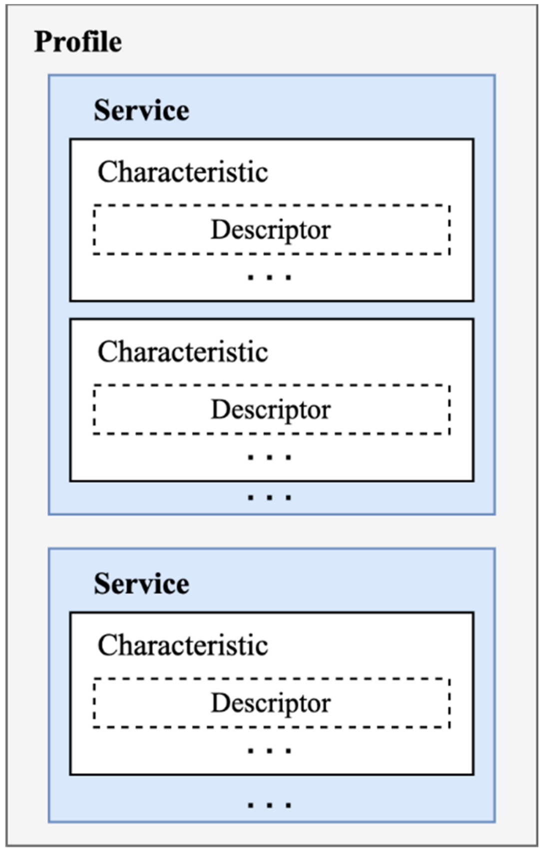

Figure 1.1 The data structure
hierarchy of GATT
Adopted from Dian et al. (2018)

1.2.2 Role and benefits of IoT in building management

A new generation of building management systems has emerged by the adoption of IoT and sensing technologies in the construction industry. A key development in this area is the introduction of cyber-physical systems (CPS), which initially introduced in the manufacturing sector. CPS has emerged as a significant solution for building management due to its ability to integrate sensing and actuation capabilities with computation and communication capabilities, thus enabling the automation and optimization of building operations (Chung et al. 2018).

By implementing an IoT solution, a considerable amount of data can be gathered and shared over the network. By synthesizing and analyzing data collected via IoT infrastructure, real-time decision-making and automation can be facilitated during the operation stage of a building. It provides the ability to remotely control, optimize the building performance, and predict future conditions (Cheng et al. 2020).

IoT and data networks have the potential to optimize various Facility Management (FM) activities, such as historical data cataloging, logistics and material tracking, building component lifecycle monitoring, and building energy controls (Wong, Ge, and He 2018).

The integration of IoT technologies marks a significant advancement in improving the efficiency of FM. This advancement involves the use of wireless sensors, which collect data directly from various building systems (Krishnamurthy et al. 2008). IoT systems, equipped with algorithms and machine learning, can autonomously make decisions, as well as providing users with crucial insights that aid them in making well-informed and optimal decisions (Rizal and Hikmatyar 2019). Furthermore, it improves operational efficiency by facilitating data collection and inter-device communication (Piette, Kinney, and Haves 2001).

1.2.3 Challenges of IoT implementation in FM

The integration of the IoT into the FM of buildings represents a significant shift towards more efficient, responsive, and intelligent building operations. However, this integration is accompanied by a range of challenges that need to be addressed to fully leverage IoT's potential in FM. This section discusses the key challenges identified in recent research.

Recent advancements in both hardware and software for automated data acquisition (DAQ) technology have been notable (Villa et al. 2021). However, most available technologies are still costly and not open-source, and users lack the ability to modify the implemented algorithms. Additionally, obtaining free access to stored data often requires the purchase of specific software. To overcome these limitations, recent studies have explored and developed customized designs for automated DAQ systems (Villa et al. 2021).

A significant challenge in the deployment of IoT in buildings is ensuring the security and privacy of the data collected and transmitted by IoT devices. The integration of IoT with cloud services, for example, requires robust algorithms to ensure secure and reliable connections, protecting data from unauthorized access and cyber-attacks (Zamkovyi et al. 2023). A review paper on security in IoT (i.e., Ub et al., 2021) highlights the various attacks IoT systems can face and proposes a taxonomy of security requirements to mitigate these risks. Moreover, the paper discusses recent security solutions, classified based on their application area, emphasizing the need for robust security frameworks to protect sensitive information.

Additionally, the lack of standardized protocols and interfaces for IoT devices complicates their integration into existing FM systems. A study on smart building systems highlights the need for a unified framework to address risks, threats, and standards, ensuring seamless interoperability among diverse systems (Zamkovyi et al. 2023).

Furthermore, the vast amount of data generated by IoT devices presents challenges in terms of collection, storage, and analysis. Efficient data management practices are essential to translating raw data into actionable insights for FM (Olimat, Liu, and Abudayyeh 2023)

The successful implementation of IoT in building management requires a workforce skilled in new technologies. This includes not only technical skills related to IoT devices and systems but also analytical skills to interpret the data generated by these systems (Dulguun 2023).

The economic aspects also pose significant challenges to the widespread adoption of IoT in buildings for FM. The initial investment in IoT technology can be significant, and the Return on Investment (ROI) may not be immediately apparent. Research on the readiness of IoT-enabled smart buildings in Malaysia, for example, highlights the challenges faced in adopting smart building technologies due to cost barriers (Kiu et al. 2021).

The integration of IoT in buildings offers promising opportunities to enhance building operations, energy management, and occupant comfort. However, addressing the challenges related to security, interoperability, data management, system reliability, and integration with existing infrastructure is crucial for realizing the full potential of IoT in this domain. Future research should focus on developing comprehensive solutions to these challenges that promote the development of smart, sustainable, and efficient buildings.

1.3 Building Information Modelling (BIM)

1.3.1 Definition and principles of BIM

BIM is a process that entails the creation and use of digital representations of a building's physical and functional characteristics. It provides a comprehensive knowledge resource for the facility, supporting informed decision-making throughout its entire lifecycle, from initial planning to demolition (Eastman 2011). It is a digital engineering approach that facilitates information management and supports collaboration throughout the procurement and management of the built environment (ISO 2020). However, it has become apparent that BIM implementation during the operation phase has not been as effective as compared to other project phases (Edirisinghe et al., 2016; Hoang et al., 2020). The integration of BIM in facility management enables stakeholders to access, update, and share information about the physical and functional aspects of a building, leading to improved decision-making, reduced operational costs, and enhanced building performance. For example, in the facility management context, BIM has the potential for active storage of documentation and other data that is used during the FM phase (Liu and Issa 2013).

FM is responsible for 80% of total costs over the life cycle of a building. BIM can significantly reduce time and resource expenditure caused by inefficient operation during this phase of construction (Liu and Issa 2013). The literature reveals that using BIM for FM has enormous potential to support collaboration and enables a more efficient operation of facilities through digital data storage, controlling and monitoring energy use, preventative maintenance, among other benefits (Durdyev et al. 2022).

1.3.2 The role of BIM in building operation and maintenance

According to a study conducted by Akcamete et al. (2010), facility operation results in the largest expenses of a building. The use of BIM for creating and updating databases at a US Coast Guard facility resulted in a significant time saving of 98% (Eastman 2011), indicating the superiority of digital data storage through BIM over traditional physical filing methods. The literature repeatedly highlights that BIM is a centralized repository for interoperable lifecycle data. BIM can be used for storage as a collaborative digital archive, providing a single location for all the documentation required to operate and maintain a facility, including operating manuals, warranties, blueprints, and product specifications (Matarneh and Hamed 2017).

Monitoring the energy performance of facilities during the operation and maintenance (O&M) phase is crucial to compare the actual energy performance with the designed parameters. BIM data can be used to predict energy performance during operation through monitoring and simulations, which can help identify any deviations from in-use performance with the predictions (Gerrish et al. 2017). In a literature review conducted by Matarneh et al. (2019), several key applications of BIM for energy management are outlined, including monitoring, analysis, and optimization of building systems for enhanced energy efficiency, the assessment of overall building energy consumption to support informed management decisions, and the visualization of sensor data within a BIM model.

1.3.3 Challenges of BIM implementation

It has been found through recent analyses that BIM for the O&M phase is still in its early stages (e.g., Z.-S. Chen et al., 2024; Goretti & Kaming, 2023). The use of BIM only as a three-dimensional model has a very limited added value in the O&M phase, and the lack of interoperability, together with the absence of open systems, discourages its use (Gao and Pishdad-Bozorgi 2019). BIM is more widely marketed to design and construction professionals rather than Facility Managers (Edirisinghe et al. 2016). A survey of active industry professionals revealed that only 7% of the 180 respondents used BIM for FM (Matarneh and Hamed 2017). Due to potential applications of BIM in the operation phase, there is a need to address the challenges related to the limited adoption of BIM for FM.

Despite the numerous benefits that BIM offers, several barriers have been reported in the literature that appear to contribute substantially to the limited adoption of BIM for FM. One of the major problems is that BIM is only likely to be used for the FM phase if it has already been applied to the project during design and construction. This is due to the large up-front cost associated with implementing BIM, which includes software, hardware and training of staff (Migilinskas et al. 2013).

During the O&M period of buildings, the environment information should be constantly monitored to allow supervisors to take measures, deal with emergencies and improve energy efficiency. The lack of data and information in as-built digital models considerably limits the potential of BIM in building management (Mannino, Dejaco, and Re Cecconi 2021). Nonetheless, building managers and decision-makers still face the need for solutions that allow them to visualize, interpret, and utilize data (Guzman and Ulloa 2020). They currently still use text or spreadsheets, which make it difficult to understand and track the real-time building's performance, and this is a way of work, which is prone to errors (Kazado, Kavgic, and Eskicioglu 2019).

The most significant causes hindering the use of BIM during the O&M phase are: (1) the use of BIM only as a three-dimensional model, which has no added value in the maintenance management phase (Munir, Kiviniemi, and Jones 2019); (2) FM workers are not involved in the creation of the model, so the information contained within the BIM system is not useful (Dixit et al. 2019); (3) the need for interoperability between BIM and FM technologies and the lack of open systems (Pärn, Edwards, and Sing 2017); (4) the lack of clear roles, responsibilities, contract and accountability framework (Pärn et al. 2017); and (5) the information contained in BIM models is static and not dynamic, as FM requires. Data is provided during the design phase but is not updated during the building life cycle (Patacas et al. n.d.).

1.4 Digital Twin (DT) in built environments

1.4.1 DT technology

The initial introduction of the DT emerged during NASA's Apollo program (Schleich et al. 2017). In this context, DT was defined as “an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin” (Negri, Fumagalli, and Macchi 2017).

Most definitions of DT focus on the real-time data flow between the physical and digital worlds (Singh et al. 2021). In fact, a DT (as shown in Figure 1.2) is a digital replica of a physical entity that consists of three main components, including the physical object, the virtual object, and the two-way data communication between them (Boje et al. 2020).

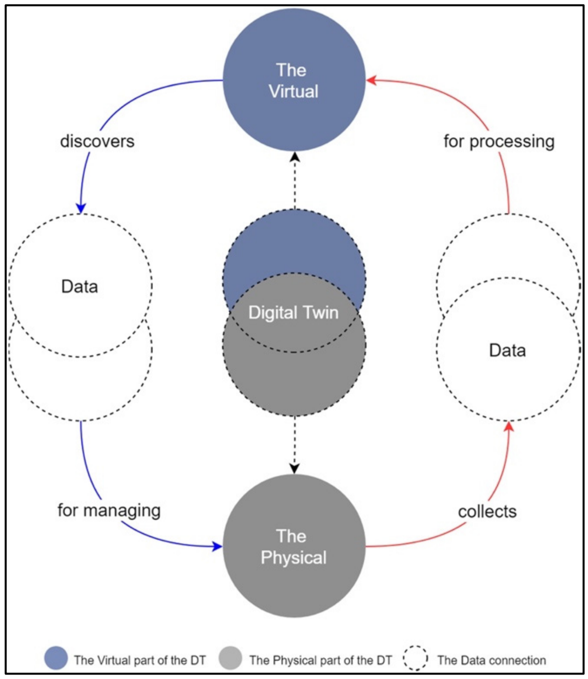

Figure 1.2 A DT's elements
Taken from Boje et al. (2020)

Several comparisons can be made between DT and cyber-physical system (CPS). Both concepts highlight the importance of physical objects and involve the transfer of data between physical objects and virtual models in real time. However, while DT requires a virtual model and a twin relationship between the physical entity and its corresponding virtual entity, CPS does not necessarily need a virtual model and focuses more on the "cyber" aspect of things (Jiang et al. 2021). One of the advantages of these systems is that all their parts are tied together in real-time, allowing them to operate based on each other's data (Al-Ali, Gupta, and Nabulsi 2018). In this regard, Davari et al. (2022) conducted a study to demystify the definitions of DT and CPS in the construction industry.

The use of DTs has gained popularity in the construction industry; most of its application has been focused on the operation and maintenance phase of buildings (Opoku et al. 2022). In the operational phase of a building, Nasaruddin et al. (2018) defined DT as “the interaction between the real-world indoor environment of the building and a digital but realistic virtual representation model of the building environment, which provides the opportunity for real-time monitoring and data acquisition”. In this definition, the indoor environment comprises information, such as air temperature, airflow, relative humidity, and lighting conditions.

The bidirectional communication between virtual and physical objects is the primary distinction between DT and BIM. DT is a dynamic and proactive model that is functional with or without human intervention, providing a more flexible and adaptable approach. In contrast, BIM models lack this feature (Desogus et al. 2023).

The integration of BIM-IoT uses the geometric and parametric features of BIM models and the real-time environmental data (such as temperature, and humidity) gathered by IoT sensors, generating a DT for real-time building monitoring and visualization. By leveraging this integrated platform, facility managers can analyze data to optimize energy use and indoor comfort, leading to operational cost savings (Kazado et al. 2019).

1.4.2 Applications and Benefits of DT in O&M

During the O&M phase of buildings, it is crucial to continuously monitor environmental data. This enables operators to promptly take action, address emergencies, and enhance energy efficiency. In this case, DT is a promising technology that can be used for real-time environmental data monitoring during the O&M phase. This is because DT enables building monitoring and analysis by facilitating dynamic analysis and simulation, using bidirectional data communication between the physical building and its virtual counterpart. There is a growing body of literature that concentrates on the application of DT during the O&M phase of buildings.

Arowoiya et al. (2023) proposed a list of DT applications in the O&M phase of buildings, including thermal comfort monitoring, energy management, and prediction for buildings' maintenance. Additionally, DT has been employed in the visualization and monitoring of indoor environments to assess people's comfort (Zaballos et al. 2020) and enhance building energy efficiency (Bortolini et al. 2022).

In this regard, Xie et al. (2020), and Lu et al. (2020) developed a DT framework to monitor the condition of assets to identify anomalies in the HVAC systems. They employed a Bayesian method based on a change point methodology to reveal abnormalities in HVAC systems in real time. Moreover, Peng et al. (2020) proposed a continuous lifecycle integration framework for a large hospital in China. In their case study, a DT solution with real-time visuals and AI diagnostics was implemented in a new control center. It allows managers to monitor and optimize hospital operations effectively to enhance maintenance and energy efficiency and reduce equipment malfunctions.

In another study, Zhao et al. (2022) reviewed four cases in which DTs were implemented during the O&M phase. The review was utilized to suggest a conceptual framework for DT that could be used for the energy efficiency enhancement of FM. The research emphasized the importance of conducting further studies to explore the potential of DT technology in addressing environmental issues, reducing energy consumption, and minimizing carbon emissions. Cheng et al. (2020) introduced a framework based on data analysis for FM in indoor systems using the integration of IoT-BIM. The framework utilized artificial neural networks (ANN) and support vector machines (SVM) to forecast the status of mechanical, electrical, and plumbing (MEP) systems. This approach has helped in scheduling maintenance tasks effectively.

1.4.3 Challenges in Implementing Digital Twin Technology

Despite the significant potential of DT technology, there are still several obstacles that need to be addressed. These include the handling of large-scale data processing, data security and privacy, cost management, technical limitations, and the real-time integration of the physical and digital worlds. In the Architecture, Engineering, Construction, and Facility Management (AEC-FM) industry, there are additional challenges related to data collecting and processing, real-time monitoring, data accessibility, user interface customization, and interaction with intelligent solutions (Halmetoja 2022).

Defining access levels and permissions for data privacy and ownership are critical concerns for DTs (Brozovsky, Haase, and Lolli 2018). These issues require attention, as they can have a significant impact on the effective use of DTs. Intellectual property rights and legal considerations should be also considered, and roles and responsibilities should be assigned to participating stakeholders. Additionally, the accessibility limitations of data should be well-defined to ensure that all stakeholders have access to the necessary data while maintaining data security and privacy (Madni, Madni, and Lucero 2019).

The development and adoption of DTs heavily rely on common data standards and interoperability. However, there is currently a lack of consensus on the various standards, technologies, and procedures that can be used to implement DTs. This lack of agreement poses another significant challenge (Shao and Helu 2020).

Integrating multiple virtual models (e.g., BIM models) with varying parametric values, spatial values, and time scales into a DT remains a significant challenge (Monsone, Mercier-Laurent, and János 2019). This difficulty hinders the ability to present virtual models that accurately depict the physical assets in a realistic and objective manner (Shahzad et al. 2022). Additionally, conventional databases are not well-equipped to handle the increasing heterogeneity and volume of DT data gathered from multiple sources (Qi et al. 2021).

Another challenge in developing DTs is ensuring high-quality data. To operate efficiently, a DT requires proper data quality, is free of noise, and is continuously and consistently streamed. Poor and inconsistent data can cause the DT to underperform, as it will be operating on flawed or missing information. The quality and quantity of IoT sensors are essential factors. Planning and analyzing device use are necessary to identify the correct data to be collected and used for the DT's efficient operation (Fuller et al. 2020).

1.5 Synthesis

This chapter explored the various aspects of comfort in built environments, IoT, BIM, and DTs in the context of real-time comfort monitoring of buildings. It identified some of the gaps and challenges within these domains that this research aims to address.

The literature points out that while both BIM and IoT individually offer significant benefits for building management, their integration is still in its infancy. This integration will lead to creating a dynamic BIM by utilizing real-time data from IoT devices, which has the potential to enhance building O&M.

Despite the potential of IoT in building facility management, challenges such as high cost of implementation, a lack of open-source solutions, and integration issues with existing BAS systems were noted. These challenges underscore the need for developing cost-effective and flexible IoT solutions that can be easily integrated into the existing BAS system.

Real-time comfort monitoring in buildings faces several challenges, including the integration of diverse sensor technologies with building facility management systems such as BAS systems, ensuring data accuracy and reliability, addressing privacy and security concerns related to occupant data, managing the high volume of data generated by IoT devices, and interpreting complex datasets to provide meaningful insights for buildings' occupants and managers.

The literature highlights the need to investigate DT applications for real-time monitoring of comfort in built environments. It emphasizes the potential of DTs in enhancing building energy efficiency and occupant comfort but notes the lack of comprehensive studies in this specific application area. Existing studies on DT focus primarily on the construction and post-construction phases, with less attention paid to the comfort monitoring application of DT during the operational phase.

This research aims to address the abovementioned gaps by proposing a solution that integrates BIM and IoT technologies to develop a DT system for real-time comfort monitoring. This includes the development of a plug-and-play network of IoT sensors and a DT platform for visualizing comfort levels in real-time, offering a novel approach for occupant comfort monitoring in built environments.

CHAPTER 2

RESEARCH METHODOLOGY

This chapter presents the methodology employed in this research, which is based on the Design Science Research (DSR) methodology (Hevner et al. 2004; Peffers et al. 2007). The DSR methodology provides a systematic approach for creating and evaluating innovative artifacts to address specific problems or challenges in a specific domain.

This methodology is particularly suitable for this study as it aims to design, develop, and evaluate a novel artifact to solve a specific problem in the field of comfort monitoring of buildings in a real-time manner.

As shown in figure 2.1, DSR follows five steps during the design, implementation, and test process namely: the problem awareness, suggestion, development, evaluation, and conclusion.

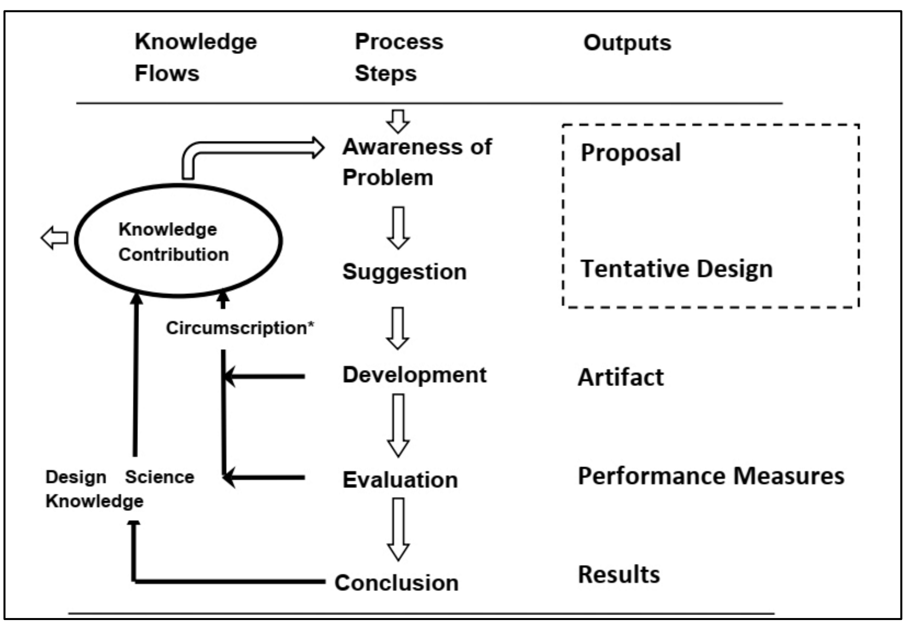

Figure 2.1 Design science research methodology steps
Taken from Hevner & Chatterjee (2010)

In the context of this research, the practical problem addressed is real-time comfort monitoring of a building using a DT platform. The proposed solution, as the artifact, is a combination of IoT sensors development and integration of sensors data with BIM to create a dashboard for real-time comfort monitoring of a building using a DT platform.

Figure 2.2 shows the DSR methodology adopted for this research. Each step is elaborated in the following subsections.

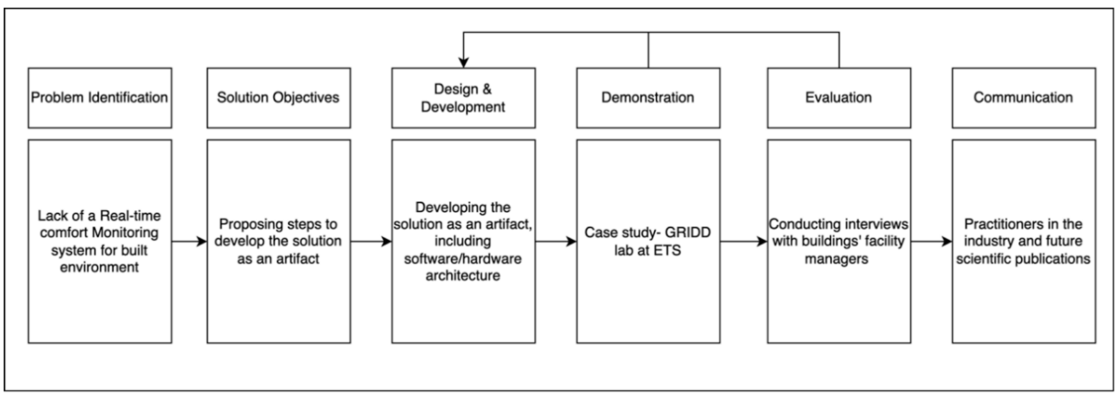

Figure 2.2 DSRM process of the thesis
Adopted from Peffers et al. (2007)

2.1 Problem identification

The lack of a real-time comfort monitoring solution for built environments is a problem that this research aims to address. Buildings account for approximately 40% of the world's total energy consumption (International Energy Agency (IEA) 2019). A significant portion of this energy consumption goes toward heating and cooling systems that are employed to maintain the thermal comfort of occupants within buildings (International Energy Agency (IEA) 2019). Furthermore, individuals spend over 80% of their time indoors (Zhao et al. 2004), where factors such as thermal, visual, acoustic, and air quality comfort level have a substantial impact on their overall well-being (Halhoul Merabet et al. 2021). However, the real-time and continuous assessment of thermal comfort is often impractical due to the requirement for measuring or estimating various environmental and personal factors by existing thermal comfort models (Pavlin et al. 2017), as outlined in Chapter 1.

In addition to the mentioned challenges, there is an absence of accessible user-friendly platforms or web-based solutions that enable stakeholders of a building to monitor the comfort levels of various areas in real time. This limitation hinders the ability of building owners, facility managers, and occupants to proactively identify and to promptly address comfort issues. Without such a tool, stakeholders are unable to make data-driven decisions to optimize energy consumption, improve occupant comfort, and enhance overall building performance.

Therefore, there is a need for the development of a solution that can provide real-time insight for facility managers into comfort levels across various species within a building, bridging the gap between theoretical models and the practical implementation of a comfort monitoring system.

Additionally, to measure required variables to evaluate the comfort level of a building, various types of sensors should be installed. Installing and adding new sensors which are compatible with the existing BAS system would be costly and time consuming. Hence, there is a need to add new types of sensors that could work independently from the existing BAS system, which mainly monitors and controls building systems. Furthermore, the current landscape of commercialized environmental sensors, known DAQ technologies, predominantly consists of expensive and closed-source solutions, limiting users' ability to modify parameters and access stored data without purchasing specific software applications. To address these challenges, there is a need to develop an open-source and cost-effective solution that allows seamless integration of new sensor types independent from the existing BAS system and provides customization options and enables open access to the data collected by the sensors.

2.2 Solution objectives

The objective is to purposefully design a solution, as an artifact, that addresses the abovementioned challenges related to real-time comfort monitoring of buildings. This solution encompasses a software\hardware architecture and the development of an IoT-based data acquisition layer and the implementation of a real-time visual dashboard for comfort monitoring integrated into a DT platform.

The first component focuses on responding to the need for developing a data acquisition layer that allows the addition of new sensor types that can operate independent of the existing BAS system. This involves proposing a flexible and modular sensor network designed for plug-and-play integration with the building's environment. By implementing a solution that supports easy integration of new sensors, building owners and facility managers would have the flexibility to expand their sensor networks beyond the constraints of the existing BAS. This would not only streamline the sensor installation process but also provide cost-effective options for monitoring the comfort levels of various areas within the building. By enabling the incorporation of independent sensors, stakeholders would have the freedom to choose sensors based on specific comfort evaluation requirements, without being limited to the pre-existing BAS infrastructure. This solution would provide a more agile and adaptable approach, reducing both the financial burden and the time required for implementing and maintaining a comprehensive comfort monitoring system in buildings.

The second component of the system is a cloud layer, which plays a crucial role in managing the sensor data and data visualization. The data layer is responsible for storing the historical sensor data, while the data visualization component focuses on creating a real-time dashboard based on the sensors' data that provides valuable insights into the comfort level of different areas within the building. Finally, a DT web application is deployed on the cloud platform, and the comfort monitoring dashboards and sensors data are integrated into the application.

The proposed solution as the artifact needs to be modular to facilitate scalability and reusability and high availability for production use cases. Figure 2.3 is the conceptual representation of a generic DT. The developed components of the proposed solution in this research that leads to the creation of a DT with comfort monitoring capability are identified in grey colored elements.

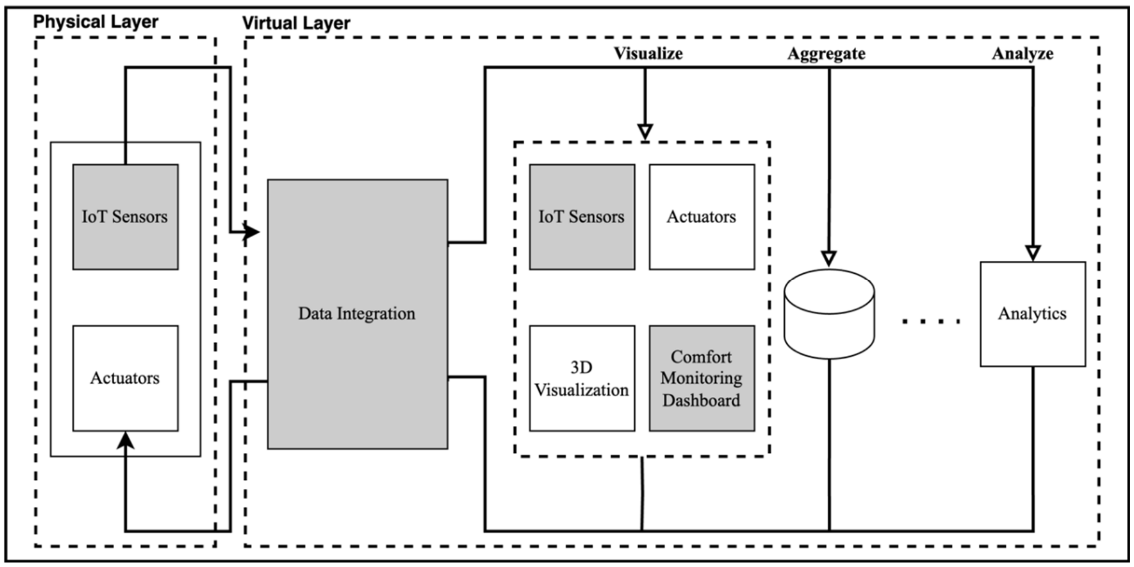

Figure 2.3 The conceptual representation of DT and the focus area of this research

2.3 Design and development

The study follows steps to create a solution artifact, which is a DT platform designed for monitoring comfort levels in built environments. The solution operates on the assumption that a BIM model is already available, with all rooms and relevant areas distinctly defined. The following six steps are elaborated in Chapter 3:

1. **Identification of variables for comfort monitoring:** The variables essential for assessing comfort levels within built environments are identified at this stage.
2. **Implementation of a plug-and-play BLE network:** BLE sensor network is implemented to provide a data acquisition layer for measuring environmental variables.
3. **Integration of sensor data to the cloud platform:** All data from the sensors are transmitted to a cloud platform for data integration and further analysis.

4. **Storing time-series data:** The sensor data is stored in a time-series format for visualization of historical data.
5. **Implementation of a comfort monitoring dashboard:** A user-friendly dashboard is created for real-time monitoring and analysis of comfort parameters.
6. **Integration with the DT platform:** Various visualization features are integrated into the DT platform to make data easy to interpret.

These steps can be followed to implement a DT solution for real-time comfort monitoring based on the specifications of a building. In Chapter 3, the roles of each step are dissected in more details. Moreover, a software architecture is presented as an instantiation artifact of the research to design and develop the solution. Chapter 4 follows these steps in a real-world scenario, showcasing the implementation of a DT system. This part of the research aims to demonstrate the adaptability and usability of the proposed solution through a case study implementation.

2.4 Demonstration

The proposed solution is demonstrated in a case study implementation. The case study is conducted at the *Groupe de recherche en intégration et développement durable en environnement bâtiment* (GRIDD) lab, which is a part of the Construction Engineering Department at École de technologie supérieure (ÉTS). The GRIDD lab is selected for this demonstration for several reasons, such as the possibility to install various sensors and the availability of digital models. Additionally, the physical and architectural specifications of the lab simplify the control of extraneous variables that could influence occupant comfort. These features also allow us to make assumptions that simplify real-time thermal comfort monitoring. Details about the lab's features, how the architecture was applied in this specific setting, and the insights generated are discussed in Chapter 4.

This demonstration is not a one-off implementation but rather an iterative process that has informed and enhanced the development phase of the research. For instance, the current configuration of the environmental sensors, as well as the user interface of the comfort monitoring dashboard, underwent multiple cycles of testing and feedback. This iterative approach ensured that the solution and its visual dashboards are both user-friendly and effective.

Through this demonstration at the GRIDD lab, the study confirms the utility and adaptability of the proposed solution, paving the way for future implementations and improvements.

2.5 Evaluation

The effectiveness of the proposed solution is evaluated through feedback from buildings facility managers, given their day-to-day experience with building systems. This user-centric solution ensures that the system is not only theoretical functional but also practically beneficial. During the evaluation, a semi-structured interviews are conducted where participants get an overview of the DT platform and explore its main functions and features. Afterward, participants provide feedback on the platform's ease of use, utility, adaptability, and offer any recommendations for enhancements. All feedback is gathered considering participants' confidentiality, ensuring anonymity, and emphasizing that participation is entirely voluntary. The feedback received from the internal building operators of the ÉTS, and external experts, confirmed the applicability and effectiveness of the proposed solution. It is important to note that the focus of this research was addressing the problem of real-time comfort monitoring of the built environment using a DT approach. Evaluating the general performance of the implemented DT platform was out of the scope of this study. In future work, a more rigorous evaluation process can be conducted to assess the performance of the implemented DT system. The final section of Chapter 5 provides a detailed description of the evaluation step of the proposed solution.

2.6 Communication

This thesis serves as a primary communication mean for sharing the research outcomes with the academic community. Anticipated future publications about this research are expected to further disseminate the findings and the proposed solution to a wider audience within academia. Importantly, the results and the proposed solution have already been shared with building operators, ensuring its practical relevance is communicated to key stakeholders.

Moreover, the GRIDD lab at the Construction Engineering Department of ÉTS University has been consistently updated on the research outcomes. This continuous communication is crucial as the lab is engaged in similar DT implementation projects. The data infrastructure laid out in this research could potentially be leveraged for monitoring various other parameters, benefiting other use cases the lab is exploring.

CHAPTER 3

THE PROPOSED SOLUTION

In this chapter, a general series of required steps is presented to develop a solution to address the research's objectives. The solution includes a software/hardware architecture as an artifact. To validate the proposed solution, an instantiation of the architecture is designed and implemented as a system for real-time comfort monitoring using a DT platform, which is used to conduct a case study (Chapter 4). In the case study, an existing HVAC system controls temperature and humidity of the rooms. However, the environment allows adding a wide range of sensors in each room, providing an ability to gather a wide range of environmental data. This case study serves as a demonstration of the proposed software/hardware architecture, which is discussed in this chapter.

3.1 Steps for developing the solution

Figure 3.1 depicts the necessary steps for proposing the solution. This chapter delves into the six major steps involved in the development of a DT for real-time comfort monitoring of built environments.

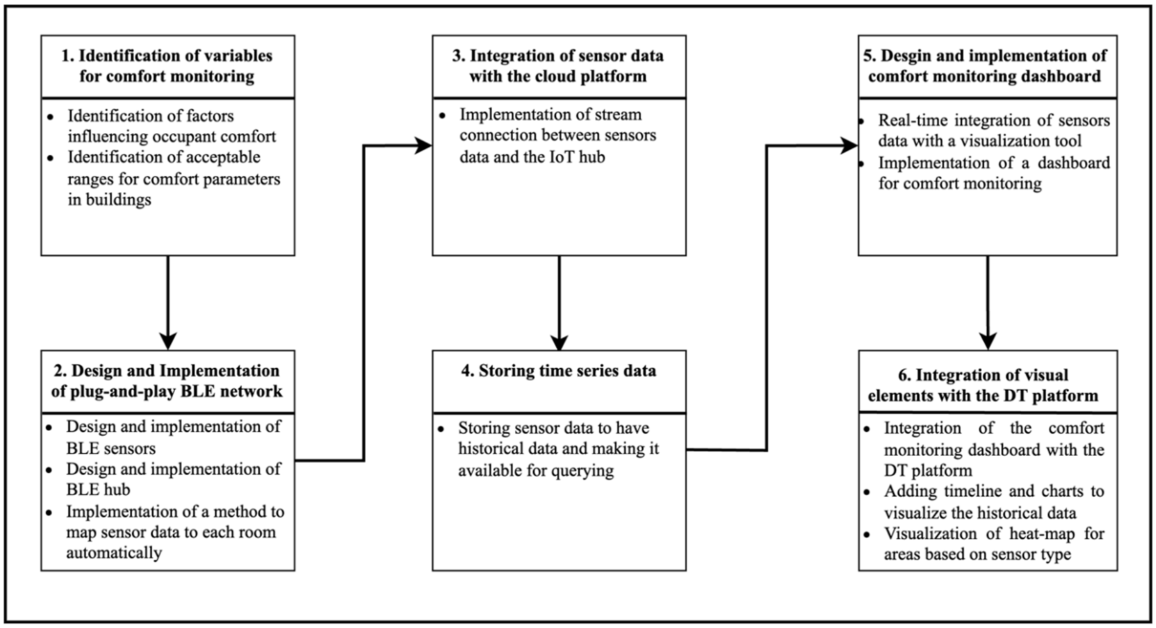

Figure 3.1 Steps to propose a real- time comfort monitoring DT solution for buildings

3.1.1 Identification of variables for comfort monitoring

Comfort in the built environment is influenced by a diverse range of factors, both tangible and intangible. To ensure optimal levels of comfort and well-being for building occupants, it is critical to identify, understand, and monitor these variables. Based on the literature review, as detailed in section 2.4, several variables emerged as significant determinants of occupant comfort. Given the scope of this thesis, the emphasis was placed on the variables that can be precisely measured using sensor technology.

The variables identified as influential for occupants' comfort, through the literature review, can be broadly categorized as:

Thermal Factors: These include parameters, such as air temperature, radiant temperature, humidity, and airflow rate. Each of these factors has a direct bearing on how individuals perceive thermal comfort in a space.

Air Quality: Good indoor air quality is fundamental for comfort and well-being. Variables such as CO_2 concentration and pollutant levels are critical indicators in this category.

Acoustic Environment: Sound levels and their characteristics play a role in creating a comfortable environment, especially in spaces such as offices or residences located in busy urban areas.

Visual Comfort: Factors such as lighting levels, glare, and daylight availability can significantly influence comfort.

More details of each variable, including the method of measurement, and the acceptable range, are presented in section 4.2.

3.1.2 Implementation of plug-and-play BLE network

To effectively measure and monitor selected comfort variables, it is essential to have a robust data acquisition layer. This requirement inspired the design of a plug-and-play network that emphasizes both on adaptability and efficiency.

Central to this network is a conceptual ”black box” of sensors. This design does not just encapsulate the current set of sensors but is flexible to incorporate additional ones as needs evolve. Once this sensor box is installed in a room, data from the sensors immediately begins streaming to the DT platform. Notably, this data is not just integrated into the cloud platform to be stored; it is automatically mapped onto the corresponding rooms within the DT, ensuring that data context is preserved.

The main component of the sensor box is a microcontroller based on BLE technology. It serves as the core processing unit, drives the sensors' operation and provides programmable input and output peripherals for the integration of additional components. However, the continuous stream of data from sensors requires a BLE hub as a gateway between sensors and a cloud platform. The main function of the hub is to continuously scan its environment, identify BLE sensor signals, establish connections, and then systematically read data at set intervals. With the continuous scanning feature, this solution is equipped with plug-and-play capability, which means that any new sensors added to the building are instantly detected and their data is integrated automatically into the existing stream.

3.1.3 Integration of sensor data to the cloud platform

For the integration of sensor data with cloud platforms, it is essential to establish a connection between the BLE hub and the cloud, providing continuous transmission of sensor data to the cloud. A reliable cloud service is required to manage IoT devices efficiently. This service should be capable of generating unique endpoints for each device, ensuring secure communication between the sensors and the cloud infrastructure. In the context of the proposed solution for real-time comfort monitoring, a critical requirement is the cloud platform's ability to handle concurrent data streams from numerous IoT devices. It is essential to process simultaneous sensor readings to ensure real-time monitoring and a quick response to environmental changes. In this research, as an instantiation of the proposed solution, Microsoft Azure cloud services[1] are used as the cloud platform. However, other cloud platforms could be employed following the same requirements defined in the proposed solution.

Central to this data integration is a BLE hub, which is responsible for gathering data from the sensors and sending data to the cloud. For this purpose, the chosen cloud service in our developed system is the Azure IoT Hub[2], which is a Platform as a Service (PaaS). It is designed to handle the massive volume of real-time data produced by numerous IoT devices simultaneously. Azure IoT Hub stands as a central point for two-way communication between IoT applications and their associated devices. Not only it enables data transfer from devices to the cloud, but it also allows cloud-based applications to send commands and set policies for

[1] https://azure.microsoft.com/en-ca
[2] https://azure.microsoft.com/en-ca/products/iot-hub

these devices. This ensures real-time data processing by efficiently routing data to the appropriate Azure services. With the help of Azure IoT Python SDK[1], the BLE hub ensures the smooth transfer of environmental sensors' data to Azure IoT Hub. The implementation details are explained in section 4.3.3.

For security and authentication, Azure IoT Hub employs individual device security credentials, reinforced with access control mechanisms. This ensures that only authenticated devices can communicate with the hub. Furthermore, every data transaction occurs over encrypted channels, offering an added layer of protection. Additionally, Azure IoT Hub features a Device Twin, designed to retain metadata, such as the model ID, room name, and coordinates of sensor. This metadata is used during the visualization phase.

Once devices are registered on the cloud and the data stream is active, it is essential to ensure historical data accessibility. This requires the data to be stored to the time-series-based format (explained in section 3.1.4). For real-time visualization of comfort monitoring, it is imperative to route the sensor data through a real-time processing service. This allows for instant queries on data and integration with a visualization platform. In the implemented solution in this research, Azure Stream Analytics[2] and Power BI[3] have been employed for these tasks (explained in section 3.1.5).

3.1.4 Storing time series data

For a DT to be effective, it must allow users to store and view past data gathered from the environmental sensors. This historical data, organized in a sequence over time, helps in visualizing trends and, potentially, in predicting future patterns. Given that the data from

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[1] https://learn.microsoft.com/en-us/python/api/overview/azure/iot?view=azure-python
[2] https://azure.microsoft.com/en-ca/products/stream-analytics
[3] https://www.microsoft.com/en-us/power-platform/products/power-bi/

sensors is ordered based on time, it is essential to store it in a specialized database built for such data.

In our implementation, the Time Series Insights (TSI)[1] database, part of the Microsoft Azure cloud platform, is used for storing sensors' data. TSI was chosen due to its scalability and smooth integration with the Azure IoT Hub. This ensures the data is stored efficiently and is easily accessible for future analysis.

3.1.5 Implementation of comfort monitoring dashboard

Following the identification of essential variables for comfort monitoring, the sensor box is designed and put into operation, focusing on capturing the relevant variables. The literature review played an instrumental role in this phase, providing guidelines to determine the acceptable range for each parameter selected. Specifically, for monitoring thermal comfort in our developed system, the PMV method is employed, which is explained in section 4.2.

In our proposed system, the sensor data is connected to the cloud platform with the Azure IoT Hub, facilitating the seamless transition of real-time data to Microsoft's Power BI platform using Stream Analytics[2] job. This is crucial as real-time data visualization offers an instantaneous overview of the monitored environment, allowing for prompt action if any parameter falls beyond its acceptable range.

Inspiration for the visualization of thermal comfort in our proposed system (Section 4.2) is drawn from the CBE Comfort Tool[3], which is known as a reference tool in the domain. The approach adopted by the tool aligns with the objective of offering clear, understandable, and actionable insights for users regarding thermal comfort assessment.

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[1] https://learn.microsoft.com/en-us/azure/time-series-insights/overview-what-is-tsi
[2] https://azure.microsoft.com/en-ca/products/stream-analytics
[3] https://comfort.cbe.berkeley.edu/

For other essential parameters, such as sound levels and air quality, we propose utilizing gauge charts for visualization. This approach is particularly effective as it focuses on the monitoring of threshold values. This not only presents the data in real-time but also clearly demarcates the comfort zones, offering an immediate understanding of whether the environment falls within the desired comfort range or if adjustments are needed.

The dashboard, thus, provides an integrated view, drawing data from various sources and translating them into meaningful, user-friendly visuals. This interface not only reflects current conditions but also empowers users to ensure optimal comfort by taking corrective action when necessary.

3.1.6 Integration of visual elements with the DT platform

Visualizing a DT effectively combines all key visualization elements and dashboards to present a clear digital reflection of the real-world environment. To create this representation, an integration of the latest BIM model and real-time sensor data is essential. Here's a simplified breakdown of the steps undertaken:

Web-based Model Viewer: A tool is needed to display the BIM model on the web. The Autodesk Forge Viewer[1] was picked and added to the DT platform for this purpose in our developed system (explained in Section 4.6.1).

Centralized BIM Model Accessibility: A unified BIM model ensures that every stakeholder gets access to the most recent version. By integrating the DT platform with a cloud-centric collaborative tool, e.g., Autodesk BIM 360[2] (a segment of the Autodesk Construction Cloud platform) in our developed system, all modifications and updates are centralized. This ensures consistent and timely updates for all users.

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[1] https://aps.autodesk.com/en/docs/viewer/v2/developers_guide/overview/
[2] https://www.autodesk.com/bim-360/

Mapping Sensor Data into the BIM Model: Sensors registered on the IoT hub are auto-mapped to the BIM model. This mapping uses the device model ID and location data from the Device Twin's metadata (explained in Section 4.3.3).

Historical Data Integration: To enable users to view and navigate historical data layered over the BIM model, the formerly established time-series database is incorporated with the system's backend.

Visualization Enhancements: Various visualization tools, including charts, timelines, calendars, animated heatmaps, is implemented on the user-end. These additions, combined with the real-time and historical data, aim to present a comprehensive, detailed, and user-friendly experience by blending aggregated data with the BIM model.

Integration of Comfort Monitoring Dashboard: The comfort monitoring dashboard, implemented using Power BI in our proposed system, is seamlessly integrated into the web application's interface. This final integration step ensures that users have a holistic view of comfort parameters.

3.2 DT software/hardware architecture

The software/hardware architecture is divided into two main components: the data collection and the cloud infrastructure.

In the data collection, BLE sensor boxes act as a data acquisition layer. Using sensors connected to a BLE microcontroller, the environmental variables that are selected for comfort monitoring, such as temperature, humidity, air quality, and sound levels will be measured. This setup is shown in Figure 3.2.

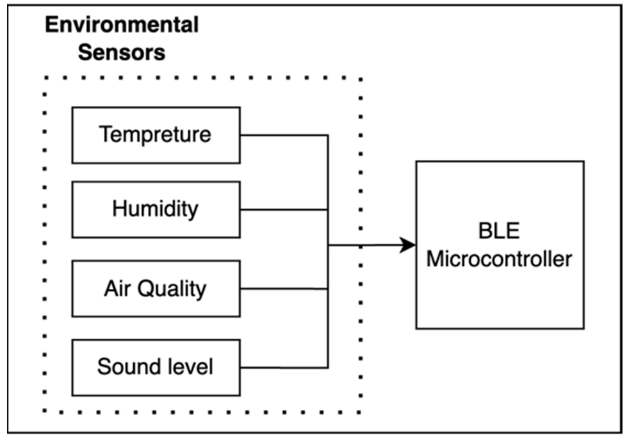

Figure 3.2 BLE sensor box schema

Figure 3.3 outlines the initial software/hardware architecture of this research.

In the data collection layer, the BLE sensor boxes broadcast measured sensor data in the environment. There is also a BLE hub that constantly scans to find BLE sensor boxes around, connects to them, and reads their data. This data then sends to the associated endpoint in the cloud, known as the IoT gateway.

The IoT gateway does several tasks. It sends the data to a database to keep a record of all past data. It also sends data to a data processing unit. This is where further analysis happens, preparing the data for visualization. Lastly, it sends metadata to the web app for mapping sensors data to the related room on the BIM model. The Real-time data processing unit sends data to a Visualization platform to have a real-time comfort monitoring dashboard.

Moreover, the latest version of the BIM model is stored in the cloud, and it is connected to a database. Information such as the geometry and characteristics of a building can be extracted from the BIM model and stored in a database. This information can be used for more advanced comfort analysis.

Finally, the User Interface is a DT web app container that uses the BIM model, real-time and historical data, and the comfort monitoring dashboard to make a DT for real-time comfort monitoring.

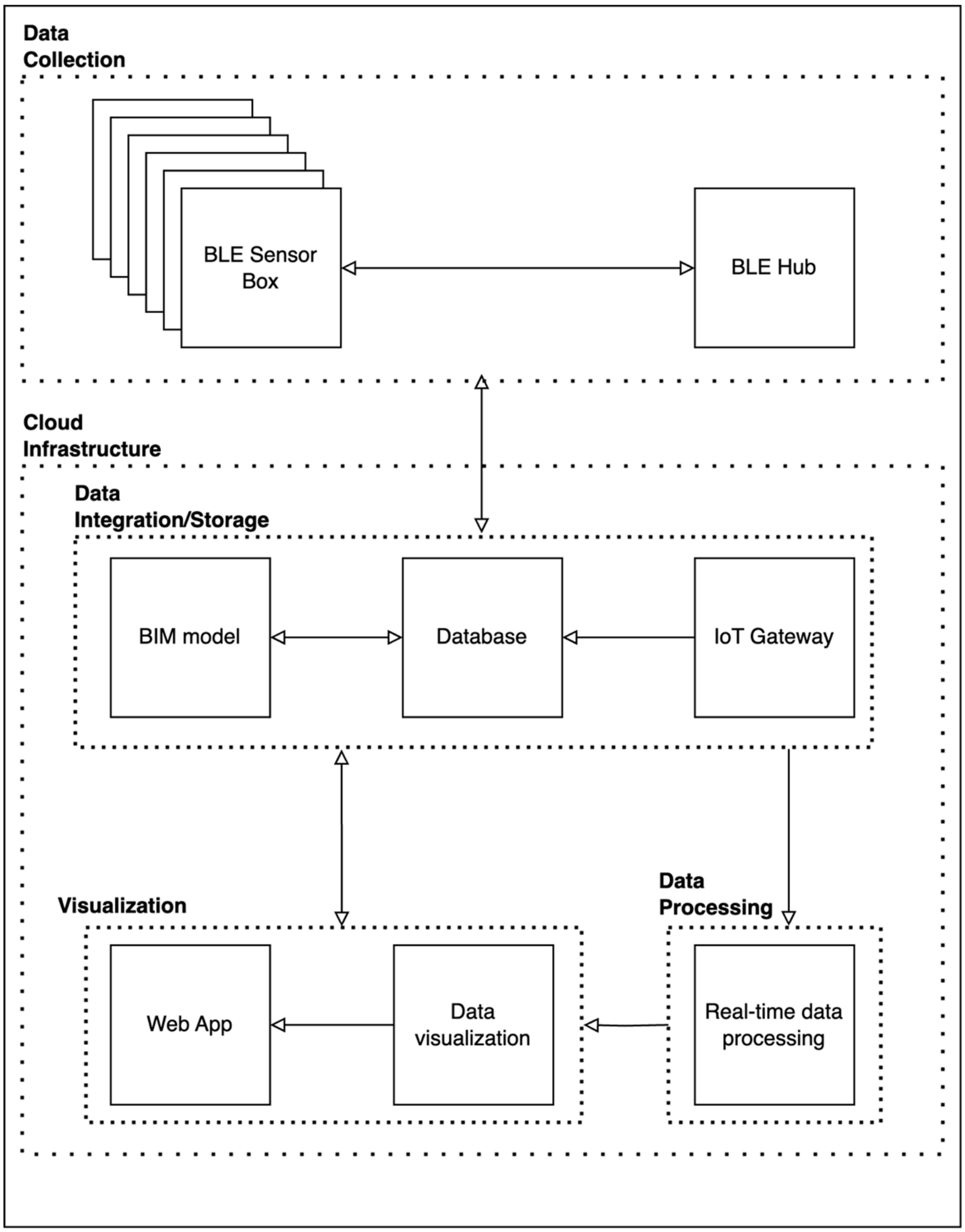

Figure 3.3 The proposed software architecture

CHAPTER 4

CASE STUDY: GRIDD LAB AT ÉTS

The proposed solution and its software/hardware architecture, which are developed as the artifacts of this research, are demonstrated in a real-world case study. The case study implementation act as a proof-of-concept that demonstrate the feasibility of the proposed solution. An evaluation step is performed and reported in Section 4.7 to validate the applicability of the proposed solution and to discuss its limitations based on the implemented proof of concept.

In this chapter, the implementation steps for the case study are reported. It follows steps for developing the solution, which are shown in Figure 3.1 and described in the previous chapter. Additionally, this chapter concludes with a discussion on the results of semi-structured interviews conducted with facility managers of buildings. It aims to provide a critical evaluation of the implemented solution and to offer a practical perspective on its usefulness and effectiveness.

The case study is conducted at the GRIDD Lab, located at ÉTS University, to validate and verify the efficiency proposed solution. The main objective is to implement a web-based DT system for real-time comfort monitoring of the lab, following the proposed solution described in Chapter 3.

The BIM model of the lab was available, and the rooms and zones required for mapping the sensors have already been defined. This study does not encompass the process of designing and enhancing the quality of the BIM model and an accurate model is considered as an input to the implementation process. To implement the cloud infrastructure of the proposed architecture, as mentioned in the chapter 3, Microsoft Azure cloud services are used in the case study. Additionally, Autodesk Forge API[1] is utilized for web-based visualization of the BIM model.

The software/hardware architecture of the DT system is illustrated in Figure 4.1. This architecture was adapted from the generic architecture (shown in Figure 3.3), which was elaborated in chapter 3.

For data collection, BLE sensor boxes are developed using Arduino microcontrollers (described in Section 4.3.2). These BLE sensor boxes play a pivotal role in collecting data from various sensors and transmitting it to the BLE hub.

The BLE hub is another important element within the architecture. In this case study, the BLE hub is developed using a Raspberry Pi[2] running the Raspbian OS (Section 4.3.3). As explained in Section 3.1.2, the primary role of the BLE hub is the continual scanning of the environment to detect nearby BLE sensor boxes, establishing connections with them, and reading their data. In this case study, to ensure efficient data transmission to the cloud and effective device management, the Azure IoT SDK for Python[3] is utilized.

For data integration, Azure IoT hub is used to implement the IoT gateway. IoT hub is a Device Provisioning Service (DPS) that functions as the gateway for IoT devices. It manages bidirectional communication between IoT sensors and the cloud by providing a unique endpoint for each sensor. It can also route stream data to various services on the Azure platform.

To implement the time series database to store data and make the historical data accessible, Time Series Insights is used, providing a robust repository for time-series data (further explained Section 4.4).

[1] https://aps.autodesk.com/
[2] https://www.raspberrypi.com/products/raspberry-pi-4-model-b/
[3] https://learn.microsoft.com/en-us/python/api/overview/azure/iot?view=azure-python

For visualizing comfort data, Stream Analytics is used as a real-time data processing unit, which allows us to apply real-time queries to sensor data and send it to the Power BI platform (Section 4.5). The Power BI platform is where the comfort monitoring dashboard is implemented, offering an interactive and informative user interface.

To maintain version control of the BIM model, BIM360[1] is connected to the DT Web App. Additionally, the web app utilizes Forge APIs[2] to enable web-based visualization of the BIM model.

The following subsections detail the components developed for the proof-of-concept case study implementation following the presented generic architecture of the proposed solution.

[1] https://www.autodesk.com/bim-360/
[2] https://aps.autodesk.com/

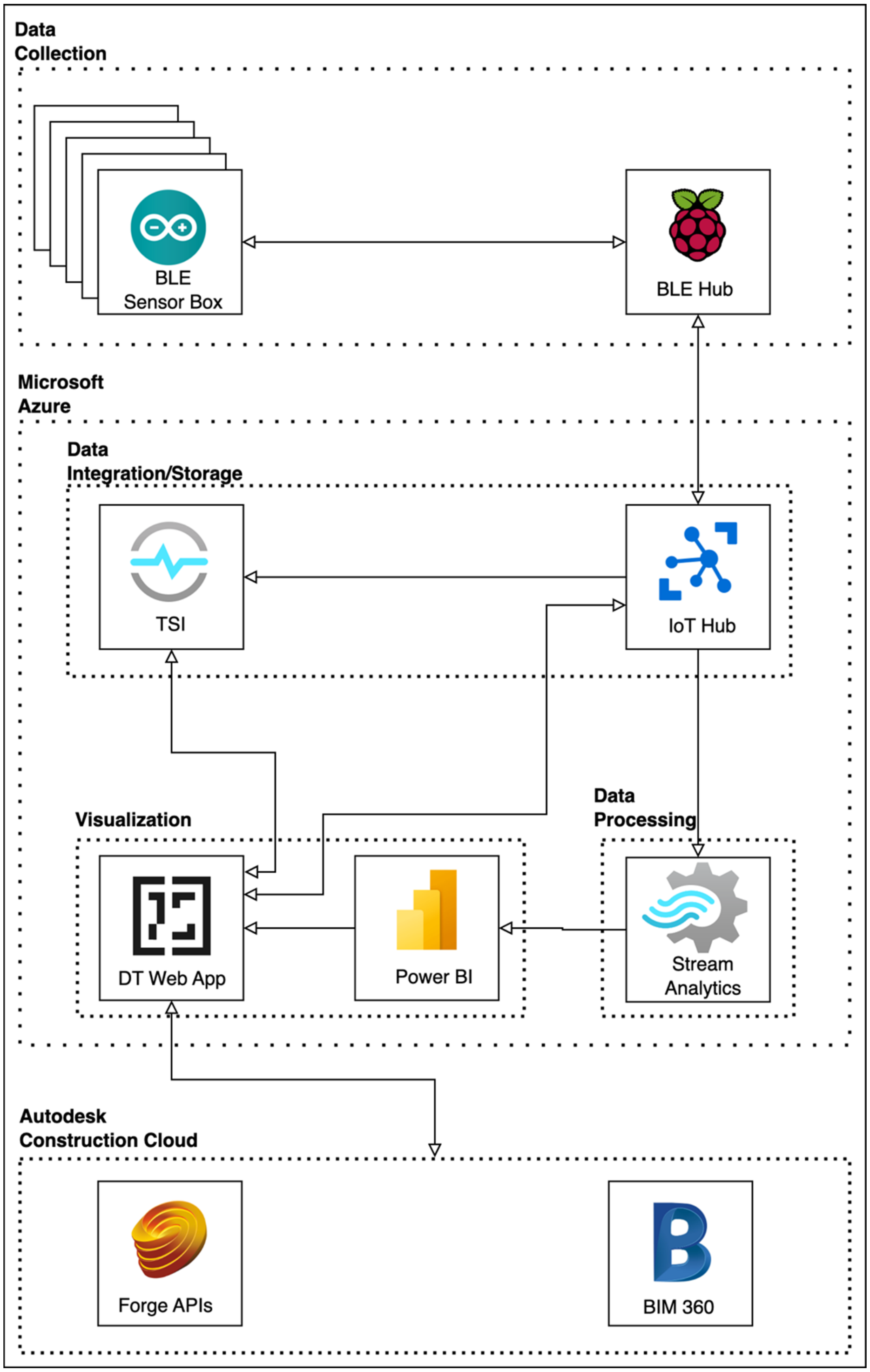

Figure 4.1 The software/hardware architecture of the implemented DT for the GRIDD lab

4.1 GRIDD Lab

The case study is implemented in the GRIDD lab at ÉTS. It has area of approximately 150 m^2 and consists of four distinct rooms, two of which are semi-closed while the other two have doors. Additionally, the lab features a large common area, which for the purposes of this study, has been divided into two sections in the BIM model. In each of these rooms and sections, a BLE sensor box is installed to measure the necessary environmental variables.

The lab is also characterized by unique architectural features such as large, non-openable windows that isolate the lab from external areas. Lighting is predominantly from overhead fixtures, and the lab utilizes an HVAC system with predetermined temperature thresholds. Notably, the lab is not exposed to natural sunlight or external wind conditions. Figure 4.2 shows the BIM model of the GRIDD lab.

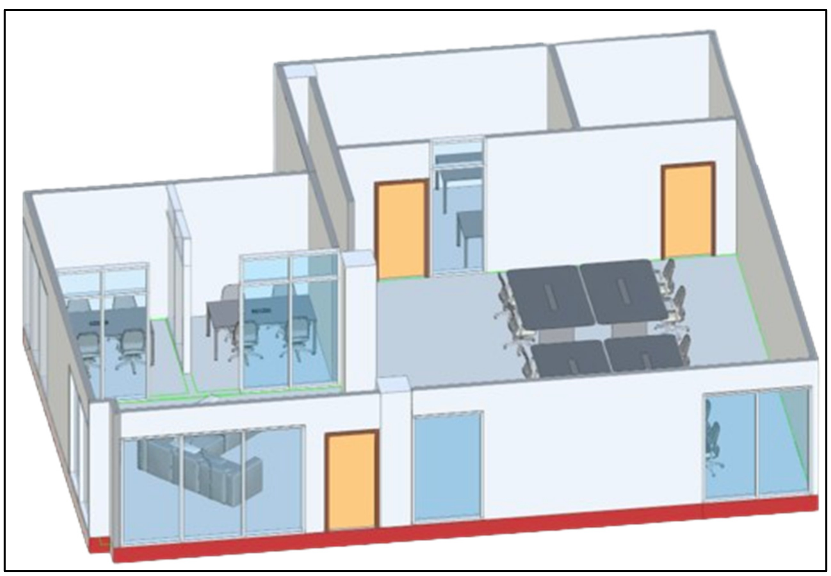

Figure 4.2 BIM model of GRIDD lab (3D view)

4.2 Identification of variables for comfort monitoring

In accordance with the findings reported in the literature review presented in Section 2.4, variable required for monitoring thermal, air quality, and acoustic comfort have been identified.

The PMV method is employed in the case study for monitoring thermal comfort. As discussed in Section 1.1.4, PMV is a comprehensive approach that takes into account multiple environmental factors, such as air temperature, mean radiant temperature, air speed, humidity, clothing insulation, and metabolic rate. This method enables a more accurate and comprehensive assessment of thermal comfort in comparison to simpler models. By quantifying the average thermal satisfaction of a large group of people on a seven-point scale, the PMV method provides a solid and objective measure for evaluating comfort levels in buildings. In the development of a comfort monitoring dashboard utilizing the PMV method, the CBE Thermal Comfort Tool for ASHRAE-55 standard is employed. Initial steps involved establishing the acceptable range for both temperature and humidity. This necessitated presuming variables, such as the mean radiant temperature, air speed, metabolic rate, and clothing level. The values for these variables are chosen based on the characteristics of the GRIDD lab, which is designed as a space for study and conducting meetings. Table 1 outlines the assumed values for each of these variables:

Table 4.1 Presumed values of PMV for comfort monitoring dashboard of GRIDD

Variables	Notes	Value
Mean radiant temperature	Considered equal to operative temperature	Equal to the air temperature from sensors
Air speed	No local control	0.1 m/s
Metabolic rate	Reading, seated	1 met
Clothing level	Trousers, long-sleeve shirt	0.61 clo

Using the assumed variable values, a static chart has been drawn, adopted from Fowler et al. (1963), to depict the acceptable temperature and humidity ranges based on sensor readings, as illustrated in Figure 4.3. Sensor data for each room is mapped on the static chart, allowing a visual assessment whether the condition of a specific room falls within the thermal comfort zone.

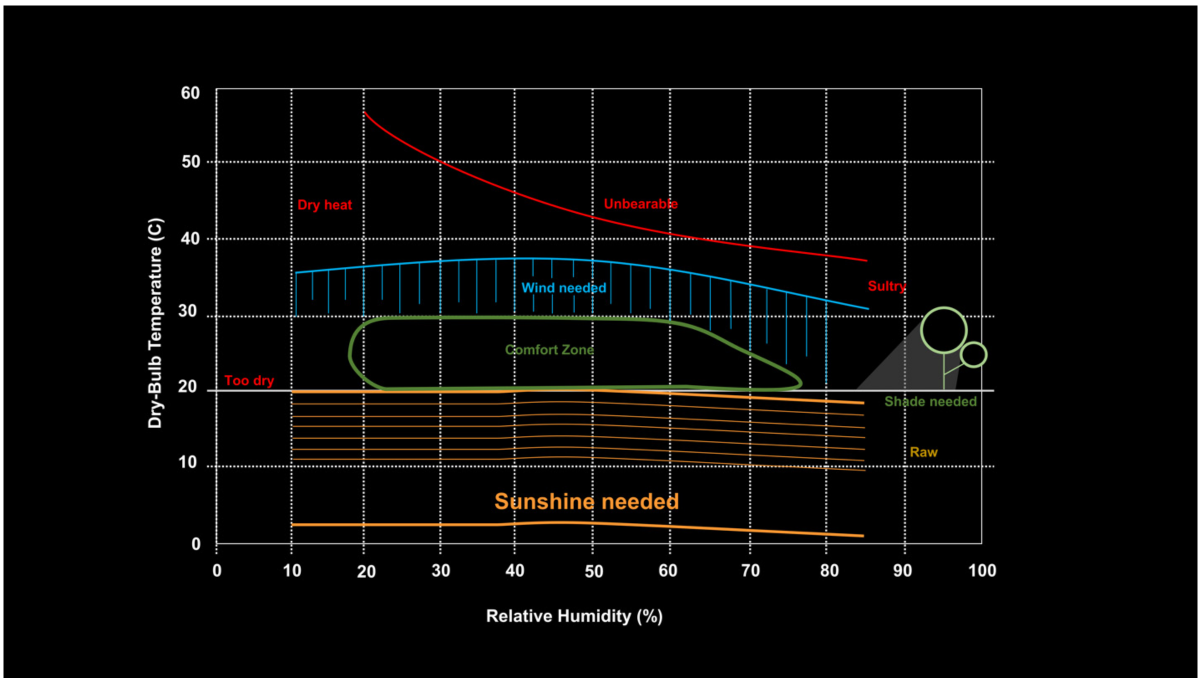

Figure 4.3 The developed thermal comfort chart

For monitoring air quality comfort, the MQ-135[1] sensor is used. It is capable of detecting a variety of harmful gases and provides an analog resistance output corresponding to the concentration of gases present in the air. It can detect levels of NH_3, NO_x, alcohol, Benzene, smoke, and CO_2 to measure gas concentrations in ppm. Based on the literature (e.g., Itharajula, 2020) and manufacturer recommendations, a threshold of less than 600 ppm has been established as the acceptable air quality range.

[1] https://www.electronicoscaldas.com/datasheet/MQ-135_Hanwei.pdf

For monitoring a sample indicator of acoustic comfort, the sound level pressure using a decibel meter sensor is used. For the purpose of measuring the noise level of the GRIDD lab as an office space, SEN0232[1] has been used. According to the literature, an individual's physiological well-being is optimal when the sound level in the workplace is maintained at below 50 dBA (Srinivasan et al. 2023). Therefore, for the purposes of the case study, 50 dBA has been defined as the threshold as one of the key indicators of acoustic comfort.

4.3 Implementation of plug-and-play BLE network

The following sub-sections delve into the implementation details of the plug-and-play BLE sensors network developed to measure the environmental variables discussed in section 4.2. This includes the BLE sensor box designed for measurement of the variables and the BLE hub to receive sensors data and pass it to the cloud platform. The BLE sensors network adopts a plug-and-play approach, meaning that once sensors are installed in a room, the BLE hub automatically detects, connects to, and reads their data. Following this step, the new sensor is registered on Azure's IoT hub, linked to the corresponding room on the DT platform, and begins transmitting data to the cloud. This streamlined process eliminates the need for any user intervention.

4.3.1 The network topology of the plug-and-play BLE sensors

For comfort monitoring, six sensors are installed in the lab to monitor each room/section. Additionally, a BLE hub is installed at the lab to receive the sensor data via the GATT[2] protocol. The hub then transmits the collected sensor data to the cloud platform, i.e., the IoT hub, using the MQTT protocol. Figure 4.4 shows the network topology used for the data communication between BLE sensors, BLE hub and the cloud platform.

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[1] https://mm.digikey.com/Volume0/opasdata/d220001/medias/docus/39/SEN0232_Web.pdf
[2] https://www.bluetooth.com/bluetooth-resources/intro-to-bluetooth-gap-gatt/

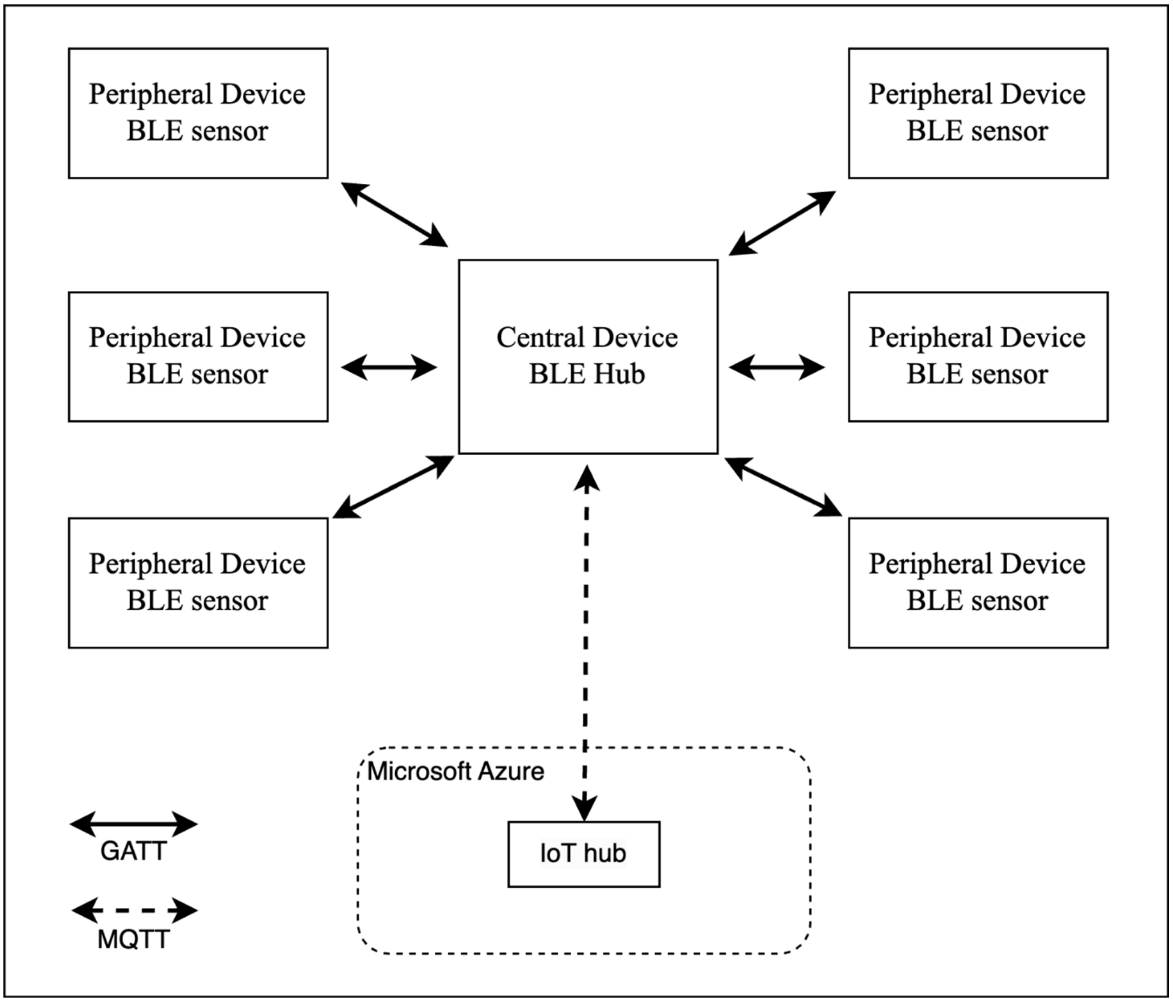


Figure 4.4 The network topology of BLE sensors and BLE hub

4.3.2 Development of the BLE sensor box

The first step in the implementation of the BLE sensors network is the development of the BLE sensor box. The BLE sensor box is designed to measure the discussed variables, including temperature, humidity, sound level, and air quality. It uses the BLE protocol to send the measured values of sensors to the BLE hub.

In the case study, the Arduino Nano 33 BLE Sense[1] is used as a development board. It is powered by nRF52840 microcontroller from Nordic Semiconductor, which includes an Arm Cortex-M4 CPU running at 64 MHz. The reason for using this development board is that it has a collection of required built-in sensors, such as temperature, humidity, pressure. Additionally, it consists of a BLE module for wireless data communication. The BLE module integrated into the Arduino Nano 33 BLE Sense allows the board to communicate wirelessly with other BLE-enabled devices.

Moreover, Arduino Nano 33 BLE Sense supports several hardware interface protocols, such as GPIO, I2C, SPI, UART and analog input, to facilitate communication with other devices and sensors.

For the measurement of temperature and humidity, HTS221 is used, which is a built-in sensor on the Arduino Nano 33 BLE, connected with the I2C interface. Moreover, to measure air quality and the sound level, external sensors using the analog interface are connected to the board. MQ-135 and Gravity analog sound level meter are used to measure air quality and sound level, respectively. Table 4.2 shows the specifications of the sensors utilized in this research.

[1] https://store-usa.arduino.cc/products/arduino-nano-33-ble-sense

Table 4.2 Sensors' specification

Sensor Name	Measurement	Range	Interface	Power Supply	Other Features
MQ-135[1]	Air Quality	10-1000ppm	Analog	5V	Detects NH_3, NO_x, alcohol, benzene, smoke, CO_2
Gravity: Analog Sound Level Meter[2]	Sound Level	30-130dB	Analog	3.3V-5.5V	Wide frequency range (31.5Hz-8.5KHz)
HTS221[3]	Temperature, Humidity	-40°C to +120°C 0-100% RH	I2C	1.7V-3.6V	Low power consumption, Factory calibrated

To connect the sensors to the development board, a prototype PCB is used, which simplifies the process of soldering the wiring. Figure 4.5 shows the schema of sensor wiring with the development board.

[1] https://www.winsen-sensor.com/d/files/PDF/Semiconductor%20Gas%20Sensor/MQ135%20(Ver1.4)%20-%20Manual.pdf

[2] https://wiki.dfrobot.com/Gravity__Analog_Sound_Level_Meter_SKU__SEN0232

[3] https://www.st.com/resource/en/datasheet/hts221.pdf

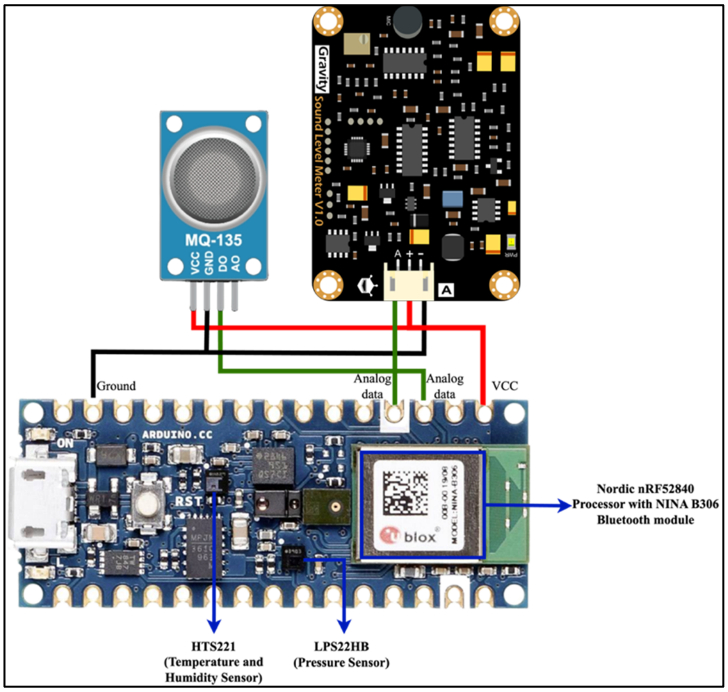


Figure 4.5 The sensors connection
with Arduino Nano 33 BLE Sense

For the implementation of the proposed solution, a C++ program was developed in the Arduino IDE and deployed on the board. The program was designed to continuously measure the variables and send the collected data to the hub in an infinite loop.

To ensure that each sensor box could be uniquely identified by the BLE hub, a *DeviceID* was assigned to each box, and the room number where the sensors would be installed was added. For the BLE data communication, GATT protocol was used. In this solution, environmental sensing is defined as the service. Six characteristics were added to the service, which includes sensor data, device ID and location. Figure 4.6 shows the data structure used in the GATT protocol.

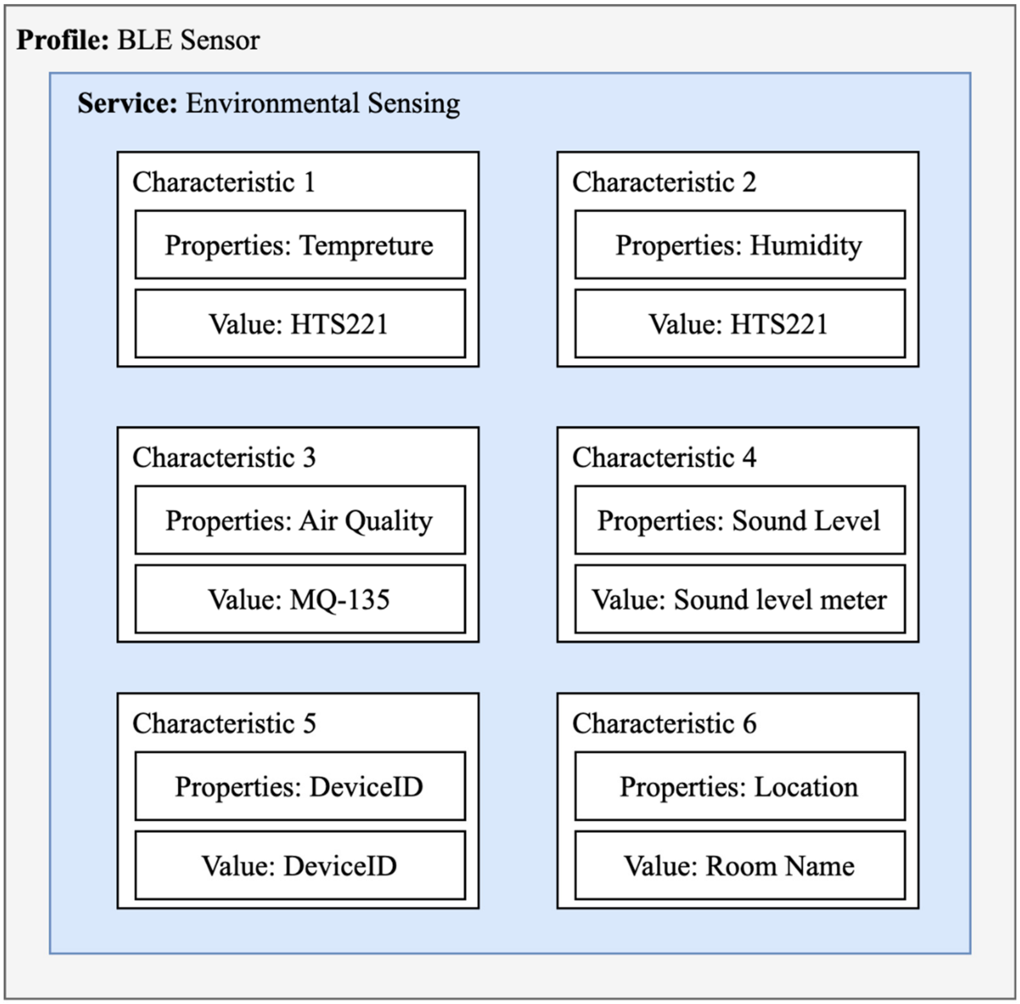


Figure 4.6 Data Structure of GATT Protocol for the proposed solution

Finally, a transparent enclosure was created, ensuring both protection and visibility of the hardware components. Figure 4.7 shows the image of the BLE sensor box in two different angles. The next step is the implementation of the BLE hub to collect sensor data and send it to the cloud.

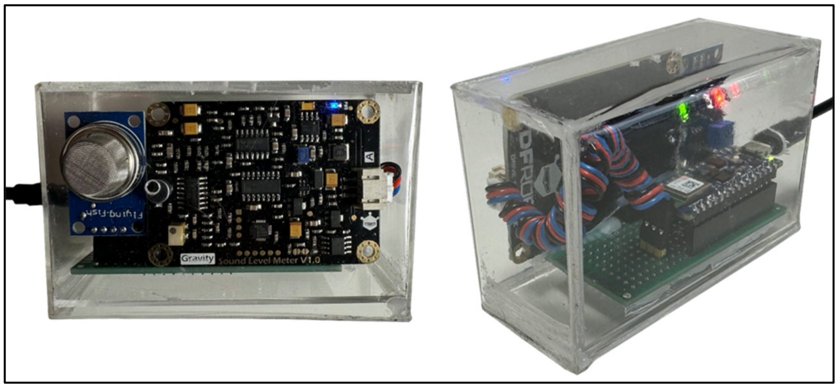


Figure 4.7 BLE sensors box

4.3.3 Implementation of BLE hub

To connect BLE sensors with the Azure cloud service, Raspberry Pi 4 Model B is used as the BLE hub. The program running on the Raspberry pi has been developed in Python and the codes are shared on GitHub[1]. The main function of the program is to scan BLE sensors, read sensors data and send it to the cloud platform.

Using the Bleak library[2] in Python, a solution has been implemented to facilitate communication between the BLE hub and BLE sensors. Bleak is a popular cross-platform Python module that provides tools for working with BLE devices. In this solution, the BLE hub initiates a scan for nearby BLE devices leveraging Bleak's asynchronous API. Upon detecting the desired BLE sensor, the BLE hub establishes a connection and requests the available GATT services. The BLE sensor advertises its services and responds with a list of its GATT characteristics. The hub can then asynchronously read these characteristics. This process is configured to repeat in an infinite loop once per minute. Figure 4.8 shows the sequence diagram of the communication process.

[1] https://github.com/psharafdin/sensor-mapping-plug-play-v2.git
[2] https://bleak.readthedocs.io/en/latest/

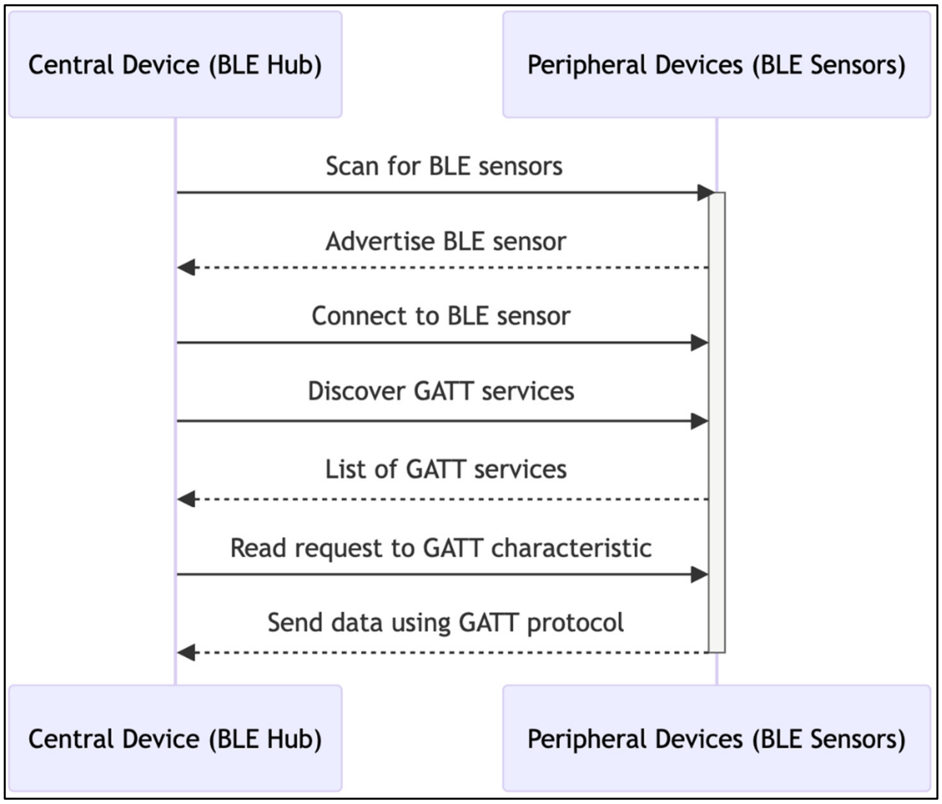


Figure 4.8 Sequence diagram for
data communication using GATT Protocol

The received data from BLE sensors includes the values of the time stamp, device ID, room name, temperature, humidity, sound level, and air quality. The BLE hub adds additional information, such as acceptable ranges of comfort for the sound level and the air quality, as defined in section 4.2. This data is used for the visualization of comfort monitoring dashboard using Power BI and will be discussed in section 5.5. To prepare the message for sending to the cloud platform, the BLE hub stores the sensors data in the format of a JSON message.

The BLE hub communicates with Azure IoT Hub using the “Primary connection string” defined at "Shared access policies" (Figure 4.9) and connects to the Azure IoT hub through the SDK (Software Development Kit). Azure IoT Hub provides the capability of bidirectional communication with the device. When the BLE hub receive sensor data, based on the “Device ID”, it can check if the device is registered on the IoT hub using the IoT Hub connection string.

A JSON file is deployed on the BLE hub to map sensors' location to the related room on the DT platform (Figure 4.10).

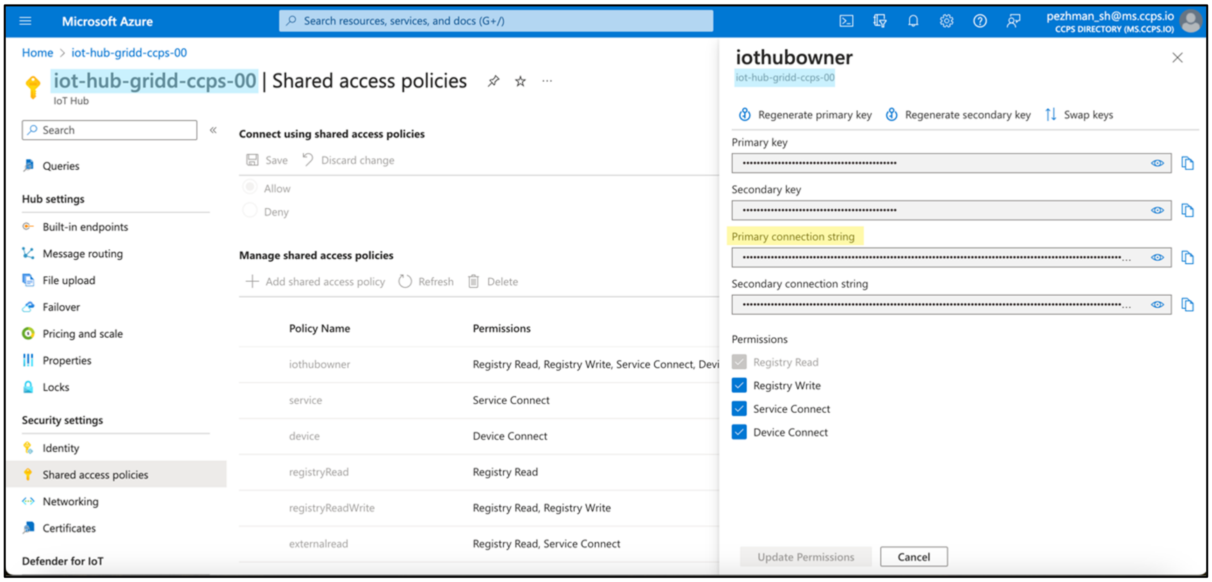


Figure 4.9 The Connection String setting in Microsoft azure IoT Hub environment

If the BLE hub received data from a new sensor, which has not been already registered, it can automatically register the new device on the IoT hub. The BLE hub uses the JSON file to find the "room name" of the sensor and assign the coordinates of the related room to the *device twin* of the device on the IoT hub. The device twin contains metadata of the device. Additionally, custom metadata can be added to it. Some custom tags, such as model ID and position of the sensor (i.e., x, y, z coordinates) are added to the device twin in order to map the sensors to the related room in the DT platform. A sample device twin is shown in Figure 4.11.

```
{
    "Rooms":
      {
        "A-1544": {

            "modelId": "84a97ecc-e088-4087-a4db-b1cb60062415-00409821",
            "name": "Expérimentation / Étudiants A-1544",
            "position": {
              "x": "17.91903066635132",
              "y": "15.892271041870117",
              "z": "0.5938320159912109"
            },
            "sensorTypes": [
              "temperature"
            ]

        },
        "A-1544.2": {

            "modelId": "84a97ecc-e088-4087-a4db-b1cb60062415-00409821",
            "name": "Salle des Serveurs/Entreposage A-1544.2",
            "position": {
              "x": "4.89924156665802",
              "y": "15.892271041870117",
              "z": "0.5938320159912109"
            },
            "sensorTypes": [
              "temperature"
            ]

        },
```


Figure 4.10 JSON script deployed on the BLE hub for mapping sensors' data

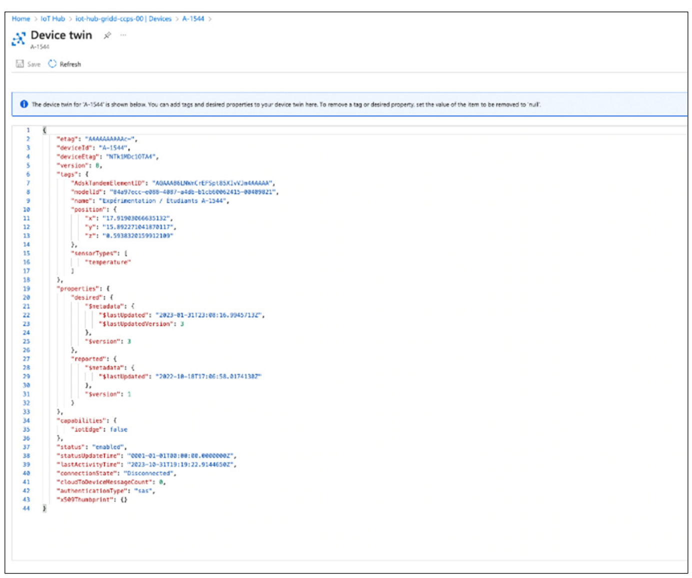


Figure 4.11 The Device Twin of a sensor

When the BLE Hub receives data from a registered sensor, it uses the Device ID to retrieve the connection string for the corresponding endpoint on the IoT hub. After obtaining the connection string, it sends the sensor data to the IoT Hub. Figure 4.12 shows the registered sensors on the IoT hub. Figure 4.13 shows the total number of messages for all devices in 24 hours.

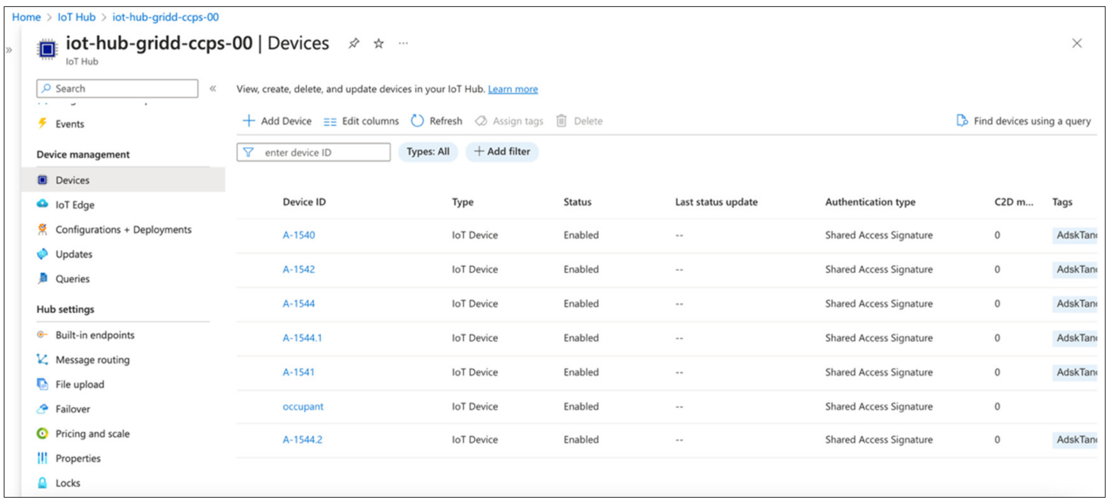


Figure 4.12 List of registered sensors on the IoT Hub

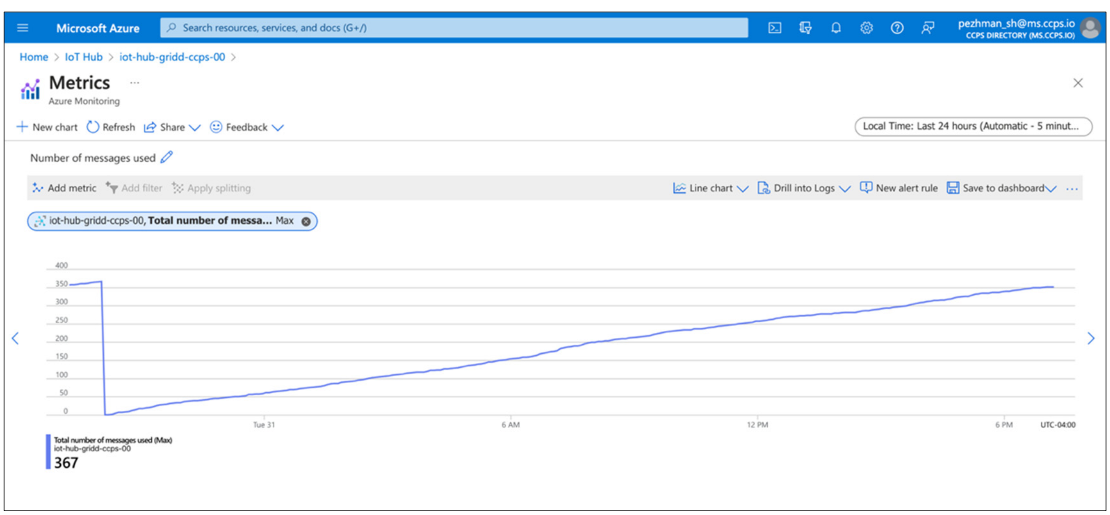


Figure 4.13 Total number of messages during a day

For the storage of sensor data, it is essential to integrate the stream data of IoT devices registered on the cloud with a database. This provides access to historical data for comprehensive analysis. Section 4.4 explains the procedure for integrating the Azure IoT Hub with a time series database to have access to the historical data.

4.4 Cloud integration of sensor data and storing time series data

The TSI is used to store time-series data from sensors due to its seamless integration with the Azure IoT Hub. The Azure IoT Hub is the source of events, and it needs to be configured in the TSI panel as an "Event Source". Additionally, in the Azure portal, the "Timestamp property name" field must be defined as "Timestamp" to reflect the timestamp generated by sensors at the time of measurement. Otherwise, TSI will use the timestamp at which the event was received by TSI instead of the actual measurement time. TSI provides a visualization of the time-series data, as shown in Figure 4.14, which displays an example of the historical data of the sensor in room A-1540, where the X-axis represents the timestamp, and the Y-axis represents the sensor measurements.

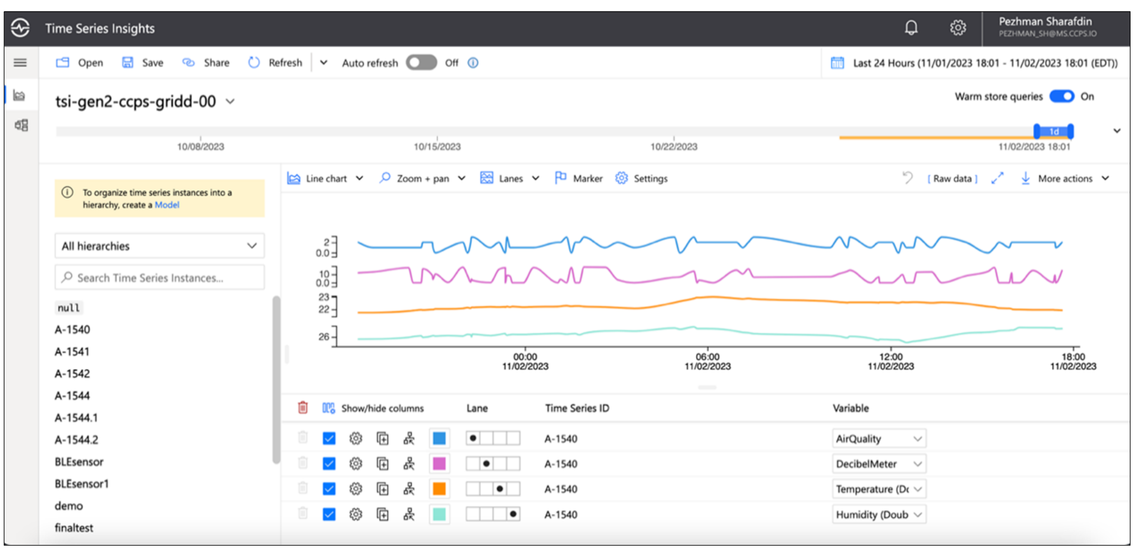


Figure 4.14 An example of historical data stored on TSI

4.5 Implementation of comfort monitoring dashboard

To create a real-time comfort monitoring dashboard using Power BI, the first step is to route the received sensor data on the IoT hub to a Power BI database. This can be achieved by deploying an event hub service and configuring it to use Stream Analytics to route the data to the Power BI database. Figure 4.15 provides a visual representation of the configuration on the Event Hub.

Once the stream of sensor data is integrated with the Power BI database, a report can be created based on the data stream. The report can be published on the web by embedding it on a report with public access. Power BI generates a unique URL for each report, which can be integrated with the DT platform. Figure 4.16 depicts the environment of the Power BI app that was used to design the dashboard for room A-1540 in GRIDD.

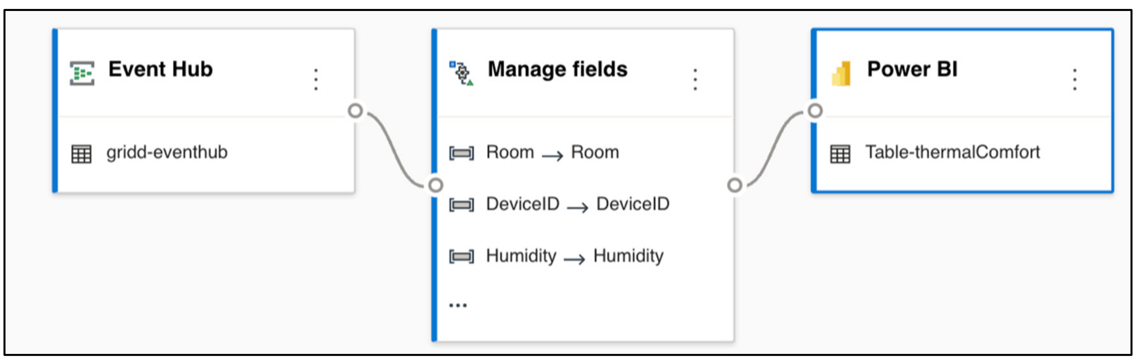


Figure 4.15 Configuration of the Event Hub for routing sensor data to Power BI database

Figure 4.16 Power BI App environment used for designing the comfort monitoring dashboard

4.6 Visualization

To visualize the data collected from the sensors and provide a user-friendly interface for real-time comfort monitoring, a web application was utilized. The web application includes a backend implemented with Node.js and a frontend developed with the React framework. In the following sub-sections, the visual components that make up the web application are discussed in detail.

4.6.1 Model viewer

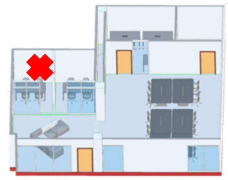
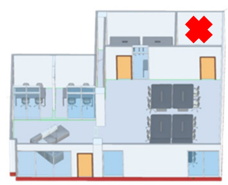
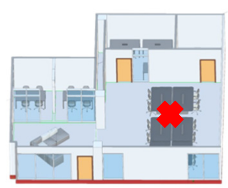
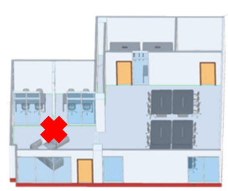
DT requires an updated BIM model of the building. To ensure that the model remains up to date, the application has been integrated into BIM 360 using the Autodesk BIM 360 API. This not only provides a collaborative environment for all stakeholders to work on the same model but also ensures that all changes are applied to a central model. Moreover, Autodesk Forge Viewer has been used to visualize the BIM model of the GRIDD lab, which is uploaded into BIM360. Figure 4.17 shows the 3D model of GRIDD lab, which is visualized using the Autodesk Forge Viewer.

Figure 4.17 The visualization of the 3D model of GRIDD on the Forge Viewer

4.6.2 Sensor mapping

In order to measure the environmental variables mentioned in section 4.2, a BLE sensor box has been installed in each of the six spaces within the GRIDD lab. The placement of each sensor on the BIM model, the type of sensor installed, and the BIM coordinates of sensors for monitoring the comfort level of each room are shown in the table 4.3.

Table 4.3 Sensors' placement at GRIDD lab

IoT Hub Device ID	Sensor Types	Sensor Location	Coordinates of sensors
A-1540	Temperature, Humidity, Pressure, Decibel meter, Air Quality		X: -18.551411628723145 Y: 2.3123373985290527 Z: 0.5938320159912109
A-1544.1	Temperature, Humidity, Pressure, Decibel meter, Air Quality		X: 9.246902227401733 Y: 2.3324332237243652 Z: 0.5938320159912109
A-1544.2	Temperature, Humidity, Pressure, Decibel meter, Air Quality		X: 4.89924156665802 Y: 15.892271041870117 Z: 0.5938320159912109
A-1544	Temperature, Humidity		X: 17.91903066635132 Y: 15.892271041870117 Z: 0.5938320159912109
A-1542	Temperature, Humidity, Pressure, Decibel meter, Air Quality		X: 9.268499851226807 Y: -0.8842639923095703 Z: 0.5938320159912109
A-1541	Temperature, Humidity, Pressure, Decibel meter, Air Quality		X: 13.64560842514038 Y: 12.195703744888306 Z: 0.5938320159912109

Using Autodesk Forge SDKs, Autodesk Forge Viewer can automatically map the sensors in the room depending on the device position in x, y, and z coordinates. By including sensor position information in the Device Twin, the application will be able to access the device's coordinates by querying metadata in the Device Twin. The backend retrieves a list of devices with metadata. Then, Autodesk Forge Viewer can map the devices in the related room using the coordinates of each sensor. Figure 4.18 depicts the sensors that have been mapped in each room.

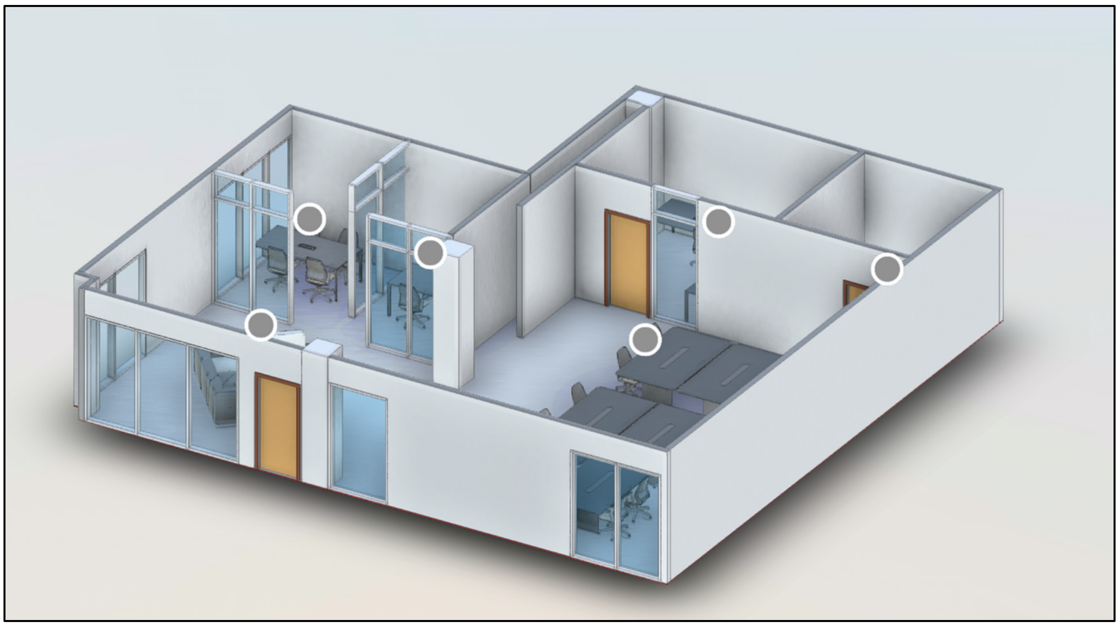


Figure 4.18 Sensors' mapping using Forge Viewer

4.6.3 Heat map and historical data

Autodesk Forge has developed ReactJS components to simplify front-end development and provide an enhanced visualization experience to end users. The web application allows users to select different types of sensor data, such as temperature, humidity, pressure, sound level, and air quality, from the drop-down menu. Based on the real-time data gathered by sensors, the application visualizes the model with a heatmap (Figure 4.19). Users can also select a range of dates from the calendar and view the heatmap of the selected sensor type on the model. Additionally, the application provides a timeline that allows users to animate the heatmap based on historical data. This feature enables visual analytics, allowing users to observe how the data changed during the selected period.

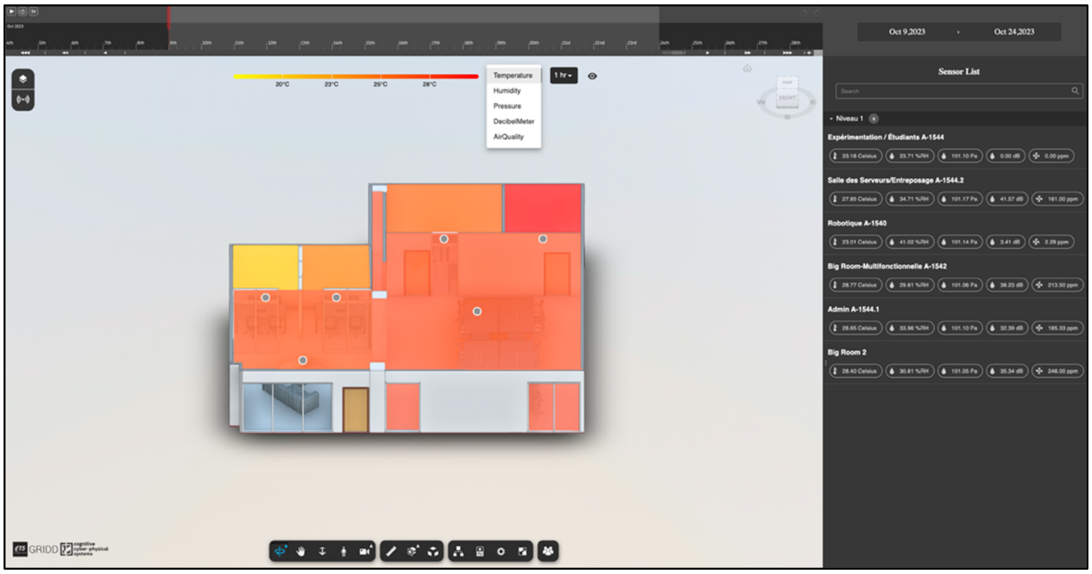


Figure 4.19 Heat map visualization

4.6.4 Comfort monitoring dashboard

As explained in section 5.5, real-time comfort monitoring dashboards for each room are designed using Power BI. Each dashboard has a unique URL that can be added to the corresponding room on the DT platform. By clicking on the visual element (blue colored circle) associated with each sensor on the interface, the related dashboard appears, providing real-time insights into the comfort of the room. For instance, Figure 4.20 displays the dashboard corresponding to room A-1540 at the GRIDD lab.

Figure 4.20 Integration of the comfort monitoring dashboard with the DT

4.7 Evaluation

To evaluate the applicability and effectiveness of the implemented DT system for building comfort monitoring, six semi-structured interviews were conducted with facility managers of various building types. The choice of semi-structured interviews for this research was driven by the need to obtain detailed and context-specific insights from facility managers regarding the applicability, adoptability, and effectiveness of the proposed DT solution for comfort monitoring in buildings. This approach allowed for flexibility in exploring topics in depth while maintaining a consistent structure across interviews.

Facility managers were chosen as the primary interviewees due to their critical role in overseeing the operational aspects of building management, including the technologies that are used for comfort monitoring of buildings. Moreover, they are the main users of the developed artifact. Their hands-on experience and understanding of the challenges and requirements in maintaining optimal environmental conditions within different types of buildings (i.e., academic and commercial) offers valuable insights into the practicality, effectiveness, and areas of improvement for the proposed DT system.

The list of interviewees was determined by considering the diversity of building types (i.e., academic and commercial) and the varying levels of technology adoption in the building management systems utilized in their environment. The goal was to gather a wide range of perspectives, covering different building environments and management complexities. The interviewee's profiles are summarized in Table 4.4.

Table 4.4 Interviewees' profile

Case	Position	Experience	Building type	Familiarity with DT and IoT	Interviewees' code
1	Director, Technical Services	26 years	Academic	Knowledgeable	ET-1
2	Director of BIM Integration	23 years	Academic	Expert	ET-2
3	Manager, Technical Coordination and Process Improvement	20 years	Academic	Knowledgeable	CO-1
4	Director, Technical Services	16 years	Commercial	Expert	PV-1
5	Senior Analyst	12 years	Commercial	Knowledgeable	PV-2
6	Director of IT	9 years	Commercial	Knowledgeable	PV-3

The interview questions focused on gathering comprehensive feedback on the proposed DT solution, covering aspects such as technology usage, system adaptability, useful features, visual elements, limitations, and suggestions for improvement. Therefore, the following guiding questions were asked:

1. What specific technology or sensor types are being used for comfort monitoring in the building?
2. Do you think the developed DT system works for different buildings or space types? How?
3. Which features of the developed DT system do you find most helpful in your field?
4. Did you find any parts of the developed DT system confusing or hard to understand?
5. Are there any issues that might stop the developed DT system from working in certain buildings or situations?
6. Do you suggest any changes or improvements for the developed DT system? Or any other technology that could be integrated with it?

The findings from the interviews are as follows:

1. **Technologies and sensors used for comfort monitoring**:
   - Many buildings already have an existing BAS, primarily used to control HVAC systems. These BAS systems typically use data from temperature and humidity sensors installed in each room to effectively adjust the temperature of areas according to the defined temperature set points (ET-1).
   - A variety of technologies and sensors are employed across different buildings for comfort monitoring. In sensitive areas, such as server rooms, humidity sensors, temperature sensors, and motion detectors are predominant (ET-2).
   - Some facilities employ CO_2 sensors in ventilation systems, maintaining air quality by regulating the mix of new and recycled air based on CO_2 levels and ensuring optimal air composition within the building spaces (PV-1).
   - Apart from the environmental sensors integrated within the buildings, specialized sensors for exhaust gas have been set up in the parking lots to measure the concentrations of CO and NO_x (PV-3).

2. **DT system usability across different building types**:

- Facility managers expressed confidence in the adaptability of the DT system across various building types, including academic libraries and densely populated buildings (ET-1, ET-2, CO-1).
- The platform's capacity to monitor comfort levels across various spaces in real-time has been identified as a critical attribute, serving as a feedback mechanism for users to report discomfort issues (CO-1).
- As the system requires an internet connection to send sensor data to the cloud platform, some managers have raised concerns about the system's functionality in buildings lacking an internet connection (ET-2, PV-2). Although this scenario is uncommon, the system can typically be connected to the internet through alternative wireless communication protocols such as 4G.

3. **Helpful features of the DT system**:
   - The DT's real-time monitoring capability, using a heat map data visualization, is highly valued (ET-2, CO-1).
   - Features such as trend analysis, comfort zone diagrams, and dynamic thresholds that are based on the specifications and applications of each space have been well-received and would be used to enhance occupant satisfaction (ET-2, PV-2).
   - As buildings' needs evolve, real-time sensor data integration with Power BI for data visualization was seen as beneficial. This integration allows for the creation of a customized dashboard that meets the facility managers' specific requirements (PV-1).

4. **Confusion or complexity of the DT system**:
   - Generally, the platform was perceived as user-friendly. However, it was recommended that the user interface would be redefined based on the end users' needs (ET-1, ET-2, PV-1).
   - As there are a variety of sensor types in use, it can sometimes cause confusion (PV-3). This emphasizes the importance of having data access that can be defined based

on the user role. Therefore, each user type can see the information of a certain sensor type, which makes the data more organized and easier to understand.

5. **Limitations and challenges**:
   - There are challenges including, the cost of a DT system implementation, compatibility with existing BAS systems, and the need for additional input sensors and controlling actuators (PV-1, PV-2, PV-3).
   - Concerns about data storage costs, especially regarding cloud usage and data privacy, were mentioned (PV-3).
   - The lack of a BIM model for existing buildings, which can add to development costs, was mentioned as a limitation (ET-2, CO-1).

6. **Suggestions for improvement and integration**:
   - As another application of the DT system, integration with asset and space management systems to enhance work order processing and asset monitoring was suggested (ET-2).
   - Integrating an occupant monitoring system for emergency response was suggested (ET-1).
   - By incorporating fault detection features into the DT system, it can be leveraged to enhance maintenance efficiency (CO-1, PV-1).
   - The need for open communication protocols that allow seamless integration with existing systems and applications was emphasized (PV-2).

Figure 4.21 illustrates the summary of evaluation findings from the interviews.

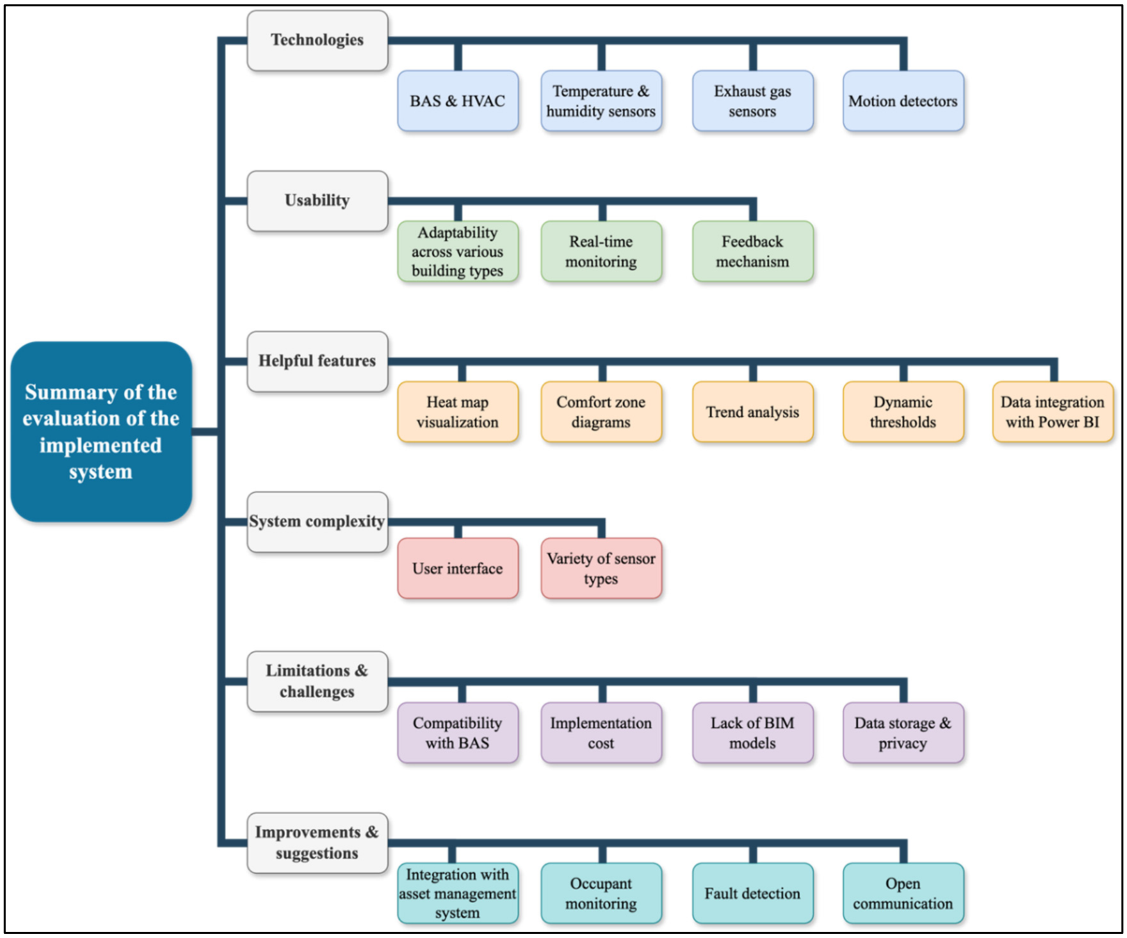


Figure 4.21 The summary of evaluation findings

The semi-structured interviews with facility managers revealed a broad spectrum of technologies and sensors in use for comfort monitoring, reflecting the diverse requirements of different building types. The DT system is generally regarded as adaptable and useful across various settings, with its real-time monitoring and data visualization capabilities being particularly appreciated.

However, challenges related to the implementation costs of a DT, compatibility with existing BAS systems, and the possibility of a need for significant infrastructural changes in older buildings are notable concerns of facility managers. To enhance the system's effectiveness and user experience, integrating it with existing management systems, ensuring open communication protocols, and addressing data privacy and security concerns are crucial points that are mentioned.

The insights gathered through these interviews provide valuable guidance for refining the DT system, tailoring it to meet the diverse needs of facility managers, and overcoming the practical challenges encountered in its implementation.

These interviews underscored the DT system's adaptability and responsiveness to varied environmental conditions and user requirements. The insights provided by facility managers emphasized the crucial role of monitoring user behavior and environmental factors to optimize both comfort and energy efficiency.

In summary, the facility managers' feedback from different building environments illuminated the DT system's versatility and adaptability. Their experiences and insights offered valuable perspectives on the system's potential to enhance comfort and efficiency across various building types and user scenarios.

CHAPTER 5

CONLUCSIONS AND FUTURE WORK

This research was conducted with the primary objective of developing a system for real-time comfort monitoring of buildings using a DT platform. As discussed in Chapter 3, the research proposed a novel solution for the integration of IoT sensors with a DT platform to facilitate the real-time visualization of comfort levels within buildings. Following the proposed solution a DT system was implemented and verified in a case study to demonstrate the applicability of the proposed solution (explained in Chapter 4). Finally, the effectiveness and usability of the implemented system were evaluated through semi-structured interviews with facility managers of buildings.

The developed solution in this thesis, addressed the following primary research question:

- How can a digital twin solution be employed for real-time comfort monitoring of built environments through the integration of BIM and IoT?

This study offers a solution to the primary research question by following the proposed steps presented in Chapter 3, which was applied to develop a software/hardware architecture of a DT system for real-time comfort monitoring. The solution requires identifying and understanding various environmental factors that significantly influence occupants' comfort, such as temperature, humidity, air quality, and sound pressure level. A plug-and-play BLE sensor network is then designed and deployed, providing flexibility for sensors installation across different environments. The data collected from these sensors is integrated into the DT platform, providing a comprehensive and real-time view of the comfort level in each space.

To assess the applicability of the proposed solution, a case study is implemented in the GRIDD Lab at ÉTS University, as described in Chapter 4. This study showcased the software/hardware architecture's practicality by highlighting the system's adaptability as the types of sensors and the building's requirements evolve over time.

Moreover, the proposed solution addresses the following four research questions:

- What environmental variables contribute to the comfort of occupants in built environments, and how can they be measured using IoT sensors?

The comfort of occupants in built environments is influenced by thermal, visual, acoustic, and air quality parameters as discussed in section 1.1. These variables are widely recognized as crucial to occupant well-being. In this research the implemented system uses IoT sensors to measure these variables in real-time, capturing data on temperature, humidity, air quality, and sound levels. These sensors then automatically map the collected data to corresponding rooms within the DT platform, providing real-time insight into the comfort level of each space.

- How can an IoT sensor network be designed to be plug-and-play, and what are the key design considerations for achieving this feature?

This thesis presents a plug-and-play network of BLE sensors, emphasizing on adaptability and efficiency. The architecture is conceptualized around a 'black box' of sensors, which is flexible enough to integrate additional sensor types as needed. The key design considerations include ease of installation, real-time data streaming, and automatic mapping of sensor data to the DT. A microcontroller based on BLE technology drives the network to connect the sensors to the BLE hub, ensuring that the data is transmitted to the cloud platform in real-time.

- What is the best fitting method to calculate the comfort level of each room in real-time?

The calculation of the comfort level in real-time requires the collection and analysis of environmental data to determine whether the conditions fulfill the comfort standards. As elaborated in section 4.2, the PVM method has been adopted to evaluate thermal comfort, while for assessing the comfort levels of acoustic and air quality, a threshold has been defined. The choice of methods and thresholds varies depending on the building's use cases.

- How can a digital twin platform visualize the indicators of comfort level and provide real-time insights for facility operators?

The DT platform visualizes comfort level indicators by integrating real-time data from IoT sensors with the updated BIM model stored in the cloud. This integration enables the creation of a real-time comfort monitoring dashboard. A real-time visual dashboard powered by Power BI is integrated and employed into the DT platform to transform sensor readings into comfort metrics, offering insight into the comfort level of each space. Various visualization methods were used to present the data in a user-friendly manner, allowing operators, such as facility managers, to monitor comfort levels and make informed decisions. Moreover, a heat map visualization method was applied on the DT platform, ensuring that sensor data is accurately represented within the context of the BIM model. These provided a dynamic and interactive tool for facility managers to assess and ensure comfort levels across different areas within the built environment.

5.1 Contributions

This research focused on real-time comfort monitoring in buildings by integrating various IoT sensors with a DT system to propose a solution for real time comfort monitoring. Most existing buildings already have BAS equipped with temperature and humidity sensors. However, to have a more comprehensive real-time comfort monitoring system, a variety of sensor types are essential. Current BAS systems often lack the flexibility to incorporate new sensor types, and other sources of data such as building models which is required for more advanced comfort assessment methods. Addressing this gap, the study proposed a novel software/hardware architecture to develop a DT system, integrating IoT sensors and BIM model specifically for real-time comfort monitoring in buildings.

An important part of the proposed solution is its hardware architecture, which adopts a plug-and-play approach. This architecture facilitates the implementation of a flexible wireless sensor network, allowing the integration of new sensor types. This plug-and-play sensor network can be effortlessly installed in various building environments. It is designed to operate independently from existing BAS systems, focusing on measuring variables critical for building comfort monitoring. It enables building owners and managers to independently expand their sensor networks without being constrained by the existing BAS.

Another contribution of this thesis is the development of an architecture that allows for the automatic integration of plug-and-play IoT sensors with BIM through a DT platform. This includes an automated method for mapping sensors to corresponding rooms to provide a heat map data visualization, thereby facilitating real-time monitoring and analysis of each space based on real-time sensory data. Moreover, the software architecture proposes a cloud-based solution to integrate real-time sensor data into Power BI to create a real-time comfort monitoring dashboard. The implemented dashboard is integrated into the DT platform to present a real-time and user-friendly visual insight into comfort levels. By providing real-time monitoring and insights into the comfort levels of each room, the system has the potential to enable building facility managers to identify and target areas for energy savings.

The architecture leverages a cloud platform where all sensor data is transmitted, integrated, and visualized. This data management approach, storing information in a time-series format, enables not only real-time visualization but also analysis of historical data patterns. The user-friendly dashboard implemented within this system is crucial for real-time monitoring and analysis of comfort parameters, utilizing various visualization methods for ease of understanding and decision-making.

In summary, the thesis presents a solution with its associated software/hardware architecture that integrates BIM and IoT technologies to develop a DT platform for real-time comfort monitoring. The architecture is not only flexible and scalable but also adaptable to the evolving needs of built environments. The solution ensures that occupant comfort is continuously monitored and maintained with accuracy, marking a step forward in the realm of smart building management.

5.2 Limitations

This research, while making contributions in the field of IoT sensor data integration and DT technology for real-time comfort monitoring of buildings, acknowledges several limitations:

- In the research methodology, the PMV method was employed for thermal comfort monitoring. However, there are various other methods to assess different aspects of thermal comfort, and in other case studies, alternative approaches such as the PPD could be utilized. Additionally, this study measured sound pressure for acoustic comfort, suitable for the low-frequency noise environment of an office area, as per the case study. In different scenarios, both sound pressure and frequency of noise should be considered for a comprehensive assessment of acoustic comfort.

- As elaborated in Chapter 4, the study utilizes the BLE protocol for the implementation of a plug-and-play IoT sensor network, connecting sensors to the cloud through a BLE hub. However, it is important to recognize that, depending on the specifications of the use cases, alternative wireless communication methods, such as MQTT, could be used. Furthermore, in certain scenarios, sensors might be configured to connect directly to the cloud, bypassing the need for a hub. This aspect points to the potential for exploring diverse communication strategies in future research iterations.

- This study primarily focused on data integration and visualization to develop a DT for real-time comfort monitoring. The proof-of-concept implementation was not aimed to perform as a commercial solution; for example, the sensors used were not of the highest accuracy. This study suggests that for applications where high precision is crucial, more accurate sensors would be utilized. This limitation presents an opportunity for future research to enhance system accuracy by employing advanced sensor technology.

- The proposed architecture was developed and deployed using Microsoft Azure cloud platform. This reliance might lead to potential vendor lock-in issues. However, the study reassures that all the components can be redeveloped and adapted based on the functionality and logic described in Chapter 3. They can be reconfigured for deployment on comparable services offered by other cloud providers, such as AWS or Google Cloud.

- The methodology used to evaluate the DT system in this thesis relied on semi-structured interviews with facility managers who were not directly involved in overseeing the GRIDD lab where the system was implemented. This approach, while useful, has some limitations. Since the feedback gathered was primarily qualitative in nature and came from individuals who did not have firsthand experience using the system in their day-to-day operations, it lacks direct observations of the system's usability and effectiveness in a real-world context. This limitation hinders the ability to comprehensively assess the system's impact on facility management practices.

5.3 Recommendations for future work

There are several promising directions for future research and enhancements to further develop and expand the capabilities of the DT system.

Integrating additional data sources into the DT system such as the number of occupants in each space and power consumption data, would significantly broaden the scope of the system. This would enable a more comprehensive approach to both comfort monitoring and energy consumption analysis within the building.

A key area for development is the establishment of bidirectional data communication with the BAS. Such integration would facilitate a dynamic interaction between the DT and BAS, where the DT could issue commands to control the BAS based on sensor readings. This would elevate the system from passive monitoring to active management of the building environment.

Further, applying ML and AI techniques to the real-time and historical sensor data could lead to predictive insights into the comfort levels of each space and their associated power consumption. This predictive capability could significantly enhance decision-making processes in building management, enabling proactive adjustments to optimize occupants' comfort while reducing power consumption.

Additionally, extracting more detailed information from the BIM model, such as building geometry, spatial relationships, and characteristics of building components, could enrich the DT system. This information would contribute to having a more accurate and advanced comfort monitoring system.

In future work, the system could also include a decision-making algorithm within the DT for automated control, coupled with an enhanced user interface for manual adjustments based on predicted values of comfort levels and energy consumption. This combination of automated and user-driven control would offer a balanced approach to maintaining optimal comfort levels while minimizing energy consumption. These advancements would transform the DT platform into a more comprehensive, intelligent, and interactive tool for effective building management.

Moreover, to strengthen future research, it is imperative to refine the evaluation methodology of the DT system by involving participants who have direct experience with its deployment. By engaging facility managers and users who interact with the DT system daily, the research can benefit from detailed insights into the system's practicality, revealing both its strengths and areas for improvement. Furthermore, incorporating a more structured and quantitative approach to the evaluation process is essential. This should include the development of systematic methods to measure the system's performance metrics, such as efficiency gains and user engagement levels. A quantitative assessment will complement qualitative feedback, leading to a comprehensive understanding of the DT system's functionality and providing a robust basis for enhancements to the system's design and application in real-time comfort monitoring.

In summary, these future directions aim to evolve the DT platform into a more robust, intelligent, and interactive system capable of not just monitoring but actively optimizing the built environment for both comfort and energy efficiency.

BIBLIOGRAPHY

Akcamete, Asli, Burcu Akinci, and James H. Garrett. 2010. "Potential Utilization of Building Information Models for Planning Maintenance Activities." Pp. 151–57 in Vol. 2010. June.

Al-Ali, AR, Ragini Gupta, and Ahmad Al Nabulsi. 2018. "Cyber Physical Systems Role in Manufacturing Technologies." in Vol. 1957. AIP Publishing.

d'Ambrosio Alfano, Francesca Romana, Bjarne W. Olesen, Boris Igor Palella, and Giuseppe Riccio. 2014. "Thermal Comfort: Design and Assessment for Energy Saving." *Energy and Buildings* 81:326–36. doi: 10.1016/j.enbuild.2014.06.033.

Andargie, Maedot S., Marianne Touchie, and William O'Brien. 2019. "A Review of Factors Affecting Occupant Comfort in Multi-Unit Residential Buildings." *Building and Environment* 160:106182. doi: 10.1016/j.buildenv.2019.106182.

ANSI/ASHRAE. 2017. "Standard 55–2017 Thermal Environmental Conditions for Human Occupancy." *American Society of Heating, Refrigerating and Air Conditioning Engineers: Atlanta, GA, USA*.

Apte, Michael G., William J. Fisk, and Joan M. Daisey. 2000. "Associations between Indoor CO2 Concentrations and Sick Building Syndrome Symptoms in US Office Buildings: An Analysis of the 1994-1996 BASE Study Data."

Arowoiya, Victor Adetunji, Robert Christian Moehler, and Yihai Fang. 2023. "Digital Twin Technology for Thermal Comfort and Energy Efficiency in Buildings: A State-of-the-Art and Future Directions." *Energy and Built Environment*. doi: 10.1016/j.enbenv.2023.05.004.

Asghari, Parvaneh, Amir Masoud Rahmani, and Hamid Haj Seyyed Javadi. 2019. "Internet of Things Applications: A Systematic Review." *Computer Networks* 148:241–61. doi: 10.1016/j.comnet.2018.12.008.

Bakmohammadi, Parnian, and Esmatullah Noorzai. 2020. "Optimization of the Design of the Primary School Classrooms in Terms of Energy and Daylight Performance Considering Occupants' Thermal and Visual Comfort." *Energy Reports* 6:1590–1607.

Bluyssen, PM, C. Roda, C. Mandin, S. Fossati, P. Carrer, Y. De Kluizenaar, VG Mihucz, E. de Oliveira Fernandes, and J. Bartzis. 2016. "Self-reported Health and Comfort in 'Modern'Office Buildings: First Results from the European OFFICAIR Study." *Indoor Air* 26(2):298–317.

Boje, Calin, Annie Guerriero, Sylvain Kubicki, and Yacine Rezgui. 2020. "Towards a Semantic Construction Digital Twin: Directions for Future Research." *Automation in Construction* 114:103179. doi: 10.1016/j.autcon.2020.103179.

Bortolini, Rafaela, Raul Rodrigues, Hamidreza Alavi, Luisa Felix Dalla Vecchia, and Núria Forcada. 2022. "Digital Twins' Applications for Building Energy Efficiency: A Review." *Energies* 15(19):7002.

Brasche, Sabine, and Wolfgang Bischof. 2005. "Daily Time Spent Indoors in German Homes – Baseline Data for the Assessment of Indoor Exposure of German Occupants." *International Journal of Hygiene and Environmental Health* 208(4):247–53. doi: 10.1016/j.ijheh.2005.03.003.

Brown, Craig, and Mark Gorgolewski. 2014. "Assessing Occupant Satisfaction and Energy Behaviours in Toronto's LEED Gold High-Rise Residential Buildings." *International Journal of Energy Sector Management* 8(4):492–505.

Brozovsky, Johannes, Matthias Haase, and Nicola Lolli. 2018. "Validation of a Digital Twin with Measurement Data."

Budaiwi, Ismail M. 2007. "An Approach to Investigate and Remedy Thermal-Comfort Problems in Buildings." *Building and Environment* 42(5):2124–31.

Burns, William. 1973. "Noise and Man." *(No Title)*.

Chan, Edwin HW, KS Lam, and WS Wong. 2008. "Evaluation on Indoor Environment Quality of Dense Urban Residential Buildings." *Journal of Facilities Management* 6(4):245–65.

Chen, Weiwei, K. Chena, VJL Gan, and JCP Cheng. 2019. "A Methodology for Indoor Human Comfort Analysis Based on BIM and Ontology." Pp. 1189–96 in Vol. 36. IAARC Publications.

Chen, Zhen-Song, Zhuo-Ran Wang, Muhammet Deveci, Weiping Ding, Witold Pedrycz, and Mirosław J. Skibniewski. 2024. "Optimization-Based Probabilistic Decision Support for Assessing Building Information Modelling (BIM) Maturity Considering Multiple Objectives." *Information Fusion* 102:102026. doi: 10.1016/j.inffus.2023.102026.

Chenari, Behrang, João Dias Carrilho, and Manuel Gameiro da Silva. 2016. "Towards Sustainable, Energy-Efficient and Healthy Ventilation Strategies in Buildings: A Review." *Renewable and Sustainable Energy Reviews* 59:1426–47.

Cheng, Jack C. P., Weiwei Chen, Keyu Chen, and Qian Wang. 2020. "Data-Driven Predictive Maintenance Planning Framework for MEP Components Based on BIM and IoT Using Machine Learning Algorithms." *Automation in Construction* 112:103087. doi: 10.1016/j.autcon.2020.103087.

Chung, Suwan, Soonwook Kwon, Daeyoon Moon, and Taekyu Ko. 2018. *Smart Facility Management Systems Utilizing Open BIM and Augmented/Virtual Reality*.

Clausen, Geo, Linda Carrick, P. Ole Fanger, Sun Woo Kim, Torben Poulsen, and Jens Holger Rindel. 1993. "A Comparative Study of Discomfort Caused by Indoor Air Pollution, Thermal Load and Noisec." *Indoor Air* 3(4):255–62.

Cowan, James P. 1993. *Handbook of Environmental Acoustics*. John Wiley & Sons.

Davari, Saman, Mehrzad Shahinmoghadam, Ali Motamedi, and Erik Poirier. 2022. "Demystifying the Definition of Digital Twin for Built Environment." Pp. 1122–29 in *9th International Conference on Construction Engineering and Project Management (ICCEPM)*. Korea Institute of Construction Engineering and Management.

De Dear, Richard J., Gail Schiller Brager, James Reardon, and Fergus Nicol. 1998. "Developing an Adaptive Model of Thermal Comfort and Preference/Discussion." *ASHRAE Transactions* 104:145.

Desogus, Giuseppe, Caterina Frau, Emanuela Quaquero, and Giulia Rubiu. 2023. "From Building Information Model to Digital Twin: A Framework for Building Thermal Comfort Monitoring, Visualizing, and Assessment." *Buildings* 13(8):1971. doi: 10.3390/buildings13081971.

Dian, F. John, Amirhossein Yousefi, and Sungjoon Lim. 2018. "A Practical Study on Bluetooth Low Energy (BLE) Throughput." Pp. 768–71 in *2018 IEEE 9th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON)*.

Dixit, Manish K., Varusha Venkatraj, Mohammadreza Ostadalimakhmalbaf, Fatemeh Pariafsai, and Sarel Lavy. 2019. "Integration of Facility Management and Building Information Modeling (BIM): A Review of Key Issues and Challenges." *Facilities* 37(7/8):455–83. doi: 10.1108/F-03-2018-0043.

Du, Liuliu, Tadas Prasauskas, Virpi Leivo, Mari Turunen, Maria Pekkonen, Mihkel Kiviste, Anu Aaltonen, Dainius Martuzevicius, and Ulla Haverinen-Shaughnessy. 2015. "Assessment of Indoor Environmental Quality in Existing Multi-Family Buildings in North–East Europe." *Environment International* 79:74–84.

Dulguun, Enkhjin. 2023. "Implementation of Cutting-Edge Technologies in Facility Management Challenges and Opportunities in the Digital Era." *Journal Dimensie Management and Public Sector* 4(4):24–33. doi: 10.48173/jdmps.v4i4.243.

Durdyev, Serdar, Mojtaba Ashour, Scott Connelly, and Amir Mahdiyar. 2022. "Barriers to the Implementation of Building Information Modelling (BIM) for Facility Management." *Journal of Building Engineering* 46:103736. doi: 10.1016/j.jobe.2021.103736.

Eastman, Charles M. 2011. *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. John Wiley & Sons.

Edirisinghe, Ruwini, Pushpitha Lalith Kalutara, and Kerry London. 2016. "An Investigation of BIM Adoption of Owners and Facility Managers in Australia: Institutional Case Study." Pp. 1–10 in. Royal Institution of Chartered Surveyors.

Fanger, P. Ole, NO Breum, and E. Jerking. 1977. "Can Colour and Noise Influence Man's Thermal Comfort?" *Ergonomics* 20(1):11–18.

Fanger, Poul O. 1970. *Thermal Comfort: Analysis and Applications in Environmental Engineering*. New York: McGraw-Hill.

Ferrara, Maria, Jean Christophe Vallée, Louena Shtrepi, Arianna Astolfi, and Enrico Fabrizio. 2021. "A Thermal and Acoustic Co-Simulation Method for the Multi-Domain Optimization of Nearly Zero Energy Buildings." *Journal of Building Engineering* 40:102699. doi: 10.1016/j.jobe.2021.102699.

Fisk, William J. 2017. "The Ventilation Problem in Schools: Literature Review." *Indoor Air* 27(6):1039–51.

Földváry, Veronika, Gabriel Bekö, Sarka Langer, Karine Arrhenius, and Dušan Petráš. 2017. "Effect of Energy Renovation on Indoor Air Quality in Multifamily Residential Buildings in Slovakia." *Building and Environment* 122:363–72.

FOWLER, M., B. GHISELIN, G. HERBERT, J. LLORCA, D. LLORCA, V OLGyAy, A. OLGyAy, D. LyNDON, VW OLGyAy, and J. REyNOLDS. 1963. "Design with Climate: Bioclimatic Approach to Architectural Regionalism."

Frontczak, Monika, and Pawel Wargocki. 2011. "Literature Survey on How Different Factors Influence Human Comfort in Indoor Environments." *Building and Environment* 46(4):922–37. doi: 10.1016/j.buildenv.2010.10.021.

Fuller, Aidan, Zhong Fan, Charles Day, and Chris Barlow. 2020. "Digital Twin: Enabling Technologies, Challenges and Open Research." *IEEE Access* 8:108952–71. doi: 10.1109/ACCESS.2020.2998358.

Ganesh, Ghogare Abhijeet, Shobha Lata Sinha, Tikendra Nath Verma, and Satish Kumar Dewangan. 2021. "Investigation of Indoor Environment Quality and Factors Affecting Human Comfort: A Critical Review." *Building and Environment* 204:108146. doi: 10.1016/j.buildenv.2021.108146.

Gao, Xinghua, and Pardis Pishdad-Bozorgi. 2019. "BIM-Enabled Facilities Operation and Maintenance: A Review." *Advanced Engineering Informatics* 39:227–47. doi: 10.1016/j.aei.2019.01.005.

Gerrish, Tristan, Kirti Ruikar, Malcolm Cook, Mark Johnson, Mark Phillip, and Christine Lowry. 2017. "BIM Application to Building Energy Performance Visualisation and Management: Challenges and Potential." *Energy and Buildings* 144:218–28. doi: 10.1016/j.enbuild.2017.03.032.

Goretti, Hannah A., and Peter Kaming. 2023. “A Review and Bibliometric Analysis of Utilizing Building Information Modeling (BIM) on Effective Operation and Maintenance (O&M)” edited by L. S. Putranto, S. Jaensirisak, J. Prasetijo, B. H. W. Hadikusumo, and D. Choi. *E3S Web of Conferences* 429:01002. doi: 10.1051/e3sconf/202342901002.

Gou, Zhonghua, Wajishani Gamage, Stephen Siu-Yu Lau, and Sunnie Sing-Yeung Lau. 2018. “An Investigation of Thermal Comfort and Adaptive Behaviors in Naturally Ventilated Residential Buildings in Tropical Climates: A Pilot Study.” *Buildings* 8(1):5.

Grondzik, Walter T., and Alison G. Kwok. 2015. *Mechanical and Electrical Equipment for Buildings*. New Jersey: Wiley & Sons.

Gubbi, Jayavardhana, Rajkumar Buyya, Slaven Marusic, and Marimuthu Palaniswami. 2013. “Internet of Things (IoT): A Vision, Architectural Elements, and Future Directions.” *Future Generation Computer Systems* 29(7):1645–60. doi: 10.1016/j.future.2013.01.010.

Guzman, Giankeving, and Wilfredo Ulloa. 2020. “Bim Application in the Operation and Maintenance Management of a Sports Infrastructure.” Pp. 949–60 in.

Halhoul Merabet, Ghezlane, Mohamed Essaaidi, Mohamed Ben Haddou, Basheer Qolomany, Junaid Qadir, Muhammad Anan, Ala Al-Fuqaha, Mohamed Riduan Abid, and Driss Benhaddou. 2021. “Intelligent Building Control Systems for Thermal Comfort and Energy-Efficiency: A Systematic Review of Artificial Intelligence-Assisted Techniques.” *Renewable and Sustainable Energy Reviews* 144:110969. doi: 10.1016/j.rser.2021.110969.

Halmetoja, Esa. 2022. “The Role of Digital Twins and Their Application for the Built Environment.” *Industry 4.0 for the Built Environment: Methodologies, Technologies and Skills* 415–42.

Hevner, Alan, and Samir Chatterjee. 2010. “Design Science Research in Information Systems.” Pp. 9–22 in *Design Research in Information Systems: Theory and Practice*, *Integrated Series in Information Systems*, edited by A. Hevner and S. Chatterjee. Boston, MA: Springer US.

Hevner, Alan R., Salvatore T. March, Jinsoo Park, and Sudha Ram. 2004. “Design Science in Information Systems Research.” *MIS Quaterly* 28(1):75–105.

Hirsch, Christian, Luca Davoli, Radu Grosu, and Gianluigi Ferrari. 2023. “DynGATT: A Dynamic GATT-Based Data Synchronization Protocol for BLE Networks.” *Computer Networks* 222:109560. doi: 10.1016/j.comnet.2023.109560.

Hoang, GV, DKT Vu, NH Le, and TP Nguyen. 2020. "Benefits and Challenges of BIM Implementation for Facility Management in Operation and Maintenance Face of Buildings in Vietnam." P. 022032 in Vol. 869. IOP Publishing.

Holton, John. 2012. *Strategy Guideline: High Performance Residential Lighting*. National Renewable Energy Lab.(NREL), Golden, CO (United States).

International Energy Agency (IEA). 2019. *2019 Global Status Report for Buildings and Construction*.

International Energy Agency (IEA). 2020. *Tracking Buildings 2020*. Paris.

ISO, EN. 2020. "19650-3 (2020), Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM)–Information Management Using Building Information Modelling." *Part* 3:1–46.

Itharajula, Manoj. 2020. "Air Pollutants Level Detection and Control in Vehicle Using an Intelligent System." Pp. 581–89 in *Emerging Trends in Electrical, Communications, and Information Technologies*, *Lecture Notes in Electrical Engineering*, edited by T. Hitendra Sarma, V. Sankar, and R. A. Shaik. Singapore: Springer.

Jeon, Jin Yong, Jong Kwan Ryu, and Pyoung Jik Lee. 2010. "A Quantification Model of Overall Dissatisfaction with Indoor Noise Environment in Residential Buildings." *Applied Acoustics* 71(10):914–21.

Jiang, Feng, Ling Ma, Tim Broyd, and Ke Chen. 2021. "Digital Twin and Its Implementations in the Civil Engineering Sector." *Automation in Construction* 130:103838. doi: 10.1016/j.autcon.2021.103838.

Kang, Kai, Jiarui Lin, and Jianping Zhang. 2018. "BIM- and IoT-Based Monitoring Framework for Building Performance Management." *Journal of Structural Integrity and Maintenance* 3(4):254–61. doi: 10.1080/24705314.2018.1536318.

Kazado, Daniel, Miroslava Kavgic, and Rasit Eskicioglu. 2019. "Integrating Building Information Modeling (BIM) and Sensor Technology for Facility Management." *Journal of Information Technology in Construction (ITcon)* 24(23):440–58.

Kiu, Mee San, Ying Jie Chin, Fah Choy Chia, and Phui Fung Wong. 2021. "The Readiness of IoT Enabled Smart Buildings in Malaysia." *Journal of Physics: Conference Series* 2053(1):012001. doi: 10.1088/1742-6596/2053/1/012001.

Krishnamurthy, Sudha, Omer Anson, Lior Sapir, Chanan Glezer, Mauro Rois, Ilana Shub, and Kilian Schloeder. 2008. "Automation of Facility Management Processes Using Machine-to-Machine Technologies." Pp. 68–86 in *The Internet of Things*, *Lecture Notes in Computer Science*, edited by C. Floerkemeier, M. Langheinrich, E. Fleisch, F. Mattern, and S. E. Sarma. Berlin, Heidelberg: Springer.

Kwong, Qi Jie. 2020. "Light Level, Visual Comfort and Lighting Energy Savings Potential in a Green-Certified High-Rise Building." *Journal of Building Engineering* 29:101198.

Lai, ACK, Kwok Wai Mui, Ling Tim Wong, and LY Law. 2009. "An Evaluation Model for Indoor Environmental Quality (IEQ) Acceptance in Residential Buildings." *Energy and Buildings* 41(9):930–36.

Landström, Ulf, Elisabeth Åkerlund, Anders Kjellberg, and Maria Tesarz. 1995. "Exposure Levels, Tonal Components, and Noise Annoyance in Working Environments." *Environment International* 21(3):265–75.

Leivo, Virpi, Mari Turunen, Anu Aaltonen, Mihkel Kiviste, Liuliu Du, and Ulla Haverinen-Shaughnessy. 2016. "Impacts of Energy Retrofits on Ventilation Rates, CO2-Levels and Occupants' Satisfaction with Indoor Air Quality." *Energy Procedia* 96:260–65.

Liu, Rui, and Raja RA Issa. 2013. "Issues in BIM for Facility Management from Industry Practitioners' Perspectives." Pp. 411–18 in *Computing in Civil Engineering (2013)*.

Loewen, Laura J., and Peter Suedfeld. 1992. "Cognitive and Arousal Effects of Masking Office Noise." *Environment and Behavior* 24(3):381–95.

Lu, Qiuchen, Xiang Xie, Ajith Kumar Parlikad, and Jennifer Mary Schooling. 2020. "Digital Twin-Enabled Anomaly Detection for Built Asset Monitoring in Operation and Maintenance." *Automation in Construction* 118:103277. doi: 10.1016/j.autcon.2020.103277.

Ma, Nan, Dorit Aviv, Hongshan Guo, and William W. Braham. 2021. "Measuring the Right Factors: A Review of Variables and Models for Thermal Comfort and Indoor Air Quality." *Renewable and Sustainable Energy Reviews* 135:110436. doi: 10.1016/j.rser.2020.110436.

Madni, Azad, Carla Madni, and Scott Lucero. 2019. "Leveraging Digital Twin Technology in Model-Based Systems Engineering." *Systems* 7(1):7. doi: 10.3390/systems7010007.

Mannino, Antonino, Mario Claudio Dejaco, and Fulvio Re Cecconi. 2021. "Building Information Modelling and Internet of Things Integration for Facility Management—Literature Review and Future Needs." *Applied Sciences* 11(7):3062. doi: 10.3390/app11073062.

Matarneh, Rana, and Sadeq Hamed. 2017. "Barriers to the Adoption of Building Information Modeling in the Jordanian Building Industry." *Open Journal of Civil Engineering* 7(3):325–35.

Matarneh, Sandra T., Mark Danso-Amoako, Salam Al-Bizri, Mark Gaterell, and Rana Matarneh. 2019. "Building Information Modeling for Facilities Management: A Literature Review and Future Research Directions." *Journal of Building Engineering* 24:100755. doi: 10.1016/j.jobe.2019.100755.

McMinn, Terrance. 2013. "A-Weighting: Is It the Metric You Think It Is?" *Acoustics 2013* 1–4.

Migilinskas, Darius, Vladimir Popov, Virgaudas Juocevicius, and Leonas Ustinovichius. 2013. "The Benefits, Obstacles and Problems of Practical BIM Implementation." *Procedia Engineering* 57:767–74.

Monsone, Cristina Rosaria, Eunika Mercier-Laurent, and Jósvai János. 2019. "The Overview of Digital Twins in Industry 4.0: Managing the Whole Ecosystem." Pp. 271–76 in.

Mui, Kwok Wai, and Ling Tim Wong. 2007. "Neutral Temperature in Subtropical Climates—a Field Survey in Air-Conditioned Offices." *Building and Environment* 42(2):699–706.

Munir, Mustapha, Arto Kiviniemi, and Stephen W. Jones. 2019. "Business Value of Integrated BIM-Based Asset Management." *Engineering, Construction and Architectural Management* 26(6):1171–91. doi: 10.1108/ECAM-03-2018-0105.

Nasaruddin, Afiqah Ngah, Teruaki Ito, and Tee Boon Tuan. 2018. "Digital Twin Approach to Building Information Management." P. 304 in. The Japan Society of Mechanical Engineers.

Negri, Elisa, Luca Fumagalli, and Marco Macchi. 2017. "A Review of the Roles of Digital Twin in CPS-Based Production Systems." *Procedia Manufacturing* 11:939–48. doi: 10.1016/j.promfg.2017.07.198.

Olimat, Hosam, Hexu Liu, and Osama Abudayyeh. 2023. "Enabling Technologies and Recent Advancements of Smart Facility Management." *Buildings* 13(6):1488. doi: 10.3390/buildings13061488.

Opoku, De-Graft Joe, Srinath Perera, Robert Osei-Kyei, Maria Rashidi, Tosin Famakinwa, and Keivan Bamdad. 2022. "Drivers for Digital Twin Adoption in the Construction Industry: A Systematic Literature Review." *Buildings* 12(2):113. doi: 10.3390/buildings12020113.

Pan, Yue. 2021. "Roles of Artificial Intelligence in Construction Engineering and Management: A Critical Review and Future Trends." *Automation in Construction* 21.

Pärn, E. A., D. J. Edwards, and M. C. P. Sing. 2017. "The Building Information Modelling Trajectory in Facilities Management: A Review." *Automation in Construction* 75:45–55. doi: 10.1016/j.autcon.2016.12.003.

Patacas, João, Nashwan Dawood, Vladimir Vukovic, and Mohamad Kassem. n.d. "BIM FOR FACILITIES MANAGEMENT: EVALUATING BIM STANDARDS IN ASSET REGISTER CREATION AND SERVICE LIFE PLANNING."

Pavlin, Boris, Giovanni Pernigotto, Francesca Cappelletti, Paolo Bison, Renato Vidoni, and Andrea Gasparella. 2017. "Real-Time Monitoring of Occupants' Thermal Comfort through Infrared Imaging: A Preliminary Study." *Buildings* 7(1):10. doi: 10.3390/buildings7010010.

Peffers, Ken, Tuure Tuunanen, Marcus A. Rothenberger, and Samir Chatterjee. 2007. "A Design Science Research Methodology for Information Systems Research." *Journal of Management Information Systems* 24(3):45–77. doi: 10.2753/MIS0742-1222240302.

Pellerin, Nicolas, and Victor Candas. 2003. "Combined Effects of Temperature and Noise on Human Discomfort." *Physiology & Behavior* 78(1):99–106. doi: 10.1016/S0031-9384(02)00956-3.

Peng, Yang, Ming Zhang, Fangqiang Yu, Jinglin Xu, and Shang Gao. 2020. "Digital Twin Hospital Buildings: An Exemplary Case Study through Continuous Lifecycle Integration." *Advances in Civil Engineering* 2020:1–13.

Perri, Massimo, Francesca Cuomo, and Pierluigi Locatelli. 2022. "BLENDER - Bluetooth Low Energy Discovery and Fingerprinting in IoT." Pp. 182–89 in *2022 20th Mediterranean Communication and Computer Networking Conference (MedComNet)*.

Piette, Mary Ann, Sat Kartar Kinney, and Philip Haves. 2001. "Analysis of an Information Monitoring and Diagnostic System to Improve Building Operations." *Energy and Buildings* 33(8):783–91. doi: 10.1016/S0378-7788(01)00068-8.

Qi, Qinglin, Fei Tao, Tianliang Hu, Nabil Anwer, Ang Liu, Yongli Wei, Lihui Wang, and AYC Nee. 2021. "Enabling Technologies and Tools for Digital Twin." *Journal of Manufacturing Systems* 58:3–21.

Rizal, Randi, and Missi Hikmatyar. 2019. "Investigation Internet of Things (IoT) Device Using Integrated Digital Forensics Investigation Framework (IDFIF)." *Journal of Physics: Conference Series* 1179(1):012140. doi: 10.1088/1742-6596/1179/1/012140.

Rojas, Gabriel, Waldemar Wagner, Jürgen Suschek-Berger, Rainer Pfluger, and Wolfgang Feist. 2016. "Applying the Passive House Concept to a Social Housing Project in Austria–Evaluation of the Indoor Environment Based on Long-Term Measurements and User Surveys." *Advances in Building Energy Research* 10(1):125–48.

Schleich, Benjamin, Nabil Anwer, Luc Mathieu, and Sandro Wartzack. 2017. "Shaping the Digital Twin for Design and Production Engineering." *CIRP Annals* 66(1):141–44. doi: 10.1016/j.cirp.2017.04.040.

Seppänen, O. A., W. J. Fisk, and Mar J. Mendell. 1999. "Association of Ventilation Rates and CO2 Concentrations with Health Andother Responses in Commercial and Institutional Buildings." *Indoor Air* 9(4):226–52.

Serghides, Despina Kyprianou, CK Chatzinikola, and MC Katafygiotou. 2015. "Comparative Studies of the Occupants' Behaviour in a University Building during Winter and Summer Time." *International Journal of Sustainable Energy* 34(8):528–51.

Shahinmoghadam, Mehrzad, Worawan Natephra, and Ali Motamedi. 2021. “BIM- and IoT-Based Virtual Reality Tool for Real-Time Thermal Comfort Assessment in Building Enclosures.” *Building and Environment* 199:107905. doi: 10.1016/j.buildenv.2021.107905.

Shahzad, Muhammad, Muhammad Tariq Shafiq, Dean Douglas, and Mohamad Kassem. 2022. “Digital Twins in Built Environments: An Investigation of the Characteristics, Applications, and Challenges.” *Buildings* 12(2):120. doi: 10.3390/buildings12020120.

Shao, Guodong, and Moneer Helu. 2020. “Framework for a Digital Twin in Manufacturing: Scope and Requirements.” *Manufacturing Letters* 24:105–7.

Shaughnessy, Richard J., Ulla Haverinen-Shaughnessy, A. Nevalainen, and D. Moschandreas. 2006. “A Preliminary Study on the Association between Ventilation Rates in Classrooms and Student Performance.” *Indoor Air* 16(6):465–68.

Singh, Maulshree, Evert Fuenmayor, Eoin P. Hinchy, Yuansong Qiao, Niall Murray, and Declan Devine. 2021. “Digital Twin: Origin to Future.” *Applied System Innovation* 4(2):36. doi: 10.3390/asi4020036.

Srinivasan, Karthik, Faiz Currim, Casey M. Lindberg, Javad Razjouyan, Brian Gilligan, Hyoki Lee, Kelli J. Canada, Nicole Goebel, Matthias R. Mehl, Melissa M. Lunden, Judith Heerwagen, Bijan Najafi, Esther M. Sternberg, Kevin Kampschroer, and Sudha Ram. 2023. “Discovery of Associative Patterns between Workplace Sound Level and Physiological Wellbeing Using Wearable Devices and Empirical Bayes Modeling.” *Npj Digital Medicine* 6(1):1–10. doi: 10.1038/s41746-022-00727-1.

Standard, CEN, and UNI Standard EN15251. 2007. “Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics.” *BS EN* 15251.

Strøm-Tejsen, Peter, D. Zukowska, Pawel Wargocki, and David Peter Wyon. 2016. “The Effects of Bedroom Air Quality on Sleep and Next-day Performance.” *Indoor Air* 26(5):679–86.

Sun, Shengjing, Xiaochen Zheng, Javier Villalba-Díez, and Joaquín Ordieres-Meré. 2019. “Indoor Air-Quality Data-Monitoring System: Long-Term Monitoring Benefits.” *Sensors* 19(19):4157. doi: 10.3390/s19194157.

T’Jonck, Kristof, Bozheng Pang, Hans Hallez, and Jeroen Boydens. 2021. “Optimizing the Bluetooth Low Energy Service Discovery Process.” *Sensors* 21(11):3812. doi: 10.3390/s21113812.

Ub, Nagesh, Nayana Ms, Shruthi Cs, Sudeep Poojary, Vaishnavi Ps, and Vshker Mayengbam. 2021. “A Review Paper of Security in Internet of Things (IoT).” *International Journal* *of Advanced Research in Science, Communication and Technology* 171–76. doi: 10.48175/IJARSCT-2101.

US Energy Information Administration. 2012. "Commercial Buildings Energy Consumption Survey (CBECS)."

Valinejadshoubi, Mojtaba, Osama Moselhi, Ashutosh Bagchi, and Ashraf Salem. 2020. "Development of an Iot and Bim-Based Automated Alert System for Thermal Comfort Monitoring in Buildings." *Sustainable Cities and Society* 102602. doi: 10.1016/j.scs.2020.102602.

Van Den Wymelenberg, Kevin, and Mehlika Inanici. 2014. "A Critical Investigation of Common Lighting Design Metrics for Predicting Human Visual Comfort in Offices with Daylight." *Leukos* 10(3):145–64.

Vardaxis, Nikolaos-Georgios, Delphine Bard, and Kerstin Persson Waye. 2017. "On the Definition of Acoustic Comfort in Residential Buildings." *The Journal of the Acoustical Society of America* 141(5_Supplement):3540. doi: 10.1121/1.4987481.

Veitch, Jennifer A., John S. Bradley, Louise M. Legault, Scott Norcross, and Jana M. Svec. 2002. "Masking Speech in Open-Plan Offices with Simulated Ventilation Noise: Noise Level and Spectral Composition Effects on Acoustic Satisfaction." *Institute for Research in Construction, Internal Report IRC-IR-846*.

Villa, Valentina, Berardo Naticchia, Giulia Bruno, Khurshid Aliev, Paolo Piantanida, and Dario Antonelli. 2021. "IoT Open-Source Architecture for the Maintenance of Building Facilities." *Applied Sciences* 11(12):5374. doi: 10.3390/app11125374.

Wang, Zhaojun, Lin Zhang, Jianing Zhao, Yanan He, and Aixue Li. 2011. "Thermal Responses to Different Residential Environments in Harbin." *Building and Environment* 46(11):2170–78.

Waye, Kerstin Persson. 2011. "Effects of Low Frequency Noise and Vibrations: Environmental and Occupational Perspectives."

Wei, Wenjuan, Olivier Ramalho, Laeticia Malingre, Sutharsini Sivanantham, John C. Little, and Corinne Mandin. 2019. "Machine Learning and Statistical Models for Predicting Indoor Air Quality." *Indoor Air* 29(5):704–26.

Wong, Johnny Kwok Wai, Janet Ge, and Sean Xiangjian He. 2018. "Digitisation in Facilities Management: A Literature Review and Future Research Directions." *Automation in Construction* 92:312–26. doi: 10.1016/j.autcon.2018.04.006.

Wu, Hangzi, Yue Wu, Xiaoying Sun, and Jing Liu. 2020. "Combined Effects of Acoustic, Thermal, and Illumination on Human Perception and Performance: A Review." *Building and Environment* 169:106593.

Xie, Xiang, Qiuchen Lu, David Rodenas-Herraiz, Ajith Kumar Parlikad, and Jennifer Mary Schooling. 2020. "Visualised Inspection System for Monitoring Environmental Anomalies during Daily Operation and Maintenance." *Engineering, Construction and Architectural Management* 27(8):1835–52. doi: 10.1108/ECAM-11-2019-0640.

Xue, Peng, Cheuk Ming Mak, and ZT Ai. 2016. "A Structured Approach to Overall Environmental Satisfaction in High-Rise Residential Buildings." *Energy and Buildings* 116:181–89.

Yang, Wonyoung, and Hyeun Jun Moon. 2019. "Combined Effects of Acoustic, Thermal, and Illumination Conditions on the Comfort of Discrete Senses and Overall Indoor Environment." *Building and Environment* 148:623–33.

Yang, Wonyoung, Hyeun Jun Moon, and Myung-Jun Kim. 2018. "Combined Effects of Short-Term Noise Exposure and Hygrothermal Conditions on Indoor Environmental Perceptions." *Indoor and Built Environment* 27(8):1119–33.

Zaballos, Agustín, Alan Briones, Alba Massa, Pol Centelles, and Víctor Caballero. 2020. "A Smart Campus' Digital Twin for Sustainable Comfort Monitoring." *Sustainability* 12(21):9196.

Zahid, Hamza, Oussama Elmansoury, and Reda Yaagoubi. 2021. "Dynamic Predicted Mean Vote: An IoT-BIM Integrated Approach for Indoor Thermal Comfort Optimization." *Automation in Construction* 129:103805. doi: 10.1016/j.autcon.2021.103805.

Zamkovyi, Mykola, Svitlana Gavrylenko, Kyrylo Khatsko, and Nataliia Khatsko. 2023. "Algorithmic Support for Building a Distributed IoT System in a Cloud Service." Pp. 1–6 in *2023 IEEE 4th KhPI Week on Advanced Technology (KhPIWeek)*.

Zhang, Fan, Richard de Dear, and Peter Hancock. 2019. "Effects of Moderate Thermal Environments on Cognitive Performance: A Multidisciplinary Review." *Applied Energy* 236:760–77. doi: 10.1016/j.apenergy.2018.12.005.

Zhao, Jianfeng, Haibo Feng, Qian Chen, and Borja Garcia de Soto. 2022. "Developing a Conceptual Framework for the Application of Digital Twin Technologies to Revamp Building Operation and Maintenance Processes." *Journal of Building Engineering* 49:104028.

Zhao, Rongyi, Shufeng Sun, and Rongyi Ding. 2004. "Conditioning Strategies of Indoor Thermal Environment in Warm Climates." *Energy and Buildings* 36(12):1281–86. doi: 10.1016/j.enbuild.2003.07.002.