Improving Occupant Behavior Understanding And Environmental Awareness In Smart Buildings

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Abstract

This thesis explores the integration of sensor technologies and user-centered design to improve building environments, with a focus on enhancing resource efficiency, occupant satisfaction, and sustainable operations. While the study's experimental component was conducted in educational buildings, the findings and insights contribute broadly to various building types.

The research employs a mixed-methods approach, combining sensor data analysis with qualitative insights from workshops and interviews to understand occupant behavior and space utilization. In the context of a newly constructed university building, sensor technology, supported by the SpaceSense toolkit, captured patterns of space usage and environmental conditions, while interactions with students and facility managers revealed preferences and operational needs. Follow-up interviews with facility managers further highlighted the effectiveness of sensor-based solutions in improving facility management and occupant well-being.

A key innovation in this study is the EcoCube device, designed to bridge communication gaps between building occupants and facility managers. The EcoCube enables users to report issues, provide feedback, and engage in building management processes, fostering a collaborative approach. The findings reveal variations in satisfaction across different spaces and underscore the importance of adaptable, user-centered solutions to meet diverse needs.

By integrating real-time environmental monitoring, occupancy data, and direct feedback mechanisms, this thesis demonstrates the potential of combining sensor technology with user-centered design to create responsive and sustainable building environments. Recommendations include refining communication channels, leveraging occupancy data for real-time decision-making, and advancing collaborative building management to support sustainable and user-friendly operations. Future work includes expanding environmental metrics to address a wider range of building types, refining communication technologies like the EcoCube for broader adoption, and employing advanced predictive analytics to enhance proactive facility management strategies.

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Abbreviations

Acronyms / Abbreviations

AI Artificial Intelligence

AIoT Artificial Intelligence of Things

AP Access Point

BIMS Building Information Modeling System

BLE Bluetooth Low Energy

EEI Energy Efficiency Index

GPS Global Positioning System

HBI Human-Building Interaction

HCI Human-Computer Interaction

HVAC Heating, Ventilation, and Air Conditioning

IAQ Indoor Air Quality

IoT Internet of Things

ML Machine Learning

MQTT Message Queuing Telemetry Transport

OCC Occupant-Centric Control

PIR Passive Infrared

PM10 Particulate Matter 10

PM2.5 Particulate Matter 2.5

QR Quick Response

RFID Radio-Frequency Identification

RSSI Received Signal Strength Indicator

RWSN Renewable Wireless Sensor Network

SBC Single-Board Computer

SH Smart Homes

TVOC Total Volatile Organic Compounds

UWB Ultra-Wideband

VOC Volatile Organic Compounds

WSN Wireless Sensor Network

I would like to dedicate this thesis to my loving parents …

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Chapter 1

Introduction

Smart buildings are transforming how we live and work by combining technology and innovation to create spaces that are efficient, sustainable, and comfortable. These advanced buildings go beyond traditional designs, adapting to user needs while improving energy efficiency and reducing operational costs. Through the use of sensors, automation, and machine learning (ML), smart buildings monitor and control essential factors such as temperature, lighting, and energy consumption. They also integrate with devices like smartphones and smart appliances, providing a seamless and convenient experience. Whether in homes, offices, hospitals, or libraries, these systems deliver tailored services that enhance daily life.

A recent report highlights the growth and potential of the global smart building market. It shows a substantial annual increase in the number of smart buildings worldwide. In 2023, the market was valued at approximately USD 96.96 billion. By 2032, it is projected to reach USD 568.02 billion, with a compound annual growth rate (CAGR) of 21.8% from 2024 to 2032. This highlights the sector's significance and anticipates a substantial increase in demand and research in the years ahead [89]. Smart buildings use technology and automation to optimize performance and user experience. Modern buildings focus on contemporary design, energy efficiency, and occupant comfort.

Modern buildings are designed to accommodate a variety of activities, such as individual work, group collaboration, meetings, and socializing, with the goal of maximizing the functionality of different spaces within the building. However, post-construction evaluations that assess the effectiveness of these spaces are often insufficient [262, 20, 130, 198]. Gaining insights into how these spaces can be improved after construction is essential for ensuring they meet the needs of building occupants individuals who use or inhabit a building, such as students, staff, or visitors. In educational buildings, for example, study spaces play a vital role in supporting academic activities. To ensure their effectiveness, these spaces must be not only well-designed but also regularly evaluated.

Traditional methods such as periodic observations, surveys, and questionnaires provide limited insights into how spaces are used, especially in dynamic environments like hot-desking. These methods capture only brief snapshots of space usage and lack continuous data. Additionally, surveys and questionnaires often suffer from low response rates and potential measurement inaccuracies, limiting their ability to optimize space design and improve occupant satisfaction [275, 308].

Recently, researchers have begun utilizing Internet of Things (IoT) technology to measure space utilization and understand occupant behavior in buildings [301, 83, 191, 23, 113]. Two main approaches have emerged: vision-based and sensor-based technologies. Vision-based methods use cameras to gather insights into how spaces are used, aiding in informed decisions about space allocation based on actual usage patterns [64, 30, 279, 281]. However, these methods face challenges related to privacy concerns, security risks, and the need for optimal lighting conditions to ensure accurate occupancy detection [119, 276, 16].

On the other hand, sensor-based approaches have proven effective in providing detailed insights that help facility managers optimize building performance and recommend practical improvements [87, 149, 11, 57]. These sensors can monitor a wide range of parameters, including temperature, humidity, occupancy, and movement, offering a comprehensive view of space utilization and environmental conditions.

In this thesis, we aim to understand occupant behavior in buildings and improve environmental awareness among occupants. We focus on an educational environment, building on previous research that explored student learning behaviors and experiences in such settings, with an emphasis on leveraging technology to enhance study and engagement strategies [79, 246, 158, 256, 96, 183]. We also aim to understand both groups within the building, occupants and facility managers, as well as the relationship between them. While different studies have explored aspects of sensor data in buildings, many have not thoroughly analyzed this data or established a direct connection between occupants and facility managers. Understanding occupant behavior, remains a significant challenge [90, 140, 284, 193]. More research is needed to understand how design elements — such as spatial layout, furniture arrangement, lighting, acoustic conditions, and indoor environmental quality — impact occupant behavior and collaboration in different spaces.

This thesis seeks to enhance the understanding of occupant behavior in educational environments, increase occupant awareness, and bridge the communication gap between occupants and facility managers. We contribute to this goal with two key outcomes: the SpaceSense toolkit, which helps analyze space usage and occupant patterns, and the EcoCube IoT device, which facilitates communication and feedback between occupants and facility managers. The ultimate goal is to leverage sensing technology and these tools to gain insights into occupant behavior across various designed spaces, identify weaknesses in the interaction between occupants and facility managers, and address these issues to improve overall building management.

1.1 Motivation

Optimizing the design and management of buildings is a growing priority across various sectors, as it directly impacts functionality, efficiency, and occupant satisfaction. The way spaces are utilized in buildings, whether for work, learning, or leisure, has a significant effect on productivity, comfort, and overall well-being. In recent years, there has been an increased focus on enhancing the effectiveness of building environments through advanced technologies. These improvements not only support operational performance but also create spaces that are more responsive to the needs of their occupants.

In particular, the design of study spaces plays a critical role in educational buildings, influencing student performance, collaboration, and engagement. While new buildings are often designed to cater to a variety of academic activities, there is often a gap between design intentions and how students actually use these spaces. Understanding how different areas are used and perceived by students is essential for creating environments that support diverse learning needs and improve academic outcomes [262, 20].

This thesis focuses on addressing the gap in understanding space utilization in educational buildings. The study begins by examining the Abacws building, which is newly constructed and offers modern, flexible study spaces designed to support academic activities. While this building may not fully represent older or differently designed educational buildings, it provides valuable insights into the usage patterns and preferences of students in contemporary learning environments. Given the recent relocation of our department to this space, our research team has observed significant variation in how these spaces are utilized. Some areas are highly favored, while others are underutilized, often due to factors such as poor lighting, uncomfortable furniture, or excessive noise levels.

Facility managers also recognize the need for a deeper understanding of student preferences and space utilization to make informed decisions about space improvements [87, 54]. By combining data from various sources, such as sensors, occupancy levels, and occupant feedback, building managers can improve the learning environment by addressing design flaws and enhancing the functionality of the spaces. For example, they can identify underutilized areas to repurpose them, adjust lighting and HVAC settings based on real-time usage, and respond more effectively to comfort-related complaints. Building managers are responsible for the day-to-day operations of buildings, such as maintenance and safety, while facility managers have a broader role, overseeing strategic planning, infrastructure, and user satisfaction.

This study addresses challenges in optimizing educational spaces by employing sensing technology and data analysis to monitor space usage and environmental conditions in the Abacws building. By integrating data on student interactions with various spaces and combining it with feedback, we aim to identify opportunities for improvement and provide actionable recommendations to enhance the design and functionality of study areas. The findings will better support both students and facility managers, contribute to the optimization of open-plan study spaces, improve communication, and offer foundational insights for further research on occupant behavior in educational environments.

1.2 Problem statement

Understanding and improving the environment within buildings is essential for enhancing occupant satisfaction and performance. Despite efforts to create effective spaces, several challenges remain. This section highlights the main issues that need to be addressed to improve space effectiveness.

Firstly, there is a lack of understanding regarding how spaces are used, making it difficult to manage and optimize them. Secondly, communication between occupants and facility managers is insufficient, limiting the ability to make informed decisions based on occupant needs and experiences. Finally, occupant satisfaction varies across different spaces, indicating the need for improvements to address diverse preferences.

These challenges affect the overall quality of the environment and require a systematic approach to resolve them. The following subsections will explore each of these problems in detail, setting the stage for proposed solutions and improvements.

1.2.1 Lack of understanding of space utilization patterns

Space utilization refers to the strategic management of available areas to meet functional requirements, adapt to changing needs, and optimize layouts through real-time monitoring technology. This technology tracks both usage patterns and environmental conditions, ensuring spaces are used efficiently while maintaining a comfortable and productive environment [211, 87]. Effective space utilization is crucial in maximizing the potential of a building, providing the best outcomes for both operational efficiency and occupant satisfaction.

Recent advancements in IoT technology have significantly improved our ability to monitor and enhance space utilization. Devices such as occupancy sensors, environmental sensors, and smart lighting systems collect real-time data, offering insights into how spaces are used [172, 296, 295, 50]. Occupancy sensors, for instance, detect whether spaces are occupied or vacant, helping identify peak usage times and pinpoint underutilized areas. Raykov et al. [220] demonstrated how passive infrared sensors, when combined with machine learning algorithms, can accurately estimate room occupancy based on motion patterns.

Environmental sensors further contribute to space optimization by monitoring temperature, humidity, and air quality, ensuring a comfortable and productive environment for occupants. For example, Zhao et al. [303] explored the use of digitally controlled lighting, sound, and visuals in smart office prototypes, which enhance cognitive performance and mood, supporting the idea that personalized ambient control can improve productivity.

Facility managers can leverage this data to optimize space usage and environmental conditions. For instance, if a space is consistently too warm, the HVAC system can be adjusted for occupant comfort. Similarly, lighting schedules can be modified for spaces that are rarely used in the evenings, reducing energy consumption. Warmerdam and Pandharipande [274] investigated the use of wireless sensors in smart lighting systems to analyze interactions between occupants and their environment, providing valuable data for building management.

Despite these advancements in building technologies, the integration and analysis of this data remains a considerable challenge. The lack of comprehensive data on space utilization hinders our ability to fully understand how spaces are used and to optimize them to meet the needs of occupants. Inefficient space utilization can lead to a variety of negative outcomes, including increased operational costs, higher energy consumption, and greater maintenance expenses. These inefficiencies contribute to the underperformance of facilities, making it difficult to create environments that support collaboration, efficiency, and occupant comfort.

In addition, inaccurate or incomplete data on space usage complicates future planning, making it difficult to adapt to changing needs or accommodate growth. Without clear insights into how spaces are being used, it is challenging to identify which areas are most effective and which might require redesign. This lack of understanding results in inefficient use of resources and suboptimal environments, ultimately undermining the building's overall performance.

Furthermore, poor space management has broader implications for sustainability. It can lead to increased waste, higher energy consumption, and a larger carbon footprint, thus obstructing efforts to achieve sustainability goals. As such, it is essential to develop effective methods for integrating and analyzing data from various sensors to provide a comprehensive understanding of space utilization. These insights are crucial for optimizing space design, improving operational efficiency, and supporting sustainability objectives.

1.2.2 Inadequate feedback mechanism between occupants and facility managers

Effective communication channels are crucial for post-occupancy evaluation (POE) in facilities management [267]. Research emphasizes the significance of facility managers' responsiveness to user feedback in fostering collaborative relationships and improving user satisfaction. In various environments, feedback from occupants is essential for creating a conducive atmosphere. However, current feedback mechanisms often suffer from being cumbersome and hinder timely responses, leading to stress and confusion among both occupants and staff [102]. Currently, feedback is collected through surveys, emails, and suggestion boxes, but these methods are often slow and lack follow-up, making timely issue resolution challenging. Recent research supports this, highlighting that traditional feedback systems, like online forms or hotlines, are effort-intensive and may discourage the submission of complaints, particularly for comfort-related issues. By reducing submission barriers through automated suggestion systems and integrating contextual data, feedback accuracy and response efficiency can be significantly improved. In fact, the introduction of an app-based solution led to a 40% increase in complaints related to temperature and air quality, providing a clearer picture of occupant comfort and more timely issue resolution [102].

While occupant feedback is crucial for facility maintenance management, traditional reporting systems frequently fall short. These systems typically lack location-specific feedback and timely communication, both of which are necessary for swift and effective responses. This limitation calls for innovative solutions, such as social media-based applications and automated chatbots, to streamline the feedback process [300]. Developing an efficient feedback system is critical for enhancing environments, particularly in technical fields where feedback mechanisms may vary. A consistent and supportive feedback process helps manage occupants' expectations, improve outcomes, and enhance their overall experience. For instance, a study utilizing NLP in mobile applications achieved 100% accuracy in classifying feedback, significantly improving response times by automating work order assignments and enhancing communication between facility managers and occupants [3].

Feedback goes beyond general opinions; it includes specific reports and comments on aspects such as broken equipment, malfunctioning technology, and cleanliness, as well as more general feedback on environmental quality. Occupants often report on lighting, noise levels, seating comfort, and the adequacy of temperature and ventilation. The effectiveness of feedback collection depends on structured data, which can be integrated with Building Information Modeling (BIM) for faster issue resolution. A system developed in a case study showed that structured feedback reduced data collection time, improved issue identification, and enhanced facility management and occupant satisfaction [12].

Without proper feedback channels, issues such as discomfort, facility malfunctions, or inefficiencies may go unaddressed, leading to decreased occupant satisfaction. When concerns are ignored, occupants may become frustrated, which ultimately lowers their overall satisfaction with the facility. Facility managers, in turn, may struggle to allocate resources effectively, as they lack the necessary insights into occupants' needs and preferences. This lack of understanding can result in misinformed decisions that misalign priorities and lead to ineffective solutions. Moreover, the lack of communication undermines trust between occupants and facility management teams, and without consistent feedback, facility improvements may not align with the actual needs of users.

Gathering comprehensive feedback is crucial for improving the environment, though it can be challenging. Traditional feedback systems often face issues like delayed responses and vague information, hindering timely resolution. For example, if occupants report discomfort due to temperature fluctuations but the feedback system doesn't capture specific details about the affected areas or times, facility managers may be unable to identify the root cause and make necessary adjustments quickly. This challenge underscores the need for advanced feedback solutions that bridge the communication gap, enabling more effective management of spaces and ultimately improving the quality of the experience.

1.2.3 Variation in occupants satisfaction across different spaces

Occupant satisfaction with their environment is closely linked to overall productivity and experience. While academic and service quality factors play a significant role, the physical environment, including the design and functionality of spaces, is also crucial. Research has shown that elements such as comfort, resource availability, and the overall atmosphere of spaces significantly influence occupant satisfaction [73].

When spaces fail to meet occupant needs, it can result in underperformance, reduced engagement, and decreased productivity. Identifying the sources of dissatisfaction is challenging without detailed insights into space utilization. If certain spaces consistently underperform, it can negatively affect overall satisfaction and the building's reputation. Moreover, redesign efforts may not address the underlying issues if the reasons for dissatisfaction are not fully understood. Inconsistent satisfaction may also highlight inefficient space utilization, which can affect building management and planning. When satisfaction varies widely, it may discourage occupants from using certain spaces, reducing overall effectiveness.

In the Abacws building, the variation in occupant satisfaction across different spaces is apparent from observational data, environmental sensor readings, and occupant feedback collected during the study. Some spaces are preferred due to features like comfortable seating, ample natural light, and quiet surroundings, while others are less popular due to poor lighting, uncomfortable furniture, or noise. Additionally, individual preferences vary; for example, some occupants may prefer bright, natural light, while others may favor dimmer, more controlled lighting. Similarly, group work areas might be valued by collaborative occupants but less appealing to those who need quiet, solitary environments. These differences highlight the challenge of designing spaces that meet diverse needs. Especially here, we focus on different design open spaces within buildings, such as those in the Abacws building, as they present unique challenges and opportunities for optimizing occupant satisfaction.

To address these issues, it is essential to analyze occupant feedback through surveys, interviews, and observations. Such data provides valuable insights into which features are most valued and which present problems. For example, if dissatisfaction with acoustics is noted, solutions like soundproofing or furniture adjustments may be explored. Likewise, if comfortable seating is frequently praised, this feature can be incorporated into other spaces.

Ultimately, improving occupant satisfaction requires a thoughtful approach that considers varying needs and preferences. By gathering and acting on feedback, facility managers can make informed adjustments to optimize spaces, ensuring they better serve all occupants and contribute positively to the overall experience. In the context of the Abacws building, such efforts will benefit students and other users, leading to more effective and enjoyable use of the study spaces.

1.3 Research questions

Following the considerations discussed, this thesis investigates the following central question: *"Is it possible to leverage sensing data and IoT systems to improve our understanding of occupant behavior, enhance communication between occupants and facility managers, increase occupant environmental awareness, and improve building management?"*

To address this broad question, the thesis will explore three specific research questions:

RQ1: How can sensing data reveal occupant behavior and preferences in various spaces, and what external factors affect their comfort?

RQ2: How do sensing data and IoT systems improve communication between occupants and facility managers, and how effective are these tools?

RQ3: How can monitoring environmental data and space utilization aid facility managers in decision-making and impact building management?

1.4 Contributions

This thesis makes several important contributions to the fields of building management, occupant behavior, and the application of sensing technologies in educational spaces. By combining surveys, system development, and data analysis, the research explores how sensor data and IoT systems can enhance occupant experiences, optimize space utilization, and improve communication between occupants and facility managers. The key contributions are as follows:

C1: Presented an overview of sensing technologies in smart buildings, showing the types of sensors used, where they are placed, and what activities they help detect.

C2: Developed SpaceSense, a reusable toolkit with adaptable dashboards, helping reveal occupant behavior and support better space use and satisfaction.

C3: Introduced EcoCube, an IoT device helping raise environmental awareness and improve communication between occupants and facility managers, with potential to be commercialized for use in educational and other settings.

C4: Built a system that helps combine data from different sources, supporting smoother integration across building environments.

C5: Explored student behavior in diverse open-design educational spaces, establishing a foundation for future research.

In summary, this thesis offers valuable insights into the integration of sensing technologies and IoT systems in building management. It demonstrates how these technologies can improve occupant experiences, optimize space usage, and enhance communication between occupants and facility managers. These contributions lay a strong foundation for future research and practical applications in educational and other building environments. Contribution C1 is addressed in Chapter 2. Contributions C2 and C7 are covered in Chapter 3, while Contributions C3 and C6 are discussed in Chapter 4. Contributions C4 and C5 are relevant to both Chapters 3 and 4.

1.5 Publications

The following publications have been published to peer-reviewed journals:

- Alsafery, Wael, Omer Rana, and Charith Perera. "Sensing within Smart Buildings: A Survey." *ACM Computing Surveys* 55.13s (2023): 1–35.

1.6 Thesis structure

This thesis is structured into six chapters, each focusing on a key aspect of improving study environments through the use of advanced technologies and research methodologies.

- The first chapter introduces the thesis, explaining the motivation behind the study, defining the problem statements, and outlining the research contributions. It provides a comprehensive overview of the research objectives and sets the stage for the detailed exploration in the following chapters.
- The second chapter delves into the research background and reviews related work. It covers key topics such as sensing technologies used in building environments, various activities occurring within buildings, the objectives of smart buildings, and the current challenges and future research directions. This chapter provides the context for the study and highlights existing knowledge gaps that the research aims to address.
- The third chapter focuses on understanding occupant behavior through sensor data in study spaces. It describes the methods used for sensor deployment and data collection, outlines the research methodology, presents key findings and insights, and discusses these results in detail. A summary at the end of the chapter ties together the main points and findings, offering a clear understanding of how sensor data can be used to to understand occupants' behavior in heterogeneous study spaces.
- The fourth chapter explores the EcoCube and its impact on enhancing human-building interaction. It includes details on the deployment of the EcoCube, the data collection process, the research methodology for assessing its effectiveness, and the key findings and insights gained. The discussion in this chapter highlights how the EcoCube contributes to making study spaces more responsive and adaptable to user needs.
- The fifth chapter provides a comprehensive discussion of the research findings from the previous chapters. It examines various aspects, including understanding occupant behavior and space utilization, improving human-building interaction, enhancing sustainability and energy efficiency in educational buildings, and the long-term effects on building maintenance and operations. This chapter also addresses how study spaces can be adapted to meet changing student needs and the challenges of implementing smart building technologies. A summary at the end consolidates the main discussion points.
- The final chapter, conclusion and future work, summarizes the overall findings of the thesis, highlights the key contributions of the research, and suggests potential areas for

future study. It reflects on the impact of the research, offering insights into how the study can inform future developments and improvements in study environments.

Chapter 2

Research background and related work

2.1 Overview

Sensing technologies have transformed the management of building environments, enabling dynamic adjustments to optimize space efficiency, energy consumption, and occupant comfort. By integrating sensors that monitor temperature, humidity, occupancy, and lighting, buildings can adapt to real-time conditions, improving both operational efficiency and user satisfaction [105]. For example, occupancy sensors can regulate HVAC and lighting systems based on room usage, reducing energy waste and lowering operational costs. Environmental sensors also play a crucial role in maintaining air quality and ensuring comfortable conditions, which enhance occupant health and productivity. As these technologies evolve, they are expected to further enhance smart building management and sustainability.

In smart buildings, human activities are increasingly integrated with sensing systems to create personalized and responsive environments. These systems can track movement, usage patterns, and individual preferences, allowing them to adjust lighting, temperature, and even open or close blinds based on real-time data. This personalization improves comfort and maximizes resource efficiency, while providing valuable insights for facility managers to optimize building layouts and services.

The primary objectives of smart buildings go beyond automation and energy efficiency. These buildings aim to optimize resource usage, improve occupant well-being, and ensure safety and security. Through real-time monitoring and intelligent management, smart buildings minimize waste, reduce operational costs, and provide a healthier indoor environment. They also feature advanced security systems to safeguard occupants.

Sensor data plays a critical role in understanding occupant behavior within smart buildings. By analyzing usage patterns and preferences, building systems can adjust environments for optimal comfort and efficiency. Additionally, this data helps facility managers make informed decisions on space utilization, cleaning schedules, and other building operations, ensuring a more adaptable and responsive environment.

Despite their benefits, smart buildings face several challenges related to privacy, security, and data management. Sensor placement, calibration, and data integration also pose technical difficulties that require sophisticated processing techniques and effective management strategies. Furthermore, presenting data in a clear and actionable format for facility managers is crucial for optimizing building operations. Overcoming these challenges demands a multidisciplinary approach that combines technological advancements with a deep understanding of user needs and behaviors.

The contributions of this thesis can be summarized as follows:

- Presented an overview of sensing technologies in smart buildings, showing the types of sensors used, where they are placed, and what activities they help detect.
- Mapped how integrated sensors and data analytics work together to support more accurate activity detection and enhance overall building performance.
- Highlighted how sensing systems are used to monitor goals like energy efficiency and occupant well-being, offering a clearer view of smart building effectiveness.
- Identified key challenges facing sensing in smart buildings today and outlined future research directions to advance the field.

This research provides valuable insights into the current state of smart building technologies and sets the foundation for future advancements in the field.

2.2 Sensing technologies in building environments

Smart building sensing technology harnesses various sensors to collect and analyze data about a building's physical environment, such as temperature, humidity, and ambient light. This data is processed by advanced devices like microcontrollers and single-board computers to derive actionable insights. For instance, sensors can detect and monitor activities within the building, such as energy consumption patterns and unusual events like falls, and provide recommendations to optimize everyday operations and reduce costs. Commonly used sensors for occupancy detection include infrared and ultrasonic sensors, which offer high accuracy. Combining these with other sensors, such as temperature and humidity sensors, can further enhance accuracy. For example, a study achieved up to 99.79% accuracy in occupancy detection using infrared and CO2 sensors [126].

Activity recognition is also supported by various sensors, including wearable motion sensors, vision systems, and embedded sensors. Infrared and pressure sensors are often employed to discern between normal actions and abnormal events, with studies achieving 98.8% classification accuracy for distinguishing violent attacks from normal actions [218], and 98.3% accuracy for activities like sitting and walking using low-resolution infrared array sensors [291]. Occupancy sensors play a significant role in enhancing energy efficiency by managing electricity loads, such as turning off lights in unoccupied spaces. Combining multiple sensors generally increases accuracy, though factors like environmental conditions can impact their effectiveness.

The deployment of sensors in buildings is guided by the need to maximize efficiency and respond to specific applications. The choice of sensors depends on factors like cost, processing time, and required accuracy. Aziz et al.Aziz et al. [15] suggested that a single sensor could be cost-effective and simplify data processing, whereas Liang et al.Liang et al. [161] advocated for using multiple sensors to improve accuracy and data collection. Additionally, Wagner et al. Wagner et al. [268] recommended multipurpose sensors for convenience and easier installation, reflecting the ongoing evolution in smart building technology.

Although numerous research papers have examined sensing technologies in smart buildings, there are still many areas that remain underexplored. This work aims to review the various sensing technologies used in different types of buildings, including the types of IoT sensors employed, their deployment locations, and the activities they monitor. We also investigate how these sensors help in understanding different building usages. For a detailed comparison of relevant review studies, see Table 2.1.

Other research has concentrated more specifically on the buildings themselves: Pan et al. [201] focused on energy efficiency in buildings and microgrids; Saha et al. [227] explored data analytics in smart buildings; and Liu et al. [168] examined the integration of Building Information Modelling (BIM) with sensors. However, none of these studies have addressed the specifics of sensor types, their deployment locations, or the activities they detect within smart buildings. There is a need for further investigation into how sensors can be utilized to better understand various activities inside buildings.

2.2.1 Sensors

Navigating the diverse landscape of sensors used in smart buildings can be complex due to variations in sensor specifications, output signal types, and their intended applications. To streamline this understanding, researchers have developed systematic classifications to better categorize and describe these technologies. Elhoushi et al. [77] and Dong et al. [71] have proposed structured methods for classifying sensors, which help clarify their roles and

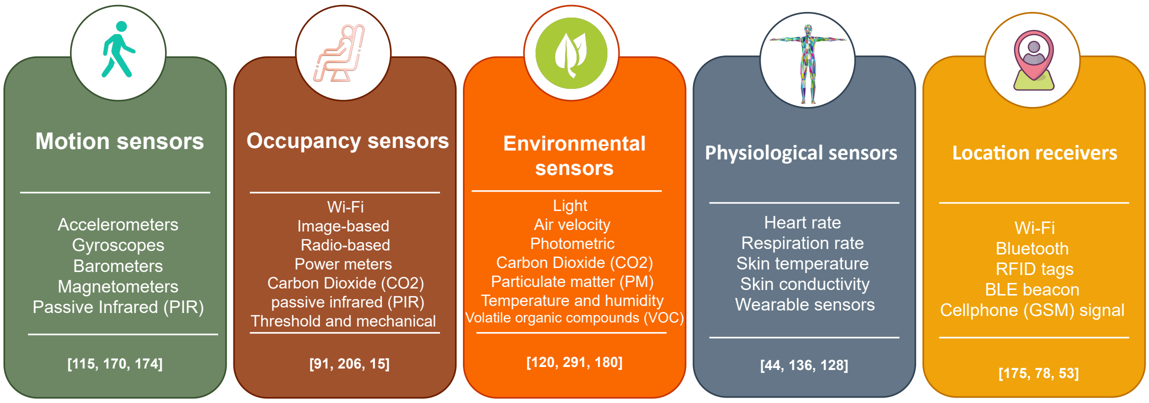


Fig. 2.1 Different types of sensors commonly used within smart buildings.

functionalities. This overview integrates their classification approaches to present a clearer picture of the most commonly used sensors in smart buildings, as depicted in Figure 2.1, some of the most commonly used sensors in smart buildings are therefore defined as follows:

- **Temperature Sensors**. These are among the most widely used sensors, and their primary function is to measure temperature changes. As the ambient temperature changes in temperature, some of the sensor's physical properties, such as resistance or voltage change. Further, there are many different temperature sensors, such as the LM35 sensor, thermal resistance sensors, and thermocouple switches. These sensors have been used in various studies for occupancy sensing [191], occupancy prediction [270], and occupancy behavior [125].

- **Humidity Sensors**. These devices accurately sense and assess the amount of water vapor in the atmosphere. Accordingly, they can measure the relative humidity and the degree of condensation in a room to achieve occupancy sensing and identify occupants' behaviors in smart buildings [125, 191].

- **Carbon Dioxide (CO2) Sensors**. These are used to measure the proportion of carbon dioxide in the air, thus assessing the emission levels of CO2 inside the building. These are widely used in occupancy sensing, and counting applications in smart buildings [219, 126].

- **Proximity Sensors**. These do not require physical contact to detect the presence of surrounding items, based on remotely assessing physical quantities related to distance and place. They can be divided into optical, inductive, and capacitive. They have been used in applications within smart buildings, such as indoor localization [169] and occupancy estimation [219].

- **Pressure Sensors**. Pressure is defined as the force perpendicular to a unit area, and pressure sensors thus monitor this force. A pressure sensor responds to pressure as a physical quantity. These are used in various areas, such as in military operations, water-lifting engines at certain pressure levels, and similar engineering applications. They are used in buildings mainly to detect human body postures [176] and activities [218, 122].

- **Infrared Sensors**. Infrared sensors are based on the principle of light detection and are usually used to estimate distances, as in most modern smartphones. There are two types of infrared sensors: transmissive and reflective sensors.

- **Motion Sensors**. These sensors are employed to monitor the motion of a person into or across a specific area. These sensors are often used in security alarm systems or lighting systems that automatically turn on when someone moves within a specified area. Although cameras may also be used in buildings to detect human presence, motion sensors have advantages of privacy and cost over cameras. They are thus often used in buildings to detect human activities [218, 133, 152].

- **Millimeter-wave radio sensors**. It uses radio waves in the millimeter wave range to detect and measure objects. It is used in various building applications, such as for security, occupant identification and detection [103], and indoor localization [138]. Table 2.2 shows some commonly used sensors within smart buildings and their uses.

Low-cost sensors have become popular for indoor environmental monitoring due to their affordability, ease of deployment, and ability to enable large-scale data collection. However, their performance is often limited by calibration drift, sensor aging, environmental interference, and variations in manufacturing quality [56]. Calibration drift, in particular, can lead to progressively inaccurate readings over time, especially for parameters like temperature, humidity, and CO_2 concentration. Studies [187, 101] have shown that temperature sensors can exhibit deviations of up to $\pm 1°C$, while CO_2 sensors often demonstrate measurement errors influenced by CO_2 concentration, temperature, and humidity, and may not achieve the accuracies specified by manufacturers without recalibration.

To maintain data quality, several strategies have been suggested. These include first, initial calibration against a laboratory-grade reference device before deployment, second, periodic in-field calibration using co-location methods where low-cost sensors are compared against each other or against a high-accuracy standard, and third, applying correction algorithms to compensate for known sensor biases and drift patterns [99, 72]. In some cases, machine learning approaches have been used to dynamically correct sensor outputs based on environmental conditions.

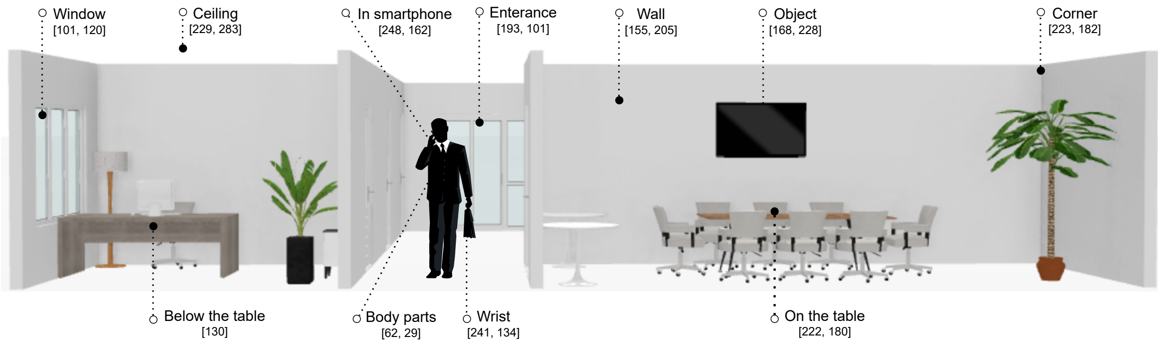


Fig. 2.2 Common sensor deployment locations within smart buildings.

Furthermore, research emphasizes the importance of reporting uncertainty margins when presenting sensor data, especially in long-term monitoring projects. Failure to account for inaccuracies can lead to misleading conclusions regarding occupant comfort, energy performance, or space utilization. Therefore, selecting appropriate sensors, validating their performance regularly, and transparently addressing their limitations are critical steps when designing IoT-based studies in educational and other building environments.

2.2.2 Sensors deployed locations

Choosing the correct location is not always easy for sensors deployed in various locations inside buildings, as the sensor location must take into account a range of different factors, including sensor coverage area, distance from the measured object, and the relevant external conditions.

The type of task to be completed must be considered when deciding on sensor deployment locations. For example, when monitoring the heartbeat every few minutes, sensors must be deployed on the wrist or other pulse point or body parts close to the heart. Figure 2.2 shows some common sensor deployment locations within smart buildings.

Laidi and Djenouri [145] proposed a means of dividing buildings into zones based on their occupancy and occupants' behaviors using PIR motion sensors. The building zones are divided into high and low-occupation zones, and a graph model is produced using a clustering algorithm. This solution was compared with two other studies, showing better accuracy and scalability. It could also be applied to different sensors, such as ultrasound. Sembroiz et al. [234] conducted a study on optimizing energy consumption in buildings that proposed a novel model to allocate optimal location to sensors and gateways. This was predicted to work with various sensor types, reducing the number of sensors and gateways required and optimizing energy consumption while maintaining sensing coverage and protection.

Studies conducted by Laidi and Djenouri [145] and Sembroiz et al. [234] proposed different solutions to effectively deploy sensors in smart buildings. Deploying sensors optimally helps optimize energy consumption [234] and sensing coverage [145] while minimizing the risk of privacy breaches and economic costs. However, other factors should also be considered, such as scalability and applicability. Further, occupation or use of different areas by people in smart buildings are not always evenly distributed; some areas are fully equipped and heavily utilized, thus requiring more sensors to cover more activities. At the same time, some other areas are underutilized. These areas should be identified to minimize the total cost and optimize building energy consumption because each assigned sensor directly or indirectly costs money, time, and resources, during the installation and maintenance phases.

Cost is an essential factor to consider when selecting and deploying sensors. There is a variety of sensing technology that can be used; some of them are more expensive. Sensing technology high in cost typically has a more range of features and capabilities, such as cameras, radar, and multi-spectral imaging sensors, when compared to fewer cost sensing technologies, such as motion and light sensors. Dong et al. [71] summarizes most of the used commercial occupancy sensing technologies used in smart buildings and finds that infrared cameras and RFID technologies are one of the most costly technologies, while reed switch, motion, and infrared technologies are the least expensive.

Privacy concerns are another important factor, as they often revolve around using sensors and other technologies that collect information about an individual's activities. Developing robust technologies is essential to ensure user privacy is maintained. Sensors should be regularly monitored for any suspicious activity. They should use various privacy-enhancing technologies to protect user data, such as data minimization methods that can reduce the amount of personal data.

In this review, the deployment locations are classified based on sensor location, sensor type, and measured activity type. Two different studies Muthukumar et al. [186] and Liang et al. [162] were found to use the same sensor type, an Infrared array sensor, to detect similar activities such as falling and movement. The sensors in each case were deployed in different locations. Another pair of studies, Papatsimpa and Linnartz [202] and Pratama et al. [210] detected similar activities and gathered data about office occupancy using sensors deployed in a similar location on the ceiling, yet used sensor types that were different, with Radar and BLE beacons used, respectively.

Another two studies, Luo et al. [175] and Samani et al. [229], used the same sensor type, a PIR motion detector, was deployed in a similar location on the ceiling to detect different activity types; one focused on the detection of abnormal activity, such as sudden falls, while

Table 2.1 Research papers on sensing technologies in smart buildings

Reference	Sensor types	Deployed locations	Activities identified	Analytics used	Purpose	Focus
Kazmi et al. [132]				✓	Review Wireless Sensor Network (WSNs) enabled Building Energy Management Systems (BEMS)	The paper focused on energy management systems
Djenouri et al. [69]			✓	✓	Review data analytics used in smart building applications. Considering various types of ML tools and applications	The paper's main focus was on ML approaches used in smart building applications
Alam et al. [2]	✓		✓	✓	Review Smart Home (SH) projects, security, comfort, and healthcare. It describes used sensors, protocols, algorithms, and systems used widely in SH	The paper focused on the SH environment. It classified sensors, communication protocols, and technologies used inside SH
Verma et al. [264]	✓				Review infrastructure, controlling, and sensing in smart buildings. The review was based on IoT sensor-actuator automation in smart buildings	The paper reviews IoT infrastructure in smart buildings, sensing, and control
Qolomany et al. [215]		✓		✓	Review big data and ML analytics in smart buildings.	The paper focused on big data and ML use in smart buildings
De Paola et al. [66]	✓	✓			Review intelligent systems for energy management. Focusing on existing architectures and methodologies	The paper focused on energy-aware intelligent management systems in smart buildings
Kumar et al. [143]	✓			✓	Review monitoring technologies in smart buildings. The review focuses on sensor-actuator-based applications	The paper reviews smart building monitoring sensing technologies
Dong et al. [71]	✓			✓	Review indoor sensing systems in smart buildings. It discussed types and applications of sensors regarding energy-saving and occupant comfort	The paper focused on sensing systems in smart buildings. It focused more on HVAC control systems
Jia et al. [124]	✓		✓		Review IoT technologies in buildings focusing on cases from academia and industry with future implementation recommendations in building construction and operation phases	The paper focused on investigating the adoption of IoT for developing smart buildings
Nguyen and Aiello [194]	✓		✓	✓	Review energy intelligent buildings based on user activities and determine activity and their impact on energy savings in three subsystems: lighting, HVAC, and plug loads	The paper specifies valuable activities and behaviors and their impact on energy saving

the other concentrated on building anomaly detection to improve energy efficiency. This illustrates that each case has different requirements for determining the appropriate location to deploy sensors. Table 2.3 demonstrates some common sensor deployment locations within smart buildings.

2.2.3 Detecting various phenomena within buildings

Sensors are being used to help facilitate the automation of various tasks, such as monitoring the energy use of a building, allowing for energy conservation. Studies conducted by Fiebig et al. [86] and Pratama et al. [210] used power meters, BLE beacons, and air quality sensors to detect occupancy in buildings. Occupancy is also predicted by [242] using very low-resolution heat sensor data to predict occupancy in smart office spaces. They have proposed two workflows one is based on computer vision, and the other on machine learning. Sensors are also used in health applications in smart buildings. It improves building occupants' safety and living conditions using various sensors such as temperature, humidity, and noise. For example, sensors can detect irregularities in the building, such as high levels of CO2 and dust particles. Also, detecting abnormal behavior, such as fall detection [133].

Managing smart buildings using sensors, IoT, and other technologies allows for recognizing potential risks and improving the overall building management experience. A study by Sembroiz et al. [234] optimized energy consumption within the building. They proposed a model that assigns the optimal location for sensors and gateways in the building while maintaining sensor coverage and protection within the building. Another study by Das et al. [64] in an educational building uses a 3D camera to recognize activities and space utilization. The testbed was a cafeteria hall, a shared space inside a university building, and the derived patterns were used to assist building managers in making informed judgments about space allocations that were properly matched with actual building use. Luo et al. [173] proposed a radar sensor network to recognize 15 human activities in the kitchen; they have collected the radar signals and they were able to reach 89% recognizing accuracy most of the time. Table 2.4 demonstrates different phenomena detected within buildings using sensors across various research studies. However, the findings from these studies are often limited by the specificity of test environments, the type of sensors used, and the scalability of the approaches to diverse building settings.

Table 2.2 Commonly used sensors within smart buildings

Sensor type	Sensor location	Number of sensors	Building type*	Objective	Reference
	Two feets above the floor	4	Indoor environment - classroom	Occupancy estimation IoT model for Indoor environments	[219]
	On return ducting, supply ducting, and middle of the room	5	Office environment - room	Occupancy estimation at low-scale level in office environment	[217]
CO2	On ceiling	Different numbers	Office environment - floor	Occupancy count estimation in office environment	[111]
	On table	2	Office environment - room	Occupancy detection in office environment	[126]
	Inside and outside the room	2	Smart home environment - room	Occupancy detection in smart home environment	[307]
	On wall around 1.5m height	6	Office environment - room	Occupancy modeling for cross spaces in office environment	[286]
	Placed on ceiling and wall	2	Indoor environment - meeting room	Activity detection include: walking, standing, sitting, lying, falling, and action change	[186]
	Placed on a flat acrylic plate	5	Smart home environment - room	Activity recognition for five different activities in 4 house rooms	[182]
Infrared	On ceiling	Hundreds	Indoor environment - building	Anomaly detection to improve building energy efficiency	[229]
	Facing the door	2	Indoor environment - room	Occupancy estimation to find number of people in the room	[92]
	On ceiling	3	Indoor environment - room	Anomalous occupancy behavior detection	[266]
	In off-the-shelf earpiece	3	Indoor environment - laboratory	Detecting eating activities include: talking, silent, eating, and walking	[21]
	On ceiling	4	Office environment - room	Office occupancy activities include: walking at different speeds, and desk work	[202]
	Placed at ceiling level	1	Educational environment - classroom	Occupancy count estimation in an indoor environment	[289]
Radar	Placed opposite of the corners	2	Indoor environment - kitchen	Kitchen activity detection with 15 activities include: walking, eating, drinking, sitting, etc.	[173]
	Mounted on a tripod stand	1	Indoor environment - room	Human activity recognition include: walking, jumping, jumping jacks, squats, and boxing	[241]
	On hand wrist	4	Indoor environment - laboratory	Recognition 10 daily human activities includes: walk, walk while carrying an object, sitting, standing, pick up an object, tie shoelaces, drinking water, answer a phone call, fall, and crouch and stand back up	[152]

Continued on next page

Table 2.2 – *Continued from previous page*

Sensor type	Sensor location	Number of sensors	Building type	Objective	Reference
	-	3	Office environment - room	Human activities classification include: walking, walking and carrying an object, sitting, standing, bending and coming back, etc.	[153]
Radar	On table	2	Office environment - room	Detect and locate the presence of multiple people	[103]
	-	12 Wi-Fi Access Point (AP)	Office environment - room	Office occupancy detection	[210]
	-	2 APs	Office environment - room	Occupancy estimation in an office environment	[14]
	-	7 and 9 APs in two floors	Office environment - floor	Occupants count estimation in an office environment	[272]
Wi-Fi	-	4 APs	Office environment - personal and shared space	Occupancy sensing-based HVAC actuation in an office environment	[19]
	-	32 AP	Office environment - floor	Occupancy detection in an office environment	[98]
	On the arm, leg, and neck	3	Indoor environment - Multivariate time-series dataset	Recognition of different activities from three datasets including downstairs, jogging, going upstairs, sitting, walking, and standing.	[120]
	On hand wrist	4	Indoor environment - laboratory	Recognition 10 daily human activities includes: walk, walk while carrying an object, sitting, standing, pick up an object, tie shoelaces, drinking water, answer a phone call, fall, crouch and stand back up	[152]
	On hand wrist	2	Office environment - room	Recognizing six different activities in the office includes: sitting, standing, lying, walking, walking upstairs, and walking downstairs	[179]
Accelerometers and gyroscopes	Attached to six body positions	3	Indoor environment - building	Recognizing set of twenty normal daily activities includes: kitchen work activities, household cleaning activities, office-work activities, etc.	[78]
	On door, fridge door, drawer, towel dispenser, and window	5	Indoor environment - building	Occupant Identification in smart home perform predefined activities: knock, opening/closing door, fridge, etc.	[106]
	In smartphone	2	Indoor environment - room	Human activity recognition system test 12 activities from dataset: standing, sitting, lying down, walking, etc.	[110]

Continued on next page

Table 2.2 – *Continued from previous page*

Sensor type	Sensor location	Number of sensors	Building type	Objective	Reference
Bluetooth Low Energy (BLE)	On ceiling	7	Indoor environment - room	Abnormal activities detection include: falling, sitting down, standing up from a chair, walking, and jogging.	[175]
	Three meters above the center of the detection area	1	Indoor environment - room	Human activity recognition of five states: lying, standing, sitting, walking, and empty	[291]
	On ceiling	-	Indoor environment - room	Group activity detection include: taking class, seminar, and discussion	[44]
	On ceiling	12	Office environment - shared, personal, and social space	Multi-Occupancy detection in an office environment	[210]
	Placed on the room corners and center	8	Office environment - room	Indoor positioning inside an office building	[216]
Pressure	On jacket	11	Controlled environment - laboratory	Human activity detection between normal motion and violent attack	[218]
	Attached on supporters at a height of 1.1m	2	Indoor environment - laboratory	Occupancy estimation in an indoor environment	[48]
	At the door way and in front of the room	2	Educational environment - classroom	Occupancy prediction in an indoor environment using IoT technology	[203]
	Cushion equipped with pressure sensors	12	Indoor environment - laboratory	Posture detection include: proper sitting, lean left, lean right, lean forward, and lean backward	[176]
Temperature	On ceiling	5	Indoor environment - building	Occupancy prediction to improving building energy efficiency	[270]
	Near the occupant	5	Office environment - building	Exploring occupant behaviors to improve office building energy. Include: window, door, and blinds status	[125]
	On table	4	Indoor environment - building	Occupancy sensing for smart buildings	[191]
	On wristband	-	Indoor and outdoor environment	Detection of migraine attacks	[142]

* Papers that do not mention the building type environment are classified as either indoor or outdoor environment based on the context of the paper.

2.2.4 IoT with AI in smart buildings

IoT and Artificial Intelligence (AI) are disruptive technologies that have revolutionized data use. IoT devices can include sensors, home appliances, and medical devices. Table 2.8 presents IoT and AI-based data analytics used for various smart building activities.

IoT Intelligence offers various functions for data processing and decision-making, using edge, fog, and cloud layers. Edge computing involves deploying computing resources closer to the source of data collection, allowing for faster data processing. This is particularly useful for instances such as autonomous vehicles, where latency can be critical. Fog computing is involves use of resources between the IoT devices and the cloud data center, often hosted on network components (such as routers and switches). The cloud layer can store and analyze large amounts of data, providing an additional layer of security and scalability for IoT devices. This is done through a network of connected IoT devices that can communicate with each other and remotely access powerful computing resources [199].

AI can be used to interpret sensor data in near-real time, such as using machine learning models to detect occupancy patterns, identify anomalies in energy consumption, or predict equipment failures. These real-time insights can support intelligent decision-making in contexts like space management, energy optimization, and maintenance scheduling in smart buildings. Combining IoT with AI-based data analysis enhances decision-making capabilities. AI-based data analysis refers to using artificial intelligence techniques like machine learning and pattern recognition to process and interpret data autonomously [88]. For instance, autonomous vehicles can make quick, accurate decisions based on sensor data and their environment, allowing them to navigate safely. However, such integration also introduces additional challenges, e.g. smart building systems must be able to integrate with existing infrastructure, which can be a challenge due to the complexity of existing systems, which requires extensive testing and debugging to ensure that the system is functioning correctly. Scalability is another key factor, as AI algorithms must be able to process large amounts of data quickly and efficiently. Security is also a key requirement, so data must always be encrypted and securely shared and processed [199, 69].

Reducing computational costs is also essential, as data processing in smart buildings can vary greatly depending on system complexity. Computational costs and energy usage will increase significantly with more complex analytics, such as real-time energy optimization and predictive analytics. Therefore, more research is needed to optimize the computational cost, e.g. Ostadijafari et al. [200] proposed an optimization approach that can successfully optimize electricity costs in commercial buildings by using occupancy information. More details about challenges are in technical challenges section 5.1.

Table 2.3 Common sensors deployment locations

Sensor location	Sensor type	Details	Reference
On ceiling	Radar	Detecting office occupancy by identifiying walking at different speeds and desk work	[202]
	Heat	Occupancy prediction in meeting room for smart offices	[242]
	Temperature, humidity, CO2	Occupancy prediction to improve building energy efficiency	[270]
	PIR motion	Abnormal activities detection include: falling, sitting down, standing up from a chair, walking, and jogging.	[175]
	Infrared Array	Object detection and tracking in commercial buildings	[100]
	PIR motion	Anomaly detection to improve building energy efficiency	[229]
	BLE beacons	Office occupancy detection	[210]
	BLE beacons	Group activity detection include: taking class, seminar, and discussion	[44]
	Camera, doppler motion, radio frequency RF	Occupancy sensing and activity recognition include: walking in a room, sitting in a chair, lying on a bed, and body turning on a bed	[304]
	RFID	Teamwork activity recognition includ: oxygen preparation, blood pressure, cardiac lead placement, temperature measurement, ear exam, and other activities	[159]
On wall or corner	Infrared array	Activity recognition include: quiescence, fall, and movement	[162]
	Camera	Occupancy sensing and activity recognition include: walking in a room, sitting in a chair, lying on a bed, and body turning on a bed	[304]
	Infrasound	Door opening and closing detection	[137]
	BLE beacons	Indoor positioning inside an office building	[216]
On/below table	Radar	Activities recognition include: walking, sitting and standing, bending to pick up a pen, drinking water, and frontal fall	[154]
	Temperature, humidity, light, CO2	Occupancy sensing in smart buildings	[191]
	PIR motion	Occupancy estimation for individual presence	[235]
	Millimeter-wave radio	Detect and locate the presence of multiple people	[103]
On the floor/ under-floor	Pressure mat	Smart floor monitoring system	[236]
	BLE beacons	Provides navigation aids for blind and visually impaired people	[49]
	Radon detector	Indoor radon gas concentration monitoring	[29]
	RFID	Navigation in indoor environment	[166]
On smartphone	Accelerometer, gyroscope, magnetometer	Activitiy detection include: walking, running, and standing	[263]
	Triaxial accelerometers and gyroscopes	Activity recognition include: standing, sitting, lying down, walking, walking-upstairs/downstairs, stand-to-sit, sit-to-stand, sit-to-lie, lie-to-sit, stand to-lie, and lie-to-stand	[110]
	Magnetic	Indoor localization	[169]
On wrist	Accelerometer, gyroscope	Human activity sitting detection include: sitting, standing, lying, walking, walking upstairs, and walking downstairs	[179]
	Wrist-mounted inertial sensors	Eating detection and food intake gesture classification	[255]
	Empatica E4 device with sensors: accelerometer, photoplethysmography, temperature, electrodermal activity	Detection of migraine attacks using Empatica E4 wearable wristband	[142]
	3-axis accelerometer	Activity recognition include: draw, wash dishes, write, and brush	[141]

Continued on next page

Table 2.3 – *Continued from previous page*

Sensor location	Sensor type	Details	Reference
On body parts	Wearable device (accelerometer, gyroscope, magnetometer, and electrocardiogram)	Presence or the absence of the fall, static or dynamic movements including fall, recognizes the fall, and six other activities	[133]
	Accelerometer, proximity, 3D printed sensor	Detecting eating episodes	[53]
	Acceleration, gyroscope, magnetometer	Recognition of individual daily activities include: kitchen work activities, household cleaning activities, office-work activities, laundry activities, and watching TV activity	[78]
	Surface electromyography	Recognizing ADLs activities include: stand-to-squat, squat-to-stand, stand-to-sit, sit-to-stand, stair-ascending, stair-descending, and walking	[282]
	Acoustic, electromyography, microphone	Eating detection include: eating, talkings, silence, coughing, laughing, sniffling, deep breathing, and drinking	[27]
	Proximity, motion, sound	Detecting proximity, movement, and verbal interaction between people	[259]
	Infrared proximity	Detecting eating activities include: talking, silent, eating, and walking	[21]
On object	PIR motion	Activity recognition for five different activities in four house rooms	[182]
	Ballistocardiography (BCG)	Classification of sleep stages	[94]
	Radar	Human activity recognition include: walking, jumping, jumping jacks, squats, and boxing	[241]
	Smart plug	Recognizing ADLs activities include: dishwasher, hair dryer, iron, oven, and washing machine	[91]
	3-axis accelerometer, dual-axis gyroscope	Occupant identification include: knock, opening/closing door, fridge, cabinet drawer, window, pulling a towel from the towel dispenser	[106]
	Pressure	Posture detection include: proper sitting, lean left, lean right, lean forward, and lean backward	[176]
	Photosensor	Activity sensing for location differentiation, detecting open doors	[117]

2.2.5 Smart building use cases

Smart buildings make use of IoT and AI to better manage their facilities, e.g. to monitor, control, and optimize the operations of a building. Berkeley Connected Campus is an example of a use case using technologies in smart buildings. It is an initiative by the University of California to connect different parts of the University using smart and IoT technologies to develop a connected campus environment These technologies are intended to improve student engagement and learning, improve pedestrian safety, and keep up with new advancements in transportation [24].

The *edge building* is an exemple of a sustainable office building in Amsterdam, focusing on being more efficient, comfortable and environmentally responsible for the occupants. The building, designed with a distributed system, uses sensors to monitor the environment and adjust settings accordingly. This system can modify parameters such as room temperature and

Table 2.4 Different phenomena to detect within buildings using sensors

To understand	Sensors used	Datasets used	Existing work
Occupancy (sensing, counting, estimation)	Heat, air quality sensors, temperature, humidity, light, CO2, Wi-Fi probe-sensing, camera, PIR, millimeter-wave radio, power meters, BLE beacons sensors	LBNL Building 59 [174], ROBOD [252], LANGEVIN [146]	[242],[270], [92], [210], [266],[235], [191],[86], [217], [286], [103]
Activity (sensing, recognition, detection)	Temperature, humidity, illumination, CO2, air quality, Wi-Fi probe-sensing, camera, radar, infrared array, fiber bragg grating, PIR, power meters, BLE beacons, geophone, electric field, 3-axis accelerometer sensor	HASC-PAC2016 [118], OPPORTUNITY [223], UT Smoking [238]	[202],[270],[100], [229],[210],[154], [266], [125], [235], [153],[191], [86]
Group activity (recognition, detection)	BLE beacons, web-cam, sound, WiFi-based indoor location, microphone, acceleration, smartphone sensors	PPS grouping [277], UT Smoking [238], ActivityNet [38]	[122],[44], [273]
Activities on a room-level within building	Infrared array, camera, 3D camera, doppler motion, millimeter-wave radio, infrasound, Radio Frequency Identification (RFID), CO2 sensor	OPPORTUNITY [223], PPS grouping [277], PAMAP2 [221]	[186],[32],[304], [103], [137],[9], [159]
Building energy consumption	PIR, temperature, humidity, illumination, CO2, accelerometer, gyroscope, magnetic, GPS, proximity, pressure sensor	KAG-energydata [39], LBNL Building 59 [174], CU-BEMS [208]	[229],[125],[280], [141]
Building indoor environmental quality	Temperature, humidity, illumination, sound, carbon monoxide (CO), CO2, formaldehyde, particulate matter 2.5 (PM2.5), particulate matter 10 (PM10), total volatile organic compounds (TVOC), pressure sensor	LANGEVIN [146], CU-BEMS [208], ROBOD [252]	[47],[214],[283]

air quality, consuming less energy while maintaining a comfortable environment. Occupants in the building can use a Mobile App to control their environment and access services [121].

A study was conducted to explore the role of sensor toolkits in current auditing by facilities managers who often have limited access to the infrastructure and insufficient existing data sources. The toolkit can be repurposed and retrofitted. An online tool was developed to generate reports from sensor data. The study's findings demonstrate that the fine-grained data enabled FMs to understand building efficiency and generate actionable suggestions for improvement [87].

Sint-Maarten Hospital in Belgium enables automated building management, improved energy efficiency, and better security. The adopted approach has been used to adjust the temperature and lighting levels in response to the number of people in a given space. It allows for better security by detecting motion and informing security staff. The hospital also uses sensors to detect when lights are on in unused rooms to reduce consumed energy and carbon footprint. This allows patients to control various functions of their rooms and improve communication with staff [239].

2.3 Activities within buildings

This section seeks to clarify the range of activities within buildings to allow a more effective analysis of activity recognition approaches. Figure 2.3 shows the hierarchy of activities within a building.

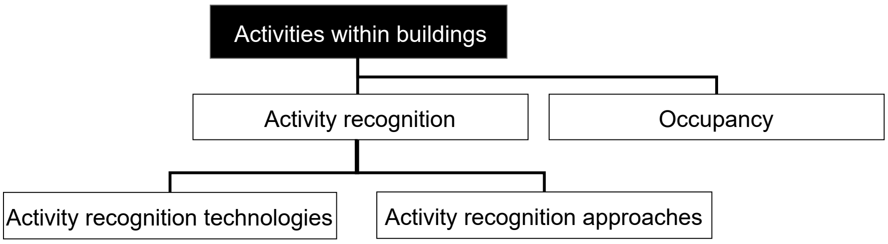


Fig. 2.3 Hierarchy of activities within buildings.

2.3.1 Occupancy

Building occupancy information is essential for several aspects of building management, including assessing energy consumption and indoor environmental quality. According to energy agency [80], buildings and construction sector account for about a third of all global energy consumption and nearly 15% of CO2 emissions; these numbers are anticipated to increase further in the next few years. This section examines the concept of occupancy sensing. Figure 2.4 shows the hierarchy of occupancy.

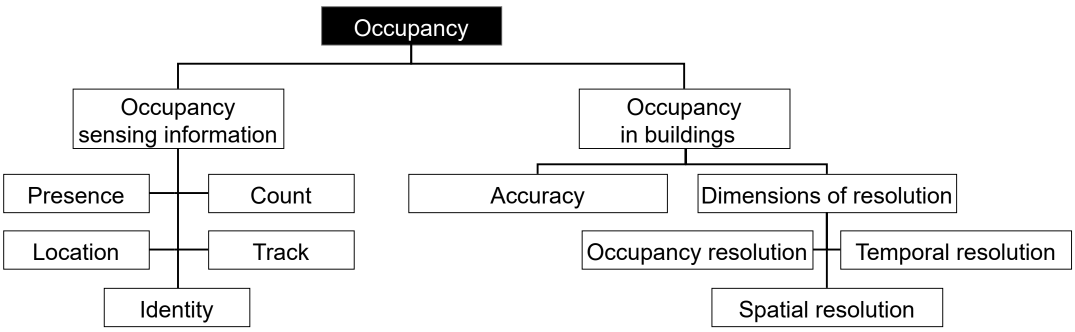


Fig. 2.4 Hierarchy of occupancy section.

Occupancy sensing information.

This can be classified based on five key properties: presence, count, location, track, and identity [251].

- **Presence.** This provides information about occupants present or absent within a given area. Occupant presence detection is used widely across various applications, including lighting control and alarm systems.
- **Count.** This provides information about the number of people in a particular area. It is also used to count the number of individuals going into or out of the given area. It is thus used in applications requiring more details about occupancy status, such as adjusting energy consumption based on occupancy numbers, e.g. in shopping malls.
- **Location.** This provides information about the current location of occupants inside a given area. The location of occupants can be used across many different applications, including healthcare and energy management applications.
- **Track.** This provides information about occupant movements between different areas. It can be used in applications such as improving emergency evacuation processes and tracking and identifying intruders in monitored areas.
- **Identity.** This provides information about occupant identity to help distinguish between different occupants, using trained algorithms to identify specific features about occupants such as facial features or smartphone MAC address. The identity of occupants can be used in security applications such as occupant access control and surveillance. However, increasingly this introduces additional challenges associated with privacy of individuals.

Occupancy in buildings.

This comprises two aspects: accuracy and dimensions of resolution. Accuracy relates to the distance between the measured value (data collected from sensors) and the ground truth data [180]. The greater the distance between the measured value and ground truth data, the lower the occupancy detection accuracy, and vice versa. The occupancy dimension focuses on three main features, which lead to different levels of resolution:

- **Occupancy resolution.** This indicates different occupancy levels, such as occupant presence or absence, calculating the number of occupants, identifying those occupants, and identifying occupant activities within the building.
- **Temporal resolution.** This represents the different frequencies over time (seconds, minutes, hours or days) of events taking place.
- **Spatial resolution.** This represents the building structure, including rooms, floors, ceilings and the building as a whole.

Figure 2.5 presents sixteen combinations of spatial, temporal, and occupant resolutions. The resolution needed is determined by the specific application. Table 2.5 shows occupancy information types with different spatial resolutions and the relevant sensors used within buildings.

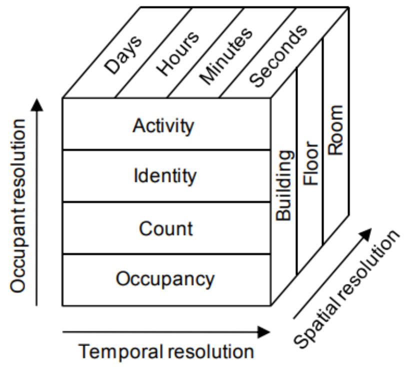


Fig. 2.5 Define sixteen resolution combinations based on application needs [180].

Occupancy information can also be used in different applications inside the building. Lau et al. [149] conducted a study to analyze spatial and temporal urban space utilization using a specially designed Renewable Wireless Sensor Network (RWSN), highlighting a few interesting observations, on hot days, morning and evening periods showed the highest space utilization, while on cloudy days, the afternoon and early evening had higher space utilization. Clear days also showed higher space utilization at night; overall, mornings demonstrated higher space usage rates than evenings. In addition, the weather was shown to have a considerable impact on how people utilise outdoor space. Moretti et al. [184] conducted a study to enhance maintenance operation tasks inside a building. Data of occupants were collected using ultrasonic sensors, which were then processed and connected to the building maintenance strategy. The system issued a maintenance notice to the contractor when a specified threshold was reached, telling the contractor to begin cleaning. Other studies, including Balaji et al. [19], Martani et al. [177], and Thanayankizil et al. [253], have focused on energy saving applications in various building environments.

2.3.2 Activity recognition

Activity recognition plays a significant role in smart buildings and represents a means for acquiring and collecting data about activities inside a building. This data helps control various applications and enhances the comfort levels inside the building, by controlling aspects such as energy consumption, temperature control, and safety. Further, single user activity refers to any activity undertaken by an individual user, such as working on a computer in an office.

Table 2.5 Occupancy information types within smart buildings.

Occupancy resolution	Spatial resolution	Used sensors	References
Presence	Building	CO2, PIR, temperature, humidity, illuminance, VOC, pressure mat, light dependent resistor, sound	[75],[265],[160]
	Floor	CO2, PIR, double-beam, acoustic, pressure mat, Wi-Fi	[98],[306]
	Room	CO2, PIR, door switch sensor, temperature, humidity, pressure, double-beam, doppler sensor, camera, acoustic, pressure mat, light, sound, microphone, Wi-Fi	[304],[126],[307], [160],[306], [237], [286],[134],[19], [203]
	Zone	CO2, PIR, distance sensor, chair sensor, microphone, light, humidity, emperature, infrared camera, Wi-Fi	[14],[181],[134], [19],[237]
Count	Building	CO2, PIR, temperature, humidity, pressure	[41], [123]
	Floor	CO2, PIR, electricity load meters, double-beam, acoustic, pressure mat, lighting, gas detection sensor, Wi-Fi	[272],[111], [306]
	Room	CO2, PIR, heat sensor, camera, temperature, humidity, pressure, ultrasonic, infrared proximity, BLE beacons, power meter, doppler radar, thermal tripwire, chair sensor, light, sound, door switch sensor, RFID, Wi-Fi	[135],[219], [51], [210],[289],[48], [306], [260],[286], [134],[287]
	Zone	CO2, PIR, velocity, temperature, humidity, light, radio, sound, RFID, microphone, long-wave infrared thermal camera, 3D stereo vision camera, Wi-Fi	[217],[64],[51], [14],[181], [76], [134],[287]
Identity	Building	Wearable wrist sensor, passive RF sensors, load sensor	[164],[139]
	Floor	Wi-Fi	[98],[177]
	Room	BLE beacons, Wi-Fi	[19],[177]
	Zone	3D camera, Wi-Fi	[64],[19]

Prastika et al. [209] and Cui et al. [63] focused on single-user activity recognition. Multi-user activities are activities of more than one user in the same location, such as where employees work on different tasks in the same office. Tan et al. [248] and Alhamoud et al. [4] sought to recognize multi-user activities.

Group activities refer to the same task or related sets of tasks by more than one user at once, such as an employees meeting in a conference room. Tang et al.Tang et al. [250] and Tang et al. [249] performed activity recognition research specifically on group activity. Li et al. Li et al. [156] classifyhybrid activity as a combination of individual and group activities happening at the same location, such as two employees working on the same task while a third one is working on a different task in the same office. Other research studies [116, 189] have attempted hybrid activity recognition. Figure 2.6 illustrates various user activities classifications in a smart building.

Fig. 2.6 Various forms of human activity recognition inside a building, including single, multi-user, group, and hybrid activity recognition.

Activity recognition technologies

Approaches and technologies to identify activities in a building can also be classified, e.g. Chen et al. [46] classified activity recognition into two main approaches based on the sensor type used: vision-based activity recognition and sensor-based activity recognition. Each approach has various technologies supporting it and the purposes for which it is best used. This thesis mainly focuses on sensor-based approaches to identifying human activities. Figure 2.7 shows a taxonomy of activity recognition technologies.

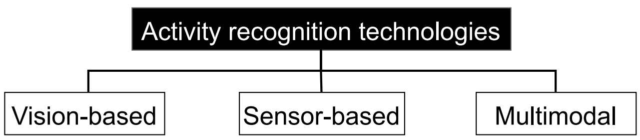


Fig. 2.7 Taxonomy of activity recognition technologies.

- **Vision-based activity recognition.** Vision-based technology generally depends on visual devices other than sensors to identify activities, such as cameras. Most of its applications are thus related to computer vision-based approaches across areas such as virtual reality, video surveillance, human-computer interaction (HCI), home monitoring and security [232]. However, it faces some obstacles regarding human activity recognition, including privacy and security issues. Further, many cameras rely on specific lighting to identify and recognize human activities [115]. This research thus focuses on the other type of human activity recognition, sensor-based approaches, due to the increased availability of this data type in most smart buildings and the reasonable price of the used sensors.

- **Sensor-based activity recognition.** This type of technology depends on using various sensors to recognize human activity. Data is collected from scattered sensors and then processed simultaneously to detect and recognize human activities. The sensors used are often very reasonably priced due to the extensive development of such technology, especially when linked with other technologies such as IoT. The sensor-based approach can also be applied across multiple different domains, and it has also been used in healthcare, security, object detection, and multiple other applications [269, 167].

  Table 2.6 shows sensor types activities identified within smart buildings, and activity recognition in the table can be defined as the ability to recognize what type of activity it is, e.g. whether a human is walking, standing, eating, etc., while activity detection is about determining whether something is there or not. Some sensors in the table can be applied to various activities, while others are most suitable for focusing on certain activities within a building.

  The sensor-based approach can be classified into three groups: wearables-based sensing, embedded sensing, and dense sensing [46]. Wearable sensors are attached to a person to recognize their activities: several studies have been conducted on wearable sensors to recognize human activities. Jalal et al. [120] and Kerdjidj et al. [133] focused on healthcare and fall detection, while Koskimäki et al. [142] focused on detecting specific medical conditions such as migraine attacks and spasticity. Chun et al. [53] and Bi et al. [27] focused on detecting eating activities using data gathered from wearable sensors positioned on the body, including neck and ear.

  The second type of sensor used is object sensing, which is based on objects with sensors, such as smartphones, that users operate daily, collecting data about users to facilitate recognition of their activities. Vaughn et al. [263], Hassan et al. [110], and Yin et al. [292] all used smartphone sensors recognising and detecting human activities such as walking, standing, running and similar movements. Other activities detected by using smartphone sensors include driving activities and group activities [44]. Further, sport-related activities, hand activities [148], stress [240], and sitting [179] are more commonly assessed using smartwatch sensors.

The third type is dense sensing, which differs from the other two types because it is not controlled or carried by a user. Instead, it relies on sensors placed around the user's location to recognize and detect user activities in that location. Various studies using this type of sensor includes studies on user activity detection [162, 291], occupancy sensing and prediction [202, 270], indoor positioning and localization [216, 169], recognizing collaborative [273] and group [122] activities, abnormal activities detection [122], and detecting location-based activities, such as activities happening in the kitchen [173] and sleep stages[94].

Wearable sensors and object/ embedded sensing methods have the drawback that they may not always be functional. For example, wearable sensors require users to wear them; some users may find them uncomfortable. Object sensing similarly requires the user to use specific objects to recognize activities. The dense sensing technique eliminates these obstacles and allows the user to carry out daily activities naturally; however, this technique still faces obstacles with data collection processes, as ground truth data intersecting with the environment may produce noise in data [115].

Another area for improvement when using sensors is reliability and availability. Sensor reliability can be improved by selecting the most appropriate sensor for a given application. Sensor availability can be improved by choosing a reliable power source and a backup source. Sensors should be regularly checked and maintained while maintaining sufficient communication range.

Table 2.6 Sensor type activities identified within smart buildings

Sensor	Activities identified	References
PIR	Occupancy sensing, estimation, and counting	[92], [266], [235], [260], [111]
	Abnormal activities detection	[175], [229], [45]
	Recognizing activities of daily living	[182]
CO2	Occupancy sensing, counting and prediction	[270], [125], [191], [9]
Temperature	Occupancy sensing and prediction	[270], [125], [191]

Continued on next page

Sensor	**Activities identified**	**References**
Humidity	Occupancy sensing	[125], [191]
Light	Occupancy sensing	[191], [125]
Wi-Fi	Occupancy estimation, counting and prediction	[14], [272], [270]
Infrared array	Activity recognition and detection	[162], [291], [186]
	Occupancy estimation	[219]
	Object detection and tracking	[100]
Proximity	Activity detection	[259], [21]
Proximity	Detection of movement and verbal interaction	[259]
	Recognizing eating activities	[21]
Pressure	Human activity detection	[218]
	Human posture detection	[176]
	Occupancy estimation and prediction	[48], [203]
Sound	Recognizing collaborative activities	[273]
	Occupancy sensing and prediction	[76], [203]
Heat	Occupancy prediction	[242]
Radar	Occupancy estimation	[289]
	Activity recognition and detection	[202], [173], [154], [153]
Accelerometer/ 3-axis	Occupant identification	[106]
	Activity recognition and detection	[120], [153], [110], [292], [141]
Gyroscope/Dual-axis	Occupant identification	[106]
	Activity recognition and detection	[120], [110], [152], [179]
Magnetometer	Activity recognition and detection	[133], [261], [152], [78]
Electrocardiogram	Activity recognition and detection	[133], [261]
Electromyography	Activity recognition and detection	[282], [27]
BLE beacon	Activity recognition and detection	[210], [44]
	Occupancy detection	[210]
	Indoor positioning	[216]
RFID	Recognizing teamwork activities	[159]
Millimeter-wave radio	Occupant identification and detection	[103]
	Indoor positioning	[138]
Electric field	Activity recognition and detection	[195]

- **Multimodal activity recognition.** This type of detection uses a combination of vision and sensor-based techniques for activity recognition. Such combinations can improve activity recognition reliability, accuracy and robustness. They may also reduce the required cost and effort. Wearable cameras have been the subject of research recently, as these need not be set in a fixed place like regular cameras [85]. Combining wearable cameras and sensors can thus provide more valuable information than wearable sensors alone. However, this combination may cost more and be more complex than applying either technology separately [85].

  Various studies on multimodal activity recognition have combined vision and sensor technologies to improve recognition. Muthukumar et al. Bouazizi et al. [32] detected a range of human activities, such as walking, standing, falling, sitting, lying and action changes, using a camera in conjunction with a low-resolution infrared array sensor. Detection of eating activities was performed by Thomaz et al. Thomaz et al. [255], who classified food intake gestures using cameras and wrist-mounted commodity sensors.

  Chen et al. Chen [45] conducted research to detect suspicious activities in volatile areas using a camera, a motion sensor, an infrared sensor and an alarm module, while activity recognition and occupancy sensing using a camera and wireless sensors were performed by Zhao et al. Zhao et al. [304] to recognize activities such as walking into a room, sitting in a chair, lying on a bed, or turning over in bed. Occupant office counts were conducted by Arendt et al. Arendt et al. [9] using 3D stereo vision cameras and CO2 sensors. Further, occupancy prediction to improve building energy efficiency conducted by Wang et al. Wang et al. [270] employed a camera and a variety of sensors. Despite the advantages of multimodal activity recognition, fusing vision and sensor data introduces several challenges. Fusion can occur at different stages: early fusion combines raw data or low-level features, but this requires synchronized and aligned data streams and can be sensitive to noise and missing data. Late fusion, where decisions from individual modalities are combined, is more robust to modality failure but may miss inter-modal dependencies. Hybrid fusion aims to balance these by integrating intermediate representations, but it increases model complexity and computational load. Choosing the right fusion strategy depends on the application context, data characteristics, and system constraints, and remains an active area of research [205, 157].

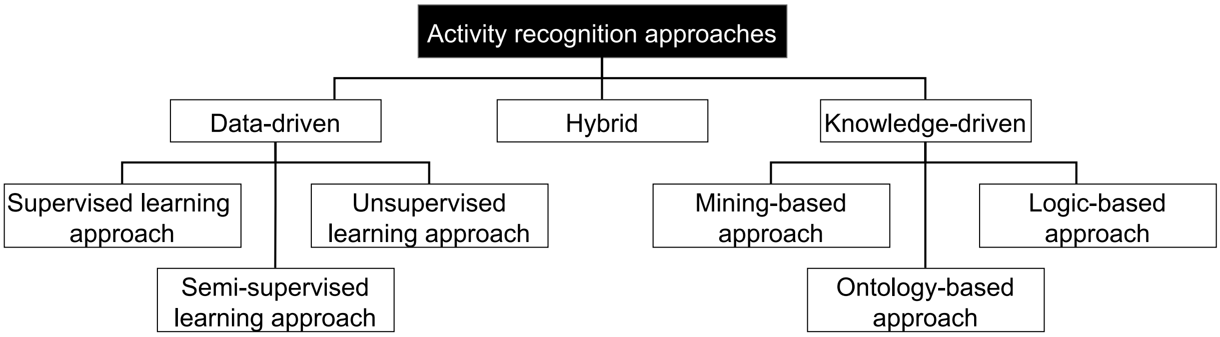


Fig. 2.8 Taxonomy of activity recognition approaches.

Activity recognition approaches

Human activity recognistion has relied on data and knowledge driven approaches, including a hybrid approach [244]. Figure 2.8 shows the taxonomy of activity recognition approaches that may be used to create effective activity models. These models help with inferences around human activities, but each approach has benefits and drawbacks for creating an activity model. Before selecting an approach, it is thus important to understand what human activity recognition entails and what makes starting a model with high accuracy particularly challenging.

The activity recognition process involves creating models that can precisely and effectively recognize human activities. To achieve this, it is essential that the same actions are performed in the same order each time the activity is undertaken. For example, making a cup of coffee may require the user to put on a kettle, find a cup, add water and ground coffee to a cafeteria, and then brew the coffee before pouring it – comprising a set of sequential steps that make up the activity of making coffee. However, other aspects can affect the model recognition process, such as the order of actions or the amount of time it takes to perform each action. This may result in the necessity for multiple models to account for these changes effectively. Thus, it is important for the optimal model to work in a dynamic environment and recognize different human activities as they occur [244]. To do this, the model must be able to process various inputs and precisely provide accurate outputs.

Recognizing human activities begins with activity modeling, a process used in software and systems development to model the activities that take place during the design and engineering of a system. Activity modeling analyzes user needs, uncovers problems, and identifies potential solutions. It uses data from various sources like sensors and cameras to identify user activities and patterns [46]. The data is then used to recognize and predict future activity patterns, which can be done using a data drive, ML-based approach, or rule-based control technique. Further, challenges with activity recognition approaches such as scalability and re-usability will be mentioned in each approach separately below.

- **Data-driven activity recognition approach.** This approach follows the process of creating an activity model from a collected dataset of users, applying different ML and data mining techniques as required. Although these may adopt different processes such as training and learning, this classification process of human activities is based on using statistical and probabilistic methods to infer user activities [46].

  This approach can thus produce models that can handle time-variant and stochastic information, being the opposite of knowledge-driven approaches, which are inappropriate for such work. However, a data-driven approach has some drawbacks: it requires collection of data for training and learning processes, and it is thus subject to issues of data scarcity: when the data is limited, or there is not enough labeled data, training may fail. There is also a re-usability problem, as the model produced for one user may be difficult to reuse with another [46].

  Activity recognition approaches often use data-driven methods to produce activity models, typically incorporating ML techniques. These ML techniques may include supervised, unsupervised, and semi-supervised learning; however, not all activity recognition methods necessarily rely on ML. The supervised learning approach is used chiefly for activity recognition. The supervised technique trains the model by using labelled data; the model should then be able to classify incoming unlabeled data by activity type using a generative, discriminative, or hybrid approach.

  The generative approach uses probabilistic models, such as Naive Bayes and Gaussian Discriminant Analysis (GDA) algorithms, to categorize data after determining how those data were generated, while the discriminative approach categorizes given input data and then uses models such as Linear regression and Support Vector Machine (SVM) algorithms. Further, Deep neural networks (DNNs) are a powerful type of AI algorithm that can analyze complex data sets and recognize patterns. They are made up of multiple layers of neurons, with each layer responsible for a different processing task. DNNs have proven highly effective in face and object recognition.

  Transfer learning is another ML technique where the model uses the knowledge it acquired from previous tasks to train for new tasks without spending much time and resources. It is used with applications such as natural language processing (NLP) and image recognition [222]. In addition, multimodal learning is an ML technique that uses multiple input modalities to process data. This is important due to the increase in unstructured data, such as images and videos, which are difficult to process with traditional models. It combines multiple data sources to produce a more detailed representation compared to what can be achieved with a single modality. For example, face recognition algorithms can use images and audio to better identify faces.

The one-shot learning technique allows the system to learn from a single example or experience. It can be helpful for tasks that involve recognizing or classifying new objects that the AI system has not seen before. Few-shot learning is similar to one-shot technique, where the models are trained using a few examples. It helps provide models that can quickly learn new tasks when large datasets are unavailable. It works by training models on meta-learning algorithms designed to learn from a few examples and apply them to new tasks. For example, a model can use an instance of a dog to learn how dogs are classified in other images [271]. Table 2.7 demonstrates the main analytics methods used to identify activities in smart building.

- **Knowledge-driven activity recognition approach.** This approach uses prior knowledge to make activity models based on various knowledge and management techniques. This process involves knowledge acquisition, representation, implementation, verification and validation. The approach is considered more robust to noise than data-driven approach semantically, logically straightforward, and easy to interpret. However, it is ineffective when handling time-varying or uncertain information, generating only static models [46]. The structure of knowledge in such models can be represented in different ways, such as networks, rules, or schemas. Overall, the approach may be classified into three main based types: mining, ontology, and logic-based.

  Mining activity knowledge from public data sources to create an activity model is a valuable approach that many organizations can benefit from. By leveraging public data sources, companies can gain insight into the context of their customer activities, the types of activities people engage in and identify associated trends. This can improve customer experience, marketing campaigns, and more effective product usage.

  Mining-based and data-driven approaches both use statistical and probabilistic models for activity recognition. However, data-driven approaches can generate personalized models tailored to individual users, while mining-based approaches typically rely on aggregated data, making them less suitable for generating personalized models. Instead, mining-based approaches focus on determining model parameters using aggregated data, which helps mitigate the data scarcity issue that can occur in data-driven methods [46].

  The ontology-based approach involves using a set of facts and tools to create an organized and logical conclusion model. This approach relies on using ontologies to represent the knowledge in a computational form. It helps with the reusing and sharing models and technologies.

Comparing this approach with the logic-based approach shows that both use the same techniques in terms of activity model recognition. However, the ontology-based approach has more access to rich resources, being supported by research in a semantic web, with resources such as APIs and advanced tools used to carry out tasks related to ontology-based approach activity recognition [46].

The Logic-based approach uses various logical forms, such as facts, rules, and expressions, to derive information regarding context. This approach is different from the data-driven approach in terms of less reliance on a large dataset to create an activity model. The activity models are thus more explicit semantically and can use low-level context to extract high-level information. This approach retains some weaknesses in representing uncertainty and fuzzy information. One way to reduce uncertainty in the model is to use sensors in the building to collect data about the environment and occupant activity. The data collected can create a more accurate and reliable model. Another possibility is to use ML algorithms that can analyze the sensor data and predict the occupants' behavior. Another area for improvement is that the activity model is not adaptable to different occupants' behaviors. It thus lacks reusability and applicability due to minimal standardization [46, 206].

- **Hybrid activity recognition approach.** Each of the previously mentioned approaches has its limitations. The knowledge-based approach produces activity models that cannot capture all user activities, and both approaches have other weaknesses. Thus, a hybrid approach may select key features from each approach to producing a better activity recognition model. Several such features were identified in research by Sukor et al. [244], who found that using a hybrid approach eliminated the data scarcity problem known as the "cold start" problem. As there is no need for a large dataset for training and learning, they could model activities initially by incorporating knowledge approach techniques, the model then moved on to a learning process using data-driven reasoning. Another important feature of a hybrid approach is scalability, which allows a model to be used in different environments without specific training. This approach automatically learns and adapts general activity models based on the previous knowledge context.

  However, there are some limitations to the proposed hybrid approach mentioned. One limit is that it does not support real-world activity scenarios that happen concurrently or work for more than one activity simultaneously.

Table 2.7 Activities, sensors, analytics used, and IoT roles in smart building environment

Activities identified	Sensor type	Analytics used	IoT roles	Reference
Activities recognition and detection	Pressure, stretch, and accelerometer	k-Nearest Neighbors (K-NN), Decision Tree (DT), and Support Vector Machine (SVM)	The sensor data was collected and stored on a Flora board and then processed in a PC to classify normal and violent human actions	[218]
	Thermopile imaging array	Connected domain extraction algorithm and Feature point localization	The sensors output sequential images are sent to a Raspberry Pi to analyze and detect three elderly activities: rest, fall, and movement	[162]
	Tri-axial inertial sensor	Genetic Algorithm(GA), DT, and SVM	The sensor data was collected and stored on Arduino Uno and then processed in a PC to detect physical activities from different datasets	[120]
Occupancy sensing	Temperature, humidity, CO2, and Wi-Fi probe	k-nearest neighbors (kNN), SVM, artificial neural network(ANN)	Sensor data is stored locally and WiFi data is sent to the cloud. The data is fused to predict occupancy and improve energy efficiency	[270]
	Accelerometer and gyroscope	SVM	The sensor data was fused and stored on Arduino Uno for different objects to identify different occupants in the smart home	[106]
	Plug-load meters and PIR	K-means clustering	The sensor data was collected and transmitted from Raspberry Pi to an external server to estimate individual occupancy in office spaces	[235]
Indoor positioning	Temperature, humidity, light, and pressure	xgboost, Random Forest (RF),DT, LightGBM, and Gradient Boosting Classifier (GBDT)	Sensors data was collected using an Arduino board, and the board uploaded the data to an external server for visualization and enable accurate indoor location	[97]
	BLE beacons	Trilateration algorithm	The Beacons sensors transmit the BLE signals to estimate the occupant's position, Arduino Mega and the smartphone are used to track the position, and then the data was sent to an external server for analysis	[40]

Continued on next page

Table 2.7 – *Continued from previous page*

Activities identified	Sensor type	Analytics used	IoT roles	Reference
Indoor positioning	Wearable wristband and smart phone	Fuzzy logic and genetic algorithm	Designed wristbands are used to receive the Received Signal Strength Index (RSSI) strength, and the corresponding MAC address is then sent to the cloud server, and then the server calculates and analyzes the received data for indoor positioning in an smart hospital environment	[43]
Building energy consumption	Temperature, light, PIR, and MQ-2 gas	Proposed lighting control algorithm	The sensor data was collected by the Arduino Mega board, the board controlled the lights in the house to reduce energy consumption	[42]
	CO_2, temperature, and humidity	Model predictive control (MPC), and long short-term memory (LSTM)	Sensors data was collected and stored in a Raspberry pi. Then the data was sent to a remote ThingsBoard platform to control smart building ventilation predictively while enhancing energy efficiency	[136]
	Temperature, humidity, CO_2, and Wi-Fi probe	k-nearest neighbors (kNN), SVM, artificial neural network(ANN)	Sensor data is stored locally and WiFi data is sent to the cloud. The data is fused to predict occupancy and improve energy efficiency	[270]
Building indoor environmental quality	CO_2, temperature, and humidity	Model predictive control (MPC), and long short-term memory (LSTM)	Sensors data was collected and stored in a Raspberry pi. Then the data was sent to a remote ThingsBoard platform to control smart building ventilation predictively while enhancing energy efficiency	[136]
	Particulate matter (PM), temperature, and humidity	On-Off Control	The sensor data was collected by the Arduino Pro Mini board and sent to a Raspberry Pi server for processing, and then the data was sent to the ESP8266 board to monitor and control the air quality in the building	[285]
	Temperature, humidity, and gas sensor	Neural network (NN), NaïveBayesian (NB), KNN, SVM, and RF	Sensor data was collected using an Arduino board and then sent to a PC for monitoring and predictive characterization of air quality	[7]

It can thus only be used to investigate consecutive or singular activities. Further, the proposed approach cannot differentiate whether used objects are relevant, arbitrary, or meaningless [244].

2.4 Sensor data and occupants' behavior

Sensor data is the information produced by a device that detects and reacts to various inputs from the physical environment [178]. This data typically includes measurements such as temperature, humidity, motion, and light levels, providing valuable insights into environmental conditions and activities [6]. For instance, in a study conducted by Laput and Harrison [147], a set of sensors with nearly 18 channels, including temperature, humidity, microphone, WiFi RSSI, 3-axis accelerometer, etc., were employed to explore the detection of different physical events in diverse room environments. Numerous applications utilize different sets of sensors for recognizing individuals' daily activities [78], detecting collaborative activities [273], identifying occupants [106], continuously monitoring stress levels [240], observing occupants' behavior [125], managing buildings [87], and optimizing energy consumption [104].

Using sensor data to understand various real-world practices, as in Finnigan et al. [87], conducting a study to investigate how to enhance energy auditing practices in buildings. The research employed a sensor toolkit with various sensors placed strategically in the building. The study results indicated that facility managers employed the insights gathered to gain a deeper understanding of building efficiency and provide meaningful suggestions for improvement. Another study conducted by Das et al. [64] focused on an educational building and utilized a 3D camera for activity recognition and space usage applications. The testbed was situated in a common area, specifically the hall cafeteria of a university building. The derived patterns helped building managers make informed decisions regarding space allocation that aligned with actual building usage. Further studies have been conducted to investigate and comprehend the events and phenomena taking place within buildings [100, 191, 31], various activities [280, 78, 297], and occupants' behavior [125, 144, 220].

Addressing individual limitations while considering costs, Yang et al. [288] explored the trade-off, progressively adding sensors to achieve acceptable accuracy in counting occupants through sensor data. However, diverse sensor combinations yielded different outcomes across rooms. As technology advances, the utilization of sensor data becomes integral for optimizing various aspects of building management. In a focused investigation, Laput and Harrison [147] deployed a compact sensor board in three buildings, showcasing clear accuracies for events like "closed door" detection, emphasizing the significance of accurate sensor data.

Notably, accuracy varied across buildings: 99% in residential, 96% in institutional Office A, 100% in institutional Office B, and 98% in the commercial building. Moreover, as we delve further into exploring sensor data in building environments, focusing on sensor data and how they help us becomes essential for informed decision-making and efficient building management practices.

Building occupant behavior refers to how people interact with the technology and systems in buildings [35]. It includes how occupants use energy, utilize different spaces, engage with building systems, ensure personal comfort, provide feedback, and adopt sustainable practices. Monitoring and analyzing occupant behavior helps optimize building operations, enhance energy efficiency, improve occupant comfort, and provide personalized experiences. The data collected from occupants' actions and preferences can be used to make decisions and continuously improve building performance. The study of smart buildings' occupant behavior serves multiple important purposes, including developing more precise building models [302], accurate prediction of energy consumption within buildings [234], and a better understanding of how spaces are utilized within the building [87].

Facility management play a crucial role in overseeing the efficient operation of smart buildings by utilizing data on occupant behavior. They rely on occupancy data and feedback to adjust environmental settings such as lighting, temperature, and air quality to meet the comfort needs of occupants while maintaining energy efficiency [87, 19, 188, 131]. Understanding how occupants use different locations within the building is particularly valuable for facility managers, as it enables them to optimize the allocation of resources such as heating, ventilation, and cleaning services.

For example, high-traffic areas, such as common study spaces, may require more frequent maintenance or adjustments to air conditioning systems based on real-time data collected from sensors and building management systems. Conversely, lesser-used areas can have reduced energy consumption during off-peak times. By closely monitoring how occupants move and utilize different spaces, facility managers can ensure that the building is operating efficiently while also adapting to the dynamic needs of its occupants. Additionally, this data informs decisions about space reconfiguration and planning, making it possible to tailor the building layout to better support occupant behavior and preferences.

Recent research highlights the integration of occupant preferences and environmental data in building management. Nacci et al. [188] presents BuildingRules, allowing occupants to customize their environments through trigger-action programming. Clear et al. [54] emphasizes environmental sensor data to enhance communication between management and occupants. Yang et al. [287] develops a multi-agent control system for effective energy and comfort management through occupant interaction, while Pasini et al. [204] explores big data technologies that transform buildings into service providers using real-time data. Dong and Andrews [70] focuses on algorithms to predict user behavior and link occupancy patterns to energy and comfort management for energy savings.

While Nacci et al. [188], Clear et al. [54], and Yang et al. [287] prioritize occupant engagement, Pasini et al. [204] and Dong and Andrews [70] emphasize data-driven approaches to improve building performance and efficiency. All share the goal of enhancing building management but differ in their specific focus areas. The literature illustrates the critical role of occupant behavior in advancing building management systems. By integrating advanced technologies and data analytics, these studies advocate for a paradigm shift toward user-centered approaches that enhance occupant comfort while optimizing energy efficiency. This shift is essential for developing environments that effectively respond to the dynamic needs of occupants.

2.5 Environmental monitoring and physical interface toolkits

Recent studies emphasize the role of IoT devices in monitoring environmental conditions [114, 305, 6]. Denefleh et al. [67] showed that smart, wireless sensors in co-living spaces could boost positive interactions among inhabitants and increase self-awareness about environmental conditions, while stressing privacy and customization. Houben et al. [112] introduced Physikit, a system making data from affordable sensors more accessible and understandable to users, thus enhancing community interaction through better data visualization. Similarly, Snow et al. [243] found that specialized displays providing indoor air quality (IAQ) information improved user engagement and understanding of workspace conditions. Additionally, John et al. [127] introduced a framework to raise awareness about indoor air pollution and its link to asthma, focusing on using IoT-based systems to improve air quality and asthma conditions.

The development of physical interface toolkits has marked a transformative step in enhancing communication between building occupants and their environments. These toolkits comprise a range of physical devices and interfaces designed to enable users to interact with building systems more intuitively and effectively. By integrating technology with physical components, these toolkits enhance occupant engagement, allowing users to give feedback on their environmental impact and energy use. Such interfaces help users understand the environmental impact of their actions, encouraging more sustainable behavior within buildings [112, 231, 165, 25].

This approach not only promotes user comfort and satisfaction but also fosters a sense of agency among occupants, motivating them to take an active role in managing their spaces. Research has shown that such interactions can lead to increased awareness of energy consumption and a greater commitment to sustainability initiatives. For instance, Lindrup et al. [165] and Houben et al. [112] present systems that utilize physical data visualizations to enhance user interaction with environmental information. The Carbon Scales developed by Lindrup et al. [165] enables collective sense-making of the climate impact of food, fostering carbon literacy through the visualization of CO2 emissions. This system emphasizes sustainability by encouraging engagement through interactive, resource-efficient designs. Similarly, Houben et al. [112] introduces Physikit, which allows users to explore environmental data via ambient physical visualizations. This enhances data comprehension and promotes personalization within homes, as participants utilized the visualizations for community engagement and social behavior, thereby making both systems crucial for democratizing environmental data and promoting sustainable practices.

Interface toolkits can facilitate communication between occupants and facility managers by providing real-time feedback on user preferences and building performance. This feedback is invaluable for optimizing operational efficiency. Studies have demonstrated that incorporating these toolkits into building design significantly enhances occupant experience and fosters a more responsive and adaptive built environment. Notably, research by Snow et al. [243], Clear et al. [55], and Bader et al. [18] presents innovative systems aimed at enhancing occupant engagement and comfort in building environments. For example, Snow et al. [243] focuses on indoor air quality (IAQ) displays, showing that localized, non-disruptive feedback in naturally ventilated offices enables users to comprehend air quality, thereby improving ventilation practices and enhancing cognitive performance. Similarly, Clear et al. [55] introduces ThermoKiosk, a digital system capturing subjective thermal comfort experiences, which fosters dialogue between occupants and facility managers to address comfort tensions. Additionally, Bader et al. [18] explores interactive smart windows, designed with fine-grained transparency control, revealing user interest in domestic applications and identifying design dimensions for integrating adaptive technologies in buildings. Collectively, these studies underscore the potential for enhanced sustainability and user control in architectural design. Overall, the integration of physical interface toolkits represents a promising avenue for improving HBI and delivering tangible benefits to occupants through enhanced communication.

2.6 Smart buildings objectives

The previous section reviewed smart buildings' capabilities for recognizing occupants and human activities. In this section, several important objectives that can be achieved using these smart building capabilities are thus outlined. Figure 2.9 illustrates some key smart building objectives that can be achieved using IoT technology combined with advanced analytics capabilities.

2.6.1 Occupant localization enhancement

This process aims to identify the location of an occupant or a device within the building. Occupant localization data is used mainly to facilitate navigation inside the building to reach the desired location [293]. Several technologies are used to measure occupant localization, including Wi-Fi-based indoor location, BLE beacons, and RFID detecting motion. Determining where occupants are located inside the building at a given time helps minimize energy consumption and costs based on occupant behaviors. It also helps to understand occupants' behaviors inside the building, which helps improve building facility design. Applications that may benefit from occupant location information within the building include energy consumption, improving safety, providing customer insights, and health systems.

The Global Positioning System (GPS) is the most common and popular location technology used in various applications. Despite its widespread use, GPS is limited in accurately locating occupants inside a building. To address this limitation, several other technologies have been developed and used for this purpose, such as Wi-Fi, Bluetooth, ZigBee, ultrasound, visible light, and Ultra-Wideband (UWB). Taking advantage of IoT technology and integrating it with such localization technologies may help enhance the accuracy of occupant localization and proximity detection within buildings [293]. A study that combined magnetic and visual sensors in the office building achieved 91% localization accuracy [216]. IoT technology can help by providing more precise information about the occupant's location using various sensors within the building, such as vision and pressure sensors. However, more research is needed on occupant localization applications due to the difficulties in their installation and maintenance.

2.6.2 Indoor air quality improvement

Nearly 90% of people's time is spent inside of buildings [26]; maintaining indoor air quality is thus essential to improving people's daily lives. Indoor air pollution can affect productivity and work performance. Recent research conducted by Sun et al. [245] estimates that a yearly

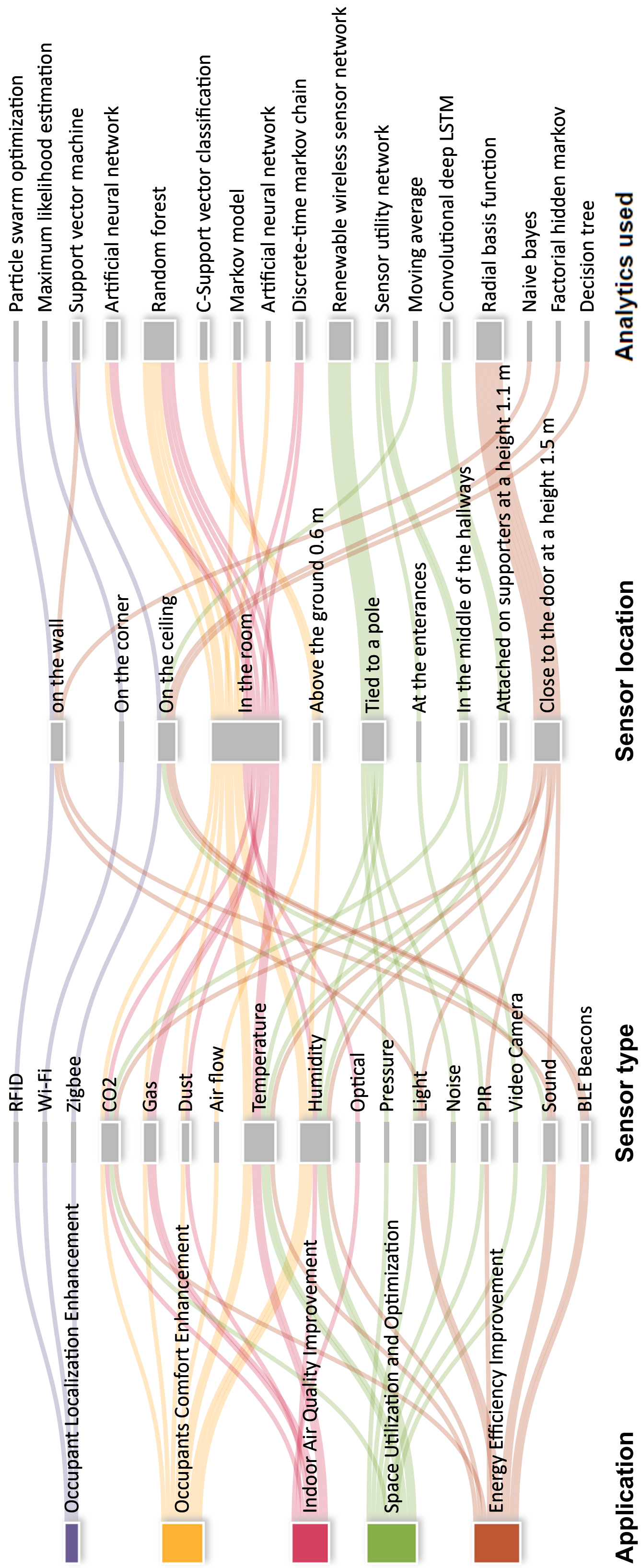


Fig. 2.9 Smart building objectives achieved by IoT technology combined with advanced analytics capabilities.

5% reduction in work productivity could cost around 20 to 200 billion US dollars in loss across the global economy.

Indoor air quality can be measured using various sensors, such as CO2, temperature, humidity, and volatile organic compounds. Adopting IoT technology and advanced analysis can help monitor indoor air quality and improve work environments. Recognizing occupants' activities can also help in understanding different occupants' pollution activities that may affect indoor air quality. It is also essential to monitor indoor air pollutants to inform building occupants about critical or dangerous levels as required and to help facility managers make relevant decisions about improving air quality in the building. According to Qabbal et al. [213], such collected data could also be used to develop indoor air quality guidelines to support different aspects of improvement such as ventilation design and occupants satisfaction.

2.6.3 Space utilization and optimization

Modern building spaces are designed to allow various activities such as individual work, group work, meetings, and socializing. These modern designs help optimal use of the multiple spaces within a building, yet there is often a lack of follow-up processes to measure the actual use of these spaces once a building is completed. Space utilization is measured in buildings using various sensing technologies such as infrared, motion, microwave, and video processing technologies.

Finnigan et al. [49] explored the role of the sensor toolkit in enhancing energy auditing practices in buildings: that study's findings showed that the fine-grained insights thus produced enabled facility managers to develop better knowledge of building efficiency that let them provide practical recommendations for improvement. Using IoT technology with various deployed sensors should help enhance space utilization within buildings, combined with advanced analytics to help develop an understanding of occupants' behaviors in different spaces to produce valuable insights.

Further, during the COVID-19 pandemic, smart buildings can be equipped with technologies that can be used to monitor and enforce maximum room capacity. Room occupancy sensors can detect how many people are in a given area, ensuring that social distancing protocols are being followed [294, 185]. Longo et al. [170] proposed a prototype called Smart Gate that monitors people's flow in the building and track their occupancy. The system was placed on one side of the entrances and primarily used a pair of time-of-flight sensors to detect people entering and exiting.

2.6.4 Occupants comfort enhancement

Occupants' comfort inside a building is one of the essential applications of smart buildings, as enhancing occupants' comfort helps to increase productivity performance and increases occupants' satisfaction levels. Various services can enhance occupants' comfort, mainly based on monitoring and controlling aspects of the indoor climate, including temperature, cooling, and noise levels. Occupant comfort can be affected by various variables, including air temperature, air quality, background noise, lighting, and other factors. Zhang et al. [298] sought to enhance building energy efficiency and occupants' thermal comfort by using a deep learning model in IoT-enabled buildings. The model proposed in their study achieved a high level of accuracy in a short period, based on finding the optimal value of the thermal comfort level for the occupants.

Different services can be monitored and controlled with the help of IoT devices and advanced analytics to be adjusted based on occupants' preferences and usage history. Acoustic sensors, for example, can detect particular types of noise, such as alarms or conversations, which can be useful for security and privacy purposes. Additionally, acoustic sensors can be used to detect the presence of people in a room, which can be used to trigger lights or other electronic systems.

2.6.5 Energy efficiency improvement

Building Information Modeling System (BIMS) is a powerful tool for improving energy efficiency in buildings by monitoring and controlling energy consumption. BIMS utilizes various sub-systems to collect, store and analyze data related to the energy consumption of the building, such as heating, cooling, lighting, and plumbing systems. This data can then be used to identify energy-saving opportunities, such as turning off unnecessary lights or systems when not in use. Traditional energy meters are used to collect information about energy consumption in each space. However, they provide only limited data. With BIMS, more detailed information can be collected, including data related to the number of occupants and their known comfort preferences.

Building sensor data can be analyzed to create an Energy Efficiency Index (EEI) that shows how much energy is used in different building areas and compares it with other buildings' consumption. Analyzed data can reveal energy consumption patterns and help make decisions about energy optimization in the building.

Occupant-centric control (OCC) and automated energy system strategies can improve buildings' energy efficiency by reducing energy consumption and environmental impact. OCC utilizes occupant behavior and preferences to optimize energy systems. Automated energy system uses sophisticated control algorithms to identify and implement energy-saving measures. The successful implementation of these technologies requires energy management systems, occupant sensing, and optimization software.

2.6.6 COVID-19 introduced applications

The COVID-19 pandemic has changed the way we live. To keep people safe, many businesses have had to implement measures to limit the capacity of their spaces and enforce social distancing. This has resulted in the development of new technologies, such as sensors, cameras, and software applications, which are used to monitor the number of people in a room and their distance from each other. Fazio et al. [84] propose scalable indoor navigation systems to navigate the user inside smart buildings using BLE beacons and smartphones. The smartphone detects the user's position over time and suggests the best route to the destination.

The proposed system can be further enhanced using AI technologies to predict user movement. For example, if a user regularly visits the same location each day, the system can use this information to suggest the quickest route to that location. The system can also provide helpful information during the user's journey, such as directions, alerts, and information about nearby points of interest.

Buildings are also being used to provide a safer environment for occupants by utilizing technologies like digital signage, automated temperature checks, and automated ventilation and air conditioning systems. Buildings are also used to create a more efficient way of working and living by enabling occupants to access their workspaces remotely.

Implementing AI and ML technologies is being used to improve the efficiency and accuracy of operational processes in buildings. In addition, developers created new applications built on top of existing smart building infrastructure to provide additional safety measures and improved efficiency. For example, smart buildings can now be used to provide automated contact tracing so that buildings can quickly respond to any potential virus outbreaks [290]. Similarly, they can be used to provide automated temperature checks and access control to ensure the safety of occupants.

2.7 Challenges and future research directions

This section clarifies the previously discussed gaps in existing research and identifies some challenges that may direct future research directions. Section 2.7.1 discusses technical challenges, including privacy and security, selecting sensor types and dealing with data uncertainty, deploying sensors and computational power, and building heterogeneous data sources. In section 2.7.2, Human-Building interaction is discussed, identifying the challenges shared between humans and buildings, the difficulty of recognizing complex activities, the challenges in delivering the explanations needed by building facility managers, and the space utilization application challenges.

2.7.1 Technical challenges

Privacy and security.

Smart buildings are becoming increasingly popular with the advent of IoT and AI technologies, bringing greater convenience and control to people. These technologies also raise significant privacy and security concerns. Privacy is a major concern for smart buildings and their devices, as the data collected can reveal a lot about occupants' behavior and interests. This data can be misused without proper protection, which can have serious privacy implications.

Security is another challenge for smart buildings; as many connected devices are installed in a building, the possibility of system hacks, data breaches, and other malicious activities increases. In addition, the consequences of such events in a smart building can be more severe since great physical damage can be caused if the security systems are compromised. Therefore, it is crucial to ensure that smart building systems have robust security measures to protect them from potential threats. This can be done using advanced authentication mechanisms, encryption technologies, firewalls, and other security protocols [263], [110]. Similarly, data protection policies should be adopted to ensure that personal data is not misused or abused.

Algorithmic bias is one of the biggest privacy concerns in AI technologies. Algorithms are only as good as the data they are trained on, and if that data is unbalanced or unevenly distributed, then the algorithms may produce biased results. Additionally, AI systems may not be transparent in their decision-making processes, making it difficult to determine why specific decisions were made and how they will affect people. It is also essential to limit access to the central AI systems that are used to control the building. AI systems often use sensitive data, such as user information, to make decisions. Therefore, access to these systems must be strictly controlled and monitored to prevent malicious activity. Further, it is essential to ensure the building itself is secure.

Buildings often combine different types of technology, such as facial recognition and motion sensors. This data must be securely stored and transmitted, and malicious actors must be prevented from accessing it [197]. IoT and AI in smart buildings offer numerous possibilities for creating energy-efficient, cost-effective, and comfortable living and working environments. With proper implementation, these technologies could revolutionize how people live and work in smart buildings.

Choosing sensors and dealing with data uncertainty.

Smart buildings rely on the data collected by sensors to make decisions that increase efficiency and reduce costs. Choosing the right sensors is therefore crucial for a successful building system. When selecting sensors, such accuracy, reliability, and power requirements must be considered. Sensors should also be chosen based on the type of data they can collect.

Different sensors are required to measure various environmental conditions, such as temperature and light. It is important to ensure that the sensors selected are compatible with the system in which they will be used. After selecting sensors, the collected data could be unreliable. It is important to understand the sources of uncertainty in sensor data, which can be divided into measurement errors and environmental effects. The first arises from factors such as the device's accuracy and the second from external factors such as temperature and light.

In addition, optimizing the energy efficiency of sensors must also be considered. For example, a framework proposed by Liang et al. [163] could keep the energy consumption of IoT devices at almost half of what was previously consumed by optimizing the sampling frequency, communication, and the models used. Therefore, further research is needed to develop suitable sensors for use in different building areas, identify potential uncertainty sources in sensor data, and minimize their impact. In addition, research should focus on developing collaborative frameworks and advanced analytics tools to identify opportunities for energy savings and improved occupant comfort.

Deploying sensors and dealing with computational power.

Once an appropriate combination of sensors is identified, those sensors must be used efficiently to obtain accurate information. Placing a sensor directly in the area of interest is the most commonly used means [186, 202], but this can be challenging since different sensors require different placement locations to offer accurate readings. For example, temperature sensors need to be placed away from windows and sunlight to provide accurate readings. Therefore, there is a trade-off between sensor locations within buildings.

Areas may have features that differentiate them from other areas in the building, so sensor placement and the number of sensors required based on those features must be considered. After deploying sensors, it is important to manage the computing power to run a building. The amount of power required depends on the complexity of the building, the number of connected devices, and the speed at which the data can be processed. IoT-enabled buildings require significant computing power and networking capabilities to manage data flows, analyze insights, and provide feedback.

Therefore, high-end servers, computers, and cloud computing solutions are required to run a smart building successfully. These solutions require high-speed networks, robust storage systems, and strong security to ensure data is not compromised. In addition, AI is needed to automate the processes and allow the building to respond quickly. It is important to carefully consider the project's specific needs and assess the existing infrastructure and technologies. This includes evaluating the performance of existing hardware, the type of cloud services needed, and the availability of AI solutions. Considering all of these elements makes it possible to create a reliable and efficient building for all its occupants.

Building heterogeneous data sources.

Data collected from buildings can be used to improve energy-saving opportunities, occupant comfort, and other systems in the building. However, the data collected can be heterogeneous and complex, making it difficult to analyze. Collecting and analyzing building data presents many challenges. For example, it can be difficult to identify different sources of energy use and their relationship to one another. The data may not be reliable or accurate, making it challenging to measure the energy used by the building and its occupants.

The data collected from buildings can be challenging to interpret. This is because the data is often collected from multiple sources, making it harder to identify patterns and relationships between different factors. It can contain a large amount of noise, making it difficult to identify patterns or trends accurately. It also may need to be completed or updated to draw meaningful conclusions. To overcome these challenges, developing systems that can effectively store, process, and manage the data collected from buildings is essential. It helps ensure that the data is up-to-date and can be easily accessed and analyzed. Using advanced analytics tools and techniques to identify patterns, trends, and relationships could help in the process of collecting data.

2.7.2 Human-building interaction

Sharing information.

Sharing the information is achieved through communication between the two parties, buildings and humans; the communication process remains challenging; many buildings are still not augmented with sensors due to the additional costs and lack of perceived value. Further, sensor data alone is insufficient for this purpose: it must be combined with advanced analytics to obtain valuable insights that can support rational decision-making. In a research study by Finnigan et al. [87], sensor data was used to generate actionable recommendations for facilities managers regarding energy auditing practices in different buildings. According to Das et al. [64], understanding occupants' behaviors and Human-Building interactions can help enhance energy consumption and minimize building costs in many circumstances.

Smart building systems typically use a variety of communication protocols, such as CAN bus, Zigbee, Bluetooth, LoRaWAN, and more. One of the most commonly used protocols for communication between devices in a smart building is Zigbee, explicitly designed for low-power, low-data-rate applications and is highly secure, reliable, and power-efficient. Low-Power Wide-Area Networks (LPWANs) provide a cost-effective way to connect low-power, low-data-rate devices over long distances. With LPWANs, smart buildings can communicate and report data back to their central systems, allowing for greater flexibility and automation while reducing energy consumption. It is best suited for buildings that do not require large amounts of data to be transmitted. For example, LPWANs can be used in buildings requiring real-time energy consumption monitoring and environmental conditions.

LPWANs often have less throughput and coverage than other networks, such as Wi-Fi or cellular, leading to poor performance in some applications. It is typically more expensive than other networks due to the additional cost of building the infrastructure required to support the network. Due to their low-power nature, they are prone to problems, and these networks require more maintenance. Further, LPWANs can be an excellent option for specific applications in smart buildings, but it is important to be aware of the potential drawbacks before implementing them [37].

Successful communication can increase understanding of various building phenomena, such as occupants' productivity and comfort. Improving communication allows facility managers to make better-informed decisions regarding different phenomena in a building. Further, featured models of Human-Building communication with optimal chosen sensors and analytics will improve the communication and desired end results.

Recognizing complex activities.

Understanding occupant activity is achieved by collecting sensor data and training an ML model to recognize activities. Static activities such as standing and sitting or dynamic activities such as walking and running all have movement ranges and produce recognizable sounds or vibrations that certain sensors can detect. Other complex activities may be harder to detect using sensors, it may be difficult to determine whether an occupant is watching a lecture or reading an e-book on a laptop.

Some activities can be easily recognized by applying vision-based techniques to monitor an occupant's activities, but these techniques have many drawbacks, including processing demand and lack of privacy. Several sensors can also recognize different activities sufficiently in isolation yet may find it challenging to recognize them when several things happen simultaneously at the same location.

There is a trade-off between the complexity level of the activity and the accuracy of recognition, especially when the activity is more complicated. More research is thus needed to efficiently recognise complex activities happening within smart buildings, as improved ML models and external data sources could improve this recognition accuracy.

Supporting facility managers with enhanced data.

Data from sensors can be variable and difficult to interpret due to noise and missing data; Some sensors even have manufacturing defects that can affect readings. Facility managers often look for high-level explanations for various phenomena in a building. They need information such as building occupancy rates for different spaces in the building with different designs that allow facility managers to renovate or improve spaces to maximize occupancy rates.

The nature of currently used sensors makes it challenging to deliver the range and types of data needed by facility managers. More reliable data cleaning frameworks and recognition solutions are thus needed to improve the final outputs. These should handle missing, incorrect and irrelevant data and prioritize the most critical data for required purposes.

Space utilization

Smart building are designed based on basic information available at the time of the design; however, this is generally insufficient to determine how different spaces inside the building will be used in practice or whether occupants will utilize them efficiently as designed. There is now a tendency to work outside of standard office buildings, based on current technological advances and improved means of communication.

Proposed solutions to optimize space usage have been developed previously by firms employing observers to take notes about occupancy in the building across different spaces over time [247]. This technique is inefficient and does not support flexible working practices such as hot-desking, it only detects occupancy at specific times rather than continuously throughout working hours. Currently, solutions have emerged based on vision-based and sensor-based technologies. Vision-based approaches that use cameras suffer from privacy and security concerns. Some also rely on outside lighting sources to identify occupants, making them prone to error.

Other solutions based on sensors can tackle issues regarding continuous occupancy detection while maintaining privacy. However, gathering continuous readings from sensors and understanding the nature of various building spaces remains challenging. The collected data can be affected by external sources, and occupants may act in ways that deliver inaccurate data about space utilization, such as changing furniture locations, blocking sensors, or incorrect readings being generated by sensors due to their relative location to other objects.

More research is thus needed to understand how spaces are being used within buildings to help in reducing costs and to help designers and facility managers understand occupant's behavior when using these spaces [87]. The collected data can be transformed into insights that help designers and facility managers in making informed decisions.

2.8 Covered and open research directions

This thesis addresses several technical and human-centered challenges outlined in this chapter. Specifically, it explores choosing appropriate sensors, dealing with data uncertainty, and building heterogeneous data sources through real-world deployments. It also contributes by presenting facility managers with more detailed data about different study spaces, occupants, and space utilization through sensing systems such as SpaceSense and the interactive EcoCube.

However, some challenges remain open for future research. These include privacy and security concerns in long-term deployments, efficient sensor deployment strategies under limited computational resources, and the recognition of complex activities beyond simple patterns. Additionally, more work is needed on how to share contextual information with occupants in a meaningful and privacy-aware manner. These areas offer rich opportunities for the research community to build upon the foundations laid in this thesis.

2.9 Summary

This chapter provides a comprehensive review of the research background and related work in the field of sensing technologies within building environments. It begins with an overview that sets the stage for understanding the role of sensors in modern smart buildings. The section on sensing technologies in building environments delves into the various types of sensors used to monitor environmental factors like temperature, humidity, and occupancy. Activities within buildings examines how sensor data is used to track and interpret human activities, improving operational efficiency and occupant comfort. The smart buildings objectives section outlines the goals of smart buildings, emphasizing energy efficiency, occupant well-being, and sustainability.

The chapter further explores sensor data and occupants' behavior, highlighting how data analytics can optimize building management and personalize occupant experiences. Environmental monitoring and occupant interaction technologies discusses advanced systems that maintain optimal indoor conditions and allow users to interact with their environment through intuitive interfaces. Finally, the chapter addresses challenges and future research directions, identifying technical challenges such as sensor integration and data security, and issues related to human-building interaction, which focuses on user acceptance and the impact of smart technologies on daily life. This summary encapsulates the chapter's focus on advancing smart building technologies and their applications, along with the ongoing challenges and potential future developments in the field.

Chapter 3

SpaceSense: Exploring the use of sensors data to understand occupants' behavior in heterogeneous study space types

3.1 Overview

Modern educational buildings are designed to support a variety of activities, including individual study, collaborative work, meetings, and social interactions. These multi-functional spaces are intended to optimize every area to accommodate diverse needs. However, a key question often remains unaddressed: How effectively do these spaces serve their intended purposes once in use? Despite the importance of evaluating space utilization, post-occupancy evaluations are seldom conducted, creating a gap in understanding how well these environments meet the evolving needs of their users [262, 20].

Study spaces in educational buildings are particularly critical for supporting the academic success of students and staff. These spaces should enhance focus, collaboration, and productivity. Continuous evaluation is necessary to ensure that study spaces remain effective in fostering academic achievement. Traditional methods for assessing space usage, such as periodic observation and surveys, often fall short in capturing dynamic and real-time usage patterns, particularly in flexible environments like hot-desking areas. Moreover, these methods can suffer from limited accuracy and low participation, diminishing their reliability as tools for understanding space effectiveness and occupant satisfaction [275, 308].

Facility managers are crucial in interpreting occupancy data and gathering occupant feedback to maintain environments that support student needs. However, a communication gap between managers and students often exists, hindering managers' ability to make data-informed decisions, as highlighted in prior research on sensor data use, environmental monitoring, and human-building interaction (see Sections 2.4, 2.5, and 2.7.2). Closing this gap is essential to enhance building performance and student engagement. Recent advances in Internet of Things (IoT) technology offer promising solutions to bridge this communication gap by providing real-time data on space usage and occupant behavior [301, 83]. While sensor-based technologies have proven effective in offering detailed insights, they often lack direct connections to facility managers, limiting their impact.

The findings of this study, while grounded in a specific context of modern educational buildings, may have implications for other educational environments, including older UK campuses or international settings. The general principles of IoT technology applied here, particularly in terms of real-time data collection and improving communication between students and facility managers, are broadly transferable. However, variations in building design, space usage patterns, and technological infrastructure may require adjustments for specific contexts. This study contributes to the growing field of Human-Building Interaction (HBI) by exploring how IoT sensors can enhance space management and student engagement, offering new insights for improving space utilization practices across different educational settings.

Our research focuses on deploying sensor nodes in various study spaces to monitor occupancy patterns, environmental conditions, and occupant behavior. The findings will inform facility managers on how to optimize space usage and improve the overall experience for students. The study also seeks to answer several key questions:

Q1: How can sensors data improve our understanding of student behavior and their use of different study spaces?
Q2: How can facility managers utilize the gained data to improve their decision-making process?
Q3: How can sensors data help us understand different occupancy patterns and identify factors influencing students' comfort in study spaces?

The key contributions of this study can be summarized as follows:

- This work presents valuable data on various open-design spaces, assessed using both qualitative and quantitative methods. To the best of our knowledge, it represents the first application of an IoT sensing toolkit in open design spaces within educational environments, aimed at gaining deeper insights into occupant behavior.

- The developed system integrates data from environmental sensors, occupancy detection, and user input, delivering insights through dashboards for facility managers.

Additionally, it features a reusable sensing toolkit that can be easily adapted and integrated into different building environments.

- Documented a collection of observed student behaviors in diverse open-design educational spaces, creating a reference point for future research and comparisons in similar environments.

The results of this work will provide valuable insights into the application of IoT technology in educational environments, laying the groundwork for future research on improving space design and management in educational settings.

3.2 Research methodology

To understand the needs and perspectives of building occupants and managers, we began with semi-structured interviews with facility managers to explore their insights into study spaces. Simultaneously, a co-design workshop with students gathered input on their needs and preferences for the spaces they regularly use.

To further investigate study space usage and the occupant-environment relationship, we developed a sensor node equipped with various sensors. These nodes were deployed in diverse study spaces, complemented by desk occupancy sensors and a Quick Response (QR) code poster for real-time occupant feedback. The collected data was transmitted to a dedicated dashboard, which presented the information in an accessible format for facility managers.

Following the experiment, follow-up interviews with facility managers were conducted to assess the dashboard's effectiveness and gather suggestions for improvement. For example, the dashboard could display the percentage of occupants expressing concerns about the cleanliness of specific study spaces, supporting informed decision-making. Figure 3.3 illustrates the proposed methodology for this thesis.

The study spanned approximately two years, encompassing initial workshops with students and facility managers, sensor node development, pilot testing, dashboard creation, data collection, analysis, and post-experiment interviews. However, the actual data collection period using the sensor nodes lasted nearly ten months. The extended duration accounts for the full research process, including design, deployment, and evaluation phases. Sensors were not replaced during this period, but regular checks were performed, including removing a sensor node once to verify calibration. Sensor reliability was monitored periodically to ensure data quality. Additionally, two brief power cuts, each lasting less than ten minutes, occurred during scheduled maintenance work in the building. While the sensor data was

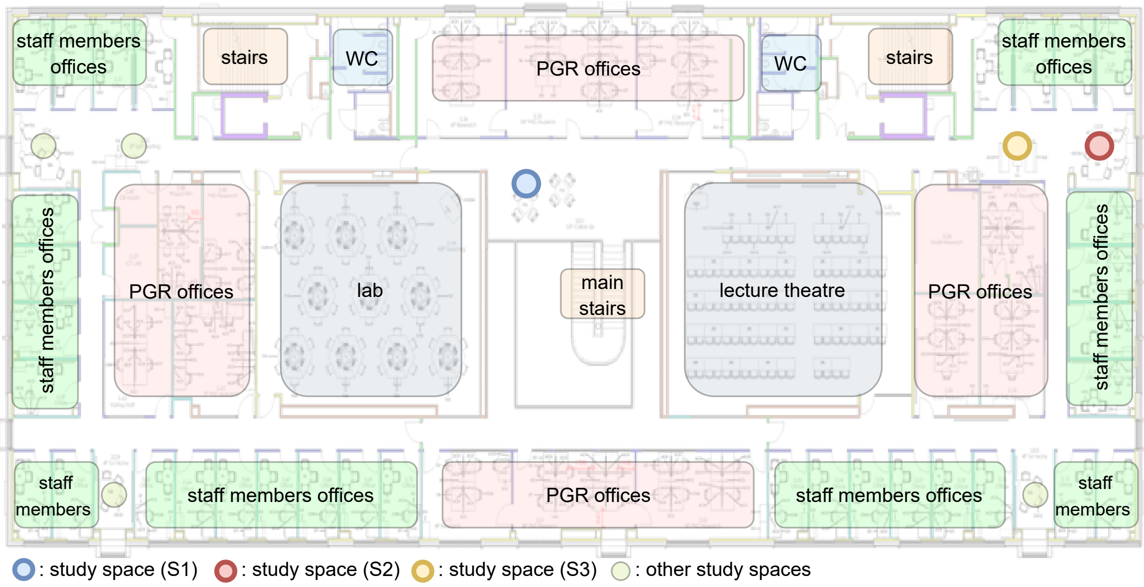


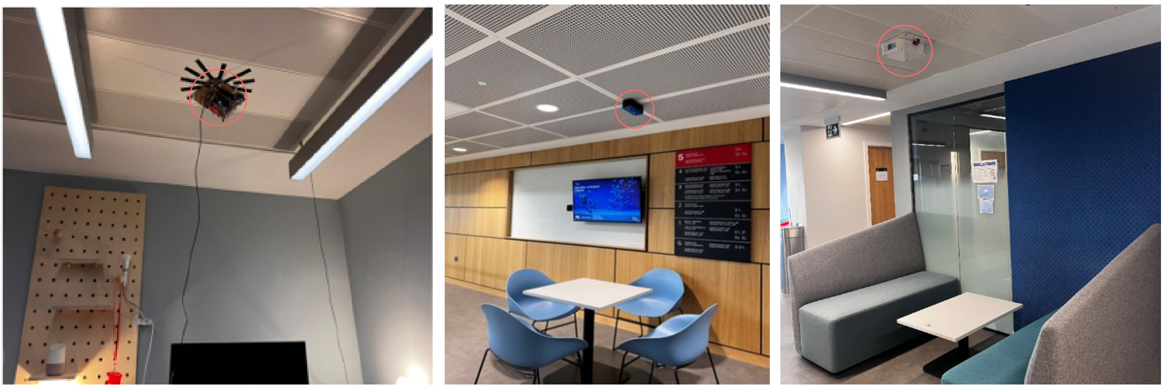
Fig. 3.1 The floor plan of the fifth floor of the building with selected study spaces.

accepted as reliable for visualization, no formal accuracy testing was conducted, which represents a potential limitation. Further, the interviews were transcribed verbatim and analyzed thematically, following the method outlined in [33]. Three primary themes emerged: acquiring data, interpreting data, and implementing insights. These themes were synthesized to form the findings presented in this article.

3.2.1 Participants

This section examines two approaches to understanding and improving building spaces. The first approach involves a workshop with university students, who are regular users of the building's study spaces. These students actively participate in designing and refining these areas, providing valuable insights based on their daily experiences.

The second approach involves semi-structured interviews with facility managers, who oversee the building's maintenance and management. Their professional perspectives help us understand the operational aspects of the study spaces. By engaging both students and facility managers, this thesis gains a comprehensive view of the current issues and potential improvements.



(a) (b) (c)

Fig. 3.2 Shows sensor node deployment at (a) the initial laboratory pilot study, (b) study spaces, and (c) the final setup after updates to the node and power sources.

Student workshop

The workshop (W1), referring to the first workshop, lasting three hours, comprised two main sections: a building walk and a co-design study spaces task. This thesis involved 18 university students, regular users of the building's study spaces, who were recruited through an announcement on the university website. For additional participant details, refer to Table 3.1. The workshop began with an informative session highlighting the significance of studying environments and distributing printed floor plans of the study spaces in the building. They have filled out a questionnaire, which can be found in Appendix C. The questionnaires designed for students before the experiment aimed to assess their needs and concerns regarding study experiences and preferences for various study spaces. Questions were based on previous research on factors influencing educational environments, such as comfort, noise levels, and lighting [87, 64, 151, 31]. This approach ensured that key aspects affecting student satisfaction and productivity were addressed.

The first part of the workshop, the building walk, Was influenced by walking methodologies previously applied in social sciences and human-computer interaction (HCI) to examine people's connections with space [60, 224]. Participants were given recording devices and asked to walk freely around the building using the floor plan, recording their thoughts and feelings about the study spaces. This engaging experience provided insights into how design elements impact behavior [61], offering a deeper understanding of how the physical environment influences students' study habits and preferences. After the walk, a focused group discussion facilitated open sharing of observations and experiences, where participants discussed the strengths, weaknesses, and suggestions for improvement for each space. This session aimed to uncover detailed, user-centric feedback on spatial functionality and comfort.

Table 3.1 Participant information for students.

Demographic	Percentage
Age	
18–24	70%
25–35	30%
Gender	
Male	41%
Female	59%
Position	
Undergraduate student	60%
Postgraduate student	40%
Time spent at university	
Less than a year	31%
1-3 years	50%
3-5 years	19%

The second section focused on the co-design task, emphasizing collective collaboration throughout the design process [230, 109, 150]. Participants, formed into six groups, used sketching materials to represent their ideal study space designs. Each group was provided with large sheets of paper, markers, and other art supplies to create detailed sketches that captured their vision for optimal study environments. After completing their sketches, the participants presented their designs to other groups, explaining their choices and thought processes. This presentation was followed by a facilitated group discussion, where participants provided constructive feedback, identifying commonalities and differences among the designs, and engaged in a reflective conversation about the overall implications of their findings.

Following this, the concept of mood boards was introduced. Participants had access to various online resources, such as images, colors, fabric samples, and furniture catalogs, to create individual mood boards that visually encapsulated their preferred study space. Each group was tasked with creating a mood board representing a study space where they would enjoy spending more time. This activity allowed participants to explore aesthetic preferences and conceptualize the emotional and sensory aspects of study spaces. After the mood board designs were completed by students, groups voted for the design they felt best represented an appealing study space. This process helped build a sense of community and a shared vision.

Throughout the workshop, facilitators documented participants' feedback, observations, and discussions using audio recordings and written notes. This data, combined with the visual representations from sketches and mood boards, will serve as the foundation for our analysis and further exploration of participants' perspectives and insights. The data collected will help

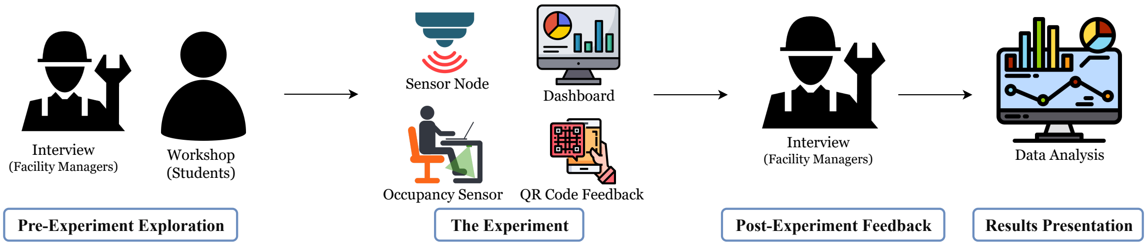


Fig. 3.3 The proposed methodology is discussed in the following sections.

identify key themes and trends in user preferences and inform future design recommendations for study spaces.

Facility managers interview

The participants in this thesis were building facility managers, each representing different roles. One manager oversaw building health and safety, another managed school operations, including budget oversight and general management tasks, and the third was responsible for technical services. Two one-hour interviews were conducted with the managers, one before deploying sensor nodes interview (I1), referring to the first interview, and the other after deployment interview (I2). These sessions were recorded to aid in data analysis. Detailed participant information is provided in Table 3.2.

The interviews were semi-structured, combining both closed and open-ended questions. This format allows the interviewer to start with a few planned questions but lets the conversation flow naturally, enabling spontaneous discussions and the inclusion of the interviewer's opinions on interesting topics [108].

The interviews were tailored to this thesis goals, focusing on user experiences in study space utilization, the use of the monitoring dashboard, HBI, and participants' overall feelings about study spaces in the building. The questions, can be found in Appendix A, were crafted based on existing literature and research aims, taking into account factors like productivity and satisfaction [68, 22, 36]. Sample questions were condensed with keywords and grouped by content to guide the interview. Following advice from Denzin and Lincoln [68], attention was paid to the conversation's rhythm, allowing new topics to emerge naturally. Transcripts from these interviews were meticulously transcribed and analyzed thematically, as detailed in [33].

Table 3.2 Participant information for facility managers.

Participant	Occupation	Job Responsibilities
FM1	Building health and safety facility manager	Supervise maintenance activities; develop and implement SHEW* policies; manage the facilities team; and oversee space allocation
FM2	Deputy school manager	Manage the school's operations, including budget oversight and general management tasks
FM3	Technical services manager	Manage labs and maker space workshops, support student projects and research, and supervise equipment usage

*Safety, Health, Environment and Wellbeing code of practice.

3.2.2 Data processing

The experiment began with a pilot study conducted in a laboratory within the university building. Initially, data collection was done locally before being sent to an external platform. Following the pilot study, adjustments were made, including switching to a fixed power source rather than using batteries and transmitting data to the platform every five seconds. Figure 3.2 illustrates the sensor node deployment at (a) the initial laboratory pilot study, (b) various study spaces, and (c) the final setup following updates to the node and power sources. The next step involved 3D printing and assembling the sensor node for deployment in three study spaces.

The collected data was sent to the ThingsBoard platform [254], an open IoT platform that facilitates data collection, processing, and visualization. To ensure data interoperability with other sources, we used JavaScript Object Notation (JSON) format for data transmission. We employed the Message Queue Telemetry Transport (MQTT) protocol, which is supported by ThingsBoard and well-suited for devices with low network capacity or limited resources—an ideal choice for our application.

In our experiment, the sensor data transmitted consisted of numerical values, with no personal information. To enhance data security, we encrypted the transmissions using Transport Layer Security (TLS). Using MQTT, we specified the server address and port for sending data, ensuring secure communication and maintaining data integrity throughout the transmission process.

ThingsBoard has proven effective in various applications, such as real-time data transmission from observatories, warning systems, and surveillance systems. The platform's real-time visualization dashboard allowed us to display and monitor the received sensor data efficiently.

To ensure data quality, we filtered out samples with missing or duplicate values, standardized the dataset timestamp, and improved noisy sensor data. As the data was collected in real-time from the sensor nodes and sent to the ThingsBoard platform for presentation on the dashboard, we first identified and removed samples with missing data, which accounted for approximately 466,560 (3%) of the total samples across all sensors. Duplicate entries were then detected and discarded, affecting around 311,040 (2%) of the dataset. To ensure consistency in the real-time data stream, we standardized the timestamp for all samples, aligning the readings from different sensors to a unified time format. This step impacted about 777,600 (5%) of the data, due to slight discrepancies in timestamp synchronization across the sensor nodes. Noise reduction techniques were then applied to improve the quality of the sensor data. We utilized moving average filters, Gaussian filters, and outlier removal methods to handle inaccuracies caused by sensor drift or environmental factors, which enhanced data quality by reducing noise in approximately 1,088,640 (7%) of the total samples. Following these steps, we achieved a more reliable and consistent dataset for analysis, ensuring that the real-time sensor data presented on the ThingsBoard dashboard was accurate and ready for meaningful interpretation.

Occasional interruptions in sensor data transmission due to Wi-Fi or power issues during building maintenance prompted us to implement a rule engine in ThingsBoard for email notifications on disconnections. Remote restart capabilities for sensor nodes were enabled using smart plugs connected to power sockets. Figure H.1 in Appendix H illustrates the Node-RED rule chain structure in ThingsBoard platform.

The dashboard was designed to be user-friendly for facility managers from different backgrounds. It includes various visualizations: pie charts representing student feedback about the study spaces, a utilization percentage widget showing the current utilization of the study spaces in the building, and a floor plan map indicating the exact utilization of study space chairs with green or red squares as can be seen in Figure 3.4. The platform allows facility managers to view current live data or historical data for specific periods.

3.2.3 Data visualization

The aggregated data from all study spaces is presented on a consolidated dashboard, designed for clarity and ease of use by facility managers, as depicted in Figure 3.4. This dashboard provides a comprehensive overview of key metrics, including current study space utilization, average air quality across all areas, outdoor air condition readings, and pie charts summarizing occupant feedback on aspects like cleanliness and comfort. The pie charts display satisfaction levels through color-coding, with green for satisfaction, yellow for neutrality, and red for dissatisfaction, and percentage values are shown when hovering over each partition. This feature helps facility managers easily interpret the data. For in-depth analysis of individual study spaces, facility managers can navigate to specific pages, exemplified by Figure 3.4 (b),

Fig. 3.4 Shows: (a) Provides a comprehensive overview of the dashboard, featuring all study spaces, while (b) Offers a detailed view of a specific study space.

which focuses on detailed insights for study space two. This view includes specific feedback from occupants, utilization statistics, and detailed sensor data readings including temperature, noise levels, and air quality.

To monitor study space utilization accurately, Pressac desk occupancy sensors [212] were installed under desks, each device facing a chair. These sensors detect chair occupancy status and transmit binary data (True or False) to the ThingsBoard platform, indicating whether a space is currently in use. Figure 3.5 (c) shows the 12 desk occupancy sensors used in our work. Further, Figure H.2 in Appendix H illustrates the process of occupancy detection and data visualization on the dashboard, outlining the steps from sensor detection to the presentation of occupancy data.

Feedback from study space occupants was gathered through workshops where participants expressed a preference for straightforward multiple-choice feedback formats. QR code posters, linked to each study space, were prominently displayed on the study desks. Scanning these QR codes directed occupants to a Google Form designed with structured questions and an optional field for image uploads, facilitating comprehensive feedback collection. The aggregation and visual representation of this feedback in pie charts on the platform are demonstrated in the process outlined in Figure H.3 in Appendix H. This approach ensures that facility managers receive clear, actionable insights into occupant satisfaction and operational conditions within the study spaces.

3.3 Sensor deployment and data collection

The sensor node, defined as a compact, self-contained unit containing sensors, processing, and communication components [228], is designed for reliable deployment in various study spaces within smart buildings, equipped with sensors to monitor environmental conditions such as temperature, humidity, occupancy, and lighting. After design, the nodes are placed in selected study spaces for continuous data collection. The next subsections provide details on the data collection process, sensor node design, study spaces, and sensor node placement.

3.3.1 Data collection

Participants were recruited through an announcement on the university website, in addition to emailing students, posting on student forums, and distributing flyers throughout the building. Facility managers were contacted via email, and they agreed to participate.

The research study began with a workshop for students and interviews (I1) with facility managers to gather insights from both perspectives. The student workshop (W1) involved 18 participants over three hours, including a building walkthrough and tasks focused on co-designing study spaces. Semi-structured interviews (I1) with three facility managers, lasting two hours, included both closed and open-ended questions. The interview outline can be found in Appendix A.

The workshop had two main sections. In the first, students were informed about the importance of study environments and were given a floor plan and recording devices to explore the building while thinking aloud. The second section focused on co-design, where participants in six groups used sketching materials to design their ideal study spaces. They also created mood boards to visually represent their preferred environments, then presented and voted on the best designs. The workshop outline is provided in Appendix B. The design of this study was guided by established methods in Human-Computer Interaction (HCI) and social sciences, particularly those emphasizing participatory design and user-centered evaluation. The student tasks were shaped by think-aloud protocols and exploratory walkthroughs commonly used to understand user experiences in HCI research [60, 224]. The co-design activities drew from collaborative design approaches to elicit participants' spatial preferences and foster creativity in shaping future environments [230, 109]. Mood board creation and group voting introduced visual and democratic elements to support inclusive design practices.

The facility managers participated in semi-structured interviews, recorded for analysis. These interviews began with planned questions but allowed for open conversation, covering topics such as space utilization, monitoring dashboard use, HBI, and impressions of the study spaces [108]. These combined approaches aimed to create a holistic, user-informed understanding of the study environment.

Table 3.3 Summary of the sensors used in the sensor node.

Sensor	**Performance**	**Used by**	**Purpose**
PIR Motion	Range: 3.2 - 12m	[92], [266]	Occupancy sensing, estimation, and counting
		[175], [229]	Abnormal activities detection
		[182]	Recognizing activities of daily living
Temperature	Accuracy: ±2%	[270], [125]	Occupancy sensing and prediction
Humidity	Accuracy: ±5%	[125], [191]	Occupancy sensing
Light	Range: up to 540 nm	[191], [125]	Occupancy sensing
Carbon Dioxide	Accuracy: 200 PPM	[270], [125]	Occupancy sensing, counting and prediction
VOC	Range: 0 - 60000 ppb	[10], [307]	Occupancy sensing and prediction
Pressure	Range: 300 $\sim$1200 mbar	[218]	Human activity detection
		[48], [203]	Occupancy estimation and prediction
Sound	Range: 3.2V $\sim$ 5.2V	[76], [203]	Occupancy sensing and prediction
		[273]	Recognizing collaborative activities
Proximity	Range: 3 - 350 cm	[259], [21]	Activity detection

(a) (b) (c)

Fig. 3.5 Shows: (a) the designed sensor node, (b) the placement of the sensor node, and (c) the used desk occupancy sensors.

3.3.2 Sensor node

To determine the most suitable sensor node for our experiment, we evaluated various existing designs used in smart buildings [190, 107, 299]. However, considering the diverse ceiling structures in the study spaces, none of the existing sensor nodes were deemed suitable. Hence, we developed our custom sensor node. Our research involved an extensive review of studies that employ sensors to gain insights into human behavior within smart buildings. These studies utilize different sensors for various purposes, including detecting human presence, counting, activities, and behavior. Our specific focus was on understanding human behavior inside smart buildings. We carefully chose nine sensors for our experiment based on our analysis of the selected studies [48, 125, 191]. We excluded other studies [141, 153] that suggested using wearable sensors such as accelerometers, gyroscopes, and magnetometers worn by occupants. Instead, our experiment emphasized dense sensing by mounting a sensor node on the ceiling. Similarly, other studies [210, 82] proposed using BLE beacon and RFID sensors. However, we did not include these sensors in our experiment due to compatibility issues with our sensor node design. To further refine our approach, pre-experiment interviews (I1) with facility managers and workshops with students (as presented earlier) highlighted key concerns regarding comfort, noise levels, air quality, and lighting in study spaces, as discussed in Section 3.4 and Section 3.5, where the results are further explored. These insights directly informed the selection of specific sensors, including VOC, carbon dioxide, humidity, sound, and light sensors, ensuring that the collected data would effectively address the occupants' expressed needs and enhance their overall study experience.

The sensors we used in this thesis comprised an ultrasonic distance sensor, a carbon dioxide (CO2) sensor, volatile organic compound (VOC) sensor, a passive infrared (PIR) motion sensor, a vibration sensor, a temperature and humidity sensor, a pressure sensor, and a sound sensor.

In this thesis, a systematic approach was used to select sensors for monitoring environmental conditions in study spaces. Sensors were sourced from Grove [233], a trusted provider of IoT components commonly used in education and research [171, 258]. The selection began with a broad list, which was narrowed down based on criteria such as performance, cost, and practicality.

Cost-effectiveness was crucial due to the large number of sensors required. Accuracy was also a key factor, as precise data on space usage, environmental conditions, and occupant behavior was essential. For example, the PIR motion sensor was selected for its range (3.2–12 meters) and acceptable temperature (±2%) and humidity (±5%) accuracy. The VOC and CO_2 sensors were chosen for real-time air quality monitoring, which was important for understanding student comfort.

Practicality of integration with the IoT platform was another key consideration. Grove sensors were compatible with the Arduino-based system and the ThingsBoard platform, ensuring seamless data collection. Availability and procurement logistics were also important, and Grove sensors were chosen for their reliability, availability, and good customer support. Further, the selected sensors, listed in Table 3.3, included the PIR motion, CO_2, VOC, pressure, sound, and proximity sensors, each chosen for their performance and relevance to the study. For example, the sound sensor assessed noise levels affecting student comfort. By considering cost, accuracy, integration, availability, and practicality, we optimized data collection and the replicability of the studyin future research.

Figure 3.6 shows the sensors used, microcontroller, and the portable battery at the beginning. Further, we employed a desk occupancy sensors to detect the presence of occupants in study spaces accurately. These sensors have demonstrated effectiveness in capturing occupancy data and providing valuable insights into the utilization of these areas [212].

The sensor node employed in this thesis is designed to prioritize occupant privacy by not collecting any personally identifiable information. Instead, it collects numerical data pertaining to the environmental conditions and occupancy of the study spaces. To collect and transmit the data, we utilized an Arduino Uno microcontroller board, which sends the data to a cloud platform. At the beginning of the experiment, the sensor node is powered by a 5.0V battery, and later it is powered by a fixed power source.

After interviewing facility managers in the building and collecting feedback from students, we were guided in the design of our sensor node. The students expressed a preference for a sensor node that was unobtrusive and situated on the table. They emphasized their desire to use the table for studying. Facility managers were in favor of a sensor node that provided valuable data about study spaces without compromising safety or privacy. Taking all this

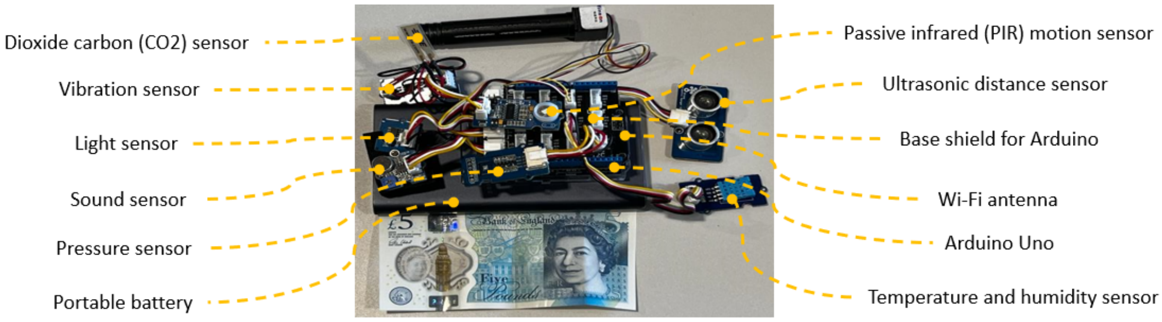


Fig. 3.6 Shows the sensors used in the sensor node.

feedback into account, we designed our sensor node to be inconspicuous. We opted for a white color, matching the ceiling, to ensure it wouldn't distract occupants. Further, we concealed the blinking lights of the chip and board within the sensor node and mounted it on the ceiling. This placement not only accommodated students' wishes to freely use the table but also addressed safety and privacy considerations.

The SpaceSence sensor node is 3D printed to facilitate easy installation on the ceilings of study spaces and to ensure optimal sensor functionality. Its design includes decorative elements and ventilation holes, allowing the sensors to accurately read data while effectively dissipating heat from the sensor chips. This sensor node is powered by a power cable and can be powered by a lightweight battery, making it easily deployable in various study spaces. For safety purposes, the node features four screw holes to securely attach the lid to the case. Figure 3.5 (a) and (c) shows the sensor node and the desk occupancy sensors used in the study, and Figure 3.7 illustrates the evolution of the sensor node.

Scaling the SpaceSense framework to larger campus environments could involve deploying multiple sensor nodes across various buildings and departments, potentially using wireless communication networks and centralized data management. This would allow for seamless data collection across diverse spaces, though additional considerations like real-time monitoring and remote troubleshooting would be necessary. The framework's modular design could offer flexibility for different campus layouts, but the full scope of implementation would require further assessment.

3.3.3 Study spaces

This project is being conducted at the newly constructed Abacws educational building, located in Cardiff, United Kingdom. The building serves as the home for Computer Science and Mathematics students. The building comprises six floors, each serving different purposes. On the ground floor, there are open study areas available for students. A significant portion

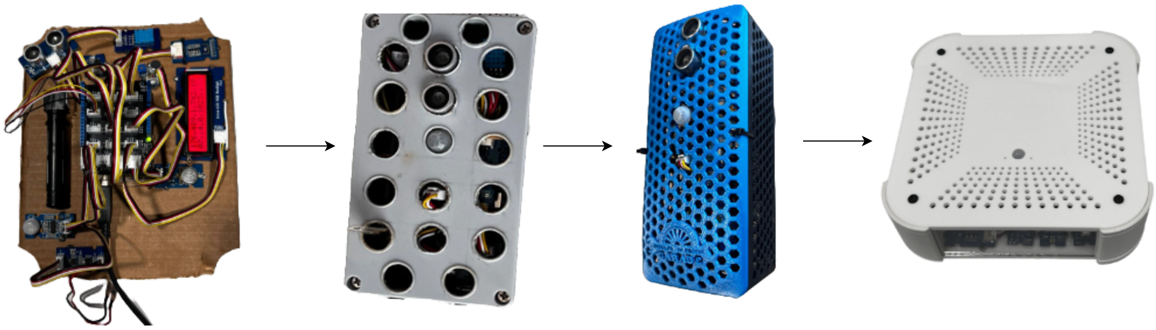


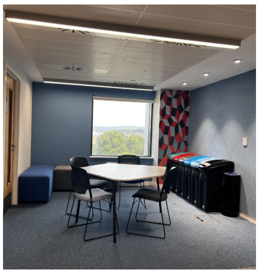
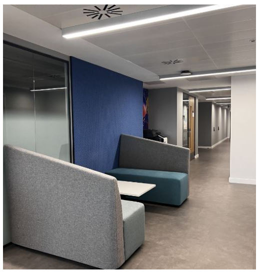
Fig. 3.7 Displays the sensor node evolution.

of this floor features a high ceiling that extends up to the first floor. The ceiling heights on the second to fifth floors are similar. The sixth floor is restricted for student access. Figure 3.9 shows (a) the Abacws building, and (b) the interior of the building with multiple stories.

The building incorporates various types of rooms designed to support both students and staff. However, not all modern buildings are equipped with sensors due to the additional costs involved and the limited perceived value and understanding of their benefits. For our experiment, we have randomly chosen three different study spaces located on the fifth floor. These study spaces differ in terms of size, furnishings, style, purpose, and maximum occupancy. While random selection helped capture variety, a more structured approach may have been better for comparing specific types of spaces, such as individual versus group areas. This would offer more targeted insights into how space design influences comfort and behavior. Future studies may benefit from a stratified selection process that aligns more directly with predefined space typologies and study goals. Table 3.4 provides more details about the chosen study space in the educational building.

The first study space (S1) is situated in the middle of the building, Situated between two offices for doctoral students. It can accommodate up to four students and is well-equipped for quick meetings and one-on-one tutoring, featuring a whiteboard on the wall. This study space can also serve as an area for eating during breaks. It does not have doors or windows and is considered a busy area due to its proximity to the main stairway entry and its central location amidst other staff and student offices. The second study space (S2) is larger than S1 and S3, located in a corner of the building. It can accommodate up to eight students and features one main desk and a portable laptop table. The seating options in this area include four regular chairs and two sofas for every two students. S2 is not considered a quiet area, as it houses a drinking fountain, waste bins, and provides an entrance to one of the staff offices in the same space.

Table 3.4 Different study space types in the educational building with details.

Study space	Dimensions (W x L)*	Desk and chair number	Occupancy	Features	Image
S1	8’3” x 12’6”	1, 4	4	• Located in the center of the building facing two PGR offices from either side. • Close to the main building staircase and staff offices. • Open area without a door and accessible from different sides. • No window. • Lighting and air conditioning are automatically controlled and adjusted by building management systems. • Has a whiteboard and a TV. • Has two wall outlets. • There are no heating or floor sockets, only two wall power sockets.	
S2	11’8” x 12’6”	2, 6	4	• Between two staff offices and opposite one of the staff office doors. • In front of a walk and study space 3 (S3). • A large window on the northwest side with blinds. • Open area with no door. • 4 floor sockets. • Lighting, air conditioning and heating are automatically controlled and adjusted by building control systems. • There are no TVs or whiteboards. • Has litter bins and a drinking fountain at the entrance.	
S3	7’2” x 4’1”**	1, 2	4	• Located on a walking path beside PGR office and next to two staff members. • No window. • Open area with no door and can be accessed from two sides. • Lights and AC are automatically controlled and adjusted by building control systems. • No heater, TV, whiteboards, or power sockets exist. • Desk height is short. • Near drinking fountain and printer placed on the walking path.	

* W: width, L: length. Dimensions are measured in feet and inches, for example 8’3” is 8 feet and 3 inches.
** Based on the dimensions of the furniture in the study space.

Fig. 3.8 Various ceiling design types in the Abacws building.

The third study space (S3) is the smallest in size and is situated on the fifth-floor walkway. It is furnished with two sofas and a short desk. Similar to S2, S3 is not a quiet area due to its location along the walkway and its proximity to a drinking fountain and printer. It is not fully equipped for studying, lacking sockets, a TV, and a whiteboard. Instead, it is primarily used for waiting, eating, or performing light tasks. Further, Figure 3.1 demonstrates the floor plan of the fifth floor in the building. This floor primarily consists of PGR and staff offices, along with a lecture hall, laboratory, and other study spaces.

3.3.4 Sensor node placement

The sensor node in this project is designed with reusability in mind, allowing it to be easily mounted and removed without drilling into ceilings or walls or causing any damage to the site. The goal is to understand occupant behavior and space utilization without leaving any traces behind. Study spaces S1 and S3 required ceiling-mounted sensor nodes, as S1 is situated in a location where wall mounting is not feasible, and S3 is located along a walkway with a glass wall nearby. On the other hand, study space S2 had suitable walls for sensor placement, with one wall adjacent to a staff office, another with a large window, and the third wall overlooking the study space.

During the placement of sensors in the three study spaces, we encountered challenges in achieving accurate readings and ensuring a reliable internet signal for data transmission to the external cloud platform. In S1 and S3, placing the sensor node in the top corner resulted in incorrect readings, as it captured data from outside the focused study space, including students passing by or using the main staircase. Additionally, distractions such as the nearby TV in the S1 study area affected the readings. In S2, sensor readings were affected by sunlight through the window and the proximity of a heater. Poor network coverage in the building corners sometimes led to data not being sent to the cloud. To mitigate these issues, the optimal placement was found to be mounting the sensor node on the ceiling at the center

Fig. 3.9 Shows (a) the Abacws building, and (b) the interior of the building with multiple stories.

of the study space, as shown in Figure 3.5 (b). This allowed for better readings, eliminating external influences like sunlight and temperature.

Although the intention was to place the sensor node in other study spaces within the building, this plan was postponed for future studies due to various challenges. Some spaces had ceiling heights equivalent to two floors, making it difficult for certain sensors to read accurately or cover the required distance. Additionally, solid ceiling constructions in some study spaces posed difficulties in mounting a temporary sensor node without leaving marks. Figure 3.8 shows the different ceiling design types of the Abacws building. Further, only one sensor node was used for each study space as it proved sufficient to cover the area of interest, eliminating the need for additional nodes. All sensors used in this study were factory calibrated.

3.4 Key findings and insights

This section presents key findings from the integration of sensor technology to understand student behavior and optimize educational environments. It examines students' perspectives on study areas, analyzes sensor data for insights into occupancy and environmental conditions, and discusses how these findings can inform decision-making and enhance student well-being in educational settings.

3.4.1 Students' views on various study areas within the building

The participants were randomly assigned into six groups, each consisting of three individuals. For confidentiality and clarity, pseudonyms were utilized to signify each participant and their respective group. For example, 'P1G2' refers to the first participant within group 2. In this segment, we present fresh insights into students' perspectives on diverse study spaces, their intended usage patterns, and preferences.

Influencing choices: The impacts of external factors on students' decisions

Students were asked to spend time in each study space and think loudly about things that distract them or could affect their comfort during utilizing that space. In general, different opinions are given regarding the different study spaces but were there some common agreement on some external factors in some spaces that they do not like and would like to be improved.

Students were getting distracted due to external noise and light conditions, leading to a disruption in their focus on tasks. Specifically, the noise levels in study space S1, as shown in the image in Table 3.4, which is located in the core of the building, became a challenge. During busy times, the noise levels escalated due to the building's high activity. This was highlighted by a participant who said, *"It's in that cross circulation in the middle of the buildings. So people are working obviously when the building will be in the whole use it will be really noisy"* (P1G1).

The lighting used in study space S1 was another factor that interfered with students' concentration. The bright artificial lights seemed to fatigue their eyes, leading to decreased focus. A student brought attention to this concern by mentioning, *"it was under a like a bright white light. I prefer a studying next to windows with like natural light"* (P2G3).

The comfort of the furniture in study spaces S1 and S2 was a point of concern for the students. In S1, the table was deemed too small for study purposes, and the chairs were uncomfortable when used for extended periods. As one student expressed, *"In terms of studying, I wouldn't like to study there because the tables are too small. The seats for a long time get uncomfortable"* (P3G3).

In the case of S2, the table was set too low, making it difficult to work on a laptop without having to hunch over. Additionally, the sofas were hard to move around, further reducing the comfort level. A student highlighted this issue by stating, *"the level of the table is very low. So it's it's like if you if you wanted to work in your on your laptop then you have to crouch and get off work that way"* (P3G5). Contrarily, some students found the setup of a low table and a sofa to be comfortable for working. As one of them explained, *"it's more comfortable* *in a setting where I can put my feet on the table, put my laptop on my legs and start working"* (P3G6).

The availability and placement of power sockets was a problem that students encountered across all study spaces. In some instances, the sockets were either non-existent or inconveniently located. For instance, study space S3 had no power sockets at all. S1 did have sockets, but they were limited to two and were positioned on the wall, which could cause disruptions for people walking by in the busy area. This issue was raised by a student who stated, *"plugs they're only at one side, so if you connect them and some people walk their side"* (P1G1). Further, having only two sockets in the study space S1 was insufficient for accommodating multiple students, especially those with multiple devices. As one student put it, *"there is only two chargers there, and maybe you have more than two students sitting on that same table and you have your, for example, your phone and your laptop. You wanna charging them? It's more crowded"* (P3G6). Study space S2 presented another issue. Some students were not even aware of the power sockets, as they were located on the ground. Those who did locate the sockets felt it would be much better if they were placed on the tables for easier access and to prevent cable congestion on one side of the table. This sentiment was captured by a student who said, *"I was not aware that that was a power socket, I would actually like power sockets on the tables"* (P2G3). This adjustment would also accommodate those with shorter charging cables, providing a more user-friendly setup.

Privacy was a crucial factor that drew students to study space S2 and away from S1. Positioned in the corner of the building and shielded by three walls, S2 offered a level of seclusion that S1, located in the center of the building next to the main staircase, did not provide. The lack of privacy in S1 was a considerable deterrent for students, with one of them stating it offered *"zero privacy"* (P2G2). In contrast, the same student found S2 to be much more accommodating in terms of privacy, commenting, *"This quite good privacy"* (P2G2).

Natural light and a pleasant view were features highly appreciated by students in study space S2. The influx of natural light was considered beautiful and conducive to studying. The view provided a relaxing visual break, allowing students to recharge. One student elaborated, *"natural light and a great view like this it inspires me to study personally. So I guess many people will feel like that. So having a natural lightest like a plus for studying, it makes us energized and doesn't make us sleepy while studying"* (P2G4). However, another student found the direct sunlight to be a bit uncomfortable while studying, stating, *"is like to stream straight to your eyes is not really comfortable when you study"* (P2G2). Another common issue students had with S2 was the location of the waste bins. They felt the bins were a distraction and could sometimes emit unpleasant smells from discarded food, which was not conducive to a productive study environment. As one student shared, *"I would wanna move* *the bins over there because I get distracted. If people are throwing the rubbish and also if it's overflowing, it might not have a nice, not pleasant smell and I won't be able to study"* (P3G3).

While the majority of students preferred study space S2 as their top choice for studying, with S1 being the least preferred, personal preferences also played a significant role in determining the appeal of the study spaces. Some students found S3 to be more to their liking due to its quiet, isolated nature and the comfort provided by the seating area. One student explained, *"it is isolated. When I was sitting there, my voice is not like separated widely. And it's more comfortable in setting on the sofa"* (P3G6). Study space S1 also had its unique appeal for certain students, particularly due to features like the movable tables and its suitability as a place to take a quick nap, as pointed out by one student who mentioned, *"it's a good place to take a nap"* (P2G2).

Focus eclipsed: The distractions in study spaces disrupting students.

In study space S1, the primary issues for students were a lack of privacy, noise levels, and discomfort from the tables and chairs. Further concerns included the space being frequently occupied due to its location in a high-traffic area, the absence of natural light, and poor accessibility to the space, which discouraged students from choosing it as a study area.

Study space S3 also presented several distractions. The most significant issues were the lack of accessibility and the discomfort caused by the tables and chairs. Additional detractions included the absence of power sockets, the space being situated near noisy equipment such as printers, and the inappropriate lighting conditions in the space.

For study space S2, the primary complaints were the lack of accessible power sockets and the presence of waste bins. Other distractions included the space being regularly occupied by others and its proximity to distracting equipment such as water fountains and printers.

Students suggested a variety of ideas to enhance the study spaces. One suggestion was the addition of more private capsule rooms to support privacy and facilitate meeting attendance. Another was the introduction of cubbyhole storage for bags under the tables or chairs. One student expressed, *"cubbyhole or something like that for the study space where you can put your bag in or put like belongings in because sometimes I always put it on the floor where the floor could be dirty or something [...] having something attached kind of clipping on to the table you can put your stuff in, or underneath the chair differently"* (P3G3). Further, students suggested storage spaces for laptops and other equipment, enabling them to freely take breaks and return to their work afterward. A student stated, *"have storage space for your laptop. So sometimes if you just wanted to switch from studying to eating, you can move your laptop and then socialize and eat something"* (P3G3).

Regarding the furniture used in the study spaces, the suggestion of adjustable tables was also brought up as a more comfortable option. As one student mentioned, *"If that is adjustable, I would sit there. I kind of feel like it's more. That would be perfect for me"* (P2G3).

Utilizing spaces: Navigating personal preferences in study space usage.

Facility managers have observed specific preferences among students when it comes to the utilization of study spaces within the building. They noticed that many students prefer corner areas for the privacy they offer, rather than the open study spaces in the building center. Additionally, these managers have observed a clear preference for study spaces equipped with whiteboards or chalkboards. This is especially true for students majoring in mathematics. As one facility manager stated, *"MATHS students typically like to work, which MATHS like academics like to work on chalkboards"* (FM3).

Another observation is that students seem to prefer sitting on sofas for their comfort. However, there is a specific issue related to power accessibility. Students like the convenience of power outlets situated in the middle of the tables, but this arrangement has led to safety concerns. Specifically, the configuration of power outlets amid the tables has resulted in numerous tripping hazards. Therefore, while students value the comfort of sofas, they also appreciate the practicality of having easily accessible power outlets, even if this design choice comes with its own set of challenges.

Students used the study spaces for various activities, including studying, socializing, attending remote classes, and napping. However, each space had more votes toward specific behaviors.

In study space S1, the majority of students primarily used the space for socializing, followed by eating and drinking. Studying came next, with attending online classes and taking naps being the least preferred. A similar pattern was seen in study space S3, with the space primarily being used for socializing and then eating and drinking. Taking naps was more common here than studying and attending online classes.

In contrast, study space S2 was preferred for studying, followed by socializing, eating and drinking. Attending online classes and napping were again the least preferred activities, as gathered from the questionnaire responses in Appendix C. Generally, students preferred to attend online classes and nap at home due to convenience. Figure 3.10 encapsulates the participants' responses about their use of various study spaces and their preferred modes of utilizing each space.

Different spaces saw different preferences when it came to individual, group work, or individual work in the company of others. In study space S1, students equally preferred

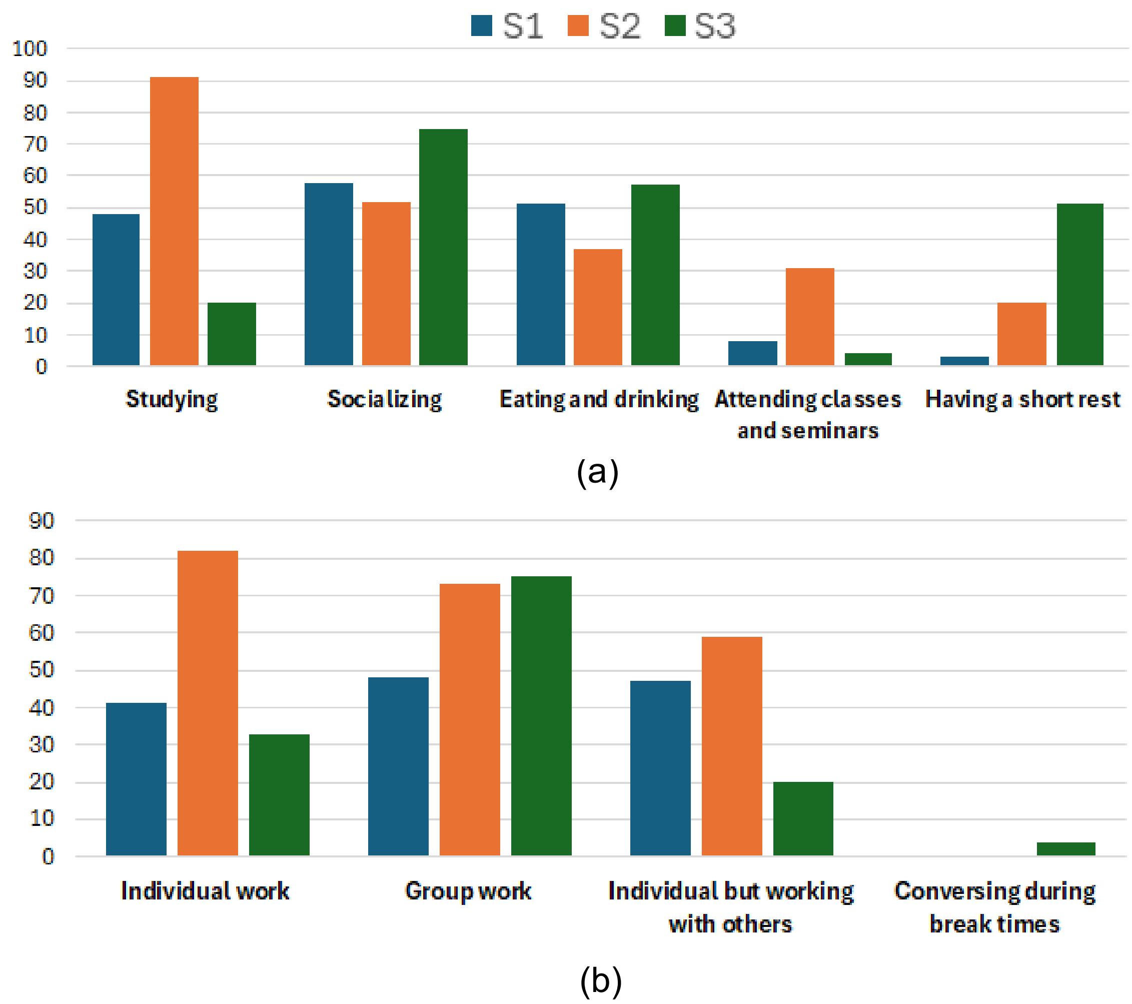


Fig. 3.10 The bar chart illustrates the participants' responses on their typical usage of each study space (a) and their desired mode of utilizing such a space (b).

group work and individual work in the company of others, with individual work being the least preferred. In study space S3, group work was the most preferred, followed by individual work. Working individually in the company of others came next, with the space being least preferred for casual chats before or after lectures. In study space S2, students primarily preferred individual work, followed by group work, and lastly individual work in the company of others. In general, students preferred to work with others in study spaces S1 and S3, while they favored individual work in study space S2.

Bridging roles: Students' understanding of facility managers' responsibilities and preferred communication methods.

When queried about the role of facility managers in the buildings, most students were aware of the position, but unclear on the specifics of what the role entailed. A minority of students, however, were knowledgeable about the duties of facility managers.

Regarding past contact with facility managers, the majority of students, 13 out of 18 participants, had never contacted facility managers before and were unaware they could do so. This was followed by 4 students who had not contacted facility managers before but knew how to reach out if needed. Lastly, 1 student had previously contacted a facility manager. When asked about improvements they would like to see from facility managers, the students' primary request was for greater responsiveness to student feedback and suggestions, which was highlighted by 41% of the students. This was followed by requests for improved communication about any changes or upgrades, indicated by 25% of the students, better temperature control, mentioned by 19%, and more regular cleaning and maintenance, noted by 15%.

Students also had other specific requests. Some expressed a desire for screens in the study spaces to allow them to connect their laptops, creating a more productive environment: *"screens that are up here. There's none around us now, but you know how they have the HDMI cables so I can use that as a second monitor"* (P1G6). Also suggested adding more plants for aesthetic appeal and improved air quality, improving airflow and ventilation, and providing hot water, which is available in other buildings: *"I know that some people prefer hot water as well, so the ASL library has a whole hot washer machine, but there's none here. Obviously, if you're postgraduate students or research or like a professor or something you can access the the 3rd floor pantry area, but obviously that's that's limited to a few people"* (P1G6).

Some students even suggested incorporating a games corner, where they could spend their breaks and potentially improve their productivity: *"a corner for some brain games like fossils and if we could indulge in some good at like that would be more productive"* (P2G2).

When it came to communicating with facility managers, most students preferred email updates, followed by notices on a building board and a dedicated website or application for communication. Social media updates were the least preferred method of communication.

Visualizing and conceptualizing ideal study spaces: Student sketches and mood boards.

During the workshop, students sketched their ideal study spaces. The first sketch, Figure 3.11 (a), features a large window for natural light, a substantial blackboard for math students, a round table for collaboration, and a secluded corner to minimize distractions. Figure 3.11 (b) shows four partitions, two dedicated to individual study, one for group work, and the last for a games room. All are supposed to have large windows on the side, with group work tables preferred to be large and round in shape. The third sketch, Figure 3.11 (c), includes vibrant colors, a screen showing real-time occupancy, a noise-level indicator, individual and group study areas, an adjustable table, a mobile whiteboard, and glass panel enclosures that can be tinted for privacy. It also suggests refreshment facilities, storage, power sockets, and plants. Figure 3.11 (d) shows different table designs for group work and individual study, a whiteboard, a large window, and a big couch with a table for resting. Figure 3.11 (e) focuses on separated study booths, a room for individual or group study with a whiteboard, fixed wall chargers for devices, and a vending machine for study essentials. Figure 3.11 (f) presents different ideas, including a long café-style table, a stand for quick activities, a movable sofa that can be adjusted up or down, plants in the study space, and an automated window opening based on air quality in the room.

For the mood board designs, the first mood board Figure 3.12 (a) emphasizes a strong connection to nature with abundant green color, large windows for natural light, and a cozy study space atmosphere. The second mood board Figure 3.12 (b) showcases large windows with sunlight, complemented by various amenities such as puzzles, a drinking water fountain, a whiteboard, and a cozy couch. The third mood board Figure 3.12 (c) presents a variety of wooden designs, featuring different study space layouts for individual work, group work, and a minimalist movable table for personal study. The fourth mood board Figure 3.12 (d) emphasizes a bold, modern aesthetic with wooden tables, green plants, natural light, and minimalistic decor. The fifth mood board Figure 3.12 (e) presents a large shared table with charging sockets, a window, a bookshelf, and a whiteboard, focusing on functionality and simplicity. The sixth mood board Figure 3.12 (f) features vibrant colors, greenery, ergonomic chairs, diverse study spaces, large windows, and under-table power sockets, aiming for a comfortable and visually stimulating environment.

After the sketching phase, student groups presented their concepts, and the other groups voted on each idea, with each group receiving five votes. The voting used a three-point system: (1) needed more development, (2) solid and on-topic, and (3) innovative and exceptional. Votes were cast anonymously to avoid any sensitivities. Group three's concept was the most favored in the sketching phase, and group six's design was the most admired in the mood board presentations. Figure 3.11 and 3.12 show the top designs, marked with a blue star.

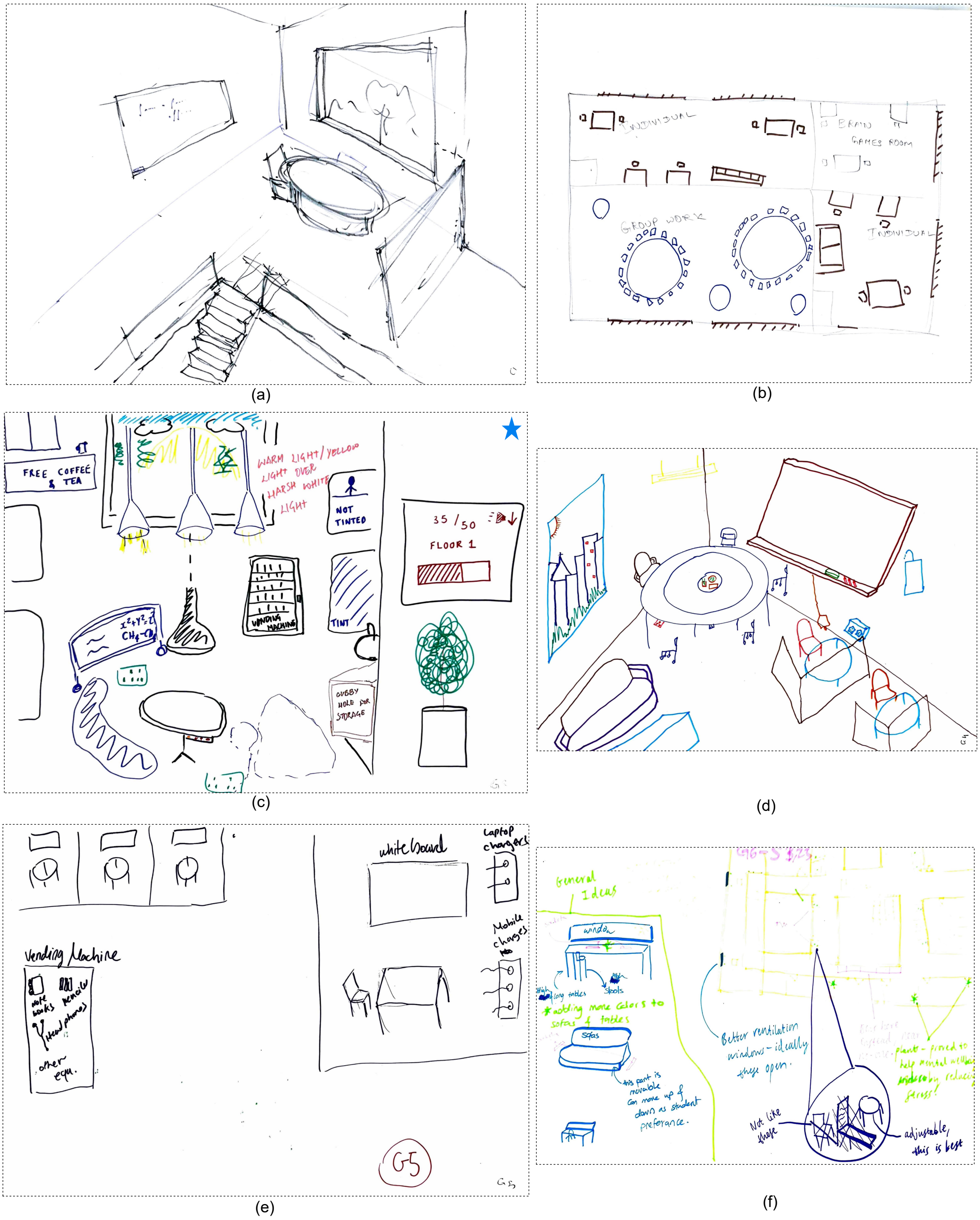


Fig. 3.11 Shows sketches created by participants during the workshop, including sketches from groups 1 to 6.

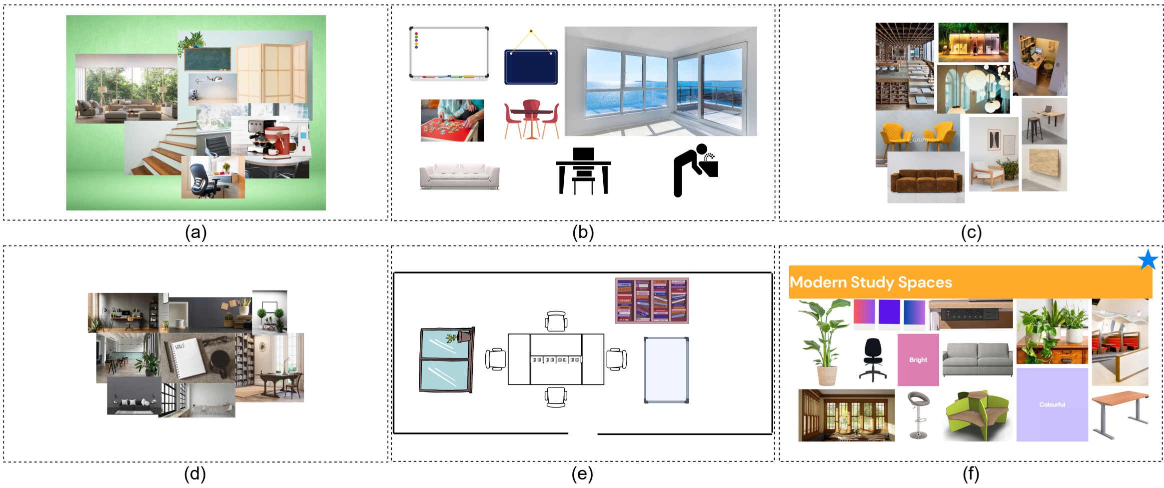


Fig. 3.12 Shows mood board designs created by participants during the workshop, from groups 1 to 6.

3.4.2 Leveraging sensor data for understanding student behavior

Students' use of study spaces varies based on factors such as location, furniture type, and other amenities. Figure 3.13 illustrates the percentage of study spaces utilized, as determined by occupancy sensors. In Study Space S1, students predominantly use the area individually. In contrast, Study Space S2 sees more shared use, followed by individual use. Study Space S3 mirrors S1, with the majority of students using it individually. This preference can be attributed to limited desk space, insufficient power sockets, and less privacy in S1 and S3 compared to S2.

Facility managers have commented on these findings, expressing a preference for all spaces to be used more collaboratively rather than predominantly individually. However, they acknowledge challenges, such as the design of S1, featuring smaller desks that can be moved for events and emergencies. Adding more power sockets is a possibility, but it may lead to an unsightly mess. Nevertheless, they plan to renovate furniture and power sockets to optimize the use of study spaces. The mean satisfaction rates of facility managers regarding their awareness of space usage, as assessed through the sensing solutions, were higher after the experiment compared to before. A Wilcoxon signed-rank test was conducted to compare satisfaction levels before and after the experiment. The results indicated a statistically significant increase in satisfaction following the experiment, $W = 9$, $z = 3.09$, $p = .002$. (W is the test statistic, z is the standardized score, and p is the p-value). Before the experiment, satisfaction levels varied more among participants, indicated by a higher standard deviation. After the experiment, satisfaction became more consistent, reflected by a lower standard deviation.

The occupancy data for these study spaces were collected over nearly ten months. As shown in Figure 3.14, occupancy peaks during exam periods, specifically at the end of February and after the Easter holiday. Study Space S2 is the most occupied, followed by S1, and then S3. S2 experiences peak usage from as early as 7 a.m., indicating students' tendency to arrive early, reserve their spots with belongings, and then leave briefly for coffee or breakfast. Facility managers have observed this behavior frequently but find it challenging to manage. They considered implementing a booking system but acknowledged difficulties in monitoring attendance and ensuring fair use of spaces. They also proposed a policy where unoccupied booked spaces could be reassigned after 15 minutes, but this could lead to concerns about privacy and surveillance among students. As one facility manager (FM2) expressed, *"I guess the biggest concern about monitoring dashboard is that kind of policing and yes, data tracking surveillance type thing? I personally don't mind being watched and work and as there's a student and not saying that they'd be watched, but if I knew that data was being collected on me or anything along those lines, I don't know."*

Some facility managers believe that offering a variety of study spaces prevents prolonged occupation of a single space, allowing more students to access study areas. For example, Study Space 3 is used intermittently by different students, unlike the other spaces that are occupied almost all day by the same individuals.

Study Space 1 is the second most utilized area after S2, peaking around 9 a.m. and tapering off after 6 p.m. This usage pattern corresponds with the building's access policy, restricting entry to card-carrying students and operating hours from 8 a.m. to 6 p.m. on weekdays, with closure on weekends. Study Space 3 sees minimal use due to its noisy environment and secluded location, making it less appealing than the centrally located and easily accessible study spaces.

To gain more insights into occupancy patterns in study spaces, we compared the usage of individual chairs in those spaces. As illustrated in Figure 3.15, We start with the three study spaces, each labeled with numbered chairs, followed with the first chart at the top shows all occupied chairs in S1, followed by two charts detailing the usage of Chair 1 and Chair 4. Chair 1 is located facing the wall near the stairs, while Chair 4 is positioned next to the wall facing the common area, offering more privacy compared to Chair 1. This difference in location and privacy suggests why students prefer working individually in S1, predominantly using Chair 4. The increased privacy of Chair 4, away from others' view, and proximity to power sockets might contribute to this preference. However, during peak exam periods starting in May, students tend to use all available chairs due to limited free spaces.

In Study Space S2, Chair 4, marked in green, was the most used. It is situated next to a large window and faces the recycling bins, as shown in Table 3.4. This location likely attracts

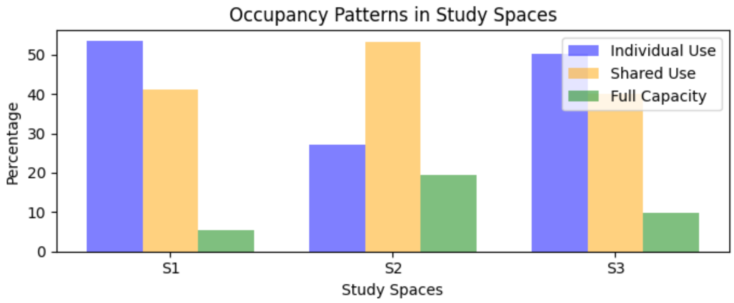


Fig. 3.13 Spaces occupancy pattern.

students who enjoy natural light and outside views to rest their eyes and avoid screen glare, prompting them to sit next to the window.

For Study Space S3, Chairs 2 and 4 were the most frequently used. These chairs are located next to the wall on the sofa, also illustrated in Table 3.4, with Chair 2 facing the large window and Chair 4 on the opposite side. From mid-May onward, Chair 4 saw increased usage compared to Chair 2. This shift can be attributed to the late sunset in June, which may affect occupants sitting in Chair 2. A similar decrease occurred in Chair 2 of Study Space 2, likely due to sunlight reflecting off screens and impacting the students sitting in that chair.

Figure 3.16 provides a summary and average usage of chairs across study spaces over time. The left side of the figure shows the number of chairs used, while the right side displays the percentage of chair usage for each study space. Overall, S2 has the highest average chair usage over the entire period, followed by S1 and S3. Additionally, S1 show a higher percentage of usage for individual chairs compared to S2, indicating a preference for specific seats in this study space.

3.4.3 Empowering decision-making with sensor data

We gathered feedback from students using study spaces through a QR code placed on each desk, soliciting their satisfaction levels regarding cleanliness, comfort, noise levels, and other factors influencing their study environment. Additionally, students were optionally invited to upload pictures of aspects they found unsatisfactory or areas they believed could be improved. These inputs were invaluable in understanding student opinions and needs related to these spaces.

Figure 3.17 (a) presents the satisfaction feedback from students for each study space. In Study Space S1, students were generally satisfied with the temperature and lighting, which is provided by ceiling lights and natural light from windows on the top floor from the building

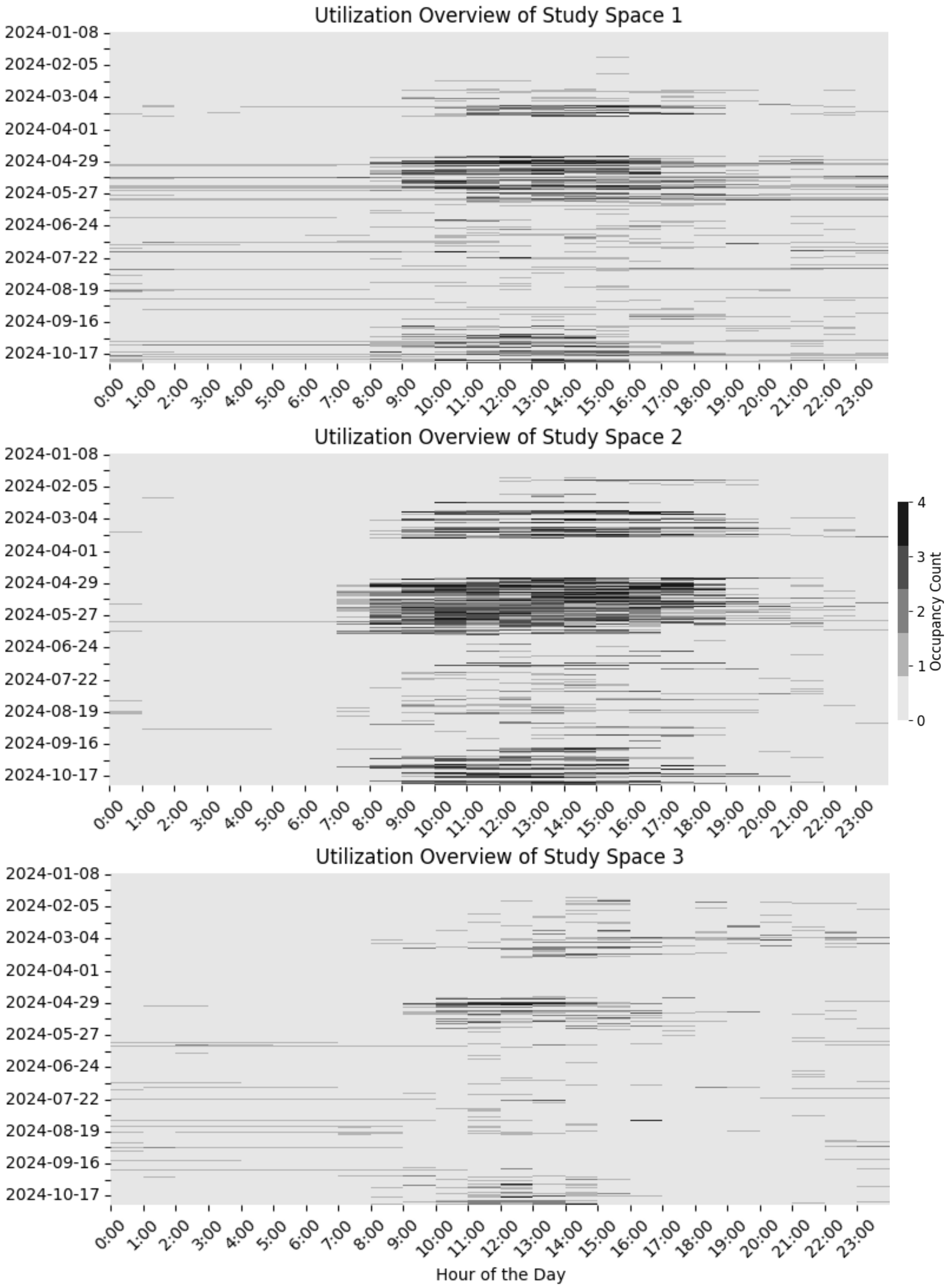


Fig. 3.14 These heatmaps show occupancy patterns for three study spaces, with values from 0 to 4. Colors represent occupied sensors, with lighter shades for lower and darker for higher occupancy.

Fig. 3.15 Occupancy patterns of chairs in three study spaces (S1, S2, and S3).

centre. However, noise levels were a concern due to its central location near stairs, offices, and lecture halls.

For Study Space S2, students expressed higher satisfaction with lighting, comfort, and overall ambiance. However, cleanliness was a point of dissatisfaction, primarily due to the presence of recycling bins and occasional food left behind, affecting the space's tidiness and attractiveness. In Study Space S3, students were satisfied with temperature and the

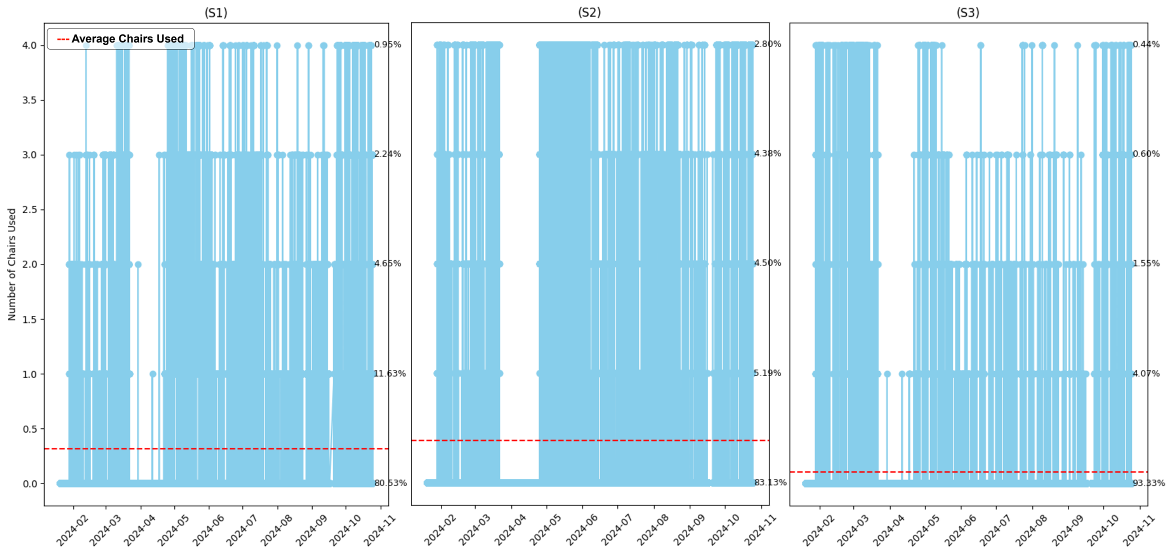


Fig. 3.16 Number of chairs used over time .

ambiance, similar to S2. However, noise was a notable issue, stemming from a nearby printer, toilets, and noise from the adjacent glass wall as can be seen in Table 3.4 for S3. These distractions occasionally disrupted students' concentration during study sessions. Further, Figure 3.18 shows a radar chart comparing three study spaces across key factors: utilization, environmental conditions, individual usage, shared usage, cleanliness, and comfort, based on sensing data and occupant feedback. It illustrates that S2 is the most shared space compared to S1, which is predominantly used for individual study. Additionally, S2 is the most utilized and comfortable space, exhibiting better environmental conditions than the other study spaces, while S1 and S3 are primarily used for individual study, with students expressing greater satisfaction regarding cleanliness in S1.

Facility managers found these insights instrumental in identifying and addressing specific issues within each study space. Figure 3.17 (b) highlights problematic areas identified by students, marked with red stars, which were shared with facility managers to inform decisions on space renovations or improvements. In S1, the central stairs were identified as the main source of noise and distraction, particularly during peak times such as the beginning and end of lectures. For S2, concerns centered around the recycling bins and water fountain within the space, impacting cleanliness and creating occasional disturbances. In S3, students pinpointed noise from the nearby printer, toilets, lifts, and adjacent hallway as significant distractions affecting their study experience.

Facility managers indicated that these student feedbacks would guide future renovations, possibly relocating noisy elements to less disruptive areas or redesigning study spaces and furniture layouts to enhance student comfort and productivity. As Facility Manager FM3

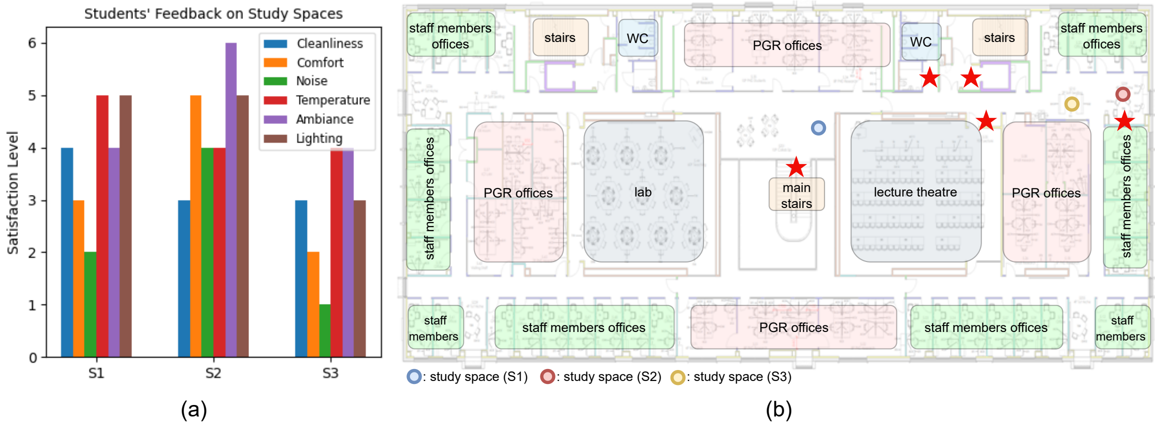


Fig. 3.17 Shows (a) students' satisfaction levels for study spaces, and (b) highlights problematic areas with red stars based on their feedback.

remarked, *"It helps us make concrete decisions about the furniture that may need changing or rearranging."*. Further, we are working to motivate students to provide feedback by updating QR code prompts, highlighting the minimal time commitment needed, to enhance the usability and satisfaction of study spaces.

The median satisfaction rates of facility managers regarding how the collected information enhances the decision-making process were higher after the experiment compared to before. A Wilcoxon signed-rank test was conducted to compare satisfaction levels before and after the experiment. The results indicated a statistically significant increase in satisfaction following the experiment, $W = 7$, $z = 2.14$, $p = .032$. The post-experiment satisfaction levels exhibited a slightly higher standard deviation than the pre-experiment levels, suggesting greater variability in satisfaction among facility managers after the experiment. This indicates mixed perceptions of the effectiveness of the sensing solutions in the decision-making process.

3.4.4 Fostering student well-being through environmental understanding

Sensor data reveals differences between study spaces located on the same floor within indoor environments, despite the central heating system being controlled uniformly by facility managers to maintain consistent environmental conditions throughout the building. Figure 3.19 presents data collected from sensor nodes installed in these study spaces, providing insights into various environmental factors.

In the top-left corner of Figure 3.19, relative humidity and temperature readings for study spaces are displayed. Study Space S2 shows the highest humidity level and the lowest temperature compared to other spaces. This suggests potential issues with ventilation in S2 [278], possibly exacerbated by a large window bringing in colder air from outside. Conversely, Study Space S1 exhibits the lowest humidity and higher temperatures relative to other spaces, indicating effective ventilation and a warmer environment possibly due to its central location within the building. Building design and ventilation systems contribute significantly to these differences among study spaces.

The top-right corner of Figure 3.19 illustrates temperature variations during day and night times, with lighter colors representing nighttime temperatures. Nighttime temperatures are generally lower than daytime temperatures across all study spaces. This variation reflects energy-saving measures such as adjusting the building's heating system, utilizing natural cooling from open windows in some areas, and the insulation properties of building materials.

In the bottom-left corner, CO2 levels in study spaces are depicted, showing higher levels in S1 compared to others. This could be attributed to S1's proximity to main stairs and offices, where increased human activity and conversations occur, influencing CO2 concentrations. Additionally, the last chart depicting VOCs levels in study spaces reveals elevated levels in S3 compared to others. VOCs are associated with "sick building syndrome," causing various discomforts among occupants [34]. Further investigation and discussions with occupants indicated that S3's proximity to a cleaning material storage room and toilets contributed to higher VOC levels. While within safe limits, facility managers are considering strategies to mitigate VOC levels in S3, potentially by adjusting cleaning practices or ventilation systems.

3.5 Discussion

We present findings from our workshop with students and observations from sensor data highlighting occupancy patterns in study spaces. This discussion explores how sensor technology enhances student experiences and optimizes study space management in educational settings. By analyzing usage patterns, sensors improve resource allocation, and create adaptable study spaces. Additionally, we discuess how sensor data enhances facility management practices to promote efficient space use and enhance student engagement.

3.5.1 Sensor capability

Sensor data have revealed some hidden behaviors and conditions in study spaces that facility managers were previously unaware of. For instance, Figure 3.19 indicates a potential issue with the heating system or uneven air distribution. This is evident when comparing S1 and S2 over several months, as S1 consistently shows the highest temperature and lowest humidity,

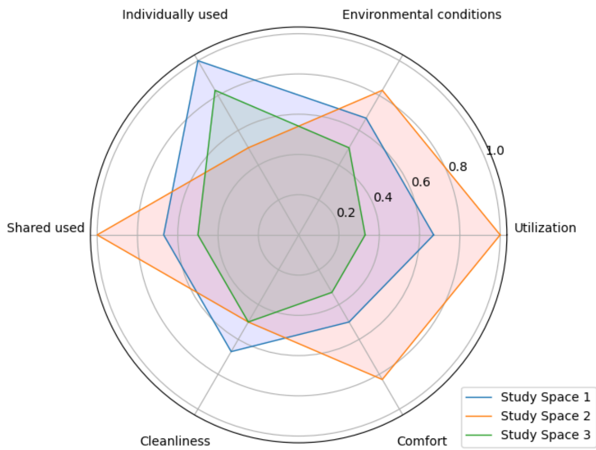


Fig. 3.18 Shows a radar chart comparing three study spaces across key factors: utilization, environmental conditions, individual usage, shared usage, cleanliness, and comfort, based on sensing data and occupant feedback.

whereas S2 exhibits the opposite trend with higher humidity and the lowest temperature, despite all study spaces being located on the same floor.

These discrepancies are not easily recognized by humans because they require a comprehensive overview to identify. Additionally, external factors such as the proximity of the cleaning room to S3 result in higher VOC gas levels there compared to other study spaces. This has prompted facility managers to consider relocating either the cleaning room or the study space. Moreover, we believe that incorporating additional sensor data, such as vibration, globe temperature, and particulate matter (PM), will aid in making more informed decisions.

Facility managers valued the presented data, especially in gauging the duration of student occupancy in specific study areas. This information is critical for assessing space utilization and student well-being. FM1 emphasized the significance, stating, *"Having data on how long students stay in one spot would help us understand their well-being. For example, as a student, I used to arrive at the library at 7:00 AM and stay for extended periods, which I now recognize as unhealthy."*

We also believe that integrating sensor data with student feedback and other building systems will significantly assist facility managers in quickly identifying and addressing issues, thereby facilitating better decision-making.

3.5.2 Student behavior toward different study spaces

Students exhibited different behaviors in study spaces regarding their arrival and departure times, usual usage hours, the impact of external factors, and whether they used the spaces individually or with others. This indicates that factors such as location, furniture, and nearby

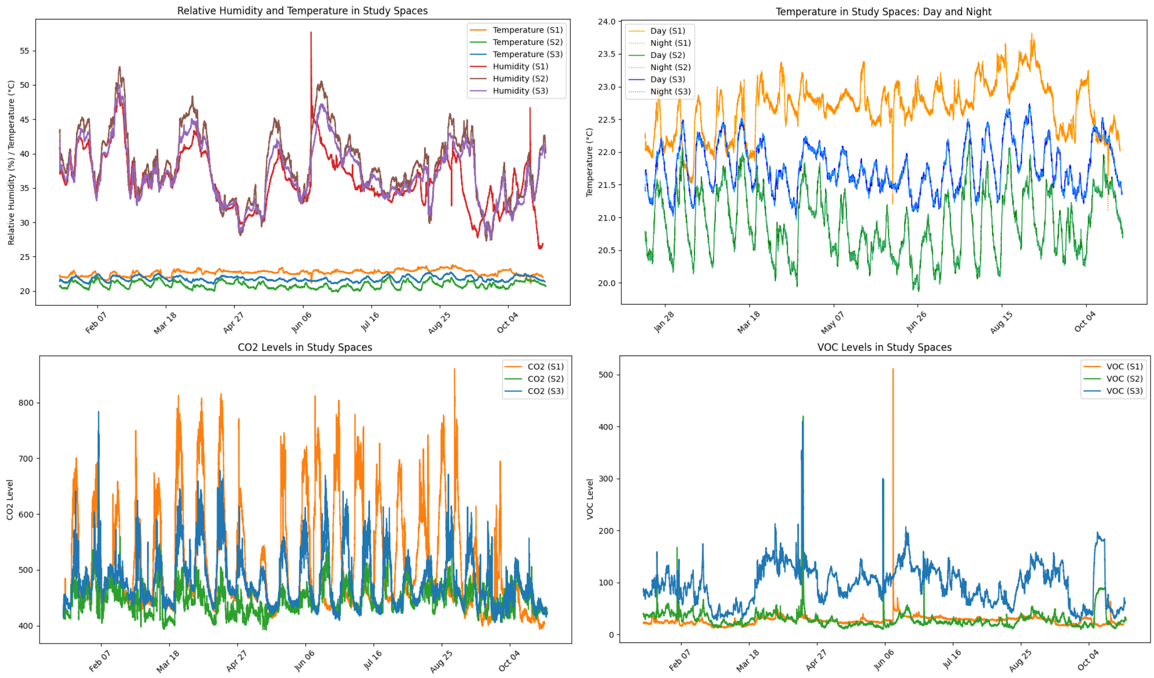


Fig. 3.19 Study space conditions: Humidity, temperature (Day/Night), CO2, VOC.

amenities need to be carefully planned from the building design phase. For example, the study space S2, located near a large window and equipped with a big table, attracted students to spend more time there compared to S1, where satisfaction was lower, as shown in Figure 3.17 (a). The utilization of these spaces also differed, with students tending to use S2 more frequently than S1 and S3, as seen in Figure 3.13. This disparity could be due to factors such as desk size, privacy, and overall furniture arrangement, leading to wasted study chairs in less preferred spaces.

Building policies also significantly impact the utilization of study spaces. Figure 3.14 illustrates that most students arrive at the building after 8 AM and leave around 6 PM, primarily because the building policy restricts access to students from other departments outside these hours. Consequently, students from the same department utilize the spaces after 6 PM and can stay as long as they wish. Adapting policies like a 24/7 access policy or extended hours policy could provide greater flexibility for study and research, allowing students and faculty to access resources at any time.

Furthermore, understanding student behavior through sensors and technology can optimize the use of study spaces and enhance student well-being. By monitoring occupancy patterns, universities can efficiently manage resources, ensuring study areas are available and not overcrowded. This data can also encourage healthier study habits by promoting breaks and reducing long periods of sitting. Leveraging technology creates a more supportive and effective educational environment.

3.5.3 Creating versatile study spaces for student needs

Analyzing the collected data, we identified several common preferences among students, such as a preference for round tables near windows and a desire for natural light. However, there were also divergent personal preferences that differed from the majority view. All groups included a window in their ideal study space designs, highlighting its importance in creating a productive and relaxing study atmosphere.

Catering to individual needs can be complex. For example, one participant expressed a preference for lower tables, which contrasts with the popular opinion: *"It's more comfortable in a setting where I can put my feet on the table, put my laptop on my legs and start working"* (P3G6). Similarly, opinions varied on movable tables. Addressing these personal preferences may not incur significant costs, but it would be beneficial to incorporate a variety of furniture and equipment to cater to the diverse needs and preferences of students. Variety in design enhances flexibility and inclusivity, accommodating the unique study habits of different individuals.

The primary needs identified by students during this thesis centered around access to natural light and a sense of privacy while studying. These aspects should be carefully considered when designing or refurbishing educational facilities to enhance students' learning experience.

Specifically, study spaces should ideally be located near windows to maximize exposure to natural light. Alternatively, effective use of artificial lighting, mimicking natural light as closely as possible, can also create a comfortable atmosphere conducive to studying. Participants often cited concerns about harsh lighting that strains the eyes or causes reflections on laptop screens, as one student noted: *"The lighting is too bright and uncomfortable, like a spotlight"* (P3G2), and another shared: *"It's like the light streams directly into your eyes, making it difficult to concentrate"* (P2G2).

Moreover, privacy was a major concern for many students. While open layouts promote collaboration, they can also affect personal privacy and create distractions. Balancing privacy with the benefits of openness can be achieved through various solutions. Recommendations from this thesis included smart tint-adjusting glass, proposed by Group 3. Other measures could include using regular glass dividers, placing plants in different locations, using desk shields, and adding bookshelves. These methods ensure necessary privacy while maintaining an open and collaborative study environment.

3.5.4 Optimizing space utilization through technology

We recommend leveraging technology to optimize space usage within the building. For instance, Group 3 proposed a screen display showing real-time occupancy levels across different floors, a concept that could significantly aid students in finding available spaces while saving time. Integration of occupancy sensors would be an effective approach in this context, benefitting both students and facility managers. Such technology can provide data-driven insights into the patterns of space utilization over time, enabling a deeper understanding of how students interact with these spaces.

A study conducted by Lau et al. [149] demonstrated this application of technology, using custom sensor nodes to evaluate spatial utilization. The study revealed intriguing patterns; for example, on hot days, spaces saw the highest use during morning and evening hours, while on cloudy days, afternoon and early evening usage peaked. Furthermore, the study indicated the profound influence of weather on the use of outdoor spaces.

It's also worth noting that some spaces designed to accommodate group study are often occupied by individuals. This scenario underscores inefficient use of available resources. To address this, we could deploy various behavioral interventions that encourage students to share spaces. For instance, designing spaces that foster interaction and collaboration - like communal tables or seating arrangements facing each other - can promote a more collective use of space. Similarly, using visual cues such as desk pads can signal that the space is meant for shared use, discouraging individuals from monopolizing it.

In conclusion, while the incorporation of technology offers immediate and efficient solutions for optimizing space usage, behavioral interventions may require more time to effect noticeable changes in occupants' behavior. However, these gradual changes can ultimately contribute to a healthier and more efficient long-term use of building resources.

3.5.5 Enhancing facility management through student engagement and feedback

The role of a facility manager encompasses various responsibilities within a building, including understanding and addressing occupants' feedback and needs. However, a noticeable gap exists between these parties. This gap may stem from facility managers' unawareness of their role or their inability to monitor the entire building due to a lack of access to advanced technology.

On the other side, most students seem unfamiliar with the role of facility managers. During our experimental workshop, we asked students about their awareness of the facility managers' role in the building. The results were striking, with only a quarter of participants

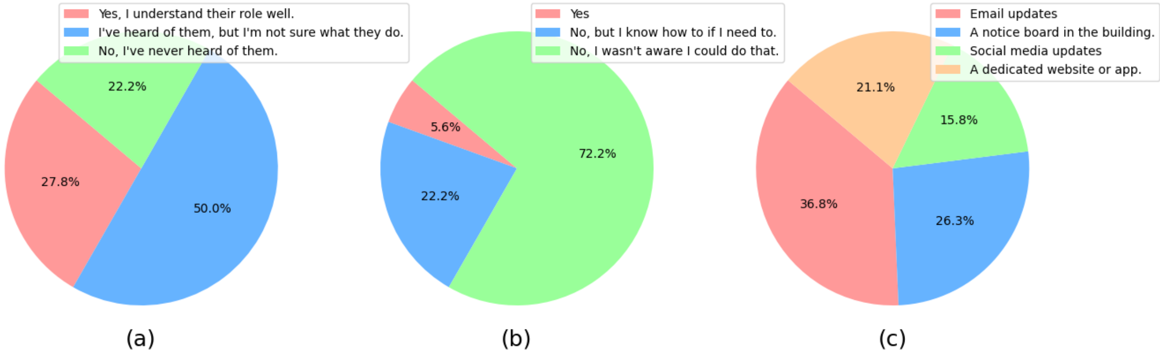


Fig. 3.20 The representation captures participant responses about their understanding of facility managers' roles (a), previous interactions with them (b), and the preferred method of contacting them (c).

indicating familiarity with the term 'facility manager'. Half the participants had heard the term but were uncertain about what the role entails. The illustration in Figure 3.20 shows participant feedback concerning their understanding of facility managers' roles, their history of interaction with them, and their favored method of contact.

3.6 Summary

This chapter explored how sensor data can improve our understanding of student behavior and optimize space usage in a university building. The study focused on how sensor technology can improve resource efficiency and space management by monitoring occupancy and environmental conditions in different study spaces. Workshops and interviews with students and facility managers helped shape the research approach.

The study addressed three key research questions in Chapter 3. First, it demonstrated how sensor data reveals distinct usage patterns across study spaces, helping identify underutilized areas and understand student behavior in response to environmental conditions. Second, it showed how facility managers can use this data to align their expectations with actual space usage, enabling more informed decisions on space allocation, maintenance, and resource management. Finally, the data highlighted factors affecting student comfort, such as temperature, lighting, and noise, offering insights into the environmental conditions that influence student well-being.

The study addressed three key questions in Chapter 1. First, it demonstrated how sensor data reveals occupant behavior and preferences, with external factors like temperature, lighting, and noise identified as significant influences on student comfort. Second, the research showed how IoT systems and sensor data can enhance communication between facility managers and occupants by providing real-time insights into space usage, feedback, and environmental conditions. Lastly, the data-driven insights into space utilization highlighted how monitoring environmental data can help facility managers make better decisions on space management and building operations, emphasizing the role of data in improving building management practices.

Although this study provides valuable insights into how sensor data can inform facility management and student behavior analysis, several questions remain unanswered. Notably, the study does not fully explore how to predict future occupancy patterns or how to integrate predictive modeling techniques into real-time facility management. Additionally, while this research has identified general trends in space usage and comfort factors, it does not account for the influence of other external variables that may affect student behavior, such as social interactions.

While this chapter highlighted key patterns in space usage and student behaviors, it did not address how to effectively help close the communication gap between building occupants and facility managers, nor did it explore reporting issues, feedback mechanisms, or increasing occupant awareness of their surrounding environment to improve space management. These gaps motivate the next experiment, which will focus on evaluating a medium device's ability to facilitate a better communication and real-time feedback to support sustainability and adaptive building management.

Chapter 4

EcoCube: An IoT-driven solution for environmental awareness and human-building interaction

4.1 Overview

In today's architecture, buildings are designed to accommodate a diverse range of activities, such as open offices, collaborative areas, and private meeting rooms. This approach aims to create a dynamic environment that maximizes space efficiency and enhances occupant productivity [128, 58]. However, cost-saving measures or adherence to standard practices in many construction projects can lead to infrastructure that may not fully meet the long-term needs of its occupants. This results in buildings that may be functional but inefficient or uncomfortable, with layouts that fail to optimize space or energy management [95]. The challenge becomes even more pronounced when considering the trade-offs between occupancy and design. A building might be designed for maximum capacity, but without taking into account the diverse needs and behaviors of the occupants, it can quickly become underutilized or inefficient.

Post-occupancy evaluations are crucial to understanding how buildings perform once in use, yet these evaluations are often neglected [155]. Without ongoing feedback, it becomes difficult to determine how spaces can be improved to meet occupants' needs over time. Facility managers are responsible for maintaining building operations, ensuring safety, and managing the use of space. They need accurate, real-time data to understand which areas are heavily used and which are underutilized, as well as insights into occupant preferences and desired improvements [6].

However, a communication gap often exists between facility managers and occupants [54]. Occupants may choose to alter their spaces independently rather than seeking help from facility managers, while facility managers may not have sufficient feedback to address the actual needs of users. This disconnect can lead to missed opportunities for improving comfort and functionality.

To bridge this gap, technology that facilitates continuous communication and data collection is essential. By deploying sensors and other technological tools, facility managers can gain real-time insights into environmental conditions and occupant comfort. A medium that is accessible, user-friendly, and always available is critical for enabling occupants to easily share feedback, fostering more responsive and effective management. Establishing an intuitive feedback mechanism allows for informed decision-making, ensuring that the building better meets the needs of its users.

The development of EcoCube was directly influenced by insights gained from the SpaceSense project, particularly the lessons learned from passive sensing and the limitations in providing occupants with a way to actively interact with the system. SpaceSense, as discussed in Chapter 3, relied heavily on passive environmental data collection, providing valuable information about space usage and environmental conditions. However, one limitation of this approach was that it did not allow for direct feedback from occupants, which could limit the ability to address specific comfort or space usage issues as they arise. This gap in communication underscored the need for an interactive feedback mechanism, which led to the development of EcoCube. By incorporating real-time feedback capabilities, EcoCube aims to actively involve occupants in building management, offering them a means to report issues and communicate their needs effectively. This shift from passive sensing to interactive feedback was driven by the understanding that occupant engagement is essential for improving both user satisfaction and the overall effectiveness of facility management.

Our research aims to deepen the understanding of HBI and promote continuous improvements in building facilities. We focus on addressing the following key questions:

- Q1: Assessing Effectiveness: How can a tangible medium effectively bridge the communication gap between occupants and facility managers?
- Q2: Evaluating Impact: In what ways does such a device influence occupant satisfaction and improve facility managers' efficiency in building management?
- Q3: Thermal Preferences: How can sensing data be used to identify preferred temperature ranges and enhance thermal comfort in open spaces?

In order to answer these questions, we conducted a study in Abacws building, as detailed in Section 3.3.3. Our process began by engaging facility managers and students to understand their specific needs, as detailed in Section 3.3.1, which guided the design of our initial prototype. This prototype was used by students to provide feedback, which informed several iterations of the design. We then collected data and presented our findings to facility managers. A real-time dashboard was developed to visualize data derived from student feedback, enhancing managers' monitoring capabilities.

We propose a device that acts as a communication medium between students and facility managers. This device aims to increase occupants' awareness of their environment, encourage feedback, and allow them to report issues and share temperature preferences. Its functional yet decorative design ensures it is suitable for integration in various spaces within the building, optimizing both space usage and occupant satisfaction. The contributions of this work are as follows:

- Development of EcoCube: We developed EcoCube, a tangible IoT device designed to bridge communication gaps between occupants and facility managers in open-plan study spaces. It enables real-time issue reporting and raises environmental awareness, offering a novel way to integrate sensing with human interaction.
- Design and Integration: EcoCube features an aesthetically neutral and unobtrusive design that blends into study environments without disrupting occupant behavior, while still providing useful environmental feedback to users and facility managers.
- Evaluation and Impact: Using workshops and interviews with students and facility managers before and after deployment, we assessed EcoCube's usability and impact. The results showed improved communication and satisfaction among both groups.

These findings contribute to the growing body of knowledge on improving communication and space management in educational environments, particularly through the use of IoT and HBI principles.

4.2 Research methodology

We conducted a workshop (W1) with students and interviews with facility managers, which revealed a significant communication gap between the two groups. Students were largely unaware of the roles of facility managers and how to effectively communicate with them. To address this, we organized an additional workshop (W2) with students to explore their preferences for a communication medium that could bridge this gap. The workshop (W2) introduced participants to various features of the study spaces in the building, explored IoT use

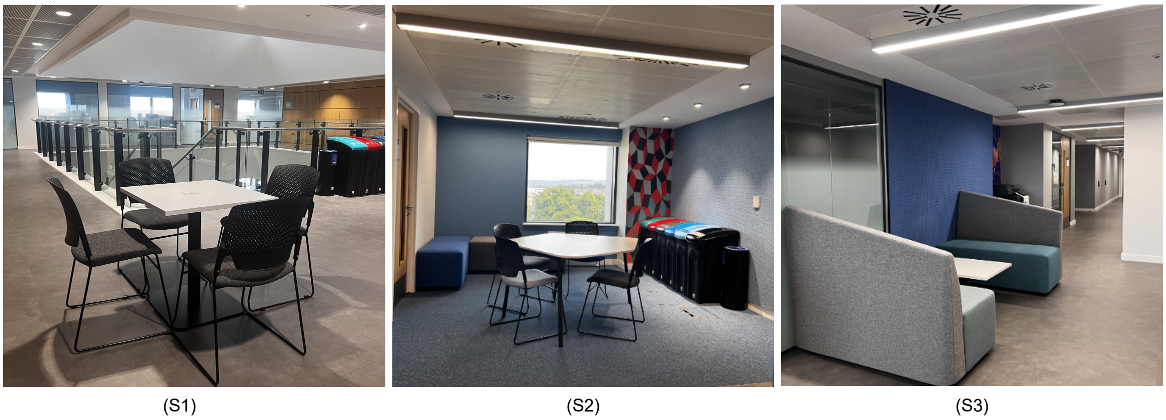


Fig. 4.1 Shows the different study spaces we assessed: S1, S2, and S3, where (S) stands for study space.

cases, discussed interface design considerations, and addressed the specific communication challenges we aimed to resolve.

The workshop (W2) involved nineteen students, aged between 18 and 35, who regularly used the building. Its purpose was to gather insights into their communication needs and preferences. Initially, participants sketched low-fidelity prototypes of a communication device, highlighting the features they desired, while we encouraged them to provide feedback on what they liked, the challenges they faced, and any additional functionalities they wished to see.

During earlier interviews (I1), facility managers had expressed support for a communication medium that would enhance interaction with students and provide more data on student behavior in different study spaces. Such data would enable managers to improve the overall student experience. In this experiment, we utilized three study spaces in a new built building located in the United Kingdom. The EcoCube device was initially deployed in a lab for pilot testing, and after its successful trial and receiving ethical approval from the school's department, we expanded its deployment to the three study spaces.

Following the experiment, interviews (I2) were conducted with facility managers to gather their feedback. These semi-structured interviews combined specific questions with open-ended discussions, aiming to capture their thoughts on the EcoCube, their impressions of the study spaces' performance, and any suggestions for improvement. The interviews were recorded, transcribed, and analyzed thematically to capture the key insights [108].

We also conducted post-experiment interviews (I3) with students to understand their experiences with the EcoCube. Participants were asked to share their thoughts on the device's features, usability, and areas for improvement. Detailed scenarios and tasks were provided for them to complete using the high-fidelity prototype, and their interactions were observed

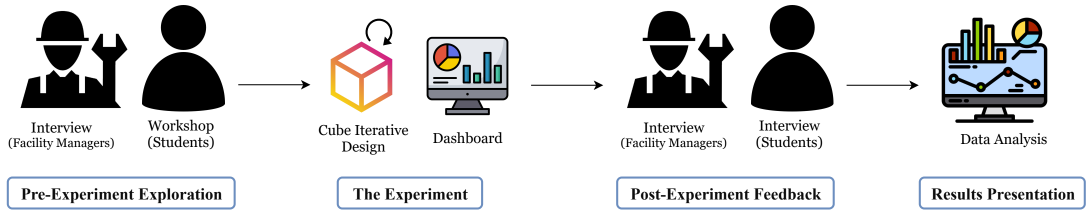


Fig. 4.2 Overview of the experiment methodology, including pre-experiment, main experiment, feedback, and results.

to gather additional feedback. NVivo software was used to organize data into themes, making the coding process more efficient. NVivo helped identify patterns and relationships in the qualitative data, adding rigor to the analysis. The data collected from these interviews were transcribed and thematically analyzed, resulting in four key themes: data acquisition, interpretation, implementation of insights, and user engagement [33]. Coding strategies included open coding to capture initial ideas, axial coding to refine and connect themes, and selective coding to highlight core themes that represented key findings.

For the quantitative analysis, we applied a paired sample t-test to compare participants' satisfaction with communication before and after using the EcoCube. The t-test is a reliable method for evaluating changes in numerical data, making it an appropriate choice for this thesis [225].

The t-test has been widely used in previous studies to evaluate the effectiveness of educational and collaboration tools. For instance, García-Magariño et al. [93] demonstrated performance improvements and ease of use in an IoT collaboration system over time. Similarly, Chochiang et al. [52] showed significant skill improvement and high user satisfaction in the use of ArViz, a tool for teaching IoT programming. Another study by Edgar [74] found that students considered iPad integration valuable and effective for learning in classrooms. These studies underscore the utility of the paired t-test in assessing tool performance and user engagement across various platforms. Figure 4.2 provides a visual overview of the methodology steps used in our experiment.

4.2.1 EcoCube design

The design of the EcoCube is inspired by various cube interfaces from the literature [112, 1] and minimalist monitors described in [243, 67]. Notable inspirations include:

- Physikit: The Physikit system, discussed by Houben et al. [112], features devices like PhysiLight and PhysiBuzz that use light and vibrations for intuitive data visualization.

This concept of utilizing simple sensory inputs for data presentation influenced the EcoCube's approach to environmental readings.

- PrivacyCube: The PrivacyCube [1] addresses privacy concerns by displaying IoT data habits within homes, fostering privacy awareness and promoting discussions among family members. This emphasis on user awareness and privacy considerations helped shape the EcoCube's design philosophy.

We also drew from commercial products with cube-like interfaces:

- CubeSensors: It provides real-time environmental data such as temperature and air quality in a compact form factor. Their design focuses on optimizing user environments through compact, informative displays [62].

- Ticktime cube: The cube serves as a versatile timer with various modes, including countdown and Pomodoro. Its compact design emphasizes convenience and eco-friendliness, aspects that influenced the EcoCube's practical and user-friendly design [257].

- Amazon fire TV cube: It enhances streaming experiences with powerful performance and voice control, integrating seamlessly with entertainment systems. This integration and user-centric design provided insights into creating an interactive and effective interface for the EcoCube [8].

The EcoCube is designed to help occupants of study spaces monitor current environmental conditions, increase their awareness of their surroundings, and provide feedback. It features a 10 x 10 x 10 cm white acrylic cube with a rotating base, allowing easy access to any side. The cube incorporates laser-cut icons and assembles without the need for tools. It includes a 4.3-inch display screen connected to an Arduino microcontroller and various sensors for measuring temperature, humidity, sound, light, and CO2. The device is Wi-Fi-enabled, transmitting data to the cloud every five seconds.

In response to post-experiment feedback, where participants mentioned issues with the screen viewing angle and the need to stand to use the device comfortably, we addressed this by 3D printing a support piece to improve screen visibility, as shown in Figure 4.9 (b). This enhancement ensures that the screen can be viewed more comfortably from different angles.

Our design principles for the EcoCube focused on several key aspects. User accessibility was a top priority, ensuring that the device could be easily interacted with from any side. We also addressed visibility and comfort based on feedback, making adjustments to improve screen visibility and enhance overall user experience. The integration with the environment was another important consideration, as we aimed to create a design that blends seamlessly with the existing study space aesthetics. Further, we emphasized functional design, incorporating various sensors and connectivity features to provide comprehensive environmental data.

The final design of the EcoCube, including the rotating base and improved screen support, is illustrated in Figure 4.9 (a) and (b). Our design was guided by the following considerations:

Usability and convenience

The EcoCube is designed with usability and convenience in mind, ensuring that it is intuitive and user-friendly even for those with no prior experience.

The main screen of the EcoCube, depicted in Figure 4.10 (a), features large, easy-to-understand icons that represent various types of environmental data. It also includes icons for sound, temperature, light, and air quality, which are prominently displayed on each side of the cube as shown in Figure 4.3. The design was carefully crafted to provide clear, immediate information at a glance. For instance, the sound icon changes color—turning yellow or red—to indicate increasing noise levels, helping occupants efficiently assess their study environment.

In addition to the primary environmental data, the main screen includes a small icon located on the lower right side of the screen for additional building instructions, such as safety tips and sustainability practices. This feature was included based on feedback from facility managers, who wanted to ensure that important building information could be easily accessed by occupants.

The EcoCube operates entirely via a touch screen, eliminating the need for physical buttons. This design choice simplifies interaction and reduces the learning process for occupants. The touch screen interface is designed to be responsive and easy to navigate, allowing students to interact with the device seamlessly. The absence of physical buttons enhances the device's sleek and modern design, while also reducing the risk of mechanical issues and improving overall durability.

Adaptation to workplace patterns

The study spaces in the building feature white ceilings and tables, creating a minimalist and cohesive aesthetic. Initially, we considered a wooden design for the EcoCube to add a natural element to the environment. However, during the workshop (W2), we discovered that the wooden design was too visually distracting for the students. To ensure that the EcoCube would integrate well with the existing decor and remain unobtrusive, we chose a white cube

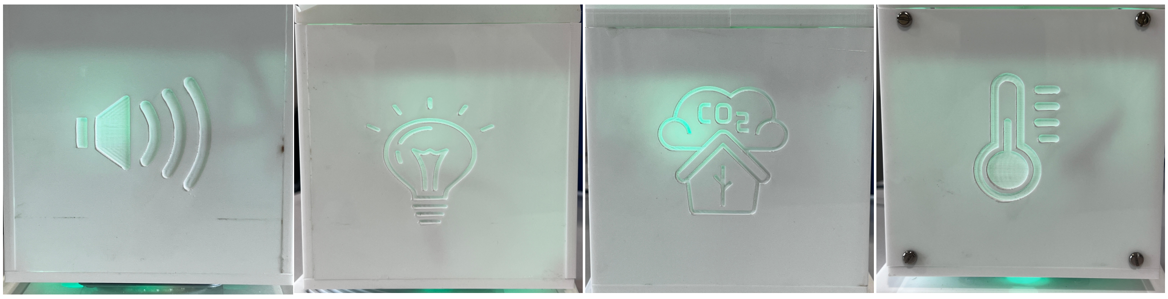


Fig. 4.3 Shows symbols for sound, light, air quality, and temperature displayed on each side of the cube.

design. This color scheme allows the device to blend seamlessly with the surroundings, maintaining the clean and neutral aesthetic of the study spaces.

The EcoCube is equipped with light indicators to monitor sound levels. These indicators are designed to be subtle and non-intrusive, intending not to disrupt the study environment. The indicators only change color after consistent data collection over approximately five minutes. This design choice minimizes unnecessary distractions and intends to communicate environmental changes in a way that is both effective and respectful of occupants' focus and productivity. By adopting this approach, the EcoCube enhances the study environment while respecting the need for a calm and uninterrupted workspace.

Screen features

The screen was designed with a user-friendly interface that prioritizes simplicity and ease of use. Displays essential information through intuitive icons, making it straightforward for users to understand and interact with the device. Key features of the screen are:

- Real-time environmental data: The screen provides real-time updates on environmental conditions, such as the current temperature. Students can also set their preferred temperature, as illustrated in Figure 4.10 (e). The interface updates dynamically to reflect these settings and other environmental changes.

- Feedback icons: The feedback icons display emojis that update based on user input to reflect their feelings about specific aspects of the study space. For example, Figure 4.10 (b) shows how the emojis can represent satisfied, neutral, or dissatisfied reactions, providing a clear and intuitive way for occupants to express their satisfaction or dissatisfaction [5].

- Issue reporting: The reporting issues page, depicted in Figure 4.10 (c), allows students to report problems by selecting from a list of common issues. Students can also choose to include their email address for follow-up and provide additional comments for facility managers, ensuring that their concerns are communicated effectively. Although available for natural use, participants were encouraged to engage with this feature as part of their interaction with EcoCube.

- Thermal comfort assessment: The screen includes features for collecting optional data about students' clothing levels and activities to assess thermal comfort, as shown in Figure 4.10 (f). This data helps in understanding and improving individual comfort levels in the study spaces.

- Building instructions: The screen provides important building instructions, including information about amenities, safety tips, and sustainability practices. This content is accessible through Figure 4.10 (g).

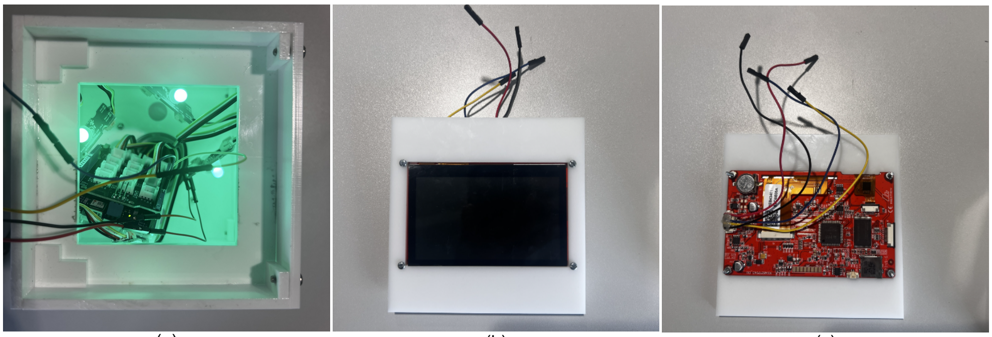
Figure 4.12 illustrates the occupant interaction flow when using the EcoCube device. The interaction begins at the main screen on the top level, from which users can access other screens, including feedback, reporting, and environmental data. This flow allows users to navigate through various screens and ultimately return to the main screen. The EcoCube's screen design is tailored to enhance user experience by providing clear, actionable information and enabling seamless interaction with the device.

Compact size and rotatability

The EcoCube's compact design is tailored to accommodate a range of desk sizes, making it versatile for different study environments. As detailed in Figure 4.1, its dimensions can fit comfortably on desks of varying sizes without overwhelming the workspace.

One of the standout features of the EcoCube is its rotatability. The device can be easily rotated, allowing users to view its display from multiple angles without having to physically move the device as shown in Figure 4.5. This feature is particularly beneficial in shared or small spaces where users may need to reposition their seating or study materials frequently. The ability to adjust the viewing angle enhances the user experience by providing easy access to the screen regardless of the device's placement on the desk.

To address feedback from participants who experienced difficulty viewing the screen clearly, a 3D-printed component was added to the final version of the EcoCube. This component allows the screen to be angled optimally for improved visibility. The adjustment ensures that occupants can view the display at a more natural angle, reducing strain and enhancing overall usability.



(a) (b) (c)

Fig. 4.4 Shows the EcoCube: (a) the inside, featuring an Arduino board, sensors, and RGB LEDs, (b) the front of the Nextion display used, and (c) the back of the display, with modified cable heads to allow screen movement.

4.2.2 Data processing and visualization

The experiment began with a pilot study conducted in a university laboratory. Initially, data collection was performed locally before being transmitted to an external platform. Based on outcomes from the pilot study, several adjustments were made, including switching from battery power to a fixed power source and configuring the data transmission to occur every five seconds. We utilized the ThingsBoard platform [254] for data management. ThingsBoard is an open-source IoT platform that facilitates the management of IoT devices, data collection, and real-time visualizations. For our project, we employed the MQTT protocol, which is well-suited for devices with limited network capacity or resources. ThingsBoard's real-time visualization dashboard effectively displays sensing data, making it an excellent tool for applications requiring clear data insights.

To maintain data quality, we implemented several processing measures. We removed samples with missing or duplicate values, standardized timestamps, and filtered out noisy sensor data to enhance the dataset's clarity on the platform. To address occasional disruptions in sensor data transmission, such as those caused by Wi-Fi connectivity issues or power interruptions during building maintenance, we configured a rule engine in ThingsBoard to trigger email notifications when disconnections occur. Additionally, we enabled the remote restart of EcoCube devices using smart plugs connected to power outlets, ensuring prompt recovery from outages.

The dashboard on ThingsBoard was designed to be user-friendly for facility managers with varying levels of technical expertise. It includes a range of visualizations, such as pie charts that represent student feedback about the study spaces, reported issues, current temperature, and the average preferred temperature by occupants. Figure 4.16 shows these pie charts display satisfaction levels, with green for satisfaction, yellow for neutrality, and red

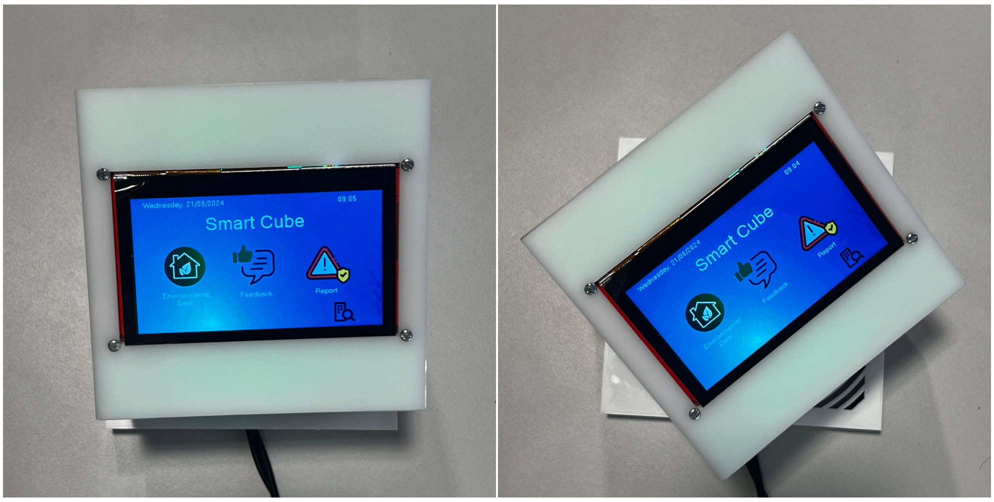


Fig. 4.5 Illustrating the EcoCube's rotatable design, which allows users to view its display from multiple angles.

for dissatisfaction. Percentage values are shown when hovering over any partition, making the data easier to interpret for facility managers. The dashboard also features line charts displaying temperature, noise, sound, and CO2 sensor data. Facility managers can view both live data and historical data for specific periods, providing a comprehensive view of environmental conditions and user feedback. To showcase the capabilities of the EcoCube to participants, we present a practical use case illustrating how Alex, a student, uses the device to manage various aspects of his study environment and communicate with building managers, which can be found in Appendix F.

4.3 EcoCube deployment and data collection

This section covers the deployment of the EcoCube and the data collection process for the experiment. We began by gathering insights from a student workshop (W2) to inform the EcoCube's design, alongside previous interviews with facility managers to ensure it met operational needs. The section discusses the study spaces where the experiment took place, the sensors and components used in the EcoCube, and its placement within these spaces to optimize data collection and enhance user interaction.

4.3.1 Data collection

We began data collection with a three-hour workshop (W1) involving eighteen university students, recruited via an announcement on the university website, as detailed in Section

Table 4.1 Participant information for students.

Demographic	Percentage
Age	
18–24	75%
25–30	22%
31–35	3%
Gender	
Male	53%
Female	47%
Position	
Undergraduate student	77%
Postgraduate student	23%
Time spent at university	
Less than a year	19%
1-3 years	63%
3-6 years	18%
Home climate region	
Tropical regions	17%
Warmer regions	35%
Colder climates	48%

3.3.1. The workshop included two main activities: a building walk and a co-design task for study spaces.

After an introduction to the building and the importance of study environments, students received printed floor plans to guide their exploration. Inspired by social science and HCI walking methodologies [60, 224], participants used recording devices to document their thoughts while freely exploring study areas. This approach offered insights into how design elements impact study behavior. A group discussion followed, where participants shared reflections on each space's strengths, weaknesses, and potential improvements.

In the second part of the process, participants were divided into six groups for a co-design task. Using the provided materials, each group sketched their ideal study spaces. Afterward, they discussed the commonalities and differences in their designs [230]. Facilitators documented feedback throughout, uncovering a communication gap between students and facility managers. Many students were unaware of the role of facility managers, assuming they should contact faculty for building-related issues, as illustrated in Figure 4.17.

To explore this further, we conducted a second workshop (W2) focused on designing a communication medium. Nineteen students were recruited through an announcement on the university website, and participant details are provided in Table 4.1. The workshop lasted two and a half hours. During this session, we identified students' needs for a communication channel with building managers. We introduced participants to IoT technology, communication interface designs, and the challenges of engaging with building managers. Students participated in group activities, where they sketched low-fidelity prototypes of a communication device. They emphasized desired features such as ease of use, real-time feedback, and intuitive design. Snapshots of the workshop (W2) can be seen in Figure 4.6, with some participant sketches shown in Figure 4.7. After presenting the prototypes, we collected feedback on what worked well and areas for improvement. The workshop (W2) outline is provided in Appendix D.

Using the low-fidelity prototypes, we developed medium-fidelity versions in a subsequent session. Participants were asked to interact with these prototypes through provided use cases simulating real-world scenarios, enabling us to observe how they navigated and interacted with the device. Feedback was collected on usability and overall user experience.

Based on participant feedback and insights from the literature on cube interfaces [112, 1], we developed a high-fidelity prototype. This final design incorporated student suggestions, including responsive interaction elements, improved visual design, and enhanced connectivity features.

During the workshops (W2), participants mentioned that noise from other occupants in the study spaces was often bothersome, and they frequently felt uncomfortable addressing it directly with others. This feedback led to the integration of light indicators on the device to signal noise levels, thereby raising awareness among occupants and promoting quieter environments.

We also gathered quantitative data on participant satisfaction with communication between students and facility managers. This was measured using a questionnaire administered before and after their interaction with the device, as shown in Appendix C and E. The questionnaires were developed based on prior research into factors affecting study experiences, such as exploring environmental data, occupant engagement, and promoting sustainable practices [112, 243, 55]. This approach intended that student needs were addressed and facilitated effective communication between occupants and facility managers, enhancing overall satisfaction in study spaces. Further, insights from previous workshops and interviews with facility managers were critical in shaping the design. A post-experiment interview (I3) was also conducted to assess participants' experiences with the device, where they provided detailed feedback on preferred features and areas for improvement. Participants were given tasks using the high-fidelity prototype, and their interactions were closely observed. This iterative process of prototyping, testing, and gathering feedback resulted in a communication

Fig. 4.6 Snapshots of the workshop (W2) conducted with student participants, and some sketches made by them.

device that is user-centered and addresses the communication challenges between students and building managers. The interview (I3) questions can be found in Appendix E.

To gain insights into the needs and perspectives of both occupants and facility managers, we conducted interviews with the facility managers responsible for the building. These managers represented distinct roles within the facility. One manager was responsible for overseeing building health and safety, another managed school operations, which included budget oversight and general management tasks, while the third focused on technical services. Each manager participated in two one-hour interviews: one prior to the deployment of the medium device and another following its implementation. These sessions were recorded to facilitate data analysis. The post-experiment interview (I2) questions can be found in Appendix G.

The interviews were conducted using a semi-structured format, incorporating both closed and open-ended questions. This approach allowed the interviewer to begin with a set of predetermined questions while also encouraging a natural flow of conversation, fostering spontaneous discussions and the inclusion of the interviewer's insights on pertinent topics. Sample questions were distilled into keywords and categorized by content to guide the interview process. In line with the recommendations of Denzin and Lincoln [68], special attention was given to the rhythm of the conversation, allowing for the emergence of new topics organically. The transcripts of these interviews were meticulously prepared and analyzed thematically, as outlined by [33].

4.3.2 EcoCube device

The EcoCube device is designed with two primary components: the cube and the base. The cube is constructed from white acrylic, a choice that aligns with the building's common color scheme of white to minimize distractions for students in study spaces.

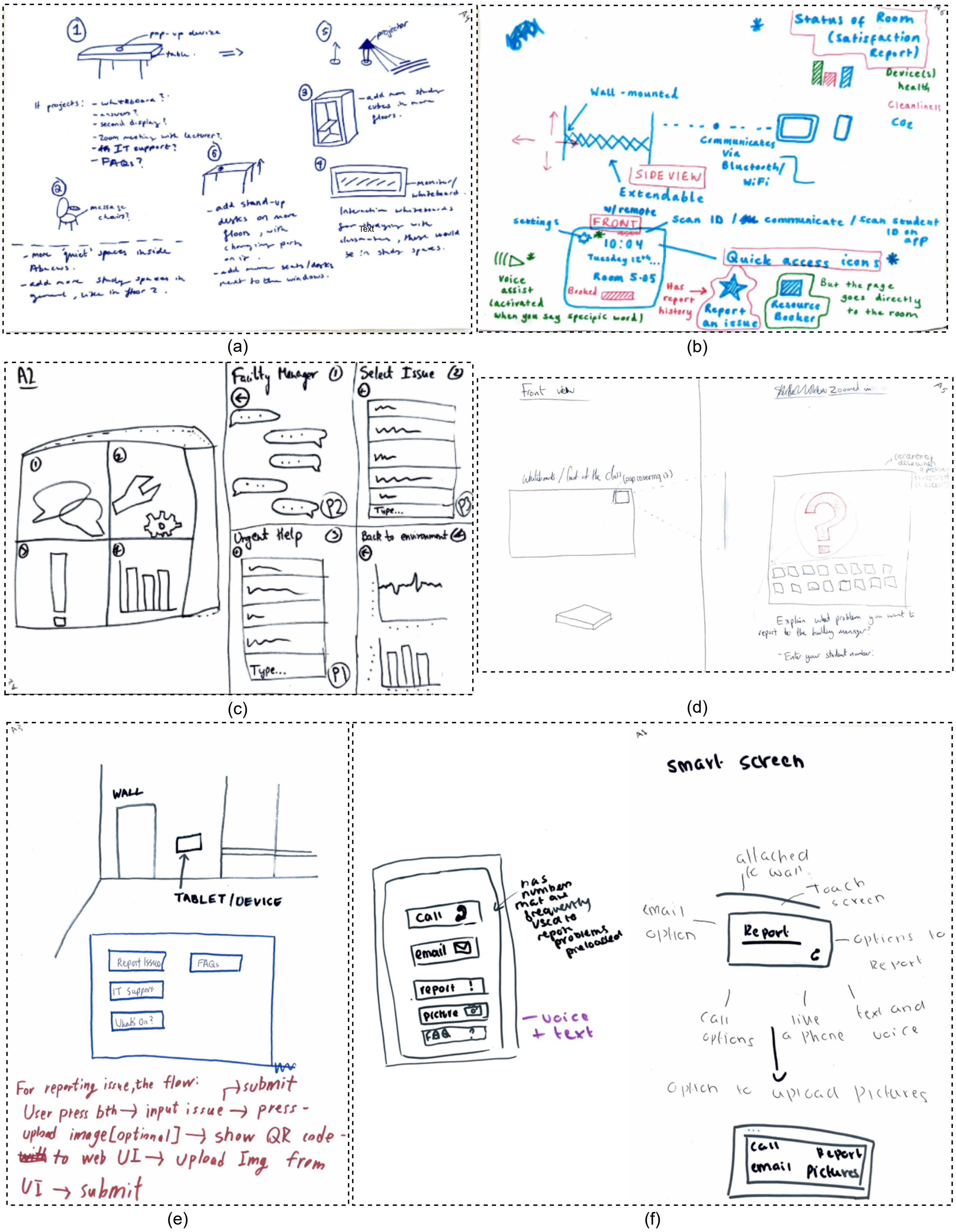


Fig. 4.7 Presents a collection of sketches created by the participants during the workshop (W2). These include sketches from groups 1 to 6, in the order from (a) to (f).

The base supports the cube and houses essential electronics, including various sensors. The EcoCube prototype employed the same set of Grove sensors used in earlier stages in section 3.3.2, , specifically the temperature sensor, sound sensor, light sensor, and carbon dioxide (CO_2) sensor. All sensors were sourced from Grove, a reputable provider of IoT components widely used for educational and research purposes. These sensors were chosen for their reliability, compatibility with the Arduino platform, and cost-effectiveness, ensuring accurate environmental monitoring within the EcoCube. Additionally, RGB LEDs were integrated into the EcoCube to provide visual feedback to users, allowing them to easily interpret the environmental conditions in real time. The LEDs changed color based on varying levels of temperature, humidity, CO_2, and light, thereby enhancing user interaction and improving the communication of building conditions. These sensors play different roles:

- Temperature, sound, light, and CO2 sensors: These sensors continuously monitor environmental conditions in the study spaces. They collect data on temperature, noise levels, lighting, and carbon dioxide concentrations. This data is displayed to occupants on the device and also transmitted to a monitoring dashboard. Detailed specifications of these sensors, including their types and capabilities, are listed in Table 4.2.
- Chainable RGB LEDs: These LEDs are used to visually indicate changes in the study environment. They were designed based on feedback from student workshop (W2) and insights from previous research. The LEDs are programmed to display three colors:
  - Green: Indicates optimal conditions.
  - Yellow: Signals moderate changes or potential issues.
  - Red: Alerts to significant disturbances or problems. This color-coding helps occupants quickly assess their environment without needing to interpret numerical data.

The RGB LEDs draw inspiration from existing research. For example, Houben et al. [112] introduces Physikit, a system that uses LEDs to create physical visualizations of environmental data, thereby enhancing user engagement. Sauvé et al. [231] describes Econundrum, a physical sculpture with LED displays that reveals the carbon emissions from community food choices, aiding users in understanding the environmental impact of their diet choices.

To manage and visualize data, the EcoCube employs an Arduino board and a Nextion display screen [192]:

- Arduino board: Handles sensor inputs, processes the collected data, and controls the LEDs and other components as can be seen in Figure 4.4 (a).

- Nextion display screen: Provides a user-friendly interface, allowing occupants to interact with the device and view real-time environmental information. The display shows data in an easily understandable format, enhancing user experience and interaction. Figure 4.4 (b) and (c) shows the used display.

In our project, we used JavaScript Object Notation (JSON) format for data transmission to ensure compatibility with other data sources. For communication, we employed the Message Queue Telemetry Transport (MQTT) protocol, which is especially suited for devices with low network capacity or limited resources, making it ideal for this thesis.

The sensor data collected during the experiment consisted solely of numerical values, with no personal information included. To enhance security, we encrypted the data using Transport Layer Security (TLS). Using the MQTT protocol, we specified the server address and port for data transmission, ensuring secure communication and safeguarding data integrity.

Overall, the EcoCube is designed to seamlessly integrate into study spaces, offering both practical environmental monitoring and interactive visual feedback to enhance the occupants' awareness of their surroundings.

Table 4.2 Summary of the sensors used in the EcoCube device.

Sensor	Performance	Used by	Purpose
Temperature	Accuracy: ±2%	[270], [125]	Environmental monitoring
Light	Range: up to 540 nm	[191], [59]	Environmental monitoring
Sound	Range: 3.2V $\sim$ 5.2V	[59], [226]	Environmental monitoring
Carbon Dioxide	Accuracy: ±50 PPM	[270], [125]	Environmental monitoring
Chainable RGB LED	Output: 256 shades of grey	[112], [231]	Displaying surrounding changes

4.3.3 EcoCube placement

We carefully considered the placement of the EcoCube to ensure it was both effective and safe within the study spaces. The EcoCube were in place for eight weeks. Initially, we tried placing the cube in different areas on the table—near the edges, in the corners, and slightly off-center. However, these spots did not work well. Students sitting farther away had trouble seeing the cube clearly, and those at certain angles found it hard to interact with. This led to some students being more engaged than others, which was not ideal for encouraging group collaboration.

We also had to think about practical issues, like the need for a nearby power source. The EcoCube needs to be close to an outlet, so we had to position it carefully. We made sure the

Fig. 4.8 Shows the final placement of the EcoCube in the study space, centrally located for optimal visibility and student interaction.

power cable was securely routed to avoid any tripping hazards for students walking around the table. Stability was another key factor; we ensured the cube wouldn't easily fall, even if students moved around or interacted with it actively.

In the previously held workshop (W2) with students, we gathered their feedback on where the cube should be placed. Most students preferred having the cube in the center of the table, as long as it did not take up too much of their personal study space. The central position made the cube easy to see and interact with for everyone, turning it into a shared focal point without disrupting individual work areas. Figure 4.8 shows the final placement of the EcoCube in the study space, illustrating how it looks and fits within the environment. Figure 4.1 shows the different study spaces we evaluated.

By placing the EcoCube in the middle of the table, close to a power source, with a safely secured cable, we achieved a setup that is accessible, safe, and effective. This placement ensures the cube is a central feature of the study space, promoting group interaction and collaboration. It allows all students to engage with both the data and each other in a meaningful way.

4.4 Key findings and insights

This section presents key findings on student interactions with facility managers and their experiences in study spaces. We start by describing how students and facility managers typically communicate. Next, we review student satisfaction across various study spaces and identify the features they prefer. We also explore how students react to temperature changes and their feedback on the communication methods used. Finally, we offer insights into the needs and experiences of building occupants. These results provide a clear view of student preferences and help inform improvements to campus facilities and services.

4.4.1 Usual communication between students and facility managers

There is a lack of communication between students and facility managers in the building. Students generally aren't aware of the facility managers' roles and are not typically asked for feedback about the study spaces. Some students believe they should contact faculty members for issues instead of reaching out to facility managers, who are responsible for the building. Even when students encounter problems like a broken chair in a study space, they often avoid mentioning it out of fear of being blamed.

This issue is confirmed by facility managers. For example, facility manager two (FM2) noted, *"It could just be a simple thing. Yeah, because then sometimes we'll get an email and not so much about this. But uh, this be broken for two weeks. I think we didn't know"*. Similarly, facility manager (FM1) said, *"So we can make buildings safer, but I think people think, Oh no, I didn't do it,' or they can think I did it,' and I'm not going for it or I'm gonna get in trouble,' and we don't want that; we want to be like, we need your voice"*. Further, during a workshop (W1) with students, we asked them about issues they faced and would like to see changed. Many of their concerns were not communicated to the facility managers, highlighting a clear gap in communication between the two parties. For example, in group 3 student 2 (G3S2) reported a lack of privacy in a study space and insufficient power sockets in another, saying, *"There is no privacy; and this one has no sockets to charge your laptop or mobile"*. Another student mentioned, *"The printers should be placed slightly away from the study spaces because they're too loud, and I would prefer more chairs, as some tables currently have only two chairs each"* (G5S1).

During the workshop (W1), when students were asked whom they would contact if they encountered any issues in the building, the majority responded that they would first approach faculty members before contacting building management, as depicted in Figure 4.17 (a). Further, when questioned specifically about their communication with facility managers in the building, the vast majority indicated they had never communicated with them, as illustrated in Figure 4.17 (b). Both students and facility managers face limitations; when students were asked if they had ever contacted facility managers regarding issues in the building, the majority responded negatively, representing 77.2% of participants, as shown in Figure 4.17 (c). Additionally, building management showed a deficiency in motivating students to provide feedback while they were in the building, as demonstrated in Figure 4.17 (d), where the majority of participants had never been asked to give feedback before.

(a) (b) (c)

Fig. 4.9 Shows (a) the final high-fidelity EcoCube design, (b) the addition of a 3D piece to adjust the viewing angle, and (c) another angle view of the device.

4.4.2 Student satisfaction levels across different study spaces

Students have mixed feelings about the features in the study spaces. The majority tend to agree on what they like or dislike about each study space in the experiment. Figure 4.18 represents the satisfaction levels for the three study spaces. These spaces, shown in Figure 4.1, have different features.

Students generally liked the natural light from the large window in study space two (S2), while they were not satisfied with S3 due to its location on a walking path. One student mentioned, *"Having natural light and a great view like this inspires me to study personally, and I guess many people would feel the same way"* (G1S1). Noise levels were also a factor; students were more satisfied with the noise levels in S2 compared to other spaces. This is likely due to S2's location in the building's corner, away from high-traffic areas. In contrast, S1 is in the center near the main stairs, and S3 is on a walking path near a printer and the building's entrance. However, S2 was rated lower for cleanliness. This could be because recycling bins are located nearby, as indicated in Figure 4.1. A student noted, *"I would want to move the bins over there because I get distracted by them; if people are throwing rubbish and it overflows, it might have an unpleasant smell, which makes it hard for me to study"* (G5S2).

Temperature satisfaction was similar across the three study spaces, as the building's temperature is centrally controlled. However, the temperature can vary slightly due to factors like sunlight heating through windows and the number of people in the area. As shown in Figure 4.13, the temperature inside the building ranges from 20 to 24 degrees Celsius, with

Fig. 4.10 Screenshots of the EcoCube screen: (a) main screen, (b) feedback screen, (c) reporting issue screen, (d) environmental data screen, (e) preferred temperature set by students, (f) collected data from students on thermal comfort, (g) additional building data including amenities, safety tips, and sustainability data, and (h) one of the building's sustainability information.

(a) (b) (c)

Fig. 4.11 Illustrates tools used to assess thermal comfort, including (a) wet-bulb globe temperature devices, (b) a wind speed meter, and (c) the EcoCube for gathering data on occupants' clothing levels and activity.

students selecting different temperature settings based on their personal preferences. Facility managers appreciate this data as it helps them improve and renovate study spaces to be more comfortable. They are also interested in additional data on how long students use the study spaces. One facility manager remarked, *"Kind of data for us to understand how long students are staying at one spot; from a well-being perspective, I know that when I was a student, I would go to the library at 7:00 in the morning and stay there for a long time, and I know that's not healthy"* (FM2).

4.4.3 Preferred study space features according to students

Students in the workshop (W2) study mentioned several features they would like to see in their preferred study spaces. They expressed their thoughts through sketches in groups, as shown in Figure 4.7. Group 1 in Figure 4.7 (a) preferred adjustable desks, projectors, and cube-style study spaces for meetings. They also emphasized the need for higher-quality chairs, including massage chairs, due to regular long study sessions. Group 2 in Figure 4.7 (b) suggested having screens in each study space displaying satisfaction reports and a wall-mounted screen that can be moved to any desired direction. They envisioned using these screens for studying, connecting via Bluetooth or Wi-Fi, and displaying information such as current time, date, study place number, and other study spaces' booking status. Access to these screens would be through scanning student ID cards or university credentials. Group 3 in in Figure 4.7 (c) focused on communication features for their ideal study space. They proposed a screen divided into four sections: one for chatting with facility managers, another for reporting issues, a third for requesting urgent assistance, and the fourth for displaying environmental data charts of the study space. Group 4 in Figure 4.7 (d) suggested placing the

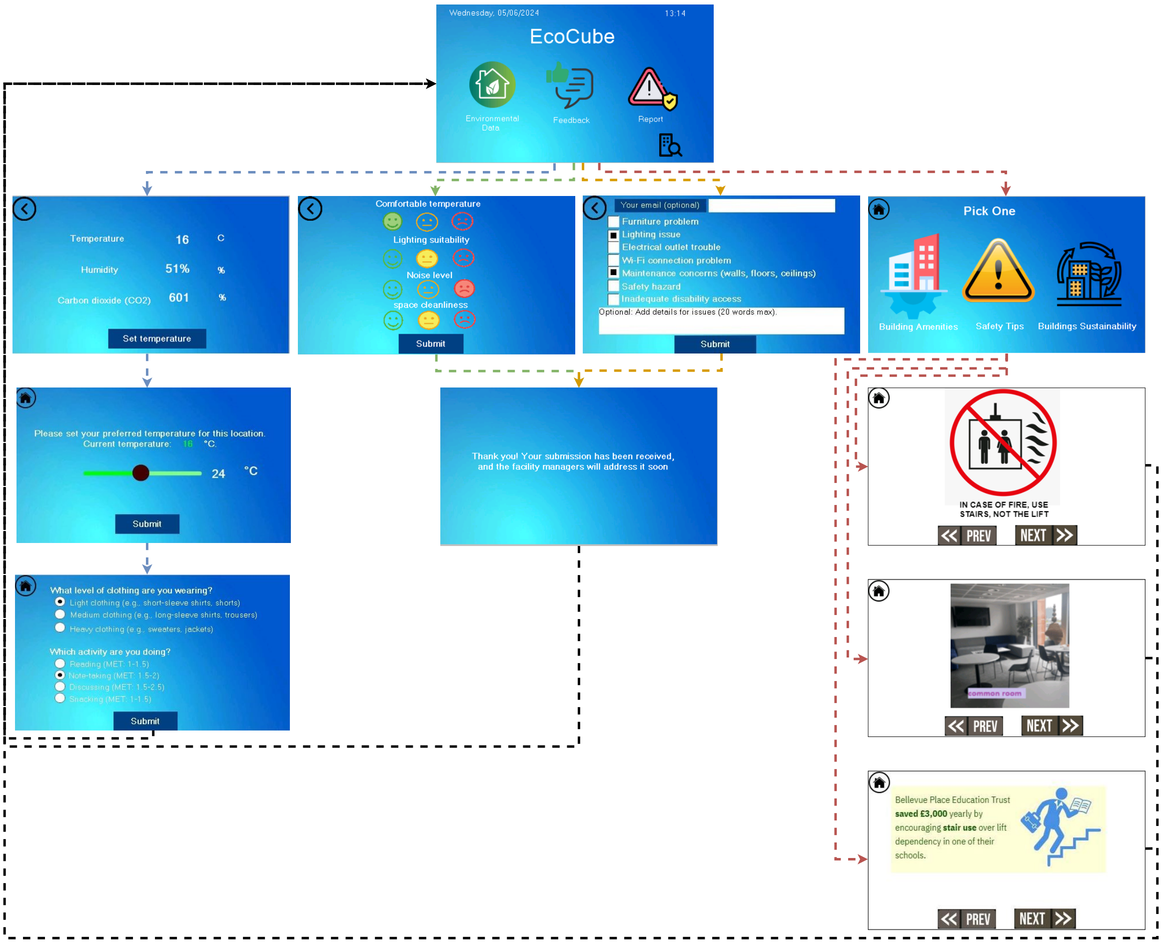


Fig. 4.12 Illustrates the occupant interaction flow when using the EcoCube device.

device on the side of the study table. The device would have a square shape and offer different options for reporting issues to facility management. Students could log in by entering their student number to use the device and submit reports. Group 5 in Figure 4.7 (e) suggested a tablet device mounted on the wall with four options on the screen: reporting issues, IT support in the building, FAQs, and updates on what's new in the building. Group 6 in Figure 4.7 (f) suggested a screen resembling a phone display with a minimalist list of options, including call, email, report, take pictures, and frequently asked questions. The report section would allow for both text and voice reporting, with the option to make a call as well.

Overall, the workshop (W2) discussions highlighted common features desired by students in any study space. These include having large windows for natural light, adjustable desks, ample power sockets, private or semi-private study areas for privacy, and comfortable spaces for both individual work and group meetings. Students expressed their preferences clearly, with one stating, *"I prefer studying next to windows with natural light or maybe a small*

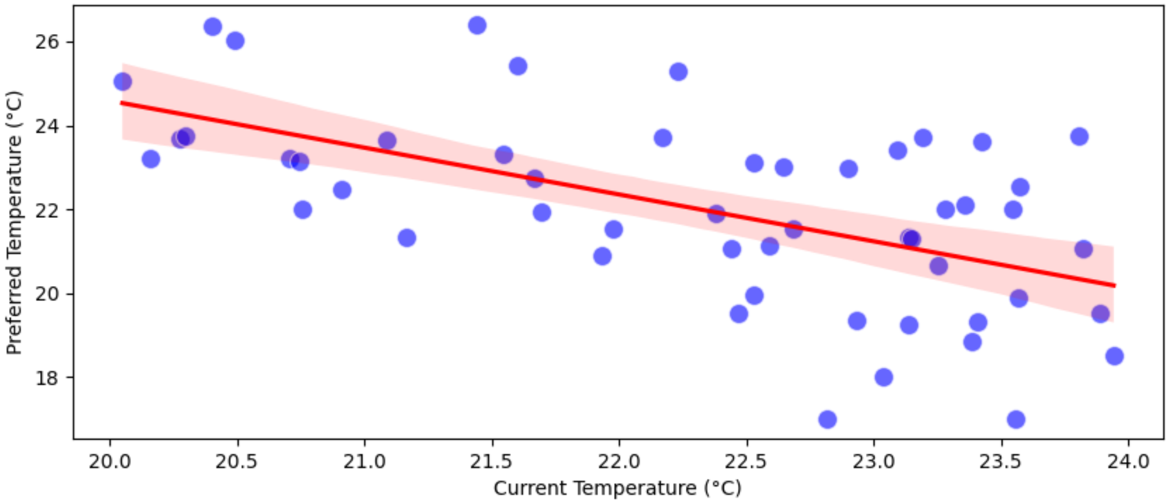


Fig. 4.13 Shows a scatter plot of occupants' preferred temperatures compared to the current temperature in study spaces.

study space[...]it makes me feel more comfortable" (G6S3). Another student emphasized the importance of air quality, saying, *"Breathing air, so I think whether it be these windows or some kind of ventilation, having more of that would be good as well; I think it would help me a lot"* (G2S1). Privacy was also a significant concern among students, with one remarking about Study Space 2, *"It's very calming, and there's more privacy. I don't have to interact with anyone, and that's the main goal. If I'm gonna study by myself, that's the main thing I'm looking for"* (G4S3). Another student concurred, stating, *"I'm pretty sure most of them would want their own time and space when they wanna study because they wouldn't come to uni to study otherwise"* (G6S2).

The student who mentioned the importance of air quality stated, *"Breathing air [...] having more of that would be good; I think it would help me a lot"* (G2S1), which could also be interpreted as contributing to 'sick building syndrome,' a condition that causes various discomforts for building occupants [34]. They also expressed a need for designated spaces to store belongings, such as cubbyholes attached to or underneath chairs, to keep their study areas organized and clean. Another student mentioned this, noting, *"Something like a cubbyhole or a designated space for the study area where you can put your bag or belongings because sometimes I end up putting them on the floor, which could be dirty. Having something attached or clipping onto the chair where you can store your stuff, or even underneath the chair, would be helpful"* (G2S3). Additional suggestions included having vending machines for refreshments and study supplies such as notebooks, headphones, pens, and other essentials, reflecting their need for convenient access to resources while studying.

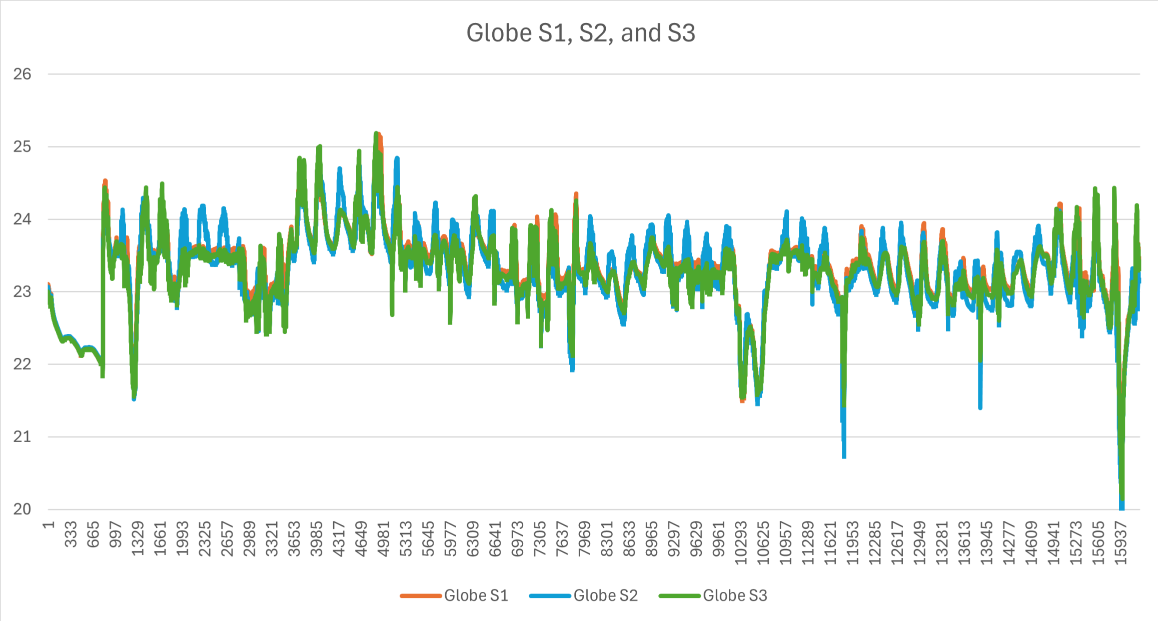


Fig. 4.14 Shows globe temperature data for the three study spaces.

Students also advocated for smart boards for collaborative work, and in the case of some mathematics students, traditional chalkboards was preferred.

4.4.4 Students' behavior with temperature changes

Students have varying opinions about the temperature in the building, each having different preferences based on their comfort needs. The building's different locations also experience varying temperatures due to factors such as sunlight through windows, heat or cold from nearby doors, and inadequate ventilation in some areas. One student expressed frustration with the lack of response from the building reception office regarding temperature issues, stating, *"The temperature? Because I called, and they can't fix that. Yeah, so they can sort it out. That's because some parts of this building are so hot, some parts"* (G5S2). In contrast, during meetings, facility managers mentioned not hearing any complaints from students about the temperature, highlighting a communication gap as previously discussed. Additionally, achieving thermal comfort in indoor environments remains challenging to satisfy occupants [13]. Factors like insulation, air circulation, and control over heating and cooling systems play critical roles in determining comfort levels. For instance, one student may feel too warm while wearing a jacket, whereas another student nearby may feel cold without one.

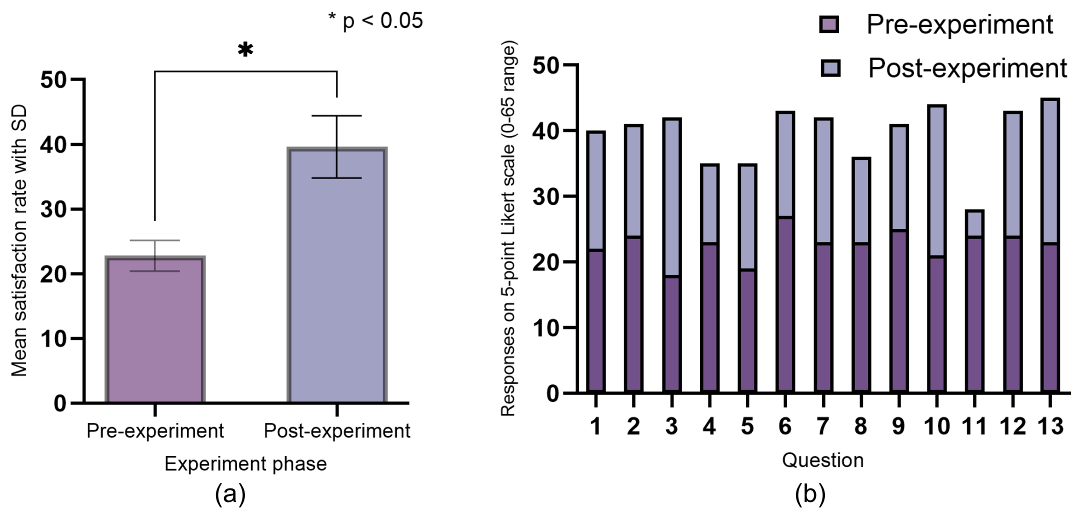


Fig. 4.15 Shows (a) mean satisfaction rates with standard deviations for communication with facility managers, before and after using the EcoCube device, and (b) responses on a 5-point Likert scale for questions before and after using the EcoCube.

This thesis aims to gather more data from students using the EcoCube device as can be seen in Figure 4.10 (f), to assist facility managers in making informed decisions. Specifically, we collect information on students' clothing and activities to evaluate thermal comfort. While facility managers have access to data on temperature, radiant temperature, air velocity, and humidity within the building, challenges remain in obtaining detailed data from students regarding their clothing insulation and specific activities. Further enhancing our assessments could involve measuring metabolic rates, which would require wearable sensors like smart watches or bands, a capability not currently implemented but could be explored in future research efforts.

To contribute more, we asked students to specify their preferred temperature in study spaces as shopwn in Figure 4.10 (e). While these inputs do not directly adjust study space temperatures controlled centrally by facility managers, they serve as a reference for understanding student preferences relative to current temperatures. Figure 4.13 illustrates a scatter plot comparing occupants' preferred temperatures with current temperatures in study spaces. It shows that when the current temperature ranges from 20 to 22 degrees Celsius, students feel cold and prefer temperatures from 21 to 26 degrees Celsius. Conversely, when temperatures range from 22 to 24 degrees Celsius, students feel hot and prefer temperatures from 17 to 24 degrees Celsius. As can be seen in the scatter plot, there is a negative correlation in certain areas of the chart. Specifically, when the current temperature exceeds 22 degrees Celsius, occupants tend to decrease the temperature. Similarly, when the temperature drops in the space, occupants prefer to increase it above 20 degrees Celsius. Additionally, the plot indicates a weaker relationship when the current temperature is above 22.5 degrees, as the data points are more widely scattered compared to those at lower temperatures. This suggests that at higher temperatures, occupants' responses become less consistent. Based on the data, the recommended current temperature range preferred by most occupants in the experiment is from 20 to 24 degrees Celsius, as it shows less variation in preferred temperatures compared to other ranges, indicating it may offer better overall comfort.

4.4.5 Students' feedback on the medium used

The quantitative data results indicate that participants experienced greater satisfaction when using the EcoCube device to communicate with facility managers. We used a paired sample t-test to analyze responses from participants before and after using the EcoCube. The test results showed a significant increase in satisfaction with communication after using the device. A paired-samples t-test was conducted, revealing a significant difference in satisfaction, $t(18) = 5.24$, $p = .002$. Here, t is the test statistic, (18) is the degrees of freedom, and p is the p-value. The mean difference in satisfaction (post-experiment minus pre-experiment) was 16.85, with a standard deviation of 5.257. This large mean difference and low p-value suggest that the EcoCube device improved participants' satisfaction with communication. Figure 4.15 presents: (a) mean satisfaction rates with standard deviations for the experiment phases, and (b) participants' responses on the 5-point Likert scale before and after using the EcoCube device.

The interview (I3) also included a System Usability Scale (SUS) questionnaire [129], which consists of ten items with Likert-type responses on a scale from 1 to 5. For even-numbered questions, lower scores are better, while higher scores are better for odd-numbered questions (1 = strongly disagree, 5 = strongly agree) [129]. The SUS score was M = 80.42; SD = 7.25; Mdn = 81.50, indicating good usability. The item "I felt confident using the EcoCube to communicate with facility managers" scored the highest (M = 4.72; SD = 0.39), while "I think the EcoCube is unnecessarily complex" received the lowest rating (M = 2.14; SD = 0.62).

Students engaged with the EcoCube device by performing tasks such as reporting issues before sharing their opinions. Figures 4.17 (e-h) display student feedback on the EcoCube device: Figure 4.17 (e) shows the desired features by students, while Figure 4.17 (f) indicates features they disliked. Figure 4.17 (g) presents the most preferred screen design for communication with building facility managers, and Figure 4.17 (h) shows the majority of students prefer anonymously reporting issues.

Overall, students expressed general satisfaction with the EcoCube's design and screen usability. One student found the interface familiar, stating, *"The icons are familiar, like*

Fig. 4.16 Shows the dashboard displaying student feedback, reported issues, current and preferred temperatures, and a line chart of sensor data.

something that I would expect to see on devices. So yeah, it's easy to use" (ST9). Another mentioned the ease of operation, saying, *"Even when my mind is somewhere else, I think I can just operate this. I don't have to put too much focus into it"* (ST10). However, opinions varied on the screen size; one student felt it was too small, suggesting, *"I think the screen is a bit small, so maybe a bigger screen like the full top"* (ST7), while another appreciated its compactness, noting, *"the size is not that big. So it can, you know, fit into like a shelf or something like that over on the wall"* (ST9). Some students preferred a multi-functional screen that could be used as a tablet, saying, *"Like I wanna kind of like throw a screen, take it out like a tablet and use it, then put it back"* (ST15).

Students also requested additional features, such as a direct contact button for building managers, with one student suggesting, *"Something where I can change or contact the building manager using this cube without even needing to say something about it"* (ST1). They also expressed interest in connecting the device to mobile phones for convenience, with one student stating, *"if there could be some communication or compatibility with your own device so that I didn't always need to use the cube"* (ST5). There was also interest in automated features, such as windows opening based on CO2 levels, with one student recalling, *"modern buildings like I went to a school where if the CO2 levels were high, the windows would automatically open type of thing"* (ST3).

Additional suggested features included adding to the screen a study timer, university campus map, and information on nearby attractions, addressing issues like poor phone signal

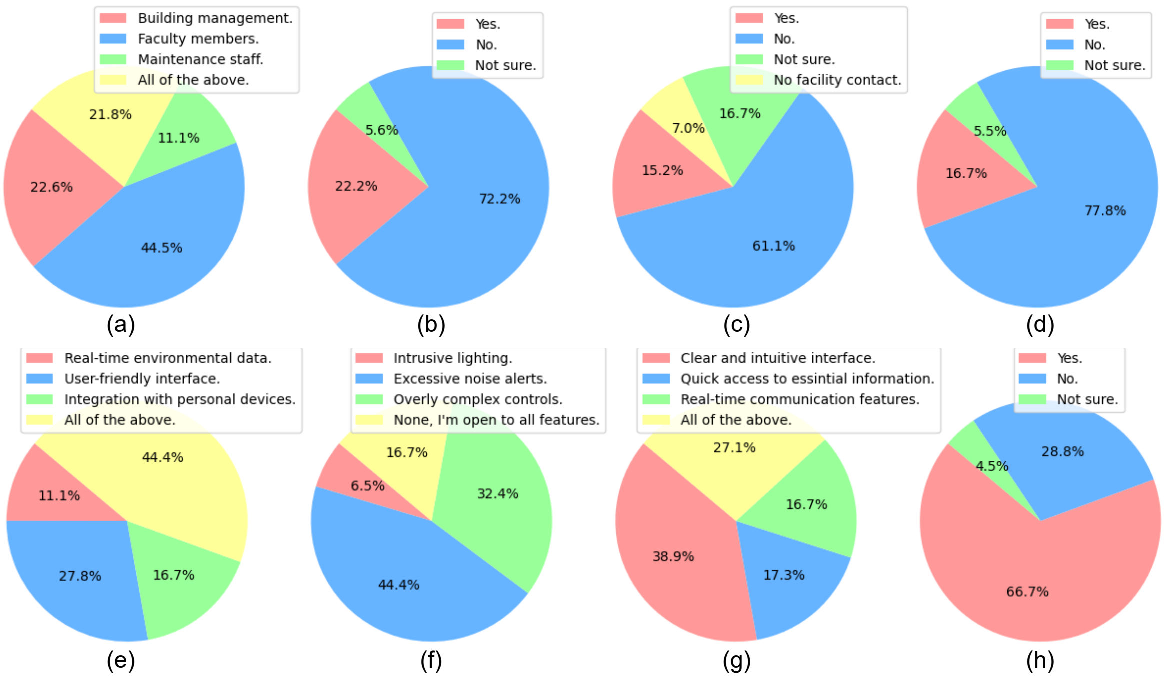


Fig. 4.17 Shows student communication with facility managers on: (a) who to contact for building issues, (b) past interactions with facility managers, (c) issues they have reported, and (d) feedback they have given. Additionally, e-f charts display student feedback on the EcoCube device, including: (e) desired features, (f) unwanted features, (g) preferred design for communicating with facility managers, and (h) the option for anonymous issue reporting.

inside buildings. Students recommended adding charging ports, an emergency button, and a wireless mobile phone charger to the device for enhanced functionality. Regarding mobility and location preferences, opinions varied; some students preferred the device to be movable yet placed in a corner, as one student suggested, *"Movable, but in a corner"* (ST8). Others preferred integration with study tables, stating, *"I don't want it to be hidden but I want it embedded inside the table but something to cover it"* (ST18). One student emphasized the importance of color-coded comfort, stating, *"it's important for me to see the colors, how different they are, because I get migraines with a lot of light"* (ST16).

During the first week of the experiment, there was a significant increase in student engagement with the EcoCube, likely driven by the novelty of the device, with an average of four students interacting with it daily. The median number of interactions per day was 4, with a range from 1 to 7 interactions, and the standard deviation was 2.3, indicating some variability in student participation. However, it is unclear whether these were individual students or the same student multiple times. Not all students provided feedback or reported issues; many merely checked the environmental readings in the study space. As the experiment

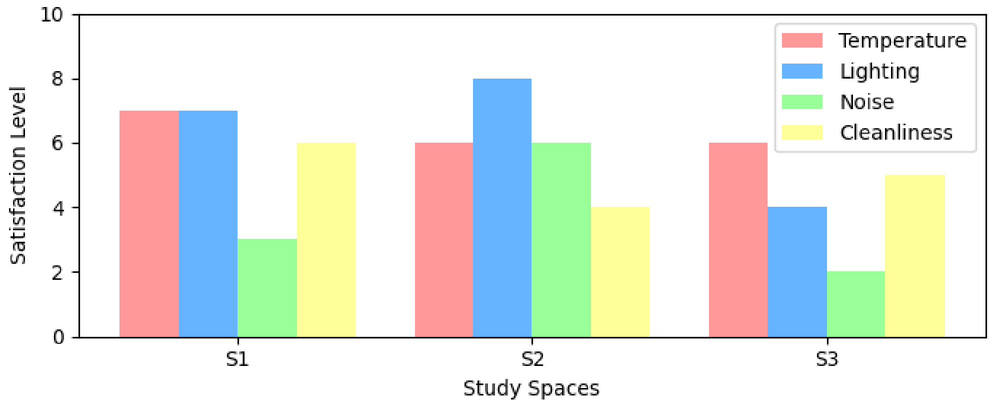


Fig. 4.18 Shows student satisfaction levels for various spaces.

progressed, usage gradually declined, and by the conclusion of the experiment, only one student on average was using the device daily. The median daily usage by students in the final week was 1, with a range from 0 to 4, and a standard deviation of 0.9, indicating more consistency in the lower usage towards the end of the study. Initially, students primarily interacted with the EcoCube to explore its features. Later, they engaged with the device to submit feedback, report issues within the study space, or monitor environmental data. Facility managers expressed satisfaction with the device, particularly its ability to provide useful data and its compliance with building safety regulations.

4.4.6 Assessing thermal comfort and student behavior in study spaces

To better understand student behavior in study spaces and assess thermal comfort, we added several sensors, as illustrated in Figure 4.11. We deployed three wet-bulb globe temperature devices and a wind speed meter [207] to collect data on globe temperature and wind speed within the building. This data was combined with information from the EcoCube, which tracked occupants' clothing levels and activities as shown in Figure 4.11 (c).

The sensors were in place for eight weeks. The globe temperature data can be seen in Figure 4.14. The results indicate that thermal comfort in all study spaces following the ASHRAE 55 standard were comfortable for occupants [65]. However, there were some differences between spaces. Study Space 2 had the highest globe temperature compared to the other spaces, likely due to direct sunlight from its large window. Study Space 1 followed, as it receives sunlight from three sides, including roof windows and nearby offices with transparent glass. Meanwhile, Study Space 3, located in a walkway and receiving sunlight from only one side, had the lowest globe temperature.

Figure 4.19 shows clothing and activity levels across the study spaces. Figure 4.19 (a) indicates that clothing levels did not vary significantly between study spaces, though Study Space 3 had fewer occupants wearing light clothes compared to others. Figure 4.19 (b) reveals that Study Space 1 had more light activity, while Study Space 3 had more sedentary activity. Study Space 2 was more balanced, with occupants engaging in both light and sedentary activities.

The higher level of sedentary activity in Study Space 3 can be attributed to the presence of a sofa, which some students have mentioned using for relaxation or short naps. In contrast, Study Space 1, located in a more active part of the building, experienced frequent changes in occupancy and higher levels of light activity.

It remains challenging to obtain precise data due to the need for more cooperation from occupants regarding their clothing and activities. Additionally, collecting data across different seasons would provide a more comprehensive understanding. Nonetheless, this assessment provides potential insights into thermal comfort and occupant behavior, which can assist facility managers in making informed decisions.

4.4.7 Understanding building occupants

Understanding building occupants remains a challenging task due to the complexity of human behavior, the diverse needs of individuals, and the constantly evolving expectations for comfort and sustainability in built environments. For example, facility managers previously attempted to create a system for booking study spaces in the building. Some students would place their belongings in a study space early, leave, and return hours later. Additionally, study spaces designed for five people were sometimes used by only one student, while others were hesitant to share the space. Although facility managers developed a booking website, they encountered issues such as students reserving spaces and not showing up, booking multiple spaces to choose the best one, or canceling reservations just minutes before the start time. They considered integrating advanced tools to monitor study spaces and improve booking efficiency but faced concerns about student comfort with monitoring, even with table occupancy sensors. As one facility manager noted, *"if people have the core spaces, would students feel comfortable enough to say? Or I've booked this space?. Could you please move? You have spaces empty because they're booked online, but they haven't turned out. Well, we have to have a rule saying if you turned up and it's free and you check the booking, they haven't turned, say 15 minutes or half? You could take space [...] I guess the biggest concern about monitoring dashboard is that kind of policing and yes, data tracking surveillance type thing? I personally don't mind being watched at work, and as there's a student and not saying that they'd be watched, but if I knew that was data being collected on* *me or anything along those lines, I don't know. So this is where I try to get that their privacy"* (FM2).

Temperature control is also challenging as it depends on personal preferences and other factors mentioned earlier. The university building has an open policy for anyone to enter during working hours, which sometimes brings in students from outside using study spaces meant for building students. This makes the building busier. As one member mentioned, *"Like open policy, like everyone can access during opening hours. Yes, we can't stop anyone, coming over and studying in one of our niches, but out of hours they can't have access[...]there are those factors of other schools nearby if they don't have space and they might have a deadline coming up sometimes, so it probably does have an impact here as well. It gets busier"*(FM3).

External factors like events happening in the building also impact study space usage. Moving furniture to allow for bigger event spaces reduces existing study spaces, especially during exam periods. As mentioned, *"Events can impact the usage because events sometimes mean moving furniture, not so much on the upper floors but on the ground floor. You probably might have to move furniture to make space for event information [...] which means students have less furniture to use to study on. So that reduces their use in terms of them being a study space. I guess if you were to go more into detail as well around project deadlines, it definitely gets a lot busier and around exam periods"*(FM2).

Understanding and addressing student feedback is crucial but often slow due to university bureaucracy. Delays stem from budget approvals and logistical issues, making swift improvements challenging. This balance between responsiveness and thoroughness is a key issue in academic administration. As mentioned, *"I guess the only thing is that I would say is that we hear student feedback quite a lot. And because it takes so long to go through various different processes of the university, it looks like it's taking us a long time to do it. But actually it's just us getting budget approval and then waiting for furniture to arrive and all of that. So I'd love to do it quicker, but that's just not realistic"* (FM1).

4.5 Discussion

We present findings from user feedback and analysis of how the EcoCube impacts building management and user experience. This discussion explores the role of user feedback in refining the EcoCube's design, highlighting how iterative changes based on user input enhance functionality and address real-world needs. We also examine the impact of the EcoCube on user satisfaction and engagement, focusing on how its features contribute to a more satisfying and interactive user experience. Further, we delve into human-centric design

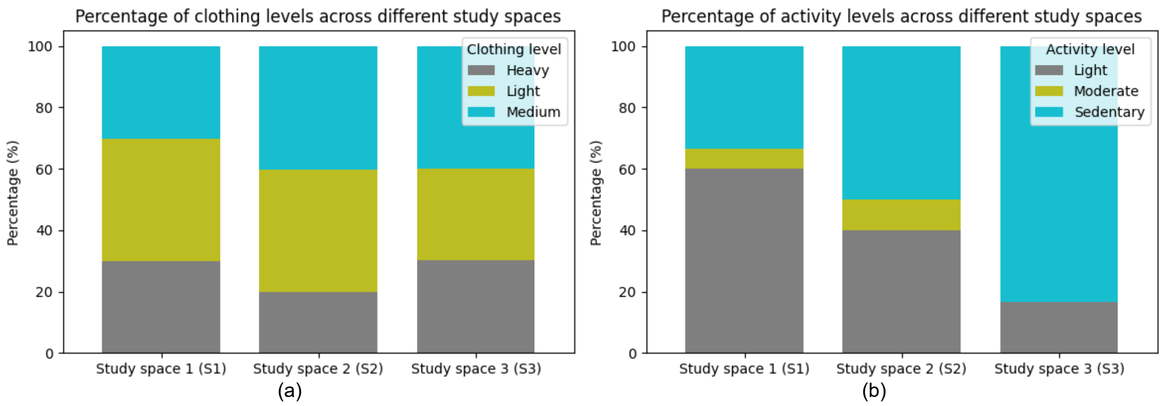


Fig. 4.19 Shows (a) percentage of clothing levels across different study spaces and (b) percentage of activity levels by occupants across different study spaces.

and adaptive environments, discussing how the EcoCube's design principles foster responsive and user-oriented spaces. The discussion extends to the influence on sustainable behavior and environmental awareness, illustrating how the EcoCube encourages eco-friendly practices and informs users about their environment. Finally, we consider the integration with emerging technologies and smart infrastructure, exploring how the EcoCube leverages technological advancements to improve building management and user interaction. By synthesizing these aspects, we aim to provide a comprehensive understanding of the EcoCube's impact and its potential for future enhancement.

4.5.1 The role of user feedback in design iterations

The iterative design process for the EcoCube highlighted the critical role that user feedback plays in refining and optimizing technology solutions. During the initial workshop (W2), students engaged in creating low-fidelity prototypes, expressing a clear preference for features such as ease of use, real-time feedback, and intuitive design. This early feedback was invaluable, as it provided foundational insights into user expectations and preferences. The sketches and ideas generated during this phase not only shaped the conceptual framework of the EcoCube but also guided the development of medium-fidelity prototypes.

The transition from low-fidelity to medium-fidelity prototypes involved incorporating the students' feedback into more functional versions of the device. During subsequent testing sessions, students interacted with these prototypes under simulated real-world scenarios. Their feedback on usability, functionality, and user experience was crucial in identifying areas for improvement. This iterative approach allowed for the refinement of features based on actual user interactions, ensuring that the final design would better meet their needs.

The development of the high-fidelity prototype was particularly influenced by the detailed feedback from these sessions. The integration of refined features, such as better visual clarity, easy-to-understand feedback and report options, and simpler navigation options, addressed many of the concerns raised by students. For instance, feedback about noise levels in study spaces led to the addition of light indicators on the EcoCube, Which alerts occupants to high sound levels and promotes awareness of their surroundings. This enhancement demonstrates how user feedback can drive meaningful changes that improve the functionality and relevance of a device.

However, despite these improvements, some students still had personal preferences that posed challenges. For example, a few participants suggested designs that would allow them to detach the top screen like a tablet for use and then reattach it after finishing. Others proposed embedding the EcoCube within the study table, covered with glass, so it could be revealed when needed, or integrating the device with mobile phones for enhanced connectivity. These diverse preferences highlight the varied needs and expectations among participants, underscoring the complexity of creating a one-size-fits-all solution.

The design of the EcoCube, inspired by various cube interfaces and commercial products, was continuously adjusted based on user input. Elements such as the device's white acrylic design, its compact size, and the integration of touch-screen technology were all informed by feedback from workshop (W2) and interviews (I3). The decision to use a white design, for example, was based on students' reactions to potential visual distractions, highlighting the importance of aligning product aesthetics with user preferences.

Incorporating user feedback also led to practical adjustments, such as the addition of a 3D-printed support piece to improve screen visibility. This change was a direct response to comments about viewing angles and device usability, showcasing how iterative design can address specific user concerns and enhance overall satisfaction. The iterative process of prototyping, testing, and feedback collection underscored the importance of involving users throughout the design cycle. By actively engaging students and incorporating their insights, the EcoCube evolved into a more user-centered solution, better equipped to address communication challenges and improve the study environment. This approach not only enhanced the device's functionality but also reinforced the value of continuous user engagement in creating effective and responsive technologies.

4.5.2 Impact of the EcoCube on user satisfaction and engagement

The introduction of the EcoCube has helped in improving communication between students and facility managers. By integrating user feedback into its design, the EcoCube has addressed key issues and enhanced user satisfaction and engagement. Students were actively involved in providing feedback through interviews (I3) where they reported issues and shared their experiences with the device. Many expressed satisfaction with the EcoCube's intuitive design and usability. For instance, one student remarked, *"The icons are familiar, like something that I would expect to see on devices. So yeah, it's easy to use"* (ST9), and another appreciated its simplicity, stating, *"Even when my mind is somewhere else, I think I can just operate this"* (ST10). This feedback underscores the EcoCube's effectiveness in offering an easy-to-use experience.

Despite this positive reception, some students suggested improvements. Concerns about the screen size were raised, with one student proposing a larger display: *"I think the screen is a bit small, so maybe a bigger screen like the full top"* (ST7). Others valued the compact size, noting that it fit well into various spaces. Additionally, there were requests for features such as a detachable tablet screen or mobile phone integration, indicating a desire for increased functionality. For example, one student wanted *"a screen that I could take out like a tablet and use it, then put it back"* (ST15), while another suggested connecting the EcoCube to mobile phones for added convenience.

The study also highlighted a significant communication barrier between students and facility managers. Many students preferred to contact faculty members for building issues, often due to concerns about being blamed for the problems they reported. Facility managers acknowledged this issue, noting that they frequently learned about problems only through delayed emails. The EcoCube has played a crucial role in bridging this barrier by enabling anonymous reporting. This feature has encouraged students to report issues more freely and has provided facility managers with a more accurate and comprehensive understanding of building concerns.

Quantitative data from the study supports this improvement. There was a noticeable increase in student satisfaction regarding communication with facility managers before and after the EcoCube's implementation. This improvement underscores the EcoCube's effectiveness in facilitating better interactions and enhancing the study environment. Overall, the EcoCube has positively impacted communication between students and facility managers, proving to be a valuable tool for both.

4.5.3 Human-centric design and adaptive environments

The EcoCube project serves as an illustrative example of how human-centric design and adaptive environments can be leveraged to improve the interaction between building occupants and facility managers. By addressing the communication gap and presenting environmental data, the EcoCube is designed to meet the needs and preferences of users while enhancing overall building management. This compact, interactive device monitors key environmental factors such as temperature, humidity, and CO2 concentrations, displaying this information on an easy-to-read screen. These features aim to help users better understand and manage their surroundings, which could lead to improved comfort and satisfaction.

The design of the EcoCube is inspired by technologies such as the Physikit, which enhances data visualization through light and vibrations, and CubeSensors, which provides real-time environmental data in a compact form. Additionally, the EcoCube follows a minimalist design approach, similar to the Ticktime Cube and Amazon Fire TV Cube, blending functionality with an aesthetically pleasing appearance. This thoughtful integration ensures that the EcoCube is both practical and visually compatible with various environments, making it a versatile tool in any setting.

One of the features of the EcoCube is its ability to collect and display data from sensors and occupant feedback on a dashboard, which helps facility managers make informed decisions that support an adaptive environment. For example, data collected by the EcoCube can inform decisions such as renovating study spaces, changing furniture, or even relocating study areas within the building. These adaptations are intended to support the student experience, creating a more flexible and responsive environment that aligns with the principles of human-centric design.

However, achieving true human-centric design requires more active user involvement. To encourage feedback, a small paper is placed near the device, prompting occupants to share their thoughts with a message like " It takes just two minutes to help make our study spaces better!" While this approach has been somewhat effective, further efforts are needed. During interviews (I3), some participants suggested offering incentives, such as vouchers or free courses, to those who provide feedback. However, concerns were raised that such incentives might lead to less thoughtful responses, as participants could focus more on winning the prize rather than providing quality feedback. Another suggestion was to introduce a pop-up window that periodically and gently prompts study space occupants to give feedback. To enhance this idea, it was proposed that the pop-up could be triggered by new occupancy data detected, ensuring that the request for feedback is timely and relevant.

Evaluating the EcoCube involves examining user interactions, feedback on environmental conditions, and changes in space usage. Preliminary findings suggest that the EcoCube can improve communication between users and facility managers by providing immediate and clear feedback on environmental factors. Users have reported feeling more aware of and in control of their environment, which may contribute to higher overall satisfaction. These results highlight the potential role of interactive displays and effective data visualization in increasing user engagement and understanding of their surroundings.

Fig. 4.20 Displays various screenshots from the EcoCube device under the 'Building Sustainability' section, designed to influence occupants' sustainable behaviors. Data references for the screenshots are provided in sources [81, 28, 196].

Further, even though smartphones are widely used, EcoCube devices offer notable advantages for environmental monitoring. They are specifically designed for precise, continuous tracking of factors like temperature and humidity, avoiding the connectivity and battery issues that smartphones might experience. EcoCube devices have a user-friendly, touchable interface that allows first-time visitors to easily provide feedback or report issues without needing to download an application.

Privacy is enhanced with EcoCube devices because they operate independently of additional software. Some users are hesitant to download applications or visit websites due to concerns about personal data collection and security risks. Unlike smartphones, EcoCube devices do not require these steps, minimizing the risk of personal information being exposed. This approach ensures that user interactions are anonymous and secure.

Moreover, the visibility of EcoCube devices in the building encourages more participation, as users see others engaging with them. Overall, EcoCube devices tend to offer better reliability, ease of use, and privacy protection, making them an effective choice for environmental monitoring and user engagement.

Despite these benefits, the implementation of the EcoCube is not without challenges. Optimizing communication channels between users and facility managers remains a critical issue. While the device has shown promise in supporting improved space usage and user satisfaction, there is still room for enhancement. Recommendations include integrating more direct communication features and utilizing real-time occupancy data to further refine space management and sustainability efforts. These improvements could help maximize the effectiveness of the EcoCube in creating truly adaptive and human-centric environments.

4.5.4 Influence on sustainable behavior and environmental awareness

The EcoCube project has made steps in influencing occupants' sustainable behavior and enhancing environmental awareness. One of its key features is its effort to raise awareness about sustainability through engaging and informative messages. These messages, drawn from research on sustainability, are presented in a concise and intriguing manner. They cover various topics such as reducing waste, conserving energy, water conservation, responsible food choices, and green building practices. For example, Figure 4.20 illustrates some screenshots from the EcoCube's sustainability section, which shows users information designed to raise their awareness about building sustainability practices and encourage more eco-friendly behaviors.

In addition to promoting sustainable behavior, the EcoCube also helps increase occupants' environmental awareness of their immediate surroundings. Users have found the real-time environmental data provided by the cube useful for understanding conditions within their building. For instance, some participants noted that while they often check the weather outside using their phones, they are less aware of indoor conditions. The EcoCube addresses this gap by providing information about indoor air quality, helping users stay informed about their indoor environment.

However, feedback from users also highlighted areas for improvement. For example, some participants expressed uncertainty about the implications of certain environmental readings, such as a CO2 level of 500 ppm. They were unclear about whether these levels were safe or problematic. In response to this feedback, we adjusted the EcoCube's display to use color-coded indicators for different environmental readings. This adjustment helps users quickly interpret data without overwhelming them with excessive details, maintaining the device's ease of use while making environmental information more accessible.

In summary, the EcoCube's efforts to influence sustainable behavior and improve environmental awareness have shown promise. By providing educational messages about sustainability and offering real-time environmental data, the EcoCube encourages users to adopt more eco-friendly practices and stay informed about their surroundings. Adjustments based on user feedback, such as color-coded data displays, further enhance the device's usability and effectiveness in fostering a greater understanding of both sustainability and environmental conditions.

4.5.5 Balancing design trade-offs and user comfort

Incorporating EcoCube devices into building design brings several important considerations and trade-offs that impact both cost and user comfort. These devices, which monitor temperature, humidity, and air quality, require a significant initial investment. However, their advanced capabilities often justify the cost by providing improved control over the building environment and enhancing overall efficiency. One of the main trade-offs is the complexity added to existing building management systems (BMS). Integrating EcoCube devices can make the system more intricate, requiring careful setup and ongoing maintenance. This means balancing the technical demands of integrating the devices with the practical aspects of managing a more complex system.

Another important factor is sensor placement. To ensure accurate data collection, EcoCube devices need to be placed strategically throughout the building. This can require adjustments to the building's layout or design, which might affect its aesthetics or functionality. It's essential to find a balance between placing sensors where they are most effective and maintaining the building's visual appeal. Privacy concerns also arise with the detailed data collected by these devices. While the data helps in optimizing environmental conditions, it also means collecting information on usage patterns that could be sensitive. Ensuring that user privacy is protected while utilizing the data effectively is crucial.

EcoCube devices enhance user comfort by allowing participants to nominate their preferred temperature for the study space, which facility managers can then use to make adjustments. This approach helps create a more stable and tailored environment based on user preferences. However, while the system focuses on energy efficiency through real-time data, there may be occasional trade-offs in comfort. For instance, efforts to save energy might lead to fluctuations in temperature or humidity, which could affect user comfort temporarily. This balance between energy efficiency and user comfort is crucial in optimizing the indoor environment.

System reliability is another critical consideration. If EcoCube devices fail or provide inaccurate data, it can negatively impact user comfort. Implementing robust systems and backup measures helps ensure that any potential issues are addressed promptly. Lastly, while EcoCube devices offer advanced functionality, their design should blend seamlessly with the building's aesthetics. To keep the look clean and consistent with the white ceiling and tables in the building, the devices are designed in white. This choice helps ensure that the devices are discreet and visually appealing, maintaining the overall comfort and style of the space.

To ensure the long-term success of EcoCube devices, several strategies can be implemented. First, fostering continuous user engagement through regular updates and education can sustain interest and usage. Providing clear communication channels between users and facility managers enhances collaboration and responsiveness to needs. Further, demonstrating the value of the EcoCube in improving user comfort and environmental conditions can motivate ongoing participation.

Another vital aspect is the adaptability of the EcoCube system. By remaining responsive to user feedback and evolving technological advancements, the system can continuously meet the changing needs of users. Lastly, building a community around EcoCube usage can encourage users to share their experiences and insights, leading to enhanced engagement and a more robust support network. In summary, integrating EcoCube devices into building design involves navigating trade-offs related to cost, complexity, privacy, and aesthetics. By carefully balancing these factors and implementing strategies for sustained success, it is possible to maximize the benefits of improved environmental management while maintaining a comfortable and attractive living space.

4.5.6 Integration with emerging technologies and smart infrastructure

Integrating the EcoCube with other devices within a building has the potential to greatly enhance the capabilities of facility managers, providing them with more detailed information and enabling better decision-making. For instance, connecting the EcoCube through IoT technology could significantly improve the system's effectiveness. IoT integration allows the EcoCube to communicate with various smart devices in the building, such as HVAC systems and lighting controls, leading to a more cohesive and responsive management system.

Some students have proposed additional features for the EcoCube, such as connecting it to mobile phones or allowing access via student ID cards. This would enable students to interact with the EcoCube through personalized accounts, accessing university services like their timetables, calendars, and homework assignments. However, integrating these features presents several challenges, particularly concerning privacy and data security. Current encryption methods and secure data handling are complicated by the limitations of the existing Arduino board, which has restricted processing power, memory constraints, and limited support for cryptographic functions. Additionally, managing access based on user roles and integrating with the university database introduces further complexities.

To address these challenges, the EcoCube currently maintains a more anonymized approach. Users can interact with the device without disclosing personal information, except when they choose to report an issue and optionally provide their email address for follow-up. This design choice helps balance user privacy with the need for feedback and issue tracking.

Despite these challenges, the integration of advanced technologies with the EcoCube promises significant benefits for facility management. Enhanced connectivity through IoT and the incorporation of new features could provide valuable insights and streamline operations. However, achieving these advancements while ensuring robust privacy and data security remains a critical challenge. As technology evolves, addressing these concerns will be crucial to fully realizing the potential of the EcoCube and similar smart infrastructure systems.

4.6 Summary

The EcoCube project represents a potential advancement in bridging communication gaps between building occupants and facility managers, with a focus on enhancing space usage, user satisfaction, and sustainability. The research touches on the following research questions presented in Section 4.1, as well as the broader questions outlined in Chapter 1:

1. **How can sensing data reveal occupant behavior and preferences in various spaces, and what external factors affect their comfort?** EcoCube monitors and displays real-time environmental data, such as temperature, humidity, light, sound levels, and CO2 concentrations, offering insights into how these factors might influence occupant comfort and engagement in study spaces. This data could help inform an understanding of occupant behavior and preferences, which aligns with the first research question in 4.1 regarding the development of EcoCube as a device designed to monitor and communicate environmental data.

2. **How do sensing data and IoT systems improve communication between occupants and facility managers, and how effective are these tools?** Through its issue reporting feature and real-time feedback on environmental data, EcoCube has the potential to improve communication between occupants and facility managers. While preliminary results suggest that communication and satisfaction levels may improve, further research would be needed to fully assess the effectiveness of these tools. This addresses the second research question in 4.1 about how EcoCube's design and integration may contribute to effective communication.

3. **How can monitoring environmental data and space utilization aid facility managers in decision-making and impact building management?** The data provided by EcoCube could support facility managers in making more informed decisions about space utilization, environmental conditions, and resource allocation. However, further investigation would be needed to determine the full extent to which this data can enhance operational efficiency and improve building management. This relates to the third research question in 4.1 regarding how EcoCube's evaluation and impact might influence decision-making processes in building management.

Drawing inspiration from technologies like Physikit and CubeSensors, EcoCube combines data visualization with user-friendly interaction. Its minimalist design, influenced by products like the Ticktime Cube and Amazon Fire TV Cube, balances functionality and ease of use. Preliminary results suggest EcoCube could enhance communication, increase user awareness, and improve engagement, providing valuable operational insights.

While EcoCube collects self-reported feedback, no analysis was done to correlate it with environmental data such as temperature. Future work could explore linking feedback with environmental data to develop models for personalized comfort prediction, improving space utilization and occupant satisfaction. Additionally, long-term effects of EcoCube use on behavior and environmental awareness should be examined by incorporating extended observation periods to assess its sustained impact. Future work could also investigate the influence of cultural and social dynamics on occupant behavior and satisfaction. Further exploration could involve scaling EcoCube to various building types, integrating gamification to boost engagement, and connecting it with existing systems to improve data collection and operational efficiency, potentially fostering collaboration and supporting more sustainable building management practices.

Chapter 5

Discussion

The discussion section of this study provides a comprehensive analysis of key findings related to the design, use, and management of educational environments. It is structured into several sections, each addressing critical aspects of modernizing and optimizing study spaces.

Understanding occupant behavior and space utilization explores how students interact with various study spaces, revealing insights into their preferences and behaviors. By analyzing real-time data and feedback, this section identifies patterns in space usage, highlighting discrepancies between the designed intent and actual use. It emphasizes the need for adaptive design strategies to better align with students' evolving needs and preferences.

Enhancing human-building interaction focuses on improving communication and interaction between building occupants and facility managers. This section discusses the role of technology in bridging gaps in communication and addressing user feedback effectively. It evaluates how tools like the EcoCube can facilitate better management practices and enhance user satisfaction by providing actionable insights into building conditions and user needs.

Sustainability and energy efficiency in educational buildings examines the impact of smart technologies on energy management and sustainability. This section highlights the benefits of integrating automated systems, such as CO2-based window openings, to improve air quality and energy efficiency. It also addresses the importance of upgrading building features to maximize energy savings and environmental comfort.

Long-term impact on building maintenance and operations discusses how ongoing improvements and renovations can affect the management and maintenance of educational buildings. It stresses the importance of iterative updates to less-utilized spaces and how affordable, small-scale changes can significantly enhance space utilization and student satisfaction.

Challenges in implementing smart building technologies delves into the various obstacles associated with deploying smart systems in educational settings. It covers issues related to privacy and security, sensor selection and data accuracy, computational power, and integrating diverse data sources. This section also highlights the need for effective HBI and robust support for facility managers to ensure successful technology adoption and operation.

Together, these sections provide a comprehensive view of how modern technologies and design strategies can be employed to create more effective, efficient, and user-friendly educational environments. They underscore the importance of continuous adaptation and improvement to meet the changing needs of building occupants and maintain operational excellence.

5.1 Understanding occupant behavior and space utilization

Understanding how students interact with study spaces is crucial for optimizing the design and functionality of educational environments. In this study, we deployed a comprehensive array of sensors across various study areas to gather real-time data on occupancy, temperature, humidity, light, sound levels, and CO2 concentrations. This quantitative data provided a solid foundation for analyzing space utilization patterns and identifying areas where improvements were necessary.

To complement this quantitative data, we conducted workshops and interviews with students and facility managers. These qualitative insights offered a deeper understanding of the context behind the data. For instance, students shared their experiences with noise levels in areas designated for quiet study and pointed out issues such as inadequate lighting in certain spaces. Such feedback was critical for interpreting sensor data and revealing discrepancies between the intended and actual use of study spaces.

The sensor data and feedback revealed that while certain areas were designed for group study and collaboration, these spaces were often underutilized or used by only one or two students at a time. This mismatch resulted in large areas being occupied by a few individuals, which was not an efficient use of space. Additionally, the intended collaborative environment did not materialize as expected. The findings emphasize the need for continuous assessment and adjustment of space design to better align with how students actually use these spaces, rather than how designers initially intended them to be used. This approach ensures that study spaces remain functional and responsive to the evolving needs and behaviors of students.

This section addresses the first research question introduced in Chapter 1: "How can sensing data reveal occupant behavior and preferences in various spaces, and what external factors affect their comfort?" The methods described and findings analyzed in Chapter 3 and 4, provide evidence-based insights into occupant behavior. Through a combination of sensor data and qualitative feedback, it potentially contributes to a better understanding of space functionality in educational environments.

The data collected highlighted several key patterns in space utilization. Figure 3.14 illustrates that most students arrived at the building after 8 AM and left around 6 PM. This pattern is influenced by building policies that restrict access for students from other departments outside these hours. As a result, study spaces are predominantly used by students from the same department after 6 PM, with no restrictions on how long they can stay. These findings suggest that adapting building policies, such as implementing a 24/7 access policy or extending hours, could provide greater flexibility for study and research. Such changes would allow students and faculty to access resources at any time, potentially leading to more efficient use of study spaces.

To further understand how students use study spaces, we analyzed the occupancy patterns of individual chairs in different areas as illustrated in Figure 3.15. For example, in Study Space S1, Chair 4, which offered more privacy and was closer to power outlets, was preferred over Chair 1 near the stairs. In Study Space S2, Chair 4, located next to a large window, was most frequently used, likely due to the natural light and outside view. Similarly, in Study Space S3, Chairs 2 and 4 were popular, with Chair 4 gaining more use as sunlight increased in June, reducing screen glare. These insights underscore the significance of different factors such as privacy, accessibility, and natural light in space design. Understanding these preferences is crucial for creating study environments that align with student needs and ensure effective space utilization.

Understanding student behavior through sensors and technology can significantly enhance space management and student well-being. By monitoring occupancy patterns, universities can manage resources more effectively, ensuring that study areas are neither overcrowded nor underused. This approach can also encourage healthier study habits by promoting regular breaks and preventing long periods of sitting, which are known to impact physical well-being.

Integrating sensor data with feedback emphasizes the importance of continuous monitoring and adaptive management strategies. For example, real-time data on space usage can inform decisions on adjusting lighting and temperature to improve comfort and efficiency. Using sensors and IoT devices to collect data on occupancy, environmental conditions, and usage patterns, facility managers can monitor metrics like CO2, lighting, and noise. This data, combined with predictive analytics, will help forecast space demands and optimize layouts, guiding decisions on expanding capacity or repurposing underutilized spaces. Predictive modeling will also identify trends, supporting long-term planning. These findings suggest that buildings can leverage technology to optimize space usage, improve occupant experience, and enhance resource efficiency.

5.2 Enhancing human-building interaction

HBI encompasses the dynamic relationship between building occupants and the spaces they use, including how they interact with building systems and respond to their environments. Effective HBI is crucial for optimizing building performance, occupant satisfaction, and operational efficiency. However, there are often significant challenges in achieving this interaction due to gaps in communication, limited access to real-time data, and insufficient understanding of building systems' roles and functionalities.

This section contributes to answering the second research question from Chapter 1: "How do sensing data and IoT systems improve communication between occupants and facility managers, and how effective are these tools?" As outlined in Chapters 4, the EcoCube played a central role in enhancing communication between users and facility managers, helping to bridge gaps in awareness and responsiveness. The findings highlight the accessibility of data and user engagement are key in supporting more adaptive and user-centered building environments.

In many cases, facility managers face difficulties in monitoring and responding to occupant needs because of inadequate technological tools or insufficient data integration. Conversely, occupants may lack awareness of the facility management processes or the roles of building systems, which can lead to misunderstandings and missed opportunities for improvement. Bridging these gaps is essential for creating more responsive and adaptive building environments that cater effectively to user needs and enhance overall functionality.

The EcoCube project highlights the potential for a solution to improve HBI, particularly in enhancing communication between building occupants and facility managers. The project has demonstrated that integrating technology can substantially improve this interaction through the use of an interactive device featuring a compact design and real-time monitoring capabilities. This device offers valuable insights into environmental conditions such as temperature, humidity, light, sound, and CO2 levels. Its user-friendly interface ensures that occupants can easily access and interpret this data, leading to improved satisfaction and better management of study environments.

The deployment of this technology has had a positive impact on communication channels. Students have reported a better experience in their study environments, due to the device's feedback features that allow them to address issues quickly. Facility managers, on the other hand, benefit from the detailed data provided, which may aid in making informed decisions about space utilization and necessary improvements. This interaction highlights the device's role in fostering a more responsive and adaptive management approach.

Despite these advancements, the project has also uncovered some challenges. Although communication between students and facility managers has improved, there remains a need for more direct and effective communication features. Additionally, optimizing space efficiency continues to be a concern. Data shows that while the technology facilitates better management and increases user engagement, further enhancements are necessary. For example, incorporating more direct feedback mechanisms and leveraging occupancy data more effectively could help address issues related to space usage and sustainability.

A significant finding from the research is the existing gap between facility managers and students. Facility managers often face difficulties in monitoring the entire building and addressing occupant feedback due to limited technological resources. Conversely, many students are not fully aware of the facility managers' roles. Workshops revealed that only a quarter of participants were familiar with the term 'facility manager,' and half had heard of it but lacked a clear understanding of its significance. Figure 3.20 illustrates the limited knowledge students have about facility managers' responsibilities and their preferred methods of communication. This disconnect underscores the need for better strategies to bridge the communication gap.

In summary, the project has shown how the use of technology solutions can enhance building management and occupant experiences. Although some progress has been made, future developments should focus on refining communication features, improving data collection, and promoting sustainability. Addressing these areas will further enhance the impact on building management practices and overall occupant satisfaction.

5.3 Sustainability and energy efficiency in educational buildings

The integration of technology in educational buildings presents significant opportunities to enhance sustainability and energy efficiency. As educational institutions strive to minimize their environmental footprint and optimize resource usage, leveraging advanced technological tools can play a crucial role.

This section addresses the third research question from Chapter 1: "How can monitoring environmental data and space utilization aid facility managers in decision-making and impact building management?" The integration of real-time environmental data into facility management allows for more informed decision-making regarding energy use and system adjustments, optimizing building operations and promoting sustainability.

One of the primary benefits of incorporating advanced technology into building management is its ability to provide detailed insights into energy consumption and environmental conditions. For instance, sensors deployed in study spaces collect real-time data on environmental conditions. This data enables facility managers to monitor and adjust building systems more effectively, thereby reducing energy waste and improving overall efficiency. By analyzing patterns in energy use and occupancy, institutions can identify opportunities for optimization, such as adjusting HVAC systems based on real-time demand.

The findings illustrate how targeted interventions can lead to substantial energy savings. For example, by analyzing occupancy patterns, facility managers can implement strategies to control lighting and HVAC systems more efficiently. Data from the study has shown that areas with high occupancy levels may require different temperature and lighting settings compared to less frequently used spaces. Adjusting these settings based on actual usage rather than fixed schedules can lead to significant reductions in energy consumption.

Moreover, the technology used in the study allows for more precise monitoring of environmental conditions, which can contribute to better indoor air quality and overall occupant comfort. For example, real-time data on CO2 levels can help ensure that ventilation systems are operating optimally, reducing the risk of excessive ventilation and the associated energy costs. Similarly, monitoring light levels can help in managing artificial lighting, reducing energy use during daylight hours.

However, despite these advantages, challenges remain in fully realizing the potential of these technologies. One challenge is ensuring that the technology is effectively integrated with existing building management systems. For instance, data from sensors must be accurately interpreted and acted upon to achieve meaningful results. This requires ongoing attention to system calibration and data accuracy.

Another challenge is promoting awareness and engagement among building occupants. While the technology provides valuable data, its effectiveness depends on how well it is utilized by facility managers and understood by occupants. Efforts to educate occupants about the benefits of the technology and how their behaviors can impact energy efficiency are essential for maximizing its potential.

One aspect mentioned by a participant is integration of automated features, such as windows that open based on CO2 levels, which can enhance air quality in the building. As the participant mentioned, *"modern buildings like I went to a school where if the CO2 levels were high, the windows would automatically open type of thing"* (ST3). Upgrading automated features in the building is better for maximizing energy savings and ensuring a comfortable, sustainable environment.

In conclusion, integrating advanced technology into buildings offers significant potential for enhancing sustainability and energy efficiency. Real-time data collection and analysis enable more informed decision-making, leading to optimized resource use and reduced environmental impact. However, achieving these benefits requires overcoming challenges related to system integration, data management, and user engagement.

5.4 Long-term impact on building maintenance and operations

The integration of advanced technologies and sustainability measures can significantly shape how buildings are managed over time. One key aspect is the shift from reactive to proactive maintenance strategies. Traditional maintenance often involves addressing issues only after they arise, which can lead to higher costs and disruptions. However, with the implementation of real-time monitoring systems and predictive analytics, facility managers can anticipate and address potential problems before they escalate [17, 50]. For instance, sensors that track the condition of HVAC systems can signal when parts are likely to fail, allowing for preemptive repairs and reducing downtime.

The data collected from these technologies provides valuable insights into building performance. This data can be used to optimize maintenance schedules, improve resource allocation, and support long-term planning. For example, analyzing trends in energy usage can help identify areas where efficiency improvements are needed, leading to better-informed decisions about upgrades and renovations.

This thesis revealed that some study spaces are used more frequently than others, with students often preferring to use these areas collaboratively for reasons such as privacy and noise levels. To address this, it is important to continuously update and improve the less utilized spaces. Renovations may not always need to be expensive; even small changes can make a big difference. For example, participants suggested using table numbers or signs to encourage students to share tables, as some students might feel hesitant to join others, and providing noise-cancellation headphones for noisy areas. Figure 5.1 illustrates two affordable solutions: (a) table mats to promote table sharing and (b) noise-cancellation headphones to address noise in study areas.

This section addresses the second research question from Chapter 1. The use of real-time data and the insights gained from occupancy patterns contribute to a more informed approach to building management. While the study did not directly implement predictive maintenance, future work could explore using real-time data for predictive maintenance and resource optimization.

In summary, the integration of advanced technologies and sustainability measures in building management not only enhances operational efficiency and reduces costs but also

(a) (b)

Fig. 5.1 Shows affordable solutions suggested by participants to enhance study space usage: (a) table mats to encourage sharing, and (b) noise-cancellation headphones for reducing noise.

supports a more proactive approach to maintenance. By leveraging real-time data and automated systems, facility managers can ensure that buildings remain in optimal condition, contribute to energy savings, and meet long-term sustainability goals.

5.5 Adapting study spaces to changing student needs

As educational environments evolve, so do the needs and preferences of students. Various factors, such as technological advancements, teaching methods, and social dynamics, influence how students interact with study spaces. Adapting these spaces to meet changing demands is essential for maintaining their relevance and effectiveness.

One key aspect of this adaptation involves understanding the diverse ways in which students use study areas. While some students prefer quiet, individual study spaces, others thrive in collaborative environments where they can engage with peers. This variation in study habits highlights the importance of offering a mix of spaces that cater to different learning styles. Flexibility in design, such as movable furniture and adaptable room layouts, allows spaces to be reconfigured to meet the needs of students.

The integration of technology is another critical factor. As students increasingly rely on digital tools for learning, study spaces must support these technologies effectively. This includes providing adequate power outlets, high-speed internet access, and areas that accommodate both individual and group work. Furthermore, incorporating smart technology such as screens displaying real-time occupancy, noise level indicators, and adjustable tables can significantly enhance the functionality of these spaces.

This section addresses the first research question from Chapter 1. The findings from Chapter 3 highlight the diverse ways students interact with study spaces, revealing the need for flexibility in design and the integration of technology. Understanding these patterns and preferences is crucial for adapting spaces to meet students' evolving needs, ensuring they remain effective and functional.

In addition to technological enhancements, the ideal study spaces envisioned by participants in this thesis, as sketched in Figure 3.11, include features such as individual and group study areas, mobile whiteboards, and glass panel enclosures that can be tinted for privacy. These spaces also suggest the inclusion of refreshment facilities, storage, power sockets, and even plants, all contributing to a more comfortable and adaptable learning environment.

Feedback from students is vital in adapting study spaces. Regularly gathering and analyzing input from students ensures that modifications are aligned with their needs. For example, if students express a need for more quiet areas during exam periods, facilities can temporarily designate certain spaces as silent study zones. Continuous feedback loops help maintain a dynamic environment that evolves in response to student requirements.

Lastly, the social aspects of study spaces are important. As students spend more time on campus, creating environments that support not just academic work but also social interaction is essential. This can include areas designed for relaxation and informal gatherings, which help foster a sense of community and support student well-being.

In summary, adapting study spaces to changing student needs requires flexible design, technological integration, regular feedback collection, and attention to the social environment. As shown in Figure 5.2, the continuous improvement cycle incorporates features, which provide valuable insights into space usage and student needs. This approach allows educational institutions to make data-driven decisions, ensuring study spaces remain effective, supportive, and aligned with student success while fostering ongoing improvements based on feedback and changing requirements.

5.6 Challenges in implementing smart building technologies

Implementing smart building technologies presents several multifaceted challenges. Privacy and security are major concerns, as these systems collect extensive data that could include sensitive information. For example, a building management system monitoring occupancy levels might inadvertently collect data on individual students' study habits. Ensuring that this data is protected from breaches and unauthorized access requires robust cybersecurity measures and stringent data privacy protocols.

This section addresses the second and third research questions from Chapter 1. The challenges highlighted here focus on ensuring accurate, secure, and real-time data collection, which directly impacts the effectiveness of communication between occupants and facility managers. Further, the proper implementation of these technologies is critical for data-driven decision-making in building management, influencing the sustainability and operational efficiency of the environment.

Choosing the right sensors is critical. Sensors must be selected based on their accuracy, reliability, and compatibility with existing infrastructure. For instance, using temperature sensors that are not well-calibrated can lead to incorrect readings, affecting HVAC system efficiency. Additionally, dealing with data uncertainty is a challenge; inaccurate sensor readings or data anomalies can lead to misleading conclusions and ineffective interventions. Ensuring that sensors provide consistent and precise data across various conditions is essential for maintaining system integrity.

Deploying sensors involves addressing computational power limitations. The system must be capable of processing and analyzing vast amounts of data in real time without performance degradation. For example, a smart lighting system that adjusts based on occupancy must quickly process data from multiple sensors to ensure timely adjustments. This requires adequate hardware and software resources, as well as efficient data management strategies.

Building a cohesive system from heterogeneous data sources adds another layer of complexity. Integrating data from different sensors and systems, such as temperature, occupancy, and energy use, requires sophisticated software that can handle and synthesize this diverse information effectively. For instance, combining data from energy meters with occupancy sensors can provide insights into how space usage affects energy consumption. Interoperability between various technologies and platforms is crucial to achieving a unified and functional smart building system.

HBI is another significant challenge. Effective communication between students and facility managers relies on intuitive interfaces that allow for easy feedback and information sharing. For example, a medium communication device in a study space might allow students to report maintenance issues or provide feedback on environmental conditions. Ensuring that these interactions are seamless can improve user engagement and satisfaction.

Supporting facility managers with enhanced data is essential for optimizing building operations. This involves providing them with actionable insights from real-time data,

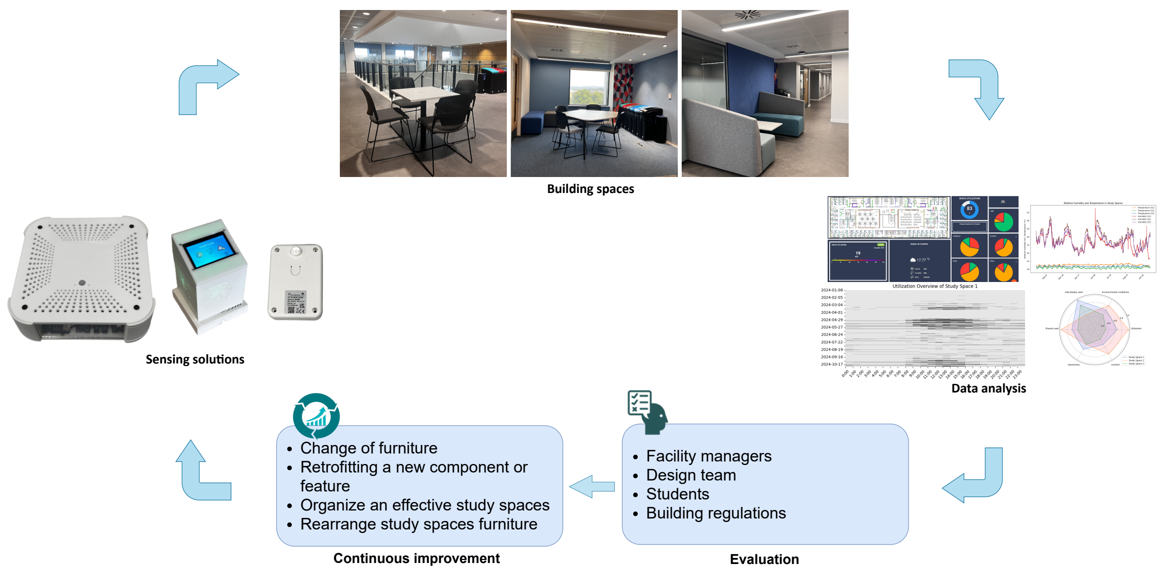


Fig. 5.2 Illustrates the continuous improvement cycle: Sensing data drives evaluations and improvements, such as furniture changes and space adjustments.

which requires advanced analytics and reporting tools. Accurate and timely information helps facility managers make informed decisions about space utilization, maintenance, and operational adjustments. For instance, real-time occupancy data can help in dynamically adjusting heating and cooling systems to save energy.

Understanding student behavior toward different study spaces is also crucial. Analyzing how students use and interact with various spaces can inform design improvements and adjustments to better meet their needs. For example, if data shows that students frequently use certain study areas for group work, while others prefer quiet individual study, space design can be adjusted to accommodate these preferences.

Lastly, fostering effective communication between students and facility managers is essential for addressing issues promptly and improving overall satisfaction. Implementing systems that facilitate clear and direct communication can help bridge gaps between occupants needs and facility management responses. Balancing these challenges is key to the successful implementation and operation of smart building technologies, ensuring that they deliver both practical benefits and enhanced user experiences.

5.7 Generalizability of findings and adaptation to other institutional settings

The findings and strategies developed in this study, while focused on educational buildings, offer valuable insights that can be adapted to other institutional settings, including hospitals and public libraries. This section explores the broader applicability of the EcoCube approach and highlights the similarities and differences between these institutional environments, with a focus on key factors such as occupant behavior, space utilization, sustainability, and technology integration. In educational buildings, understanding occupant behavior and optimizing space utilization is critical for enhancing student experience and academic performance. Similarly, hospitals and public libraries also require an understanding of how different spaces are used to improve overall space efficiency. In hospitals, this could involve monitoring the use of waiting rooms, patient rooms, and staff areas, while in public libraries, it would focus on study areas, quiet zones, and multimedia spaces. While educational environments prioritize flexible learning spaces, hospitals may need to consider privacy and accessibility when adapting spaces for different patient needs. Public libraries, on the other hand, may focus on noise levels and ensuring spaces accommodate varying group sizes.

The EcoCube's interactive features were designed to improve communication between facility managers and occupants. This concept could be extended to hospitals and libraries, where real-time feedback could be gathered to enhance comfort and functionality. In hospitals, interactive systems could allow patients and staff to provide immediate feedback on room conditions, while in public libraries, similar systems could be used to gauge user satisfaction with noise levels, seating comfort, and lighting. However, in hospitals, heightened privacy and confidentiality concerns would need to be addressed more rigorously than in educational or library environments.

Sustainability and energy efficiency are fundamental to the effective management of any building, and the EcoCube's real-time data collection provides valuable insights into improving these aspects. In hospitals, real-time monitoring of energy-consuming systems like HVAC, lighting, and medical equipment can help reduce energy waste and lower operating costs. Public libraries can also benefit from monitoring energy use in common areas and study spaces. However, hospitals may require more detailed data on air quality and other critical systems, which would necessitate additional environmental monitoring.

The ability to use real-time data for predictive maintenance is beneficial in all institutional settings. In educational buildings, this helps to optimize space usage and prevent unnecessary disruptions. Hospitals and libraries would similarly benefit from predictive maintenance to ensure that essential systems are functioning optimally without interruption. Hospitals would need specialized models to track critical systems, while libraries could focus more on routine maintenance of lighting, HVAC, and furniture.

The adaptability of spaces is essential in educational buildings to accommodate different student needs. Hospitals must also be flexible, as patient needs can change frequently, requiring different configurations of rooms or communal areas. Public libraries need to adapt their spaces to accommodate various activities, such as group study, individual reading, or community events. While libraries may focus on multi-use spaces and noise management, hospitals will require more specialized designs to cater to patient care and privacy needs.

The integration of technologies faces challenges in all institutional settings. In educational buildings, user adoption and technological integration with existing systems were key challenges, as identified in this thesis. Similar issues are present in hospitals and libraries, where technologies must be carefully implemented to ensure ease of use, security, and integration with critical systems. In hospitals, strict privacy standards and regulatory requirements must be met, while libraries may prioritize ease of interaction and enhancing user experiences.

The EcoCube's approach to enhancing occupant behavior, space utilization, and communication between facility managers and occupants can be effectively adapted to other institutional environments, such as hospitals and public libraries. While these institutions share similarities, they also present unique challenges, particularly in areas such as privacy, security, and system integration. Future research should explore how these strategies can be tailored to meet the specific needs of different institutional settings, ensuring that they provide value across various building types.

5.8 Summary

This section provides a comprehensive look at how to improve educational spaces through various strategies. First, understanding occupant behavior and space utilization is crucial. The study shows that study spaces are often used differently than intended. For example, areas meant for quiet study might be used for group work, or vice versa. This highlights the need for flexible designs that can adapt to real student needs and behaviors.

Next, enhancing HBI focuses on improving communication between students and facility managers. Tools like the EcoCube help by offering real-time feedback and allowing students to report issues directly. This better communication helps facility managers address problems more quickly and effectively.

In terms of sustainability and energy efficiency, integrating smart technologies can make a big difference. For instance, windows that automatically open based on CO2 levels can improve air quality and save energy. However, these systems need to be supported by better system integration, data management, and user engagement. Without these elements, the benefits of smart technologies are limited.

Long-term impact on building maintenance and operations highlights the importance of making small, cost-effective changes to improve study spaces. For example, adding table mats to encourage sharing or providing noise-cancellation headphones could make study areas more functional and comfortable. Regular updates based on user feedback are key to maintaining and improving these spaces over time.

Finally, challenges in implementing smart building technologies address several obstacles. These include ensuring privacy and security, selecting the right sensors, managing data uncertainty, and integrating data from various sources. Effective communication and support for facility managers are essential to overcome these challenges. For example, balancing data collection with privacy concerns requires careful planning and strong security measures.

This scetion explored key themes related to improving educational spaces, including understanding occupant behavior and space utilization, enhancing human-building interaction, promoting sustainability and energy efficiency, and considering long-term impacts on building operations and maintenance. It also addressed challenges in implementing smart technologies in such contexts. A final section discussed the generalizability of these findings to other institutional settings such as hospitals and public libraries, outlining how adaptive strategies could be transferred, what modifications would be needed, and what challenges might arise.

Overall, creating better educational environments involves understanding how spaces are used, improving communication, using smart technologies wisely, and making ongoing improvements. By addressing these areas, educational spaces can become more responsive and effective for everyone.

Chapter 6

Conclusion and future work

This thesis thoroughly examines how the integration of sensor technologies and effective communication tools can enhance building environments. By utilizing IoT devices, the collected data supports improved occupant comfort and assists facility managers in making informed decisions to optimize building operations.

The study's experimental component focused on educational buildings, analyzing sensor data from newly constructed university facilities alongside feedback from workshops and interviews with students and facility managers. This approach, supported by the SpaceSense toolkit, provided a comprehensive understanding of space usage and highlighted opportunities for improvement. Key findings include patterns of space occupancy that reveal both underutilized and high-demand areas, offering actionable insights for better space management and resource allocation.

A central focus of the research was the EcoCube device, an IoT-driven communication tool that bridges the gap between building occupants and facility managers. By enabling users to report issues, share feedback, and participate in management processes, the EcoCube enhanced user satisfaction and informed facility decisions. Variations in satisfaction across different spaces and environmental conditions emphasize the need for adaptable and user-centered solutions to address diverse occupant needs.

The study highlights the importance of real-time environmental monitoring and feedback mechanisms for maintaining responsive and sustainable building environments. By combining sensing technologies with effective communication tools, facility managers can create more adaptable and resource-efficient spaces, improving both occupant experiences and operational outcomes.

The thesis concludes with recommendations for future research and practical applications. Future work should explore the use of predictive analytics to anticipate space utilization trends and refine management strategies. Expanding environmental metrics and further advancing communication tools like the EcoCube will be critical for driving innovation in smart building management. These insights provide a foundation for creating dynamic, user-centered, and sustainable environments across a wide range of building types, ensuring they effectively meet the needs of both occupants and managers.

6.1 Research contributions

6.1.1 Overview of sensing technologies in smart buildings

A survey was conducted to explore the use of sensing technologies in smart buildings, identifying the types of sensors, their deployment locations, and the activities they help detect. This contribution offers valuable insights into how various sensing technologies are applied to improve space management, occupant comfort, and enhance facility management strategies. It helps in addressing several technical challenges outlined in Chapter 2, including selecting suitable sensors and deploying sensors in buildings, challenges which point to the broader direction of designing robust, scalable sensing infrastructures that can adapt to varied building environments. This direction supports the long-term goal of creating more intelligent and responsive smart buildings.

6.1.2 Developing SpaceSense as a reusable toolkit to optimize space usage and enhance occupant satisfaction

SpaceSense, a sensing toolkit designed to gather insights into occupant behavior, was developed to optimize space usage in educational buildings. By analyzing the data collected, SpaceSense helps improve user satisfaction and provides actionable information for facility managers, supporting data-driven decisions that enhance space efficiency and occupant comfort. Additionally, SpaceSense is a reusable and adaptable toolkit that provides clear, actionable data through user-friendly dashboards, facilitating efficient building management. This contribution helps in addressing human-building interaction challenges, such as supporting facility managers with enhanced data, improving space utilization, and enabling more effective sharing of information. These challenges focus on bridging the gap between occupant needs and facility management strategies, ultimately promoting a more collaborative and responsive management approach in educational and other building environments.

6.1.3 Introducing EcoCube to raise environmental awareness and improve communication between occupants and facility managers

EcoCube, an IoT-driven device, was introduced to raise environmental awareness and improve communication between building occupants and facility managers. The device allows occupants to increase their awareness of their surrounding environment, report issues, provide feedback, and provides data about their thermal comfort. The study also demonstrated how integrating data from EcoCube improved satisfaction levels among both user groups. This work helps in addressing human-building interaction challenges related to sharing information and enhancing communication, while also supporting facility managers in understanding occupant needs, challenges discussed in Chapter 2. It contributes to bridging the communication gap and fostering more collaborative building management.

6.1.4 Building a system for data interoperability across building environments

An adaptable system was developed to support data interoperability from multiple sources, ensuring smoother integration and more reliable data flow. This system supports facility managers in making informed decisions about building operations. It helps address the technical challenge of integrating heterogeneous data sources, supporting the smooth and reliable flow of information across systems, as outlined in Chapter 2 challenges section. This approach facilitates more efficient building management by ensuring that disparate data sources can be seamlessly combined and utilized.

6.1.5 Exploring student behavior in open-design educational spaces

The study explored student behavior across a variety of open-design spaces in an educational setting. By analyzing how students use different space types, this research provides a basis for future studies on behavior and space design. This contribution helps in addressing human-building interaction challenges related to recognizing complex activities and understanding space utilization, which contributes to the broader research direction described in Chapter 2. It emphasizes the importance of leveraging data-driven approaches to optimize space design and enhance user experience.

6.2 Future work

We identify several key research challenges and opportunities for advancing smart building technologies. First, exploring the scalability of the EcoCube involves adapting the device for larger and more diverse facilities. Second, enhancing communication tools with multi-functional designs and additional utilities, such as movable screens and emergency buttons, aims to improve user interaction. Third, utilizing predictive analytics for building efficiency will allow data to forecast space usage and optimize facility management. Finally, integrating wearable technology, such as smartwatches, can provide valuable insights into occupant comfort. However, a key challenge remains that improvements to study spaces and facilities take time, due to delays in university processes and logistical hurdles. These areas present promising directions for improving building systems and enhancing the user experience.

6.2.1 Scalability of the EcoCube in larger facilities

Future research should explore the scalability of the EcoCube or similar communication mediums in larger buildings and different types of facilities beyond educational environments. While the EcoCube has proven effective in educational settings, adapting it for use in larger and diverse facilities presents several challenges.

First, scaling the EcoCube to cover extensive areas in larger buildings involves managing multiple units and ensuring that data remains accurate and consistent. Strategies for optimal placement and integration are needed to avoid data gaps and maintain effective communication with central systems.

Second, research should investigate how the EcoCube or similar devices perform in various building types, such as commercial offices, healthcare facilities, and industrial spaces. Different environments have unique needs and conditions, so adapting these technologies to meet diverse requirements is crucial. This includes tailoring functionality and ensuring compatibility with different building management systems.

Additionally, integrating the EcoCube or similar communication mediums with existing technologies in these new settings is important. This involves exploring how they can work with other systems for energy management, security, and operational efficiency. Addressing these scalability challenges will help in enhancing building management practices across a range of environments.

6.2.2 Multi-functional design and additional utilities

Future work should focus on developing a multi-functional design for communication mediums like the EcoCube, incorporating additional utilities that address user needs and enhance overall functionality. Feedback from students has highlighted several desired features that could significantly improve the utility of such devices.

One key enhancement is the integration of a movable screen, similar to a tablet, which can be detached and reattached as needed. This would allow users to interact with the device more flexibly and access information or controls in different parts of a study space. Adding an emergency button to the device is another important feature, providing a quick and accessible way for students to alert facility managers or emergency services in urgent situations.

In addition, the ability to scan student ID cards directly on the device could streamline access and personalization, allowing the system to provide tailored information and services specific to individual students. This functionality could be used to manage access to certain study spaces or resources based on student profiles.

Another requested feature is the capability to book study spaces through the device. This would simplify the process of reserving study areas, integrating scheduling features that allow students to book and manage study sessions directly from the communication medium.

Incorporating these multi-functional features would not only address the specific needs and preferences of students but also enhance the overall user experience, making the communication medium a more versatile and valuable tool in different environments.

6.2.3 Predictive analytics for building efficiency

Future work should focus on integrating advanced predictive models and AI-driven insights into building management systems to optimize space utilization, improve energy efficiency, and enhance overall occupant experience. The rich data collected through sensors offers a strong foundation for more advanced decision-making that can support dynamic, real-time management of building environments.

Predictive models can analyze both historical and real-time sensor data to predict space usage patterns and help facility managers prepare for future space demands. By processing data such as occupancy levels, usage frequency, and environmental conditions, trends can be forecasted, peak usage times identified, and potential overcrowding or shifts in space needs anticipated. This enables more efficient resource allocation, ensuring optimal space use while repurposing underutilized areas.

In addition to improving space management, predictive models can help optimize energy efficiency. For example, by predicting when certain areas will be empty, energy consumption for lighting, heating, and cooling can be reduced in those areas. This leads to energy savings and reduces overall operational costs. Furthermore, these models can recommend adjustments to environmental settings based on real-time usage, ensuring comfort while conserving resources.

These models also have a key role in proactive maintenance. By detecting patterns in the sensor data, early signs of issues in systems like HVAC, lighting, or plumbing can be identified. For instance, abnormal energy consumption or temperature changes could indicate malfunctioning equipment. Addressing these problems early prevents larger failures, reducing downtime and costly repairs.

Moreover, these predictive models can enhance the understanding of complex activities within spaces. While basic data such as occupancy is collected, more advanced analysis can differentiate between various activities, such as group study, individual work, or meetings. This deeper understanding helps improve space design, tailor environmental settings to activities, and increase user satisfaction.

Finally, the integration of real-time data with predictive insights allows for dynamic adjustments to both environmental conditions and space configurations. For instance, lighting or seating arrangements can be adjusted to meet users' needs, making the space more flexible and responsive.

In conclusion, predictive models have the potential to transform building management by forecasting trends, optimizing resources, and improving both space utilization and occupant comfort. With data-driven decision-making, facility managers can take proactive actions that lead to energy savings, better maintenance, and overall improvements in building efficiency.

6.2.4 Integration of wearable technology

Integrating wearable technology, such as smartwatches, can enhance our understanding of occupant comfort in study spaces. Smartwatches can track key physiological data, including heart rate and body temperature, which reflect the metabolic rate of individuals. This data provides valuable insights into how thermal comfort affects occupants.

By collecting and analyzing this data, we can gain a clearer picture of how different environmental conditions, like temperature and humidity, influence comfort levels. This allows facility managers to make informed adjustments to HVAC systems, ensuring a more comfortable and efficient study environment.

While wearables may not provide real-time feedback directly to facility managers, the data collected can be analyzed periodically to identify trends and patterns. This analysis can guide long-term adjustments and improvements in environmental controls. Integrating smartwatches and other wearable devices helps create study spaces that are more adaptable and responsive to individual needs, ultimately improving overall comfort and productivity.

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Appendix A

Pre-experiment semi-structured interview questions

A.1 General background questions

- Email address
- Occupation
- Job responsibilities
- Area of expertise

A.2 Study spaces utilization

- Can you describe the different types of study spaces within your facility?
- How would you rate the utilization of these study spaces?
- What are the peak and off-peak usage times for these study spaces?
- Are there any factors that impact the usage of these study spaces (e.g., time of year, events, etc.)?
- In your opinion, how do external factors impact students' choices of study spaces (e.g., temperature, noise, etc.)? Why?
- Are there specific spaces that students prefer for particular tasks, such as homework? If so, why do you think that is the case?

- Do you think there are improvements that could be made to increase utilization? If yes, what are they?
- What information would you like to know about the usage of study spaces in the building?

A.3 Using monitoring dashboard

- Have you considered using a monitoring dashboard to oversee space utilization in your facility?
- What features or information would you like to see incorporated into such a dashboard?
- How do you envision a dashboard like this assisting you in your daily tasks and decision-making processes?
- How often do you believe you would engage with this dashboard?
- Can you provide examples of scenarios where having a monitoring dashboard would have improved your efficiency or decision-making?
- Are there any concerns you might have about using a monitoring dashboard for space utilization?

A.4 Human building interaction

- How do students typically reach out to you for queries or issues related to the facility?
- How would you describe the frequency and nature of the interactions you have with students?
- Are there preferred communication channels students use to contact you?
- Can you recall any notable instances where student interactions have led to significant changes or improvements in the facility?
- What kind of feedback do you usually receive from students about the facility?
- Are there any challenges you've faced in terms of interacting with students?
- Do you have any systems in place or plan to implement to streamline the communication process between you and the students?

A.5 Issues and suggestions

- What are some challenges you've encountered in managing this facility?
- How have you addressed these challenges?
- What ongoing issues do you wish to resolve regarding the facility management?
- What suggestions or improvements would you like to implement to enhance the facility's operations or usability?
- If resources were not a concern, what would be your top priorities for enhancing the facility?

Appendix B

Workshop Outline: Exploring existing study spaces

B.1 Introduction and orientation

- Begin by introducing the purpose of the workshop and its relevance to the participants.
- Explain the significance of studying environments and how they can impact productivity and well-being.
- Provide a brief overview of the activities they will be undertaking.

B.2 Exploration of existing study spaces

- Divide participants into groups and assign each group to a different study space within the building.
- Instruct participants to spend some time in each space, exploring and observing its features, ambiance, and functionality.
- Encourage participants to take notes and record their thoughts and opinions regarding each study space, answering questions in the provided paper.
- Participants will be recorded while thinking aloud about their experiences and observations in each study space, allowing for a deeper understanding of their reactions and preferences.

B.3 Exploration of existing study spaces

- Show the floor plan of the building to provide participants with a spatial context for their exploration.
- Divide participants into groups and assign each group to a different study space within the building.
- Instruct participants to spend some time in each space, exploring and observing its features, ambiance, and functionality.
- Encourage participants to take notes and record their thoughts and opinions regarding each study space, answering questions in the provided paper.
- Participants will be recorded while thinking aloud about their experiences and observations in each study space, allowing for a deeper understanding of their reactions and preferences.

B.4 Group discussion and idea sketching

- Bring the participants back together for a focus group discussion.
- Facilitate a conversation where participants can share their observations, experiences, and opinions about the study spaces they explored.
- Provide materials like sketching paper, pens, and colored pencils.
- Instruct participant groups to sketch their ideas of an optimal study space design, incorporating elements they found inspiring or lacking during their exploration.

B.5 Presentation and sharing of sketches

- Ask participants to present their sketches to other groups.
- Encourage participants to explain their design choices and the rationale behind their ideas.
- Facilitate a group discussion where participants can provide feedback and ask questions about each other's designs.

• Introduce the concept of mood boards as a visual representation of design ideas.

- Provide participants with access to various online resources, such as images, colors, fabric samples, and furniture catalogs.
- Instruct participants to create their own mood boards by selecting and arranging materials that represent their ideal study space design.
- Allow participants sufficient time to explore online resources and create their mood boards individually.

B.6 Presentation and reflection

- Give each group an opportunity to present their mood boards to other groups.
- Encourage participants to explain the elements they included and why they believe those elements contribute to an effective study space.
- Facilitate a discussion where participants can provide feedback, share thoughts, and discuss commonalities or differences among the mood boards.
- At the end of the presentations, ask each group to nominate the best work among the other groups, fostering a spirit of collaboration and friendly competition.

B.7 Wrap-up and conclusion

- Summarize the main findings and insights from the workshop activities.
- Discuss any recurring themes or ideas that emerged from the participants' sketches and mood boards.
- Thank the participants for their valuable contributions and their active engagement throughout the workshop.

Appendix C

Occupants questionnaire questions

C.1 General background questions

- Email address
- Age
- Current academic position
- Duration spent at university

C.2 Measuring occupant experiences within study spaces

Q1: How satisfied are you with the overall ambiance of the study space?
Q2: How would you rate the noise level in the study space?
Q3: Are there enough seating options available for you in the study space?
Q4: How comfortable are the chairs and tables in the study space?
Q5: Is the lighting in the study space adequate for your study needs?
Q6: Do you find the temperature in the study space to be comfortable?
Q7: Are there enough power outlets available for you to charge your devices?
Q8: How would you rate the cleanliness and tidiness of the study space?

Table C.1 represents the Likert and nominal scaling used for different questions presented to occupants when we conducted the questionnaire.

	Questions regarding occupant experiences in study spaces							
Likert and nominal scaling	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
	1 - Very dissatisfied	1 - Too noisy	Yes	1 - Very uncomfortable	1 - Too dim	1 - Too cold	Yes	1 - Very dirty and messy
	3 - Neutral	3 - Moderately noisy	No	3 - Moderately comfortable	3 - Adequate	3 - Comfortable	No	3 - Moderately clean and tidy
	5 - Very satisfied	5 - Completely quiet		5 - Extremely comfortable	5 - Too bright	5 - Too hot		5 - Immaculately clean and tidy

Table C.1 Measuring occupant experiences within study spaces.

C.3 Questions permitting multiple selections for each study space

Q1: Are there any distractions in the study space that hinder your focus?

- The space is usually occupied.
- The space lacks privacy.
- The space is near noisy equipment like a printer.
- The space is not easily accessible.
- The space lacks natural light.
- The space lacks accessible power sockets.
- The tables or seats are uncomfortable.
- The tables or seats are immovable.
- The space is poorly maintained.
- The space is unclean.
- The bins are overflowing.
- The space is overcrowded.
- The space is noisy.
- The lighting is inappropriate.
- The temperature is inappropriate.
- Other (please specify).

Q2: Why do you prefer this study space?

- The space is less crowded.
- The space offers more privacy.
- The space has better access to natural light.
- The space has accessible power sockets.

- The tables and seats are comfortable.
- The space is well-maintained.
- The space is clean and tidy.
- Other (please specify).

Q3: How do you usually use this study space?

- Studying
- Socializing
- Eating and drinking
- Attending classes and seminars
- Taking naps
- Other (please specify).

Q4: How do you prefer using this study space?

- Individual work
- Group work
- Working with others
- Other (please specify).

C.4 Photo feedback on study space issues

- Would you provide a picture of any issue in the study space you do not like? (Optional)

Appendix D

Workshop outline: Toolkit design

D.1 Welcome and overview

- Greeting participants and creating a welcoming atmosphere.
- Brief overview of the workshop's purpose and objectives, emphasizing the importance of effective communication between students and building managers.
- Introduction to the concept of the toolkit, highlighting how it aims to facilitate this communication through innovative IoT solutions.

D.2 Ice-breaker activity

- A quick, engaging activity designed to encourage participant interaction and foster comfort among attendees, such as a fun question or team-building exercise.

D.3 Part 1: Idea generation and brainstorming

D.3.1 Introduction to brainstorming session

- Explanation of brainstorming rules and creative thinking techniques to promote open dialogue.
- Emphasis on maintaining an open-minded and non-judgmental attitude, allowing all ideas to be considered.

D.3.2 Group division

- Splitting participants into small groups to ensure focused brainstorming and encourage collaboration among peers.

D.3.3 Brainstorming round 1: Toolkit design

- Each group discusses and lists potential design elements for the toolkit, such as user interface components and interactive features.
- Encouragement of innovative and practical ideas, focusing on how the toolkit can address specific communication needs identified by students.

D.3.4 Brainstorming round 2: Toolkit features

- Groups brainstorm possible features and functionalities of the toolkit, including:
  - User-friendly interface for easy navigation.
  - Real-time feedback mechanisms for instant communication.
  - Customizable options for users to tailor their experience.
- Focus on ensuring the toolkit is unique and truly useful for enhancing communication between students and building managers.

D.4 Part 2: Sketching and visualization

D.4.1 Introduction to sketching session

- Brief tutorial on basic sketching techniques and visual representation, equipping participants with the skills to visualize their ideas effectively.

D.4.2 Group sketching activity

- Each group sketches their proposed toolkit design and features, emphasizing clarity and creativity in their visual representations.
- Encouragement to consider the practical aspects of their designs, such as usability and functionality.

D.4.3 Idea showcase

- Groups display their sketches on a common board or wall.
- Participants walk around to view each sketch, providing notes and feedback on the designs, which fosters collaborative improvement.

D.5 Part 3: Collaboration and refinement

D.5.1 Group collaboration

- Groups refine their ideas based on feedback and observations from other works.
- Opportunity for participants to merge ideas with other groups, fostering a collaborative environment.

D.5.2 Presentation of refined ideas

- Each group presents their refined design and feature ideas to the larger workshop audience, explaining their thought process and how their designs meet student needs.

D.6 Part 4: Voting and nomination

D.6.1 Voting procedure explanation

- Clear explanation of the voting process for nominating the best designs and features, ensuring transparency and fairness.

D.6.2 Voting session

- Participants vote for their favorite designs and features from other groups.

D.6.3 Announcement of popular choices

- Tallying votes and announcing the most favored designs and features, celebrating the creativity and efforts of all participants.

D.7 Conclusion

D.7.1 Wrap-up and acknowledgments

- Summarizing the workshop outcomes, including key insights and the most popular ideas.
- Acknowledging the contributions and creativity of all participants, emphasizing their role in shaping the toolkit.

D.7.2 Feedback collection

- Collecting feedback on the workshop's structure, activities, and overall experience for future improvements.

D.7.3 Closing remarks

- Thanking participants for their involvement and enthusiasm throughout the workshop.
- Discussing next steps for toolkit development based on the workshop's outcomes and feedback.

D.8 Post-workshop

D.8.1 Compilation of ideas

- Organizing and documenting the collected ideas and sketches for further development, ensuring that valuable insights are not lost.

D.9 Additional context

- We identified students' needs for a communication channel with building managers, recognizing the importance of effective communication in improving the overall campus experience.
- During the workshop, we introduced participants to IoT technology, various interface designs used for communication, and the challenges associated with engaging building managers.

- Students participated in group activities where they sketched low-fidelity prototypes of a communication device, emphasizing desired features such as ease of use, real-time feedback, and intuitive design.
- This collaborative effort aimed to empower students to contribute meaningfully to the development of solutions that enhance communication and foster a stronger connection with facility management.

Appendix E

Semi-structured interview questions

E.1 Demographic information

- Age:
- Current Academic Position (e.g., Undergraduate, Graduate, PhD):
- Duration Spent at University (e.g., 1 year, 2 years):
- Origin of Race/Ethnicity:

E.2 Introduction to device features

- At the beginning of the evaluation, we asked participants to perform a demonstration use case to ensure they had utilized all the features of the device.
- To showcase the capabilities of the EcoCube to participants, we presented a practical use case illustrating how Alex, a student, uses the device to manage various aspects of his study environment and communicate with building managers, which can be found in Appendix C.

E.3 General experience

- How would you describe your overall experience with the smart cube device?
- What do you like most about the device? Please specify any features that stood out to you.

- Is there anything you dislike about the device? If so, please explain what you found unsatisfactory.
- On a scale of 1-5, how satisfied are you with the smart cube device? (1 being very dissatisfied, 5 being very satisfied)
- What aspects of the device do you believe could be improved to enhance your experience?
- Would you consider using the smart cube device in other environments or settings? Why or why not?

E.4 Usability

- How easy was it to understand and use the device? Please describe any learning curve you experienced.
- Did you encounter any difficulties while using the device? If yes, please elaborate on those challenges.
- Are there any features you found particularly helpful or confusing? Please provide specific examples.
- On a scale of 1-5, how would you rate the overall usability of the device? Consider factors such as interface design, navigation, and ease of access.
- In what ways could the device's user interface be improved to better assist you?
- How intuitive did you find the navigation of the device's features?
- Were the instructions provided with the device clear and helpful?

E.5 Environmental readings

- Did the light icons and screen on the device help you become more aware of your surrounding environment? Can you give an example of a situation where this was beneficial?
- Were the environmental readings provided by the device clear and easy to understand? Please specify any readings that you found particularly informative or confusing.

- On a scale of 1-5, how satisfied are you with the accuracy of the environmental readings? Please provide any specific instances where you noticed discrepancies.
- Were there any environmental factors that you felt were not adequately monitored by the device?
- How often did you refer to the environmental readings throughout your time in the study space?
- Did you suggest changing the temperature while using the device? If yes, did you change it more than once in the same session, and if so, why?
- Did you select your clothing level and activity while using the device to help assess your thermal comfort? How did this information affect your experience?
- In your opinion, how could we improve your thermal comfort in building spaces? Please provide specific suggestions or features you would like to see.

E.6 Feedback submission

- How was your experience with the feedback submission feature? Did you find it easy to navigate and use?
- Is there anything that would encourage you to provide feedback more frequently, such as reminders or incentives?
- On a scale of 1-5, how satisfied are you with the feedback submission process? What would enhance this experience?
- Did you feel your feedback was valued and taken into consideration?
- What other suggestions do you have for improving the feedback submission section?
- How were you providing feedback before using the device? Which method did you prefer and why?
- Would you prefer an alternative method for providing feedback (e.g., app-based, verbal)?

E.7 Issue reporting

- How did you find the issue reporting feature? What aspects did you appreciate, and what would you like to add or change?
- On a scale of 1-5, how effective do you think the issue reporting feature was in resolving your concerns?
- What additional functionalities would make the issue reporting feature more effective for you?
- Did you feel confident that your reported issues would be addressed appropriately?
- How were you reporting issues before using the device? If applicable, which method did you prefer and why?
- In your opinion, what other locations in the building would benefit most from the reporting feature of the device?

E.8 Effectiveness in communication

- How effective do you think the device was in bridging the communication gap between you and the facility managers? Please provide examples.
- Did you receive any responses or actions based on the feedback or reports you submitted through the device? How timely were these responses?
- On a scale of 1-5, how satisfied are you with the communication facilitated by the device? What could improve this aspect of the experience?
- In what ways could the communication features be enhanced to better serve your needs?

E.9 Satisfaction and impact

- How would you rate your overall satisfaction with the smart cube device's performance? (1-5 scale)
- Do you believe the smart cube device positively impacted your experience in the study space? Please explain.

- On a scale of 1-5, how likely are you to recommend the smart cube device to other students? Why or why not?
- Did the device enhance your ability to concentrate or study effectively? Please provide examples.

E.10 Suggestions for improvement

- Based on your experience, what improvements or additional features would you suggest for the smart cube device?
- Are there any specific environmental factors (e.g., noise levels, air quality) you wish were better monitored or reported by the device?
- Would you recommend any changes to how the device is integrated into the study spaces? Please provide detailed suggestions.
- Do you have any recommendations for how we can encourage more students to use and benefit from this device? Consider promotional strategies or engagement initiatives.
- Are there any other devices or technologies you believe could complement the smart cube to improve the study environment?

E.11 Part 2: Additional features

- Please sketch any additional features you'd like to see in the device. Consider functionality, design, and user interaction.
- If you have ideas to enhance the device's design (e.g., aesthetics, interface layout), feel free to share them here.
- How do you envision the ideal communication device for interacting with facility managers in a study space?
- What types of notifications or alerts would you find useful on the device?

E.11.1 Part 3: System usability scale (SUS) for EcoCube

- I found the EcoCube easy to use for reporting issues in study spaces.

- I found the EcoCube unnecessarily complex.
- I think I would frequently use the EcoCube to provide feedback.
- I think the EcoCube is difficult to navigate.
- I felt confident using the EcoCube to communicate with facility managers.
- I found the EcoCube confusing to use.
- The EcoCube provides clear and understandable information about environmental conditions.
- I felt frustrated using the EcoCube.
- I think the EcoCube improves communication between students and facility managers.
- I think the EcoCube is not effective in managing building issues.

Appendix F

Demonstration

To showcase the capabilities of the EcoCube to participants, we present a practical use case illustrating how Alex, a student, uses the device to manage various aspects of his study environment and communicate with building managers.

F.1 Checking and setting temperature

- Upon entering the study space, Alex realizes the temperature is uncomfortable for studying.
- He interacts with the EcoCube to view the current temperature displayed on its interface, which provides real-time visualization of the environmental conditions.
- Alex adjusts the temperature setting by interacting with the EcoCube's intuitive touch controls. As he modifies the temperature, the display updates immediately, confirming his changes visually.
- He notes the importance of having the ability to adjust the temperature quickly, especially during long study sessions. He then chooses the level of clothing he is wearing and the type of activity he is doing to provide additional context about his thermal comfort for the building manager.

F.2 Sending feedback about the study space

- Alex aims to provide feedback regarding several environmental aspects: temperature, lighting, noise levels, and cleanliness.

- He navigates to the “Feedback” section on the EcoCube and is presented with a simple interface that categorizes these aspects.
- For each category, he can select his satisfaction level from options such as "Happy", "Neutral", or "Not Happy." This user-friendly interface simplifies the feedback process.
- After selecting his preferences, Alex submits the feedback. He appreciates how quickly he can voice his concerns and suggestions, which he believes will help improve the study environment for himself and others.

F.3 Reporting a furniture problem

- Noticing that the chair in his study area is broken, Alex decides to report this issue using the EcoCube.
- He selects the “Report” option and identifies “Furniture problem” from the list of issues.
- In the text field, Alex types “Broken chair in the study space” to describe the issue clearly.
- He is also prompted to enter his email address for tracking purposes, allowing him to receive updates on the status of his report.
- After confirming the report by pressing a button, he appreciates the streamlined process, which enables quick communication of issues to building managers.

F.4 Checking building safety information

- Interested in understanding safety protocols, Alex accesses the safety section on the EcoCube’s interface.
- Here, he can view vital information such as emergency procedures, evacuation routes, and general safety guidelines specific to the building.
- This feature helps him feel more secure and informed while studying, as he recognizes the importance of being prepared for emergencies.

F.5 Observing noise level indicators

- Observing some background noise in the study area, Alex wants to monitor how the EcoCube responds to it.
- He claps his hands to generate noise and watches the EcoCube's noise level indicators.
- The light indicators change color based on the detected noise levels: green for quiet, yellow for moderate, and red for loud.
- This visual feedback allows Alex to gauge the environment and adjust his behavior accordingly, enhancing his focus during study sessions.

F.6 Demonstration summary

- Through this demonstration, the EcoCube's functionality is highlighted, showcasing its role in managing the study environment effectively.
- Alex's interactions illustrate how the EcoCube facilitates temperature adjustments, feedback submission, issue reporting, access to safety information, and monitoring noise levels with intuitive visual indicators.
- Participants observed how these features can significantly enhance their study experience and improve communication with facility managers.

Appendix G

Post-experiment interview questions

This section outlines the semi-structured interview questions designed for facility managers following the completion of the experiment. The purpose of these interviews is to gather insights regarding the effectiveness and impact of both the EcoCube and the sensing toolkit on facility management practices.

G.1 Initial impressions and integration

- What were your initial impressions of the EcoCube and the sensing toolkit?
- How did you find the process of integrating these technologies into the building's existing systems?
- Were there any specific challenges encountered during the integration phase?
- How did your team respond to the introduction of these technologies?

G.2 Receiving occupant feedback

- Can you describe the types of feedback you have received from occupants through the EcoCube, particularly regarding thermal, acoustic, and air quality comfort?
- How has this feedback compared to previous methods of communication you've used with occupants?
- What trends have you noticed in the feedback data collected from both the EcoCube and the sensing toolkit?
- Have there been any surprising or unexpected comments from occupants?

G.3 Issue reporting and response

- Could you share your experience with receiving reports of issues or damages in the space through the EcoCube?
- How have these tools impacted your response time and efficiency in addressing reported issues?
- Have you implemented any new protocols based on the reporting features of these devices?
- Can you quantify any improvements in issue resolution since these devices were introduced?

G.4 Enhancing communication with occupants

- In what ways have the EcoCube and sensing toolkit improved your communication with building occupants?
- Have you noticed any changes in the frequency or quality of interactions with occupants since implementing these devices?
- How have these tools facilitated communication during peak usage times in the building?
- Are there specific features of the EcoCube or sensing toolkit that you believe have been particularly effective in enhancing communication?

G.5 Data insights and decision-making

- How effective do you find the data collected from the EcoCube and sensing toolkit in capturing and analyzing space usage?
- What specific insights have you gained from this data regarding how students use the study spaces?
- How has the feedback and data received influenced your decision-making regarding space management in the building?

- Can you give an example of a decision that was informed by insights gained from either the EcoCube or the sensing toolkit?
- Have you made any changes to building policies or practices as a result of the insights gained from these devices?
- How do you predict data influencing future management decisions?
- How satisfied are you with how the sensing solutions enhance your awareness of space usage?
- In what ways have these solutions impacted your decision-making processes?

G.6 Challenges and suggestions for improvement

- What challenges, if any, have you faced while using the EcoCube and sensing toolkit?
- Based on your experience, what improvements would you suggest for both devices?
- Are there any features that you find particularly beneficial or lacking in the EcoCube and sensing toolkit?
- How would you prioritize the suggested improvements for each device?

G.7 Overall impact and future use

- Overall, how would you assess the impact of the EcoCube and sensing toolkit on your management of the building spaces?
- Do you see potential for further use or expansion of these technologies in your facilities management practices?
- What aspects of these devices do you think should be emphasized in future implementations?
- How do you envision the role of technology evolving in your facility management strategy?
- Overall, how satisfied are you with the EcoCube and sensing toolkit in terms of their contribution to your facilities management?

G.8 Recommendations for other facilities

- Based on your experience, would you recommend the EcoCube and sensing toolkit to other facility managers?
- What advice would you give to others considering implementing similar systems?
- Are there specific contexts or types of facilities where you believe these devices would be especially beneficial?
- What lessons have you learned that could be helpful for others in the field?

Appendix H

Illustrations of dashboard organization and components

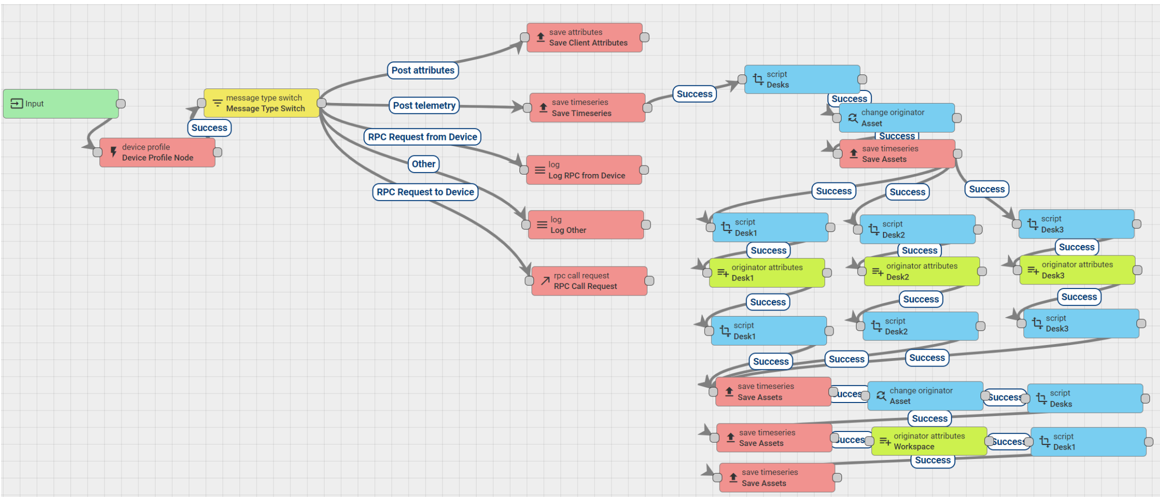

Fig. H.1 The Node-RED rule chain structure in ThingsBoard platform.

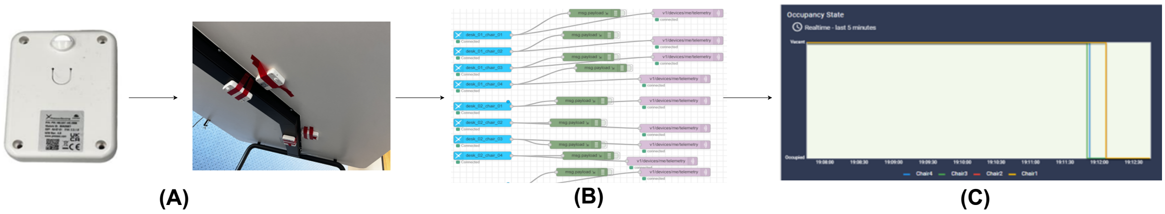

Fig. H.2 Illustrates (a) the Pressac desk occupancy sensor positioned beneath the desk, (b) the management of data from various sources, and (c) the presentation of different chair occupancies on the dashboard for the facility manager.

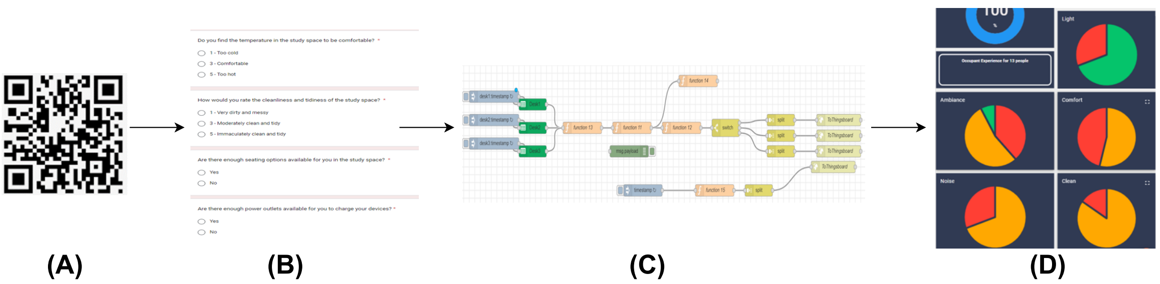

Fig. H.3 Represents (a) the QR code scanned by the occupant, (b) the form completed by the occupant, (c) the processing of data from the form for presentation on the dashboard, and (d) the occupant feedback visualized in a pie chart on the dashboard.