SpaceSense: Exploring the Use of Sensors Data to Understand Occupants' Behavior in Heterogeneous Study Space Types

WAEL ALSAFERY, Cardiff University, UK
OMER RANA, Cardiff University, UK
CHARITH PERERA, Cardiff University, UK

Sensor technology in buildings is intended to cut costs and enhance resource efficiency. This study employed a mixed-methods approach, utilizing both qualitative and quantitative data, to investigate how people use various open-design spaces in a new university building. Initial workshops and interviews with students and facility managers helped clarify their preferences and operational needs. The sensor data provided valuable insights into how students use these spaces, which in turn improved how facility managers understand students' needs and behaviors. Follow-up interviews with facility managers gave additional perspectives on how effective the sensor-based solutions are in educational settings. The study identified patterns in space usage and discovered opportunities to improve educational facilities. It emphasizes the importance of monitoring both how spaces are used and the environmental conditions. Additionally, it highlights the need for continuous observation to support student well-being and enhance facility management. Future research will look into using predictive modeling to better manage space and will expand environmental metrics to further improve educational environments, supporting sustainability and contributing to sustainable societies.

CCS Concepts: • **Human-centered computing → Empirical studies in ubiquitous and mobile computing**; **Collaborative and social computing systems and tools**.

Additional Key Words and Phrases: Sensing systems, human behaviour, productivity, open deisgn spaces, empirical study

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1 INTRODUCTION

Modern building spaces are meticulously designed to accommodate a range of activities, including individual study, collaborative work, meetings, and social interactions. These multi-functional layouts aim to optimize every area, yet a critical question often goes unaddressed: How effectively are these spaces serving their intended purposes once the building is in use? Surprisingly, post-occupancy evaluations are rarely conducted, leaving a gap in understanding how well these environments meet the evolving needs of their users [7, 43, 66, 85].

In educational buildings, well-designed study spaces are vital for supporting the academic needs of students and staff, providing them with environments that enhance focus, collaboration, and

Authors' addresses: Wael Alsafery, Cardiff University, CF24 2FL, Cardiff, UK, Alsaferywa@cardiff.ac.uk; Omer Rana, Cardiff University, CF24 2FL, Cardiff, UK, ranaof@cardiff.ac.uk; Charith Perera, Cardiff University, CF24 2FL, Cardiff, UK, pererac@cardiff.ac.uk.

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productivity. Continuous evaluation of these spaces is essential to ensure they remain conducive to academic success.

Traditional methods to assess space use, such as periodic observation of room occupancy, offer limited insights, capturing only brief snapshots and lacking the real-time accuracy needed to understand dynamic usage patterns throughout the day [90]. This approach falls short, especially in settings like hot-desking or flexible workspaces, where occupancy fluctuates frequently. Similarly, while surveys and questionnaires can capture occupant opinions, they face challenges like low response rates and potential measurement inaccuracies, reducing their effectiveness as tools for gaining authentic insights into space usage and occupant satisfaction [108].

Facility managers play a pivotal role in interpreting occupancy data and gathering occupant feedback to maintain environments that truly support students' needs. Past studies emphasize the significant influence of facility management on student satisfaction and academic performance [60, 65, 84]. However, a communication gap often exists between managers and students, limiting managers' insights into the real experiences and preferences of students. Closing this gap is essential for facility managers to make data-informed decisions that enhance student well-being and engagement.

Our study builds on this understanding, as we seek to leverage technological tools to help bridge the gap between facility managers and students. Motivated by previous research on student learning behaviors and experiences in educational environments, this study explores how technology can enhance studying and engagement strategies [28, 54, 59, 69, 80, 82]. Recently, researchers have started using Internet of Things (IoT) technology to measure the actual use of spaces and understand occupant behavior in buildings [10, 30, 40, 63, 104]. Current approaches rely on vision-based and sensor-based technologies. The vision-based approach employs camera technologies, which have been effective in providing reasonable results and aiding informed judgments about space allocations consistent with actual usage [11, 23, 94, 96]. However, this approach faces challenges related to privacy and security issues, and some cameras depend on lighting to identify occupants [5, 41, 91].

The alternative sensor-based approach, as seen in various studies [4, 20, 31, 49], provides detailed insights that empower facility managers to enhance building performance and offer practical improvement recommendations. These sensors can track various parameters such as temperature, humidity, occupancy, and movement, giving a comprehensive view of space utilization. However, these studies often fall short in thoroughly analyzing sensor data and establishing a direct connection between occupants and facility managers.

Human-Building Interaction (HBI) is crucial in this context, as it examines how occupants engage with their physical environments. By integrating HBI principles, we can better understand how design elements influence occupant behavior and satisfaction [1]. Understanding occupant behavior, particularly in open-space designs, remains challenging [32, 45, 64, 97]. More research is needed to understand how study spaces' designs and locations may impact occupant behavior in different spaces. Additionally, we need to develop methods that use real-time data analysis for effective space management.

The primary focus of our work is to use sensor data to understand how people behave in different types of spaces, uncovering insights that may not be immediately apparent. Additionally, we aim to improve communication between students and facility managers, fostering better collaboration. This study will address the following 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?

To address these questions, a study was conducted in a newly constructed university building featuring a variety of modern study spaces designed for various activities, each with unique purposes. The study examined the effectiveness of a sensor node designed to optimize smart building functionalities. This node, equipped with various sensors, was designed for easy deployment across different study spaces and buildings, placed within various areas of the building.

In addition to deploying the sensor nodes, workshops with students and interviews with facility managers were conducted both before and after the deployment. A dashboard was developed to provide facility managers with real-time access to data on the building's study spaces. The study also analyzed participants' behavior across different study spaces. The key contributions of this work 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 supports data interoperability from multiple sources and provides outputs to various dashboards. Additionally, it features a reusable sensing toolkit that can be easily adapted and integrated into different building environments.
- The experiment examined student behavior within a sample of diverse open-design spaces in an educational setting, establishing a foundational framework for future research on student behavior in such environments.

The remainder of this paper is organized as follows: Section 2 reviews related work, while Section 3 provides a detailed description of the methodology employed. Section 4 covers the deployment of sensor nodes and details regarding study spaces. Sections 5 and 6 present the study results and discussions. Finally, Section 7 concludes the paper.

2 RELATED WORK

In this work, we focus on three related areas of smart building facilities: sensor data, occupants behavior, and space utilization.

2.1 Sensor Data

Sensor data is the information produced by a device that detects and reacts to various inputs from the physical environment [57]. This data typically includes measurements such as temperature, humidity, motion, and light levels, providing valuable insights into environmental conditions and activities [2]. For instance, in a study conducted by Laput and Harrison [48], 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 [27], detecting collaborative activities [88], identifying occupants [36], continuously monitoring stress levels [79], observing occupants' behavior [42], managing buildings [31], and optimizing energy consumption [35].

Using sensor data to understand various real-world practices, as in Finnigan et al. [31], conducting a study to investigate how to enhance energy auditing practices in buildings. The research employed a sensor toolkit with various sensors placed 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. [23]

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 understand the events and phenomena occurring within buildings [12, 34, 63], various activities [27, 95, 102], and occupants' behavior [42, 47, 73].

Addressing individual limitations while considering costs, Yang et al. [99] 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 [48] 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.

2.2 Occupants Behavior

Building occupant behavior refers to how people interact with the technology and systems in buildings [15]. 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 [105], accurate prediction of energy consumption within buildings [78], and a better understanding of how spaces are utilized within the building [31].

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 [6, 31, 44, 61]. 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. [61] presents BuildingRules, allowing occupants to customize their environments through trigger-action programming. Clear et al. [19] emphasizes environmental sensor data to enhance communication between management and occupants. Yang and Wang [98] develops a multi-agent control system for effective energy and comfort management through occupant interaction, while Pasini et al. [68] explores big data technologies that transform buildings into service providers using real-time data. Dong and Andrews [25] focuses on algorithms to predict user behavior and link occupancy patterns to energy and comfort management for energy savings.

While Nacci et al. [61], Clear et al. [19], and Yang and Wang [98] prioritize occupant engagement, Pasini et al. [68] and Dong and Andrews [25] 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.

2.3 Space Utilization

Space utilization in buildings refers to the strategic management and efficient use of available areas to meet varying functional requirements, adapting to dynamic operational and environmental considerations [71]. This includes optimizing layouts and integrating real-time monitoring technology to track usage patterns and environmental conditions, emphasizing efficient usage by occupants. It also underscores the proactive role of facility managers in managing and optimizing spaces to align with organizational needs [31].

Recent advancements in IoT technology have significantly enhanced the capability to monitor and improve space utilization within buildings. IoT devices, such as occupancy sensors, environmental sensors, and smart lighting systems, play a crucial role in gathering real-time data on how spaces are utilized [18, 55, 100, 101]. Occupancy sensors can detect when spaces are occupied or vacant, providing insights into peak usage times and identifying underutilized areas. For instance, Raykov et al. [73] has demonstrated the potential of a single passive infrared sensor (PIR) sensor combined with nonparametric machine learning algorithms to accurately estimate room occupancy by analyzing motion patterns. The system updates occupancy estimates every 30 seconds and was validated with data from more than 50 trials.

Environmental sensors monitor factors like temperature, humidity, and air quality, ensuring that spaces are comfortable and conducive to productivity. Zhao et al. [106] explores Mediated Atmospheres (MA) in a smart office prototype, where digitally controlled lighting, sound, and visuals influence cognitive performance, mood, and physiology. Biosignal sensors assessed MA's impact on occupant focus and stress recovery, revealing significant effects on perception and physiological responses, supporting MA's potential to enhance wellbeing and productivity through personalized ambient control.

Facility managers utilize this data to optimize space by analyzing occupancy patterns and environmental conditions. They adjust layouts, heating, ventilation, and air conditioning (HVAC) settings, or scheduling to maximize efficiency. For instance, with sensor data indicating fluctuating occupancy, managers might reallocate space or introduce hot-desking to optimize usage. Warmerdam and Pandharipande [89] explores location data analytics using wireless sensors in a smart lighting system to assess interactions among occupants and their environment through zone positioning based on radio signal strength data. This method aims to enhance building management by evaluating occupancy density, environment characteristics, crowd detection, and occupant connectivity in a simulated open-plan office. Lee et al. [51] propose OccSim, a system designed to simulate occupancy behaviors in 3D building models and evaluate virus transmission risks during the COVID-19 pandemic. Addressing the need for effective tools among stakeholders like designers and facility managers, OccSim preempts transmission risks and illustrates complex human-building interactions. Their stakeholder evaluation underscores OccSim's potential to inform decision-making in architectural design and digital twin applications.

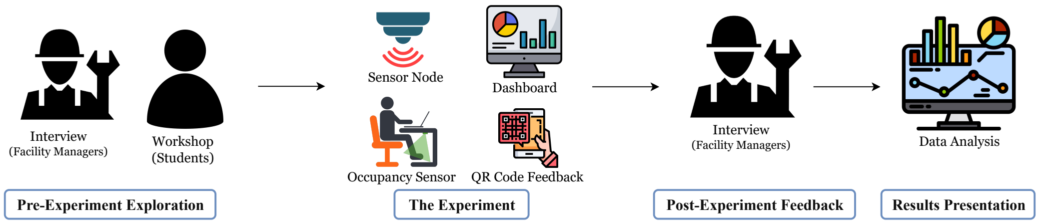


Fig. 1. The proposed methodology is discussed in Sections 3, 4, and 5.

3 METHODOLOGY

To understand the needs and perspectives of both building occupants and facility managers, we began with semi-structured interviews with facility managers, focusing on their insights and preferences regarding study spaces. At the same time, we conducted a co-design workshop with students to gather their input on the spaces they regularly use, including their needs and preferences.

Recognizing the value of a tool to deepen understanding of study space usage and the occupant-environment relationship, we developed a sensor node equipped with various sensors. These sensors were placed in diverse study spaces, supplemented by desk occupancy sensors and a Quick Response (QR) code poster for real-time occupant feedback. The collected data was then transmitted to a dedicated dashboard, simplifying data presentation for easy access by facility managers.

We employed a mixed-methods approach, integrating both quantitative and qualitative data. For quantitative data, we used NVivo software to analyze the facility managers' interviews, assigning satisfaction ratings on a 1-5 scale according to the framework in [77]. We calculated the average satisfaction ratings to evaluate how the sensing solutions enhanced facility managers' awareness of space usage, improved information quality for decision-making, and calculated standard deviations to assess rating variability. A bar chart display the average satisfaction rates with standard deviations. Figure 7 illustrates these mean satisfaction rates, with (a) representing enhanced awareness of space usage and (b) showing influence on decision-making processes. Following the experiment, additional semi-structured interviews with facility managers provided feedback on the dashboard's effectiveness and explored areas for improvement. Figure 1 presents the methodology followed in our study.

The study took approximately two years, involving initial workshops with students and facility managers, development and pilot testing of the sensor node, dashboard development, data collection, analysis, and post-experiment interviews. Interview data was transcribed and analyzed thematically utilizing the method in [13], leading to three primary themes: data acquisition, data interpretation, and insight implementation. NVivo facilitated the coding process, systematically organizing data within these themes. This process enabled the identification of patterns and relationships in the qualitative data, strengthening the analysis. Coding strategies included open coding to capture initial concepts, axial coding to refine and link emerging themes, and selective coding to extract the core themes representing key findings. These findings were synthesized to form the conclusions presented in this paper.

3.1 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.

Table 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 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, our study gains a comprehensive view of the current issues and potential improvements.

3.1.1 Student Workshop. The workshop, lasting three hours, comprised two main sections: a building walk and a co-design study spaces task. Our study 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 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 B. 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 [12, 23, 31, 52]. 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 [21, 74]. 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 [22], 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.

The second section focused on the co-design task, emphasizing collective collaboration throughout the design process [39, 50, 76]. 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

Table 2. Participant information for facility managers.

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.

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

3.1.2 Facility Managers Interview. The participants in our study 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 and the other after deployment. These sessions were recorded to aid in data analysis. Detailed participant information is provided in Table 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 [38].

The interviews were tailored to our study 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 [9, 16, 24]. Sample questions were condensed with keywords and grouped by content to guide the interview. Following advice from Denzin and Lincoln [24], 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 [13].

3.2 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. 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 [81], 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. We enhanced the dataset presentation on the platform. 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 16 in Appendix C 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 2. The platform allows facility managers to view current live data or historical data for specific periods.

3.3 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 2. 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 2 (b), 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 [92] 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 (c) shows the 12 desk occupancy sensors used in our work. Further, Figure 17 in Appendix C 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,

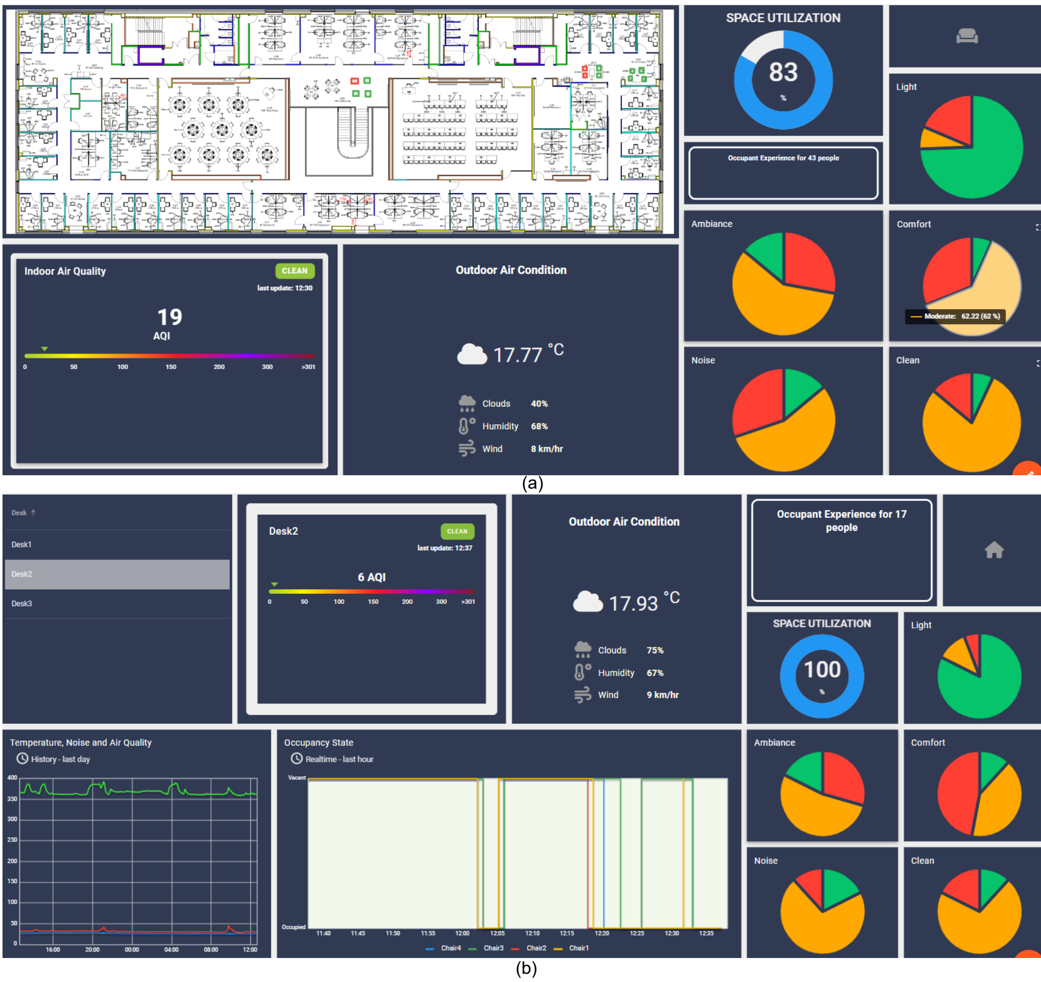


Fig. 2. (a) Provides a comprehensive overview of the dashboard, featuring all study spaces, while (b) Offers a detailed view of a specific study space.

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 18 in Appendix C. This approach ensures that facility managers receive clear, actionable insights into occupant satisfaction and operational conditions within the study spaces.

4 DEPLOYMENT

The sensor node is designed for deployment in different spaces within buildings. It accommodates various sensors and components. After designing the sensor node, it is positioned in the ceiling of the study spaces based on data accuracy readings from our pilot study. Details about the toolkit and specific sensors are provided in the next section.

Table 3. Summary of the sensors used in the sensor node.

Sensor	Performance	Used by	Purpose
PIR Motion	Range: 3.2 - 12m	[33],[86]	Occupancy sensing, estimation, and counting
		[56],[75]	Abnormal activities detection
		[58]	Recognizing activities of daily living
Temperature	Accuracy: ±2%	[87],[42]	Occupancy sensing and prediction
Humidity	Accuracy: ±5%	[42],[63]	Occupancy sensing
Light	Range: up to 540 nm	[63],[42]	Occupancy sensing
Carbon Dioxide	Accuracy: 200 PPM	[87],[42]	Occupancy sensing, counting and prediction
VOC	Range: 0 - 60000 ppb	[3],[107]	Occupancy sensing and prediction
Pressure	Range: 300mbar~1200mbar	[72]	Human activity detection
		[17],[67]	Occupancy estimation and prediction
Sound	Range: 3.2V~5.2V	[26],[67]	Occupancy sensing and prediction
		[88]	Recognizing collaborative activities
Proximity	Range: 3 - 350 cm	[83],[8]	Activity detection

4.1 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 [17, 42, 63]. We excluded other studies [46, 53] 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 [29, 70] 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 with facility managers and workshops with students highlighted key concerns regarding comfort, noise levels, air quality, and lighting in study spaces. 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 our study comprised an ultrasonic distance sensor, a carbon dioxide (CO_2) 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. Table 3 summarizes the sensors employed in our sensor node. 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 [92].

The sensor node employed in our study 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. To determine the most suitable sensor node for our experiment, we evaluated various existing designs used in smart buildings [37, 62, 103]. 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.

(a) (b) (c)

Fig. 3. Shows: (a) the designed sensor node, (b) the placement of the sensor node and (c) the used desk occupancy sensors.

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 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 (a) and (c) shows the sensor node and the desk occupancy sensors used in the study.

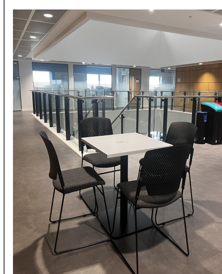
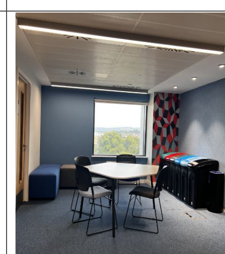
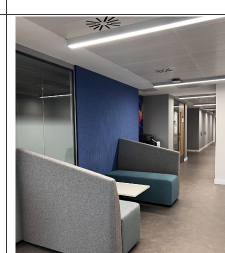
4.2 Study Spaces

This project is being conducted at a newly constructed educational building located in the 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 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.

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. Table 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

Table 4. Different study space types in the educational building With details on each study space.

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.

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.

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 4 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.

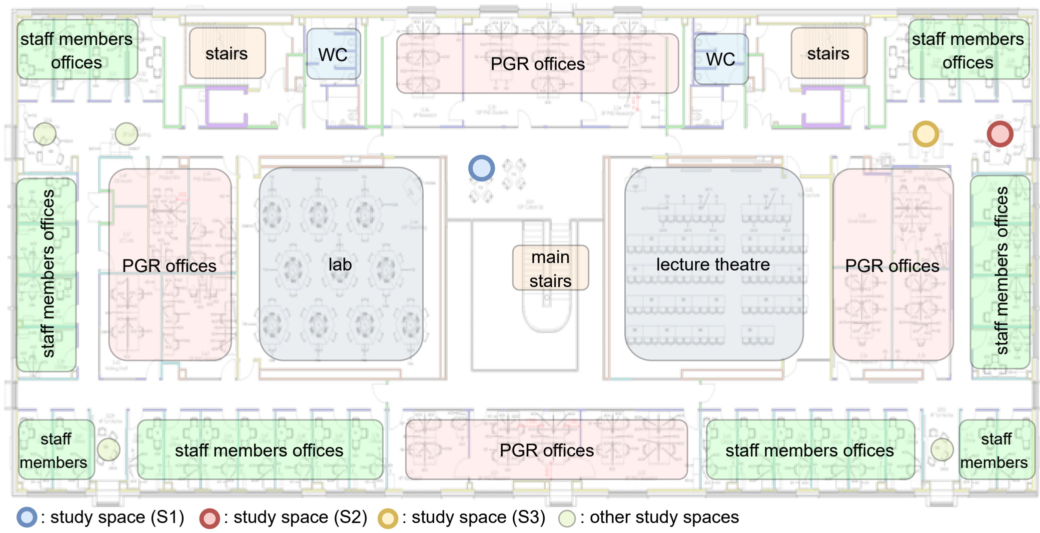


Fig. 4. The floor plan of the fifth floor of the building with selected study spaces.

4.3 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 of the study space, as shown in Figure 3 (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. 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.

5 FINDINGS

This section presents key findings from integrating sensor technology to understand student behavior and optimize educational environments. It explores students' views on study spaces, analyzes sensor data for occupancy and environmental insights, and discusses how these findings empower decision-making and promote student well-being in educational settings.

5.1 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.

5.1.1 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 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).

5.1.2 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).

5.1.3 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. Generally, students preferred to attend online classes and nap at home due to convenience. Figure 5 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 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.

5.1.4 Bridging Roles: Students' Understanding of Facility Managers' Responsibilities and Preferred Communication Methods. When queried about the role of facility managers in the buildings, most

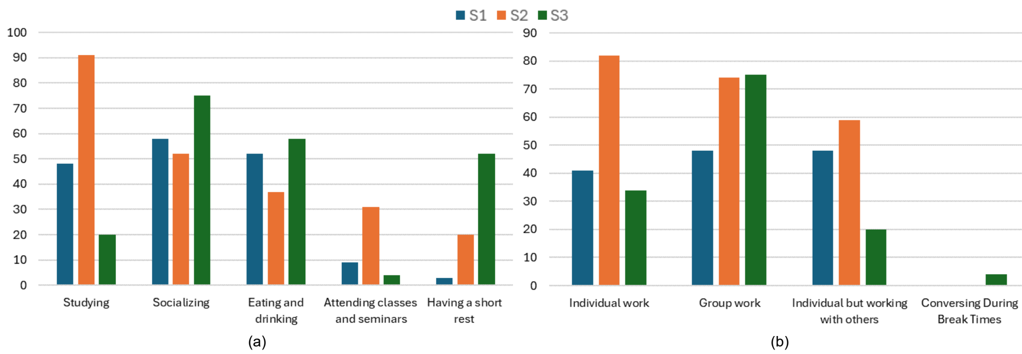


Fig. 5. The bar chart illustrates the participants' responses on their typical usage of each study space (a) and their desired mode of utilizing such a space (b).

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, a majority of students knew they could reach out to them if necessary, although some had never done so. 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. This was followed by improved communication about any changes or upgrades, better temperature control, and more regular cleaning and maintenance.

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.

5.1.5 Visualizing and Conceptualizing Ideal Study Spaces: Student Sketches and Mood Boards. During the workshop, students sketched their ideal study spaces. The first sketch Figure 6 (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. The second sketch Figure 6 (b) 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. The third sketch Figure 6 (c) 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.

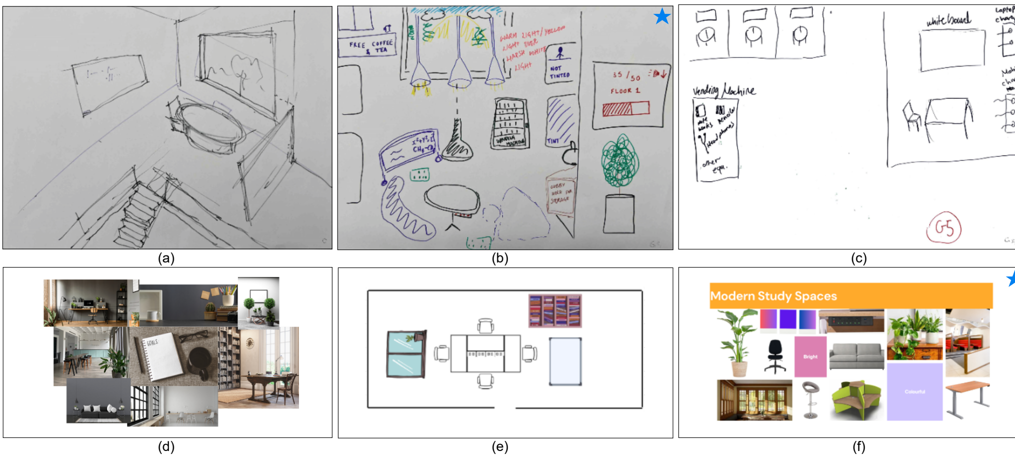


Fig. 6. This figure shows sketches and mood board designs created by participants during the workshop. It includes sketches from groups 1, 3, and 5, and mood boards from groups 2, 4, and 6.

For the mood board designs, the first mood board Figure 6 (d) emphasizes a bold, modern aesthetic with wooden tables, green plants, natural light, and minimalistic decor. The second mood board Figure 6 (e) presents a large shared table with charging sockets, a window, a bookshelf, and a whiteboard, focusing on functionality and simplicity. The third mood board Figure 6 (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 6 shows the top designs, marked with a blue star.

5.2 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 8 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. Figure 7 (a) illustrates that 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. The p-value was less than 0.05, indicating that the differences in satisfaction levels before and after the experiment are statistically significant. The first bar

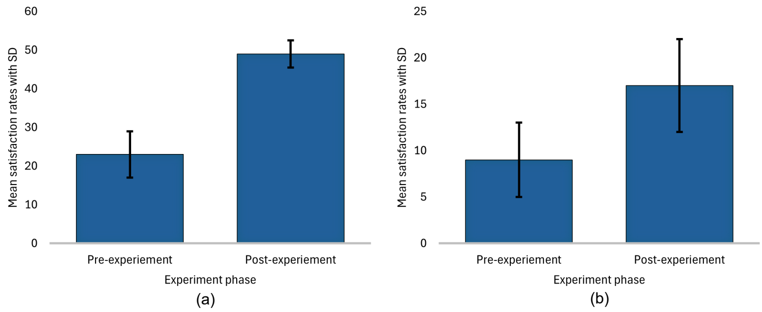


Fig. 7. Shows (a) mean satisfaction rates with standard deviations for how sensing solutions enhance facility managers' awareness of space usage, and (b) their impact on decision-making processes.

(pre-experiment) displays a higher standard deviation, signifying greater variability in satisfaction levels among participants. In contrast, the second bar (post-experiment) shows a lower standard deviation, indicating a more consistent satisfaction level following the experiment.

The occupancy data for these study spaces were collected over nearly ten months. As shown in Figure 9, 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 10, 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.

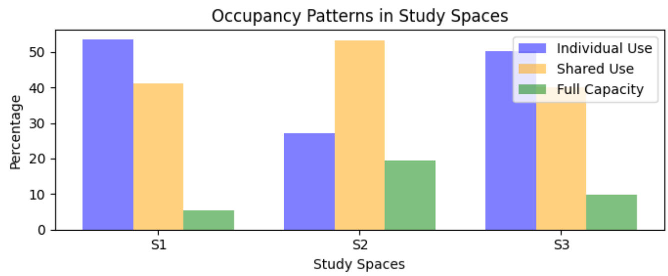


Fig. 8. Spaces occupancy pattern.

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 4. This location likely attracts 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 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 11 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.

5.3 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 12 (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 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 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 4 for S3. These distractions occasionally disrupted students' concentration during study sessions. Further, Figure 13 shows a radar chart comparing three study

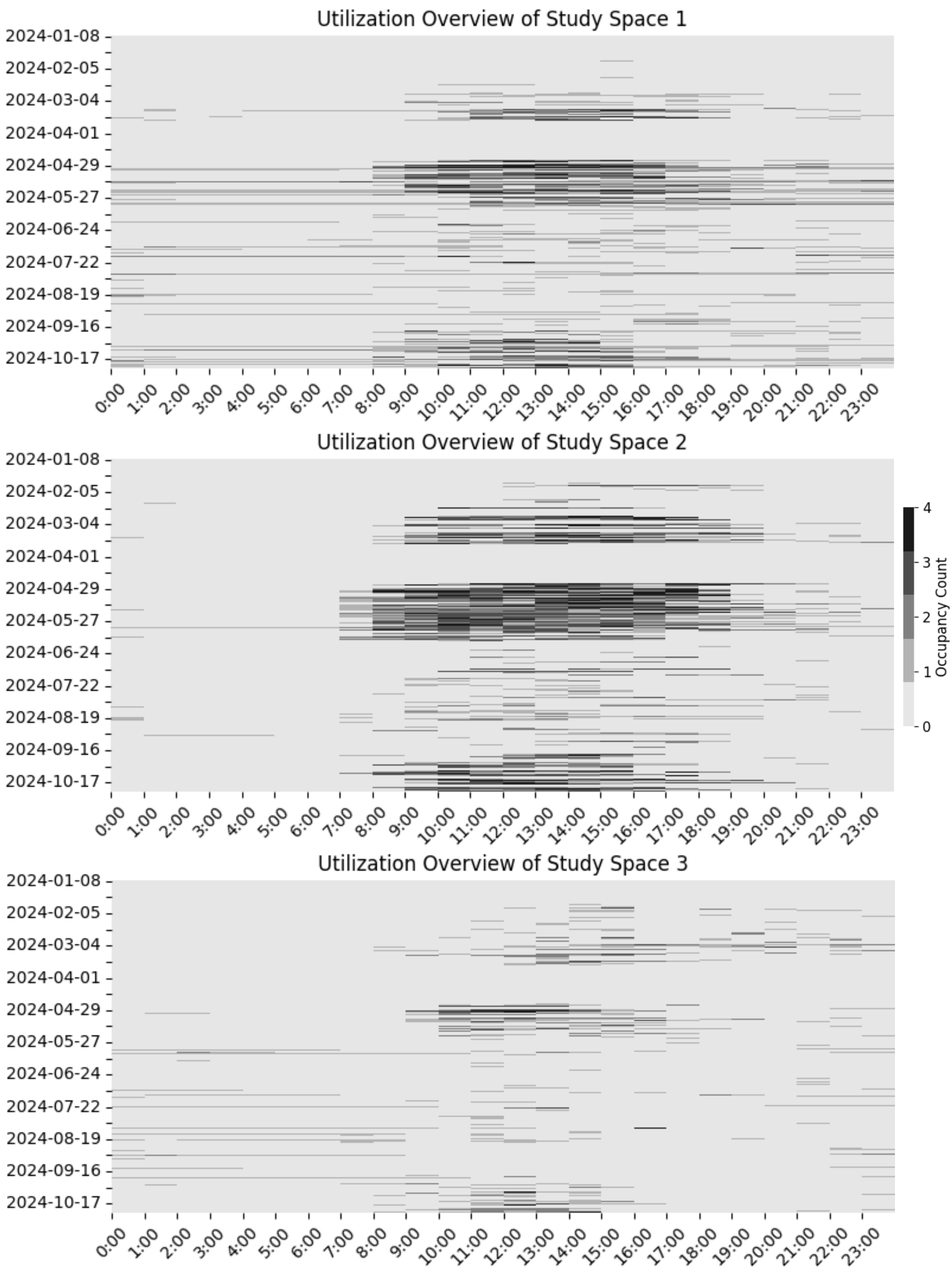


Fig. 9. These heatmaps show occupancy patterns for three study spaces, with values from 0 to 4. Colors represent occupied sensors, with lighter shades for lower and darker for higher occupancy.

Fig. 10. Occupancy patterns of chairs in three study spaces (S1, S2, and S3).

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 12 (b) highlights problematic areas identified by students, marked

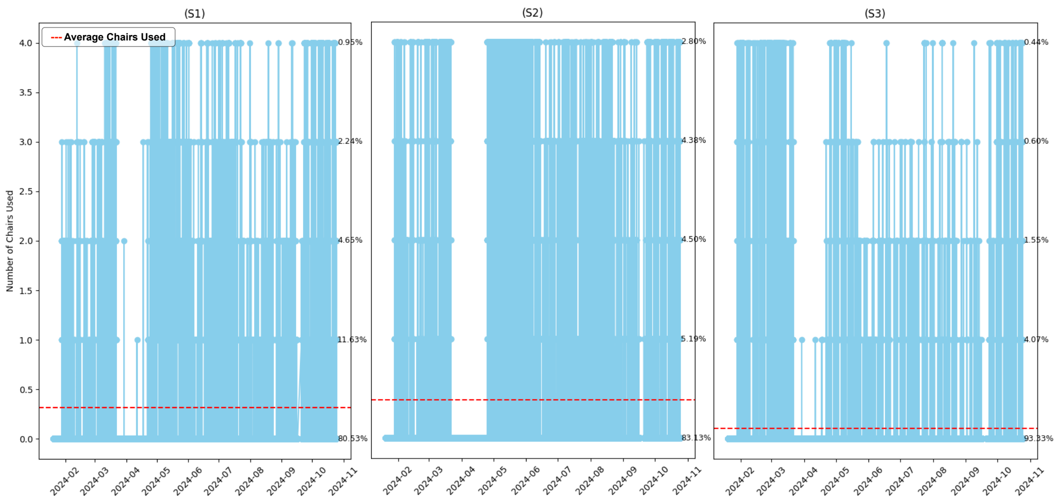


Fig. 11. Number of chairs used over time .

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 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.

Figure 7 (b) illustrates that the mean satisfaction rates of facility managers regarding how the collected information enhances the decision-making process were higher after the experiment compared to before. The p-value was less than 0.05, indicating that the differences in satisfaction levels before and after the experiment are statistically significant. The second bar (post-experiment) exhibits a slightly higher standard deviation than the first bar (pre-experiment), suggesting greater variability in satisfaction levels among facility managers after the experiment. This indicates mixed perceptions of the effectiveness of the sensing solutions in the decision-making process.

5.4 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 14 presents data collected from sensor nodes installed in these study spaces, providing insights into various environmental factors.

In the top-left corner of Figure 14, 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 [93], possibly exacerbated by

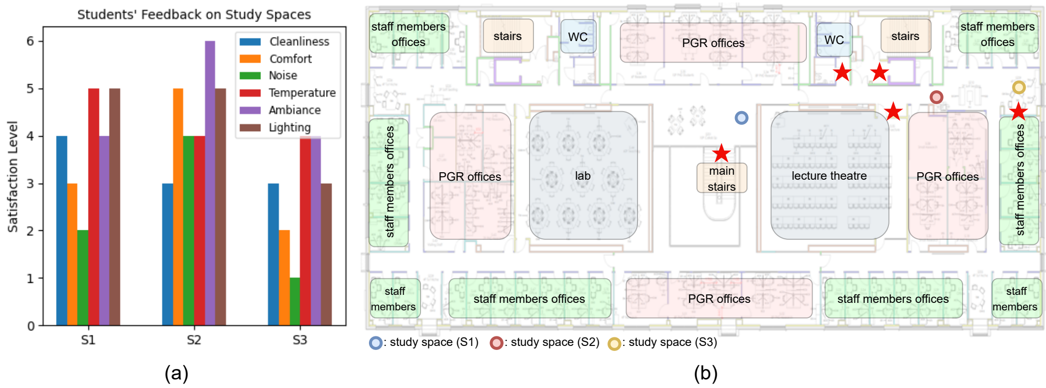


Fig. 12. (a) shows students' satisfaction levels for study spaces, and (b) highlights problematic areas with red stars based on their feedback.

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 14 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 [14]. 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.

6 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 discuss how sensor data enhances facility management practices to promote efficient space use and enhance student engagement.

6.1 Sensor Capability

Sensor data have revealed some hidden behaviors and conditions in study spaces that facility managers were previously unaware of. For instance, Figure 14 indicates a potential issue with the heating system or uneven air distribution. This is evident when comparing S1 and S2 over several

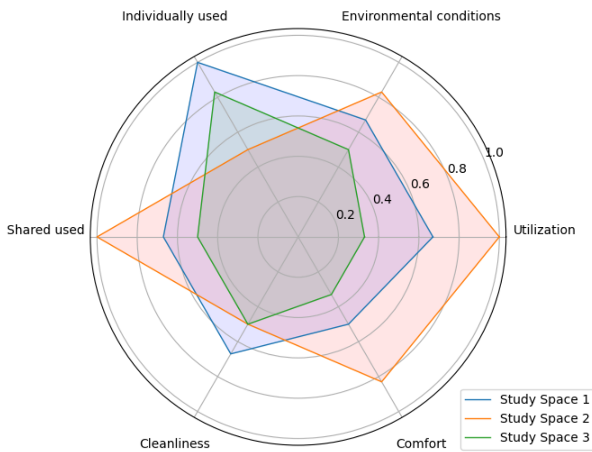


Fig. 13. Shows a radar chart comparing three study spaces across key factors: utilization, environmental conditions, individual usage, shared usage, cleanliness, and comfort, based on sensing data and occupant feedback.

months, as S1 consistently shows the highest temperature and lowest humidity, 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.

6.2 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 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 12 (a). The utilization of these spaces also differed, with students tending to use S2 more frequently than S1 and S3, as seen in Figure 8. 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.

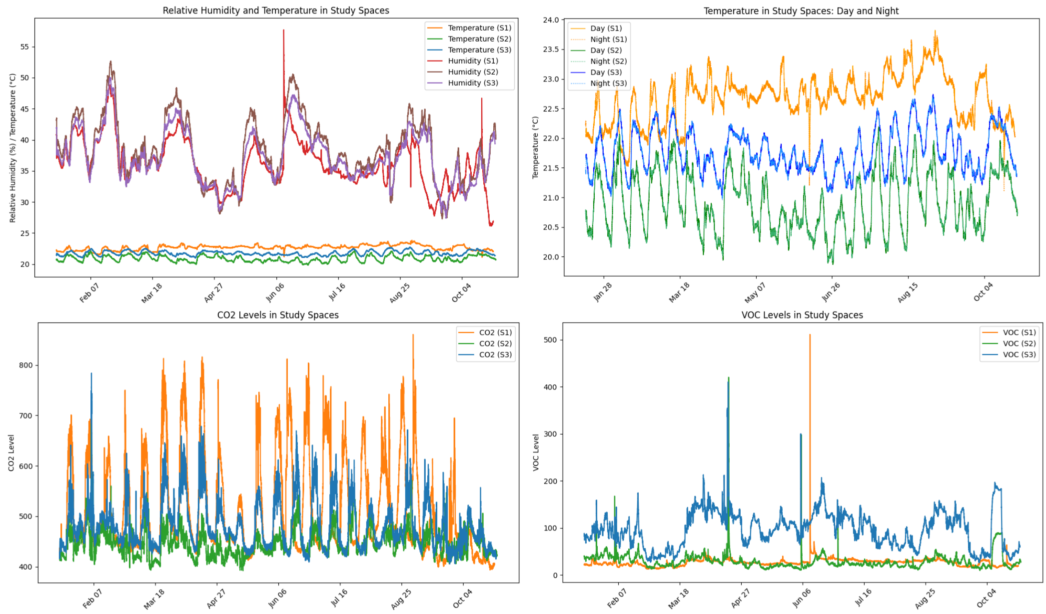


Fig. 14. Study space conditions: Humidity, temperature (Day/Night), CO2, VOC.

Building policies also significantly impact the utilization of study spaces. Figure 9 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.

6.3 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 our study 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 our study 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.

6.4 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. [49] 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.

6.5 Enhancing Facility Management for 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

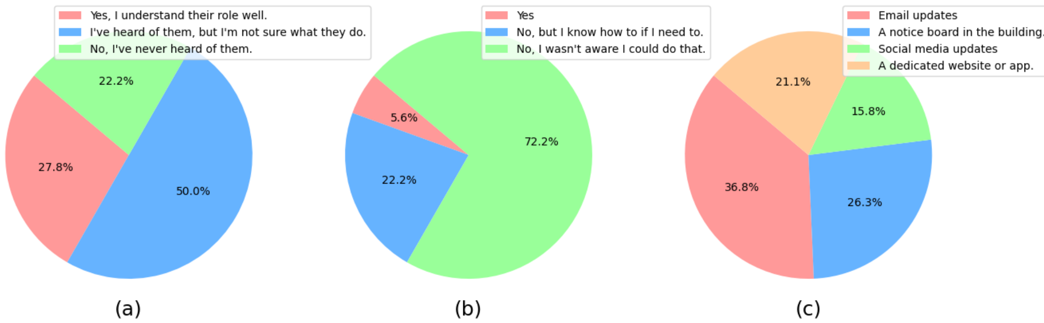


Fig. 15. The representation captures participant responses about their understanding of facility managers' roles (a), previous interactions with them (b), and the preferred method of contacting them (c).

the building. The results were striking, with only a quarter of participants 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 15 shows participant feedback concerning their understanding of facility managers' roles, their history of interaction with them, and their favored method of contact.

7 CONCLUSIONS

This study investigated how integrating sensor technology can help understand student behavior and improve educational environments. By employing a mixed-methods approach, we examined both qualitative and quantitative data, gaining valuable insights into how students use open-design study spaces and their behavioral patterns. The findings have the potential to improve communication between students and facility managers, supporting more informed decision-making. Our findings show that monitoring how spaces are used and the surrounding environmental conditions is crucial for improving facility management and supporting student well-being. These insights help create better educational environments by addressing issues like space utilization and comfort. Further, future research could focus on using predictive modeling to optimize space usage and expand the environmental metrics we measure. This could provide even more ways to enhance educational settings, promote sustainability, and contribute to sustainable societies by ensuring they meet the needs of students and facility managers effectively.

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A APPENDIX: SEMI-STRUCTURED INTERVIEWS 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 (HBI)

- 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?

B APPENDIX: QUESTIONNAIRE QUESTIONS

B.1 General Background Questions

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

B.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?

Likert and nominal scaling	Questions regarding occupant experiences in study spaces							
	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 5. Measuring occupant experiences within study spaces.

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

B.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).

B.4 Photo feedback on study space issues

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

C ILLUSTRATIONS OF DASHBOARD ORGANIZATION AND COMPONENTS

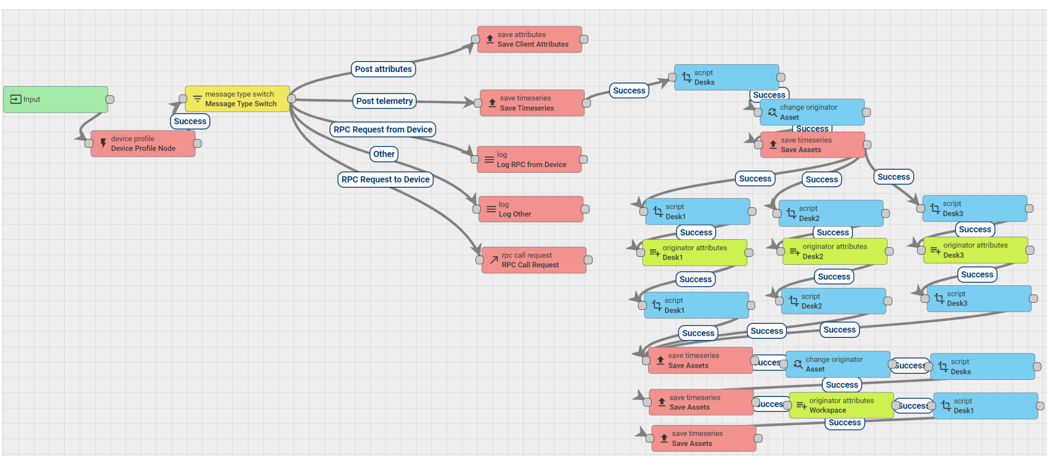

Fig. 16. The Node-RED rule chain structure in ThingsBoard platform.

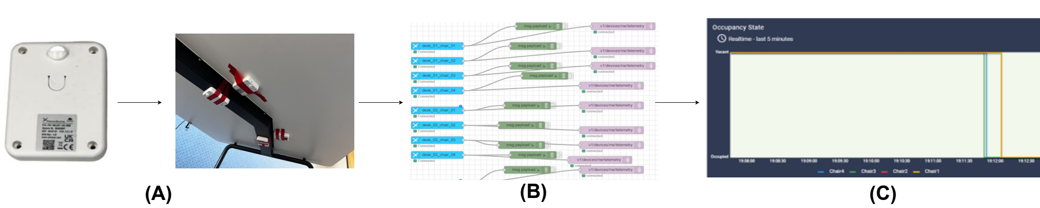

Fig. 17. Illustrates (A) the Pressac desk occupancy sensor positioned beneath the desk, (B) the management of data from various sources, and (C) the presentation of different chair occupancies on the dashboard for the facility manager.

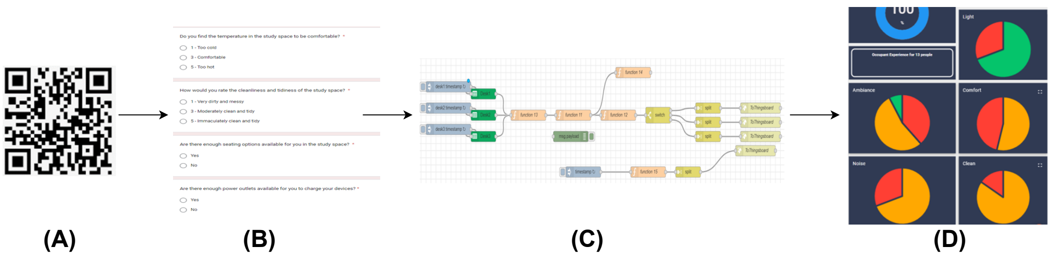

Fig. 18. Represents (A) the QR code scanned by the occupant, (B) the form completed by the occupant, (C) the processing of data from the form for presentation on the dashboard, and (D) the occupant feedback visualized in a pie chart on the dashboard.