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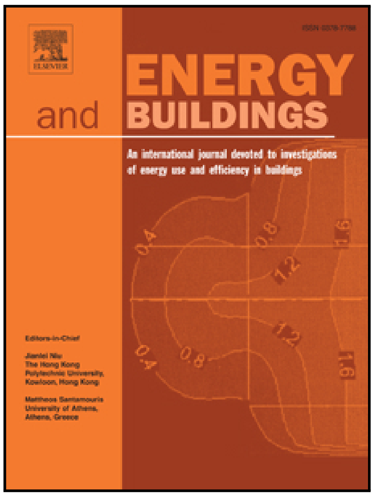

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EcoCube: An IoT-Driven Cube for Environmental Awareness and Human-Building Interaction

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ABSTRACT

Efficient communication between building occupants and facility managers is essential for optimizing space usage, improving user satisfaction, and promoting sustainable practices. This study investigates the effectiveness of the Internet of Things (IoT)-enabled EcoCube device in addressing communication challenges within open design study spaces in a university setting, aiming to create more responsive and adaptive built environments. By integrating principles of social computing and IoT-based sensing and feedback mechanisms, the EcoCube enables students to report issues, share feedback on space preferences, and actively engage in building management processes. Findings reveal differences in satisfaction levels across various study spaces and environmental conditions, emphasizing the need for adaptable solutions to accommodate diverse user needs. Key challenges include improving communication channels and enhancing space efficiency to support sustainability goals. Integrating direct communication features and leveraging occupancy data for real-time management are recommended to advance building sustainability and user satisfaction. As a contribution to IoT research in the context of HBI, this study highlights the EcoCube's potential to foster collaborative building management, enhance user experience, and support sustainable operations through innovative technology and user-centered design.

1. Introduction

In today's architecture, buildings are designed to accommodate diverse activities, incorporating spaces like open offices, collaborative areas, and private meeting rooms. This approach aims to create a dynamic environment that enhances both space efficiency and occupant productivity [1, 2]. However, in many construction projects, standard practices or cost-saving measures can sometimes lead to infrastructure that, while functional, may not fully meet the long-term needs of its occupants. These practices can result in buildings that are inefficient or uncomfortable, with suboptimal layouts and poor energy management [3]. The challenge becomes even more evident when considering the trade-offs between occupancy and design. A building might be designed for maximum capacity, but without considering the diverse needs and behaviors of the people using the space, it can quickly become underutilized or inefficient.

Post-occupancy feedback is often neglected once a building is completed [4]. While facility managers require data on space utilization and occupant preferences to optimize operations, a persistent communication gap often exists [5]. Occupants frequently modify their environments independently, while managers lack the structured feedback necessary to implement meaningful improvements [6, 7]. Bridging this gap requires accessible, user-friendly technology that enables continuous data collection and real-time environmental monitoring.

Educational buildings present a distinct context compared to offices or homes. Occupancy follows the academic calendar rather than a fixed working pattern, and study spaces are typically shared and open-plan, used by different students from day to day rather than assigned to a single occupant. Universities also increasingly operate under institutional sustainability targets, adding pressure to manage these spaces efficiently. These differences mean that findings from HBI and FM research conducted in offices or homes may not transfer directly to educational settings, and informed the choice of literature discussed below, as well as design decisions for EcoCube, such as anonymous reporting and a shared, communal device rather than one paired to an individual occupant.

Existing research on enhancing human interaction with built environments spans three interconnected domains: Human-Building Interaction (HBI), Facilities Management (FM), and Physical Interface Toolkits. Each domain addresses aspects of user experience and operational effectiveness within architectural and infrastructural contexts.

HBI explores how individuals engage with their surroundings through technology and design. Literature identifies diverse perspectives for improving these interactions, ranging from technological advancements to psychological well-being [8–11]. For instance, Floris et al. [11] developed an IoT-based cloud platform to monitor environmental parameters like Total Volatile Organic Compound (TVOC) levels and occupant density. Similarly, Jazizadeh et al. [8] addressed the limitations of fixed HVAC settings by proposing a participatory sensing framework. Using a

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fuzzy rule-based model, they integrated real-time occupant preferences into climate control, optimizing both comfort and energy efficiency. Further experimental advancements include MakeSense, an IoT testbed that facilitates behavioral data collection and situation-aware applications in natural environments [12].

Beyond sensing technology, research emphasizes architectural design as a catalyst for enhanced HBI. Lee et al. [13] demonstrated that office layouts significantly influence social territoriality and productivity, introducing the concept of socio-spatial comfort. In residential contexts, Nguyen et al. [10] investigated responsive architecture via dynamic walls, identifying key qualities that optimize spatial positioning to enrich user experience. Complementing these design-centric studies, Kobal Grum [9] highlighted the psychological dimension of HBI, proving that poor housing quality directly correlates with occupant stress. Together, these works underscore the necessity of an interdisciplinary approach—merging IoT sensing, architectural flexibility, and psychological insights—to create truly responsive built environments.

Facilities Management (FM) integrates personnel, processes, and technology to ensure the safety, efficiency, and comfort of physical spaces. Recently, FM has converged with Human-Computer Interaction (HCI) to enhance building sustainability and user experience [14]. The rise of smart buildings and IoT has shifted FM toward real-time monitoring [15–17], predictive maintenance [18, 19], and data-driven decision-making [20, 21]. However, the efficacy of these systems depends on the quality of occupant interaction, highlighting the necessity of HCI in this domain. Research suggests that applying HCI principles to FM—specifically in the design of interfaces for lighting, temperature, and security—increases the usability of smart systems and fosters deeper occupant engagement [22]. Technical frameworks such as the IoT Meta-Control Firewall (IMCF+) exemplify this integration by balancing occupant comfort with energy efficiency. Using the AI-based Green Planner algorithm, IMCF+ optimizes device usage based on renewable energy availability, achieving significant CO_2 reductions with minimal user impact [23]. Similarly, the "Mites" system provides a scalable sensing architecture that prioritizes user privacy and intuitive interfaces to encourage participation in institutional environments [15]. These advancements illustrate that aligning FM with HCI not only improves building performance but also transforms stationary structures into responsive, user-centric environments that support long-term sustainability.

Physical interface toolkits have emerged as a pivotal advancement in facilitating intuitive communication between occupants and their environments. By integrating technology with tangible components, these toolkits enhance engagement and foster a sense of agency, allowing users to move from passive inhabitants to active managers of their spaces [24–27]. For instance, "Carbon Scales" uses physical data visualization to foster carbon literacy [26], while "Physikit" utilizes ambient physical cues to democratize "black box" environmental data within home environments [24]. These systems demonstrate that tangible interfaces can effectively translate complex sustainability metrics into actionable user insights.

In professional and educational settings, interface toolkits provide real-time feedback loops that optimize operational efficiency. Research by Snow et al. [28] on indoor air quality (IAQ) displays shows that localized, non-disruptive feedback improves ventilation practices and cognitive performance. Similarly, the "ThermoKiosk" system captures subjective thermal comfort experiences to facilitate dialogue between occupants and facility managers, resolving comfort tensions through digital interaction [29]. These studies highlight the potential for tangible interfaces to replace traditional, static feedback methods—such as surveys and questionnaires—which lack real-time technological interaction and often suffer from low engagement [30–32].

Despite the diversity of existing solutions, including task-specific devices for IAQ [28] or energy auditing [33], and several commercial solutions such as CubeSensors that rely on mobile applications [34], a gap remains for a unified, always-available communication medium. While devices like "TickTime" [35] and "PrivacyCube" [36] explore cube-based forms for time management and privacy awareness, our study introduces EcoCube. Designed to be an accessible and user-friendly tangible medium, EcoCube bridges the communication gap by allowing occupants to report issues, monitor environmental data, and share preferences with minimal effort. This approach not only increases occupant awareness but also provides facility managers with the detailed, real-time data necessary for informed, user-centric decision-making.

We aim to enhance Human-Building Interaction (HBI) through a tangible communication medium. This research addresses three primary questions:

- How can a tangible medium bridge the occupant-manager communication gap?
- How does such a device influence occupant satisfaction and management efficiency?
- How can sensing data identify preferred temperature ranges in open spaces?

To address these, we conducted a study in a new educational building in the UK. Following iterative design workshops with students and facility managers, we developed EcoCube, a device designed to increase environmental awareness and facilitate feedback. We also developed a real-time dashboard to visualize occupant data for management. The contributions of this work include, to our knowledge, the first application of a tangible IoT sensing medium to bridge communication gaps in educational open-plan spaces, the implementation of a non-disruptive design that integrates into real-world environments, and a mixed-methods assessment demonstrating improved occupant satisfaction and facility management efficiency.

Table 1
Student participant demographics.

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

Table 2
Details of participants for facility managers.

Part.	Occupation	Responsibilities
FM1	Facility manager	Oversee maintenance operations; develop and implement SHEW* policies; manage facilities team; and coordinate space allocation.
FM2	Deputy school manager	Responsible for managing school operations, including budget management and general administrative tasks.
FM3	Technical services manager	Oversee laboratories and maker workshops, provide support for student projects and research, and supervise equipment usage.

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

2. EcoCube Deployment and Data Collection

This section outlines the deployment of the EcoCube and the data collection process for our experiment. We began by gathering insights from a student workshop to inform the design of the EcoCube, alongside interviews with facility managers to ensure it aligned with operational needs. We will describe the study spaces where the experiment was conducted, the sensors and board used in the EcoCube, and its placement within these spaces to optimize both data collection and user interaction.

2.1. Data Collection

We began data collection with a three-hour workshop involving eighteen university students, recruited via an announcement on the university website. The workshop included two main activities: a building walk and a co-design task for study spaces.

After an introduction to the building and the importance of study environments, students received printed floor plans to guide their exploration. Inspired by social science and HCI walking methodologies [37, 38], participants used recording devices to document their thoughts while freely exploring study areas. This approach offered insights into how design elements impact study behavior. A group discussion followed, where participants shared reflections on each space's strengths, weaknesses, and potential improvements.

In the second part of the process, participants were divided into six groups for a co-design task. Using the provided materials, each group sketched their ideal study spaces. Afterward, they discussed the commonalities and differences in their designs [39]. Facilitators documented feedback throughout, uncovering a communication gap between students and facility managers. Many students were unaware of the role of facility managers, assuming they should contact faculty for building-related issues, as illustrated in Figure 9.

To explore this further, we conducted a second workshop focused on designing a communication medium. Nineteen students were recruited through an announcement on the university website, and participant details are provided in Table 1. The workshop lasted two and a half hours. During this session, we identified students' needs for a communication channel with building managers. We introduced participants to IoT technology, communication interface designs, and the challenges of engaging with building managers. Students participated in group activities, where they sketched low-fidelity prototypes of a communication device. They emphasized desired features such as ease of use, real-time feedback, and intuitive design. Snapshots of the workshop can be seen in Figure 1, with some participant sketches shown in Figure 2. After presenting the prototypes, we collected feedback on what worked well and areas for improvement.

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

Based on participant feedback and insights from the literature on cube interfaces [24, 40], we developed a high-fidelity prototype. This final design incorporated student suggestions, including responsive interaction elements, improved visual design, and enhanced connectivity features.

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

We also gathered quantitative data on participant satisfaction with communication between students and facility managers. This was measured using a questionnaire administered before and after their interaction with the device. The questionnaires were developed based on prior research

Figure 1: Snapshots of the workshop conducted with student participants, and some sketches made by them.

into factors affecting study experiences, such as exploring environmental data, occupant engagement, and promoting sustainable practices [24, 28, 29]. This approach ensured that student needs were addressed and facilitated effective communication between occupants and facility managers, enhancing overall satisfaction in study spaces. Further, insights from previous workshops and interviews with facility managers were critical in shaping the design. A post-experiment interview was also conducted to assess participants' experiences with the device, where they provided detailed feedback on preferred features and areas for improvement. Participants were given tasks using the high-fidelity prototype, and their interactions were closely observed. This iterative process of prototyping, testing, and gathering feedback resulted in a communication device that is user-centered and addresses communication challenges between the two parties.

To gain insights into the needs and perspectives of both occupants and facility managers, we conducted interviews with the facility managers responsible for the building. These managers represented distinct roles within the facility. One manager was responsible for overseeing building health and safety, another managed school operations, which included budget oversight and general management tasks, while the third focused on technical services. Each manager participated in two one-hour interviews: one prior to the deployment of the medium device and another following its implementation. These sessions were recorded to facilitate data analysis. Comprehensive participant information is provided in Table 2.

The interviews were conducted using a semi-structured format, incorporating both closed and open-ended questions. This approach allowed the interviewer to begin with a set of predetermined questions while also encouraging a natural flow of conversation, fostering spontaneous discussions and the inclusion of the interviewer's insights on pertinent topics. Sample questions were distilled into keywords and categorized by content to guide the interview process. In line with the recommendations of Denzin and Lincoln [41], special attention was given to the rhythm of the conversation, allowing for the emergence of new topics organically. The transcripts of these interviews were meticulously prepared and analyzed thematically, as outlined by [42].

2.2. EcoCube Device

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

The base supports the cube and houses essential electronics, including various sensors. The device features multiple sensors: temperature, sound, light, CO2, and chainable RGB LEDs. These sensors play different roles:

- Temperature, sound, light, and CO2 sensors: These sensors continuously monitor environmental conditions in the study spaces. They collect data on temperature, noise levels, lighting, and carbon dioxide concentrations. This data is displayed to occupants on the device and also transmitted to a monitoring dashboard. Detailed specifications of these sensors, including their types and capabilities, are listed in Table 3.

- Chainable RGB LEDs: These LEDs are used to visually indicate changes in the study environment. They were designed based on feedback from student workshops and insights from previous research. The LEDs are programmed to display three colors:

  - Green: Indicates optimal conditions.
  - Yellow: Signals moderate changes or potential issues.
  - Red: Alerts to significant disturbances or problems. This color-coding helps occupants quickly assess their environment without needing to interpret numerical data.

The RGB LEDs draw inspiration from existing research. For example, Houben et al. [24] introduces Physikit, a system that uses LEDs to create physical visualizations of environmental data, thereby enhancing user engagement. Sauvé et al. [25] describes Econundrum, a physical sculpture with LED displays that reveals the carbon emissions from community food choices, aiding users in understanding the environmental impact of their diet choices.

To manage and visualize data, the EcoCube employs an Arduino board and a Nextion display screen [43]:

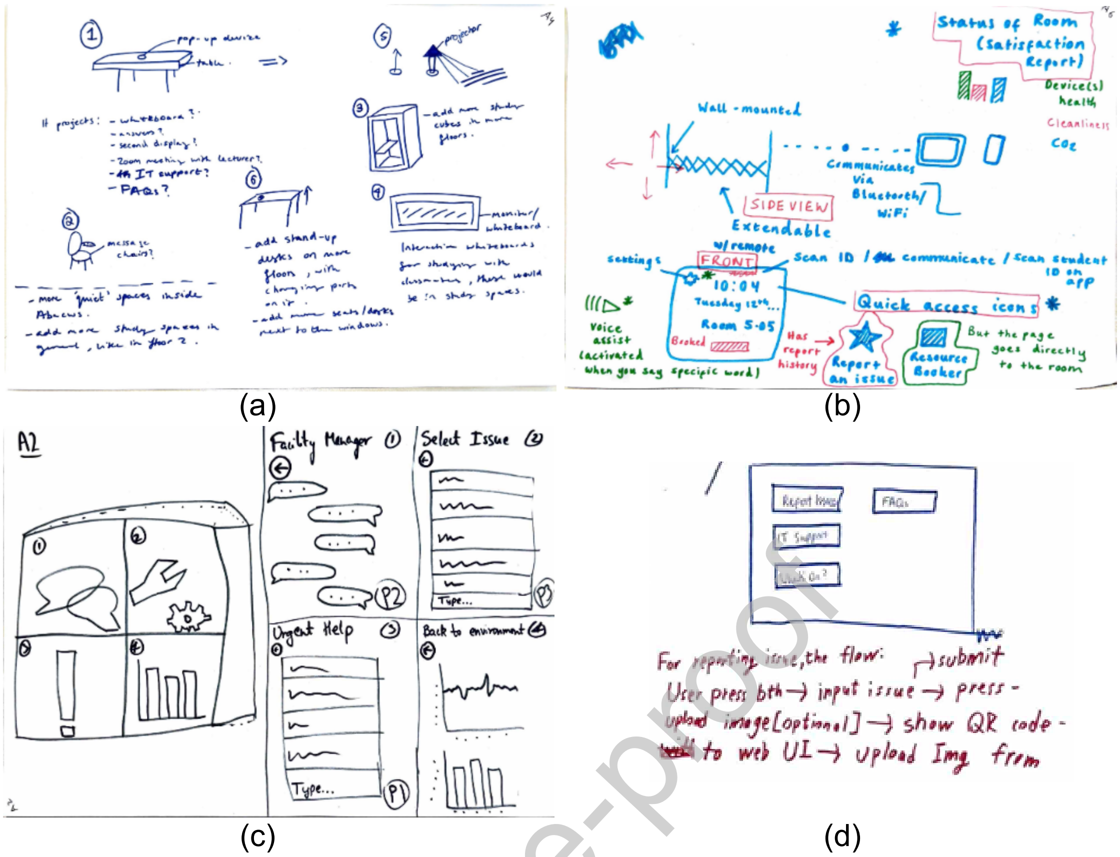


Figure 2: A collection of sketches created by participants during the workshop: (a) Group 1, (b) Group 3, (c) Group 5, and (d) Group 6.

- Arduino board: Handles sensor inputs, processes the collected data, and controls the LEDs and other components.
- Nextion display screen: Provides a user-friendly interface, allowing occupants to interact with the device and view real-time environmental information. The display shows data in an easily understandable format, enhancing user experience and interaction.

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

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

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

Table 3
Summary of the sensors used in the EcoCube device.

Sensor	Performance	Used by	Purpose
Temperature	Accuracy: ±2%	[44, 45]	Environmental monitoring
Light	Range: up to 540 nm	[46, 47]	Environmental monitoring
Sound	Range: 3.2V–5.2V	[47, 48]	Environmental monitoring
Carbon Dioxide	Accuracy: ±50 PPM	[44, 45]	Environmental monitoring
RGB LED	256 shades	[24, 25]	Displaying changes

2.3. EcoCube Placement

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

We also had to think about practical issues, like the need for a nearby power source. The EcoCube needs to be close to an outlet, so we had to position it carefully. We made sure the power cable was securely routed to avoid any tripping hazards for students walking around the table. Stability was another key factor; we ensured the cube wouldn't easily fall, even if students moved around or interacted with it actively.

In the previously held workshop with students, we gathered their feedback on where the cube should be placed. Most students preferred having the cube in the center of the table, as long as it did not take up too much of their personal study space. The central position made the cube easy to see and interact with for everyone, turning it into a shared focal point without disrupting individual work areas. Table 4 shows the different study spaces we evaluated.

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

3. Methodology

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

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

During earlier interviews, facility managers had expressed support for a communication medium that would enhance interaction with students and provide more data on student behavior in different study spaces. Such data would enable managers to improve the overall student experience. In this experiment, we utilized three study spaces in a new built building located in the United Kingdom. The details of the study spaces are shown in Table 4. The EcoCube device was initially deployed in a lab for pilot testing, and after its successful trial and receiving ethical approval from the school's department, we expanded its deployment to the three study spaces.

Following the experiment, interviews were conducted with facility managers to gather their feedback. These semi-structured interviews combined specific questions with open-ended discussions, aiming to capture their thoughts on the EcoCube, their impressions of the study spaces' performance, and any suggestions for improvement. The interviews were recorded, transcribed, and analyzed thematically to capture the key insights [49].

We also conducted post-experiment interviews with students to understand their experiences with the EcoCube. Participants were asked to share their thoughts on the device's features, usability, and areas for improvement. Detailed scenarios and tasks were provided for them to complete using the high-fidelity prototype, and their interactions were observed to gather additional feedback. NVivo software was used to organize data into themes, making the coding process more efficient. NVivo helped identify patterns and relationships in the qualitative data, adding rigor to the analysis. The data collected from these interviews were transcribed and thematically analyzed, resulting in four key themes: data acquisition, interpretation, implementation of insights, and user engagement [42]. Coding strategies included open coding to capture initial ideas, axial coding to refine and connect themes, and selective coding to highlight core themes that represented key findings.

For the quantitative analysis, we applied a paired sample t-test to compare participants' satisfaction with communication before and after using the EcoCube. The t-test is a reliable method for evaluating changes in numerical data, making it an appropriate choice for our study [50].

The t-test has been widely used in previous studies to evaluate the effectiveness of educational and collaboration tools. For instance, García-Magariño et al. [51] demonstrated performance improvements and ease of use in an IoT collaboration system over time. Similarly, Chochiang et al. [52] showed significant skill improvement and high user satisfaction in the use of ArViz, a tool for teaching IoT programming. Another study by Edgar [53] found that students considered iPad integration valuable and effective for learning in classrooms. These studies underscore the utility of the paired t-test in assessing tool performance and user engagement across various platforms. Figure 3 provides a visual overview of the methodology steps used in our experiment.

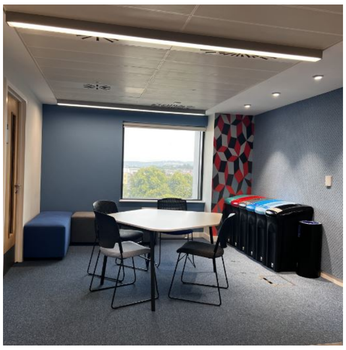
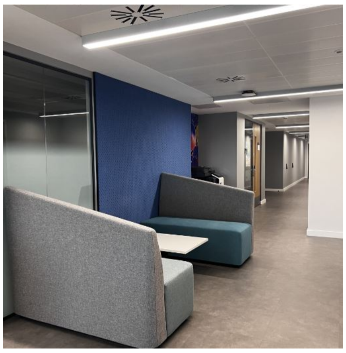
3.1. EcoCube Design

The design of the EcoCube is inspired by various cube interfaces from the literature [24, 40] and minimalist monitors described in [28, 54]. Notable inspirations include:

- Physikit: The Physikit system, discussed by Houben et al. [24], features devices like PhysiLight and PhysiBuzz that use light and vibrations for intuitive data visualization. This concept of utilizing simple sensory inputs for data presentation influenced the EcoCube's approach to environmental readings.

- PrivacyCube: The PrivacyCube [40] addresses privacy concerns by displaying IoT data habits within homes,

Table 4
Various types of study spaces in the educational building, with detailed information about each.

Space	Dimensions	Features	Image
S1	8'3" x 12'6"	• Located in the center of the building, with two PGR offices on either side. • Close to the main staircase and staff offices. • Open space with no door, accessible from different sides. • No windows. • Lighting and air conditioning are automatically controlled by building systems. • The space has no dedicated heat emitter or floor sockets. • Includes a whiteboard and a TV. • Has two wall outlets.	
S2	11'8" x 12'6"	• Located between two staff offices, directly across from one of the office doors. • In front of the walk and study space 3 (S3). • Features a large window on the northwest side with blinds. • Open area with no door. • Lighting and air conditioning are automatically controlled by building systems. • The space has a dedicated heat emitter and is equipped with four floor sockets. • No TVs or whiteboards available. • Contains litter bins and a drinking fountain at the entrance.	
S3	7'2" x 4'1"	• Situated on a walking path next to the PGR office and two staff members. • No windows. • Open area without a door, accessible from two sides. • Lighting and air conditioning are automatically controlled by building systems. • The space has no dedicated heat emitter, floor sockets, TV, or whiteboards. • Desk height is low. • Close to a drinking fountain and a printer located on the walking path. • The study space dimensions determined by furniture size.	

fostering privacy awareness and promoting discussions among family members. This emphasis on user awareness and privacy considerations helped shape the EcoCube's design philosophy.

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

- CubeSensors: It provides real-time environmental data such as temperature and air quality in a compact form factor. Their design focuses on optimizing user environments through compact, informative displays [34].

- Ticktime cube: The cube serves as a versatile timer with various modes, including countdown and Pomodoro. Its compact design emphasizes convenience and eco-friendliness, aspects that influenced the EcoCube's practical and user-friendly design [35].

- Amazon fire TV cube: It enhances streaming experiences with performance and voice control, integrating seamlessly with entertainment systems. This integration and design provided insights into creating an interactive and effective interface for EcoCube [55].

The EcoCube is designed to help occupants of study spaces monitor current environmental conditions, increase their awareness of their surroundings, and provide feedback. It features a 10 x 10 x 10 cm white acrylic cube with a rotating base, allowing easy access to any side. The cube incorporates laser-cut icons and assembles without the need for tools. It

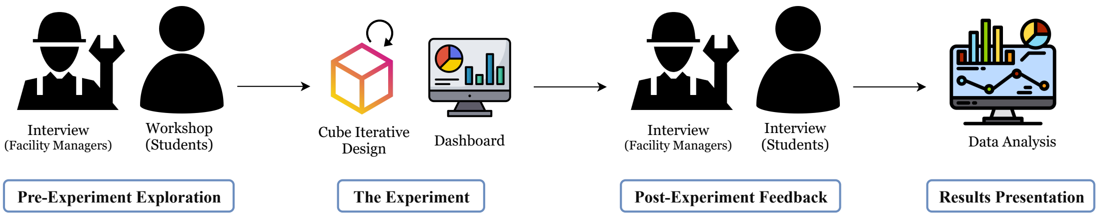


Figure 3: Overview of the experiment methodology, including pre-experiment, experiment, feedback, and results.

includes a 4.3-inch display screen connected to an Arduino microcontroller and sensors for measuring temperature, humidity, sound, light, and CO2. The device is Wi-Fi-enabled, transmitting data to cloud every five seconds.

In response to post-experiment feedback, where participants mentioned issues with the screen viewing angle and the need to stand to use the device comfortably, we addressed this by 3D printing a support piece to improve screen visibility, as shown in Figure 5 (b). This enhancement ensures that the screen can be viewed more comfortably from different angles.

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

The final design of the EcoCube, including the rotating base and improved screen support, is illustrated in Figure 5 (a) and (b). Our design was guided by the following considerations:

3.1.1. Usability and Convenience

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

The main screen of the EcoCube, depicted in Figure 6 (a), features large, easy-to-understand icons that represent various types of environmental data. It also includes icons for sound, temperature, light, and air quality, which are prominently displayed on each side of the cube as shown in Figure 4. The design was carefully crafted to provide clear, immediate information at a glance. For instance, the sound icon changes color—turning yellow or red—to indicate increasing noise levels, helping occupants efficiently assess their study environment.

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

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

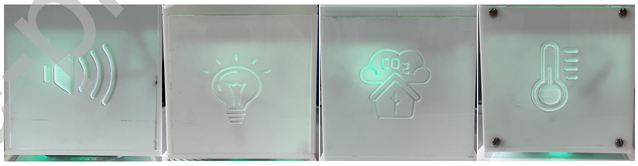


Figure 4: Shows symbols for sound, light, air quality, temperature are displayed on each side of the cube.

3.1.2. Adaptation to Workplace Patterns

The study spaces in the building feature white ceilings and tables, creating a minimalist and cohesive aesthetic. Initially, we considered a wooden design for the EcoCube to add a natural element to the environment. However, during the workshop, we discovered that the wooden design was too visually distracting for the students. To ensure that the EcoCube would integrate well with the existing decor and remain unobtrusive, we chose a white cube design. This color scheme allows the device to blend seamlessly with the surroundings, maintaining the clean and neutral aesthetic of the study spaces.

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

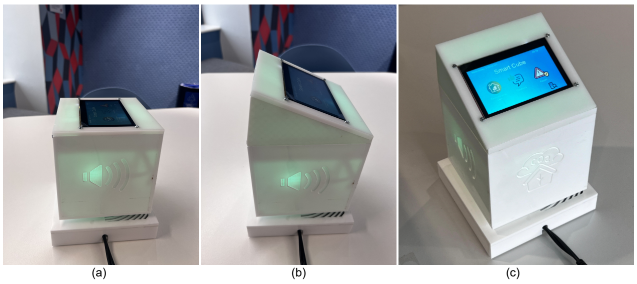


Figure 5: Shows (a) the final high-fidelity EcoCube design, (b) the addition of a 3D piece to adjust the viewing angle, and (c) another angle view of the device.

3.1.3. *Screen Features*

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

- Real-time environmental data: The screen provides real-time updates on environmental conditions, such as the current temperature. Students can also set their preferred temperature, as illustrated in Figure 6 (e). The interface updates dynamically to reflect these settings and other environmental changes.

- Feedback icons: The feedback icons display emojis that update based on user input to reflect their feelings about specific aspects of the study space. For example, Figure 6 (b) shows how the emojis can represent satisfied, neutral, or dissatisfied reactions, providing a clear and intuitive way for occupants to express their satisfaction or dissatisfaction [56].

- Issue reporting: The reporting issues page, depicted in Figure 6 (c), allows students to report problems by selecting from a list of common issues. Students can also choose to include their email address for follow-up and provide additional comments for facility managers, ensuring that their concerns are communicated effectively.

- Thermal comfort assessment: The screen includes features for collecting optional data about students' clothing levels and activities to assess thermal comfort, as shown in Figure 6 (f). This data helps in understanding and improving individual comfort levels in the study spaces.

- Building instructions: The screen provides important building instructions, including information about amenities, safety tips, and sustainability practices. This content is accessible through Figure 6 (g).

Figure 7 illustrates the occupant interaction flow when using the EcoCube device. The interaction begins at the main screen on the top level, from which users can access other screens, including feedback, reporting, and environmental data. This flow allows users to navigate through various screens and ultimately return to the main screen. The EcoCube's screen design is tailored to enhance user experience by providing, actionable information and enabling interaction with the device.

Figure 6: Screenshots of the EcoCube screen: (a) main screen, (b) feedback screen, (c) reporting issue screen, (d) environmental data screen, (e) preferred temperature set by students, (f) collected data from students on thermal comfort, (g) additional building data including amenities, safety tips, and sustainability data, and (h) one of the building's sustainability information.

3.1.4. *Compact Size and Rotatability*

The EcoCube's compact design is tailored to accommodate a range of desk sizes, making it versatile for different study environments. As detailed in Table 4, its dimensions can fit comfortably on desks of varying sizes without overwhelming the workspace.

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

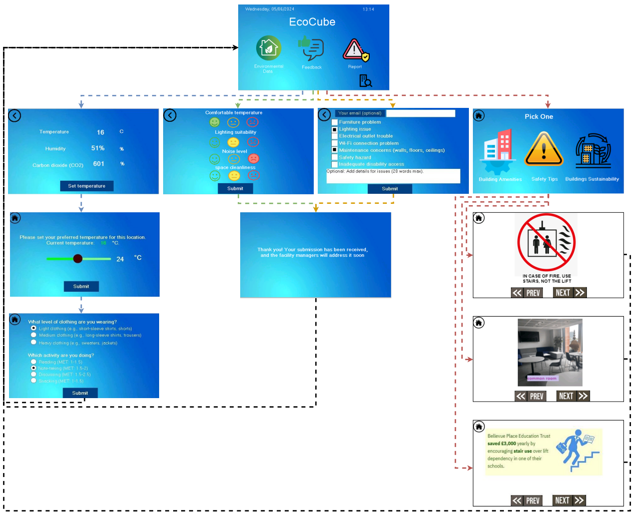


Figure 7: Illustrates the occupant interaction flow when using the EcoCube device.

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

3.2. Data Processing and Visualization

The experiment began with a pilot study conducted in a university laboratory. Initially, data collection was performed locally before being transmitted to an external platform. Based on outcomes from the pilot study, several adjustments were made, including switching from battery power to a fixed power source and configuring the data transmission to occur every five seconds. Battery power was tested during the pilot study but was not reliable enough to sustain continuous data transmission every five seconds over an eight-week deployment, and would have required frequent manual recharging. This made a fixed power source more practical for the current study, but it does limit where the EcoCube can be placed, since it must remain close to an outlet. A lower-power version could reduce this constraint, for example by transmitting data less frequently, using a lower-power display mode, or combining a small battery with indoor solar charging. However, indoor solar energy harvesting typically provides much less power than outdoor use, so this would need further testing before it could support reliable, long-term deployment. Future work should explore these low-power alternatives to allow more flexible placement and easier scaling to larger buildings.

We utilized the ThingsBoard platform [57] for data management. ThingsBoard is an open-source IoT platform that facilitates the management of IoT devices, data collection, and real-time visualizations. For our project, we employed the MQTT protocol, which is well-suited for devices with limited network capacity or resources. ThingsBoard's real-time visualization dashboard effectively displays sensing data, making it an excellent tool for applications requiring clear data insights.

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

The dashboard on ThingsBoard was designed to be user-friendly for facility managers with varying levels of technical expertise. It includes a range of visualizations, such as pie charts that represent student feedback about the study spaces, reported issues, current temperature, and the average preferred temperature by occupants. Figure 8 shows these pie charts display satisfaction levels, with green for satisfaction, yellow for neutrality, and red for dissatisfaction. Percentage values are shown when hovering over any partition, making the data easier to interpret for facility managers. The dashboard also features a line chart displaying temperature, humidity, and CO2 sensor data over a 7-day period, with data collected every 5 seconds, with yellow representing CO2, green representing humidity, and red representing temperature. To allow all three sensor readings to be viewed together on a single scale, humidity is scaled by a factor of 10 in the chart, so a value of 350 represents 35% humidity; this was done to give facility managers a single, combined view of all sensors rather than requiring separate charts for each. The line chart is interactive, displaying the corresponding sensor name when the mouse is placed over a line, and is intended to help facility managers identify anomalies and review recent environmental trends rather than only a single instantaneous reading. Facility managers can view both live data and historical data for specific periods, providing a comprehensive view of environmental conditions and user feedback. To showcase the capabilities of the EcoCube to participants, we present a practical use case illustrating how Alex, a student, uses the device to manage various aspects of his study environment and communicate with building managers.

4. Key Findings and Insights

This section presents key findings on student interactions with facility managers and their experiences in study spaces. We start by describing how students and facility managers typically communicate. Next, we review student satisfaction across various study spaces and identify the features they prefer. Finally, We explore how students react to temperature changes and their feedback on the communication methods

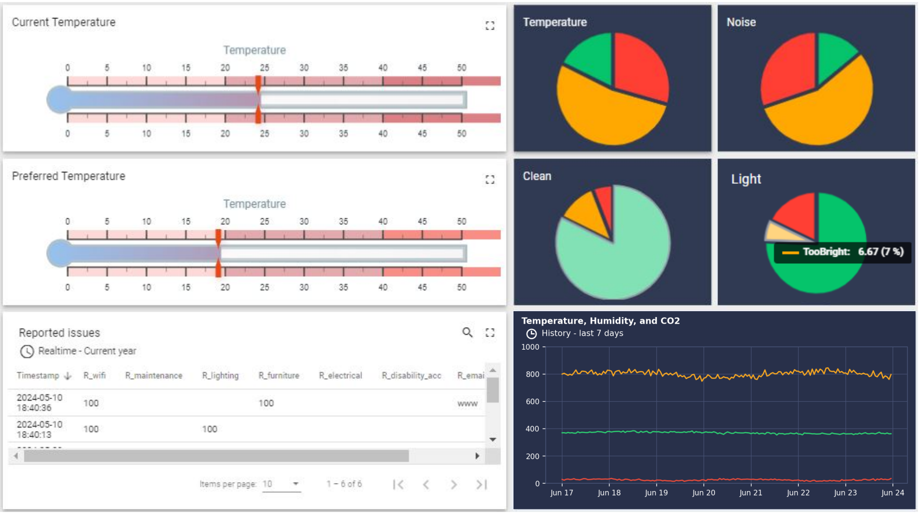


Figure 8: Shows the dashboard displaying student feedback, reported issues, current and preferred temperatures, and a line chart of sensor data.

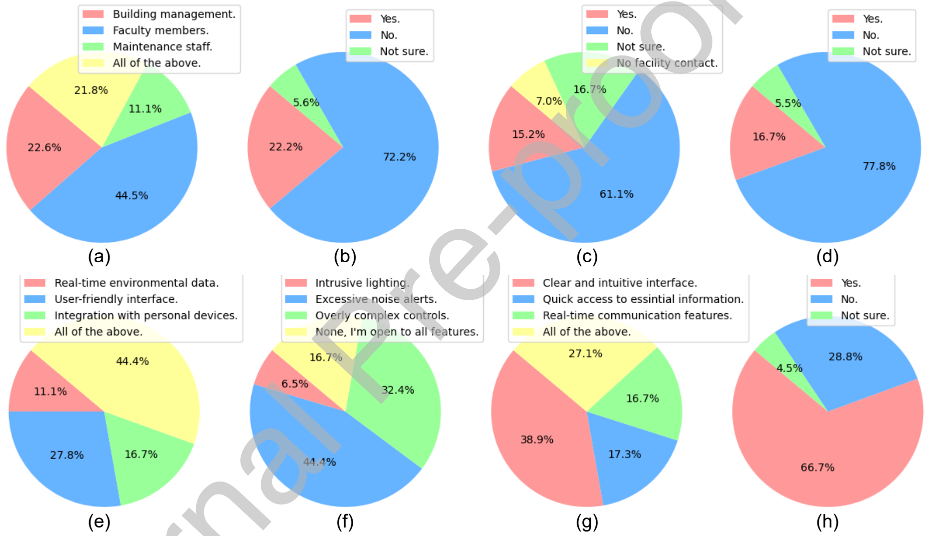


Figure 9: Shows student communication with facility managers on: (a) who to contact for building issues, (b) past interactions with facility managers, (c) issues they have reported, and (d) feedback they have given. Additionally, e-f charts display student feedback on the EcoCube device, including: (e) desired features, (f) unwanted features, (g) preferred design for communicating with facility managers, and (h) the option for anonymous issue reporting.

used. These results provide a clear view of student preferences and help inform improvements to campus facilities and services.

4.1. Usual Communication Between Students and Facility Managers

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

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

During the workshop, when students were asked whom they would contact if they encountered any issues in the building, the majority responded that they would first approach faculty members before contacting building management, as depicted in Figure 9 (a). Further, when questioned specifically about their communication with facility managers in the building, the vast majority indicated they had never communicated with them, as illustrated in Figure 9 (b). Both students and facility managers face limitations; when students were asked if they had ever contacted facility managers regarding issues in the building, the majority responded negatively, representing 77.2% of participants, as shown in Figure 9 (c). Additionally, building management showed a deficiency in motivating students to provide feedback while they were in the building, as demonstrated in Figure 9 (d), where the majority of participants had never been asked to give feedback before.

4.2. Student Satisfaction Levels Across Different Study Spaces

Students have mixed feelings about the features in the study spaces. The majority tend to agree on what they like or dislike about each study space in the experiment. Figure 10 represents the satisfaction levels for the three study spaces. These spaces, shown in Table 4, have different features.

Students generally liked the natural light from the large window in study space two (S2), while they were not satisfied with S3 due to its location on a walking path. One student mentioned, *"Having natural light and a great view like this inspires me to study personally, and I guess many people would feel the same way"* (G1S1). Noise levels were also a factor; students were more satisfied with the noise levels in S2 compared to other spaces. This is likely due to S2's location in the building's corner, away from high-traffic areas. In contrast, S1 is in the center near the main stairs, and S3 is on a walking path near a printer and the building's entrance. However, S2 was rated lower for cleanliness. This could be because recycling bins are located nearby, as indicated in Table 4. A student noted, *"I would want to move the bins over there because I get distracted by them; if people are throwing rubbish and it overflows, it might have an unpleasant smell, which makes it hard for me to study"* (G5S2).

Temperature satisfaction was similar across the three study spaces, as the building's temperature is centrally controlled. However, the temperature can vary slightly due to factors like sunlight heating through windows and the number of people in the area. As shown in Figure 12, the temperature inside the building ranges from 20 to 24 degrees Celsius, with students selecting different temperature settings based on their personal preferences. Facility managers appreciate this data as it helps them improve and renovate study spaces to be more comfortable. They are also interested in additional data on how long students use the study spaces. One facility manager remarked, *"Kind of data for us to understand how long students are staying at one spot; from a well-being perspective, I know that when I was a student, I would go to the library at 7:00 in the morning and stay there for a long time, and I know that's not healthy"* (FM2).

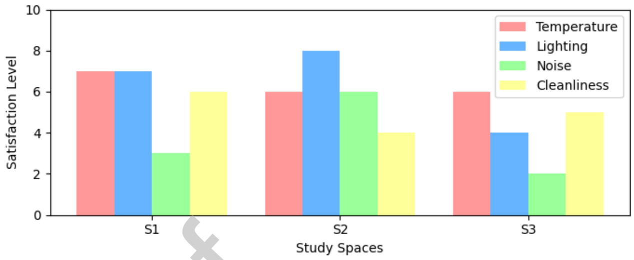


Figure 10: Shows student satisfaction levels for various spaces.

4.3. Preferred Study Space Features According to Students

Students in the workshop study mentioned several features they would like to see in their preferred study spaces. They expressed their thoughts through sketches in groups, as shown in Figure 2. Group 1 preferred adjustable desks, projectors, and cube-style study spaces for meetings. They also emphasized the need for higher-quality chairs, including massage chairs, due to regular long study sessions. Group 3 suggested having screens in each study space displaying satisfaction reports and a wall-mounted screen that can be moved to any desired direction. They envisioned using these screens for studying, connecting via Bluetooth or Wi-Fi, and displaying information such as current time, date, study place number, and other study spaces' booking status. Access to these screens would be through scanning student ID cards or university credentials. Group 5 focused on communication features for their ideal study space. They proposed a screen divided into four sections: one for chatting with facility managers, another for reporting issues, a third for requesting urgent assistance, and the fourth for displaying environmental data charts of the study space. Group 6 suggested a tablet device mounted on the wall with four options on the screen: reporting issues, IT support in the building, FAQs, and updates on what's new in the building.

Overall, the workshop discussions highlighted common features desired by students in any study space. These include having large windows for natural light, adjustable desks, ample power sockets, private or semi-private study areas for privacy, and comfortable spaces for both individual work and group meetings. Students expressed their preferences clearly, with one stating, *"I prefer studying next to windows with natural light or maybe a small study space[...]it makes me feel more comfortable"* (G6S3). Another student emphasized the importance of air quality, saying, *"Breathing* *air, so I think whether it be these windows or some kind of ventilation, having more of that would be good as well; I think it would help me a lot"* (G2S1). Privacy was also a significant concern among students, with one remarking about Study Space 2, *"It's very calming, and there's more privacy. I don't have to interact with anyone, and that's the main goal. If I'm gonna study by myself, that's the main thing I'm looking for"* (G4S3). Another student concurred, stating, *"I'm pretty sure most of them would want their own time and space when they wanna study because they wouldn't come to uni to study otherwise"* (G6S2).

The student who mentioned the importance of air quality stated, *"Breathing air [...] having more of that would be good; I think it would help me a lot"* (G2S1), which could also be interpreted as contributing to 'sick building syndrome,' a condition that causes various discomforts for building occupants [58]. They also expressed a need for designated spaces to store belongings, such as cubbyholes attached to or underneath chairs, to keep their study areas organized and clean. Another student mentioned this, noting, *"Something like a cubbyhole or a designated space for the study area where you can put your bag or belongings because sometimes I end up putting them on the floor, which could be dirty. Having something attached or clipping onto the chair where you can store your stuff, or even underneath the chair, would be helpful"* (G2S3). Additional suggestions included having vending machines for refreshments and study supplies such as notebooks, headphones, pens, and other essentials, reflecting their need for convenient access to resources while studying. Students also advocated for smart boards for collaborative work, and in the case of some mathematics students, traditional chalkboards was preferred.

4.4. Students' Behavior with Temperature Changes

Students have varying opinions about temperature in the building, influenced by factors such as sunlight, nearby doors, and poor ventilation in some areas. One student expressed frustration about unresolved temperature issues, stating, *"The temperature? Because I called, and they can't fix that. Yeah, so they can sort it out. That's because some parts of this building are so hot, some parts"* (G5S2). In contrast, facility managers reported receiving no complaints, revealing a communication gap. Achieving thermal comfort remains difficult, as preferences depend on personal factors like clothing and activity. Preferences may also be shaped by occupants' prior climate exposure. Participants in this study came from a mix of home climate backgrounds (17% tropical, 35% warmer, 48% colder regions, Table 1), which may partly explain why individual temperature preferences varied even under similar building conditions. For example, one student might feel too warm wearing a jacket, while another feels cold without one.

EcoCube data, illustrated in Figure 12, show that when temperatures exceed 22°C, occupants tend to prefer cooler settings, and when temperatures drop below 22°C, they prefer warmer ones. A linear regression fitted to the data confirms this inverse relationship, with preferred temperature declining steadily as current temperature rises. However, preferences become inconsistent above 22.5°C, reflected in the widening confidence interval around the fit. The optimal comfort range appears to be 20–24°C, where preferences are more stable.

Preferred temperature was collected by asking students to set a value on the device (Figure 6e), which assumes a working understanding of dry-bulb temperature in degrees Celsius. This was not verified or explained to participants beforehand, and given the range of home climate backgrounds represented in this study (Table 1), interpretations of a given temperature value may not have been consistent across participants. Humidity was recorded only through the on-device sensor (Figure 6d) and was not collected as a stated preference in the same way as temperature. This reflects a design choice to prioritise temperature as the primary comfort variable, though a similar preference input for humidity could be added in future iterations.

To support facility managers, we used EcoCube to collect student feedback on preferred temperatures, clothing, and activities, as shown in Figure 6 (e, f). While managers already have data on temperature, humidity, and air velocity, they lack occupant-specific details like clothing insulation and activity levels. Future research could explore wearable devices, such as smartwatches, to gather more accurate data on metabolic rates and improve thermal comfort assessments.

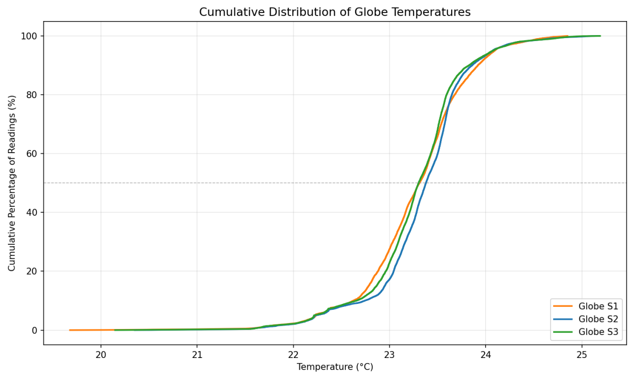


Figure 11: Shows the cumulative distribution of globe temperature data for the three study spaces.

4.5. Students' Feedback on The Medium Used

Quantitative results show that participants were more satisfied communicating with facility managers when using the EcoCube.

A paired-samples t-test revealed a significant increase in communication satisfaction after using EcoCube (N = 18, $p < 0.05$), with a mean pre-experiment score of 23.50 (SD = 2.71) and a mean post-experiment score of 27.89 (SD = 5.03). The mean difference was 4.39 (SD = 4.88), with a large effect size (Cohen's d = 0.90), indicating an improvement in participants' communication satisfaction and overall

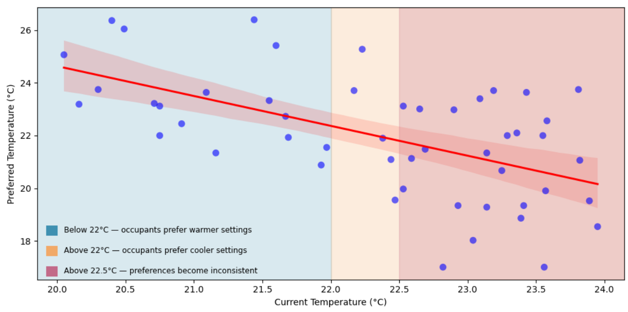


Figure 12: Shows a scatter plot of occupants' preferred temperatures compared to the current temperature in study spaces.

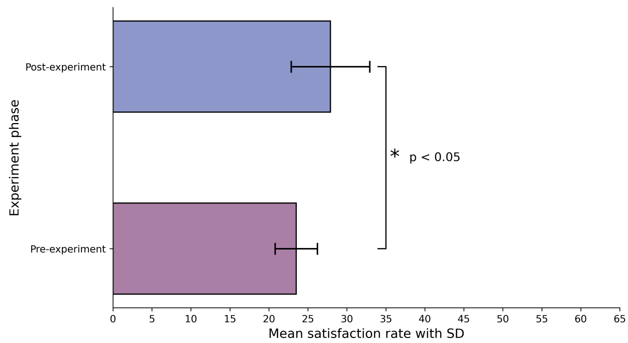


Figure 13: Shows mean satisfaction rates with standard deviations for communication with facility managers, before and after using the EcoCube device.

user experience. Figure 13 displays mean satisfaction rates before and after using EcoCube.

The System Usability Scale (SUS) questionnaire confirmed good usability (M = 80.42, SD = 7.25, Mdn = 81.50). The statement "I felt confident using the EcoCube to communicate with facility managers" scored highest (M = 4.72, SD = 0.39), while "I think the EcoCube is unnecessarily complex" scored lowest (M = 2.14, SD = 0.62).

Students engaged with EcoCube by reporting issues and giving feedback. Figures 9 (e-h) show desired and disliked features, preferred screen designs, and the preference for anonymous issue reporting. Overall, students expressed satisfaction with EcoCube's design and usability. Some appreciated its familiar icons and ease of use, with one noting, "Even when my mind is somewhere else, I can just operate this" (ST10). Opinions on screen size varied—some wanted a larger display, while others valued its compactness.

Students suggested new features, including a direct contact button for facility managers, mobile phone connectivity for convenience, automated controls such as windows adjusting to CO2 levels, and additional functions like a study timer, campus map, information on nearby attractions, charging ports, and emergency buttons. They also expressed design preferences, such as making the device mobile, integrating it into study tables, and using color-coded feedback to indicate comfort levels.

During first week, usage was high, driven by novelty of the device. Over time, engagement declined to one student per day by the end of the study. While some students feedback or reported issues, others primarily checked environmental data. Facility managers appreciated EcoCube's useful data and compliance with safety regulations, highlighting its value for building management.

4.6. Assessing Thermal Comfort and Student Behavior in Study Spaces

To better understand student behavior in study spaces and assess thermal comfort, we added several sensors, as illustrated in Figure 14. We deployed three black globe temperature devices and a wind speed meter [59] to collect data on globe temperature and wind speed within the building. This data was combined with information from the EcoCube, which tracked occupants' clothing levels and activities as shown in Figure 14 (c).

The sensors were in place for eight weeks. The globe temperature data for the three study spaces, presented as a cumulative distribution, can be seen in Figure 11. The results indicate that thermal comfort in all study spaces following the ASHRAE 55 standard were comfortable for occupants [60]. However, there were some differences between spaces. Study Space 2 had the highest globe temperature overall compared to the other spaces, likely due to direct sunlight from its large window. Study Space 1 and Study Space 3 showed closely overlapping temperature profiles, with neither consistently higher across the full range — Study Space 3 ran slightly warmer at lower-to-moderate temperatures, while Study Space 1, receiving sunlight from three sides including roof windows and nearby offices with transparent glass, edged warmer at the upper end of the distribution. Study Space 3, located in a walkway and receiving sunlight from only one side, still recorded the narrowest overall range and lowest peak temperatures among the three spaces.

Figure 15 shows clothing and activity levels across the study spaces. Figure 15 (a) indicates that clothing levels did not vary significantly between study spaces, though Study Space 3 had fewer occupants wearing light clothes compared to others. Figure 15 (b) reveals that Study Space 1 had more light activity, while Study Space 3 had more sedentary activity. Study Space 2 was more balanced, with occupants engaging in both light and sedentary activities.

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

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

Figure 14: Illustrates tools used to assess thermal comfort, including (a) black globe temperature devices, (b) a wind speed meter, and (c) the EcoCube for gathering data on occupants' clothing levels and activity.

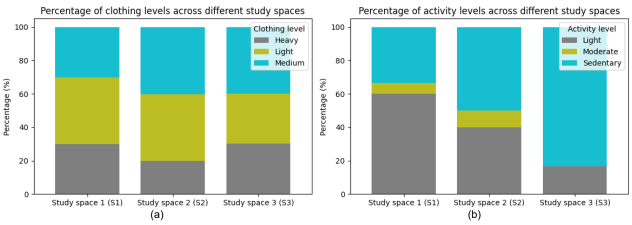


Figure 15: Shows (a) percentage of clothing levels across different study spaces and (b) percentage of activity levels by occupants across different study spaces.

5. Discussion

We present findings on how the EcoCube impacts building management and user experience, emphasizing the role of user feedback in refining its design. The discussion highlights how EcoCube's features improve user satisfaction, engagement, and communication. It also explores how human-centric design principles foster responsive environments and how EcoCube promotes sustainable behavior and environmental awareness. Together, these insights offer a comprehensive understanding of EcoCube's impact and potential for future improvement.

5.1. The Role of User Feedback in Design Iterations

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

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

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

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

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

This decision was based on informal feedback during the design workshops, rather than a formal assessment of distraction. No validated measure of concentration or study performance, such as a task-based test or a standard distraction questionnaire, was used during the deployment. Students did not raise distraction as a concern in the post-experiment interviews, but this was not asked about directly, so it should not be taken as evidence that no distraction occurred. Future studies could include a short concentration or focus measure, taken before and after using tables with and without the device, to assess this more directly.

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

5.2. Impact of the EcoCube on User Satisfaction and Engagement

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

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

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

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

While EcoCube improved communication satisfaction overall, engagement was not sustained throughout the deployment. Usage was highest during the first week, likely due to the novelty of the device, and declined to approximately one user per day by the end of the eight-week study (Section 2.3), reflecting a novelty effect commonly reported in studies of new interactive technologies. Several strategies could help sustain engagement beyond this initial period, including lightweight gamification, dynamic rather than static content, such as rotating the sustainability messages described in Section 5.3, and making the device more event-driven, so it becomes prominent only when conditions change significantly rather than requiring occupants to check it on their own. Future work should also test this over a longer deployment, to determine whether usage stabilises at a useful level or continues to decline.

5.3. Influence on Sustainable Behavior and Environmental Awareness

This discussion uses two related terms: sustainable practices, referring to building- or operational-level actions such as recycling schemes or green building operations, and sustainable behaviour, referring to individual actions taken by occupants, such as reducing energy use or choosing the stairs over a lift. EcoCube's contribution in this study is limited to presenting informational content intended to encourage such behaviour (Figure 15); no data on actual behaviour change, such as energy use or stair use, was collected before or after deployment. The discussion below should therefore be read as describing EcoCube's potential to influence behaviour through this informational content, rather than as evidence that behaviour actually changed.

The EcoCube project has made steps in influencing occupants' sustainable behavior and enhancing environmental awareness. One of its key features is its effort to raise awareness about sustainability through engaging and informative messages. These messages, drawn from research on sustainability, are presented in a concise and intriguing manner. They cover various topics such as reducing waste, conserving energy, water conservation, responsible food choices, and green building practices. For example, Figure 16 illustrates some screenshots from the EcoCube's sustainability section, which shows users information designed to raise their awareness about building sustainability practices and encourage more eco-friendly behaviors.

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

However, feedback from users also highlighted areas for improvement. For example, some participants expressed uncertainty about the implications of certain environmental readings, such as a CO_2 level of 500 ppm. They were unclear about whether these levels were safe or problematic. In response to this feedback, we adjusted the EcoCube's display to use color-coded indicators for different environmental readings. This adjustment helps users quickly interpret data without overwhelming them with excessive details, maintaining the device's ease of use while making environmental information more accessible.

In summary, the EcoCube's informational content on sustainability and its real-time environmental data have the potential to support more eco-friendly practices and greater environmental awareness, though this study did not directly measure whether occupant behaviour changed as a result.

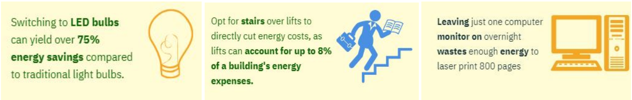


Figure 16: Displays screenshots from the EcoCube device under the 'Building Sustainability' section, designed to influence occupants' sustainable behaviors. Data references for the screenshots are provided in [61–63].

5.4. Practical Considerations for Scaling Occupant Feedback

While more open reporting is likely to increase the number of messages facility managers receive, this can be managed without adding significant workload. The ThingsBoard rule engine, already used to send alerts when a device disconnects (Section 3.2), could be extended to group repeated reports of the same issue into a single ticket, and to prioritise issues that recur or persist over isolated, one-off comments. The dashboard already summarises feedback using pie charts (Figure 8); a similar summary view for reported issues would let facility managers see overall patterns first and look into individual reports only when needed. Future work should test these methods in larger buildings, where report volume is likely to be higher.

Occupant preferences for temperature also varied, and it is not realistic to satisfy every individual at the same time. EcoCube data showed that preferences cluster within a comfort range of 20–24°C, consistent with the ASHRAE 55 standard (Section 4.4, Figure 12), but become less consistent above 22.5°C. This suggests that facility managers can use EcoCube data to set a single schedule for each space within this observed range, rather than trying to adjust conditions for every individual. Where conflicts remain, for example one occupant feeling too warm while another feels cold, these are unlikely to be solved by adjusting a single, centrally controlled space, and may be better addressed through simpler, lower-cost options such as personal fans or seating choice. Reports that affect health, safety, or many occupants should still be prioritised over individual comfort preferences.

5.5. Limitations

This study was conducted in a single educational building at one UK university, with a sample of students aged 18–35, predominantly 18–24 years old and predominantly undergraduate, though postgraduate students were also represented, and drawn from a range of home climate backgrounds (Table 1). These findings may not generalise to other building types, such as offices or hospitals, to other climates, or to populations outside a university setting. Replicating this study across multiple buildings, institutions, and climates would help test how well these results hold beyond the current context.

Usability was assessed primarily through the SUS questionnaire and interview feedback; the screenshots included in this paper (Figures 6,16) illustrate the interface but are not themselves evidence of usability, and should not be read as such. The visual design of EcoCube was not developed with input from a UI/UX or visual design specialist, and it is possible that interface aesthetics influenced how positively participants rated their experience, independent of the device's functional usability. Involving a design specialist would likely improve both the interface and the reliability of future usability evaluations, and is recommended before any production-ready version is developed.

5.6. Revisiting the Research Questions

This study set out to answer three research questions. On bridging the occupant-manager communication gap (RQ1), the workshops and interviews showed a clear gap prior to deployment, with most students unaware of facility managers' roles and reluctant to report issues for fear of being blamed (Section 4.1). EcoCube addressed this gap through anonymous, structured reporting, which students and facility managers both engaged with over the deployment (Section 5.2). On occupant satisfaction and management efficiency (RQ2), satisfaction with communication improved after deployment, supported by the paired t-test and SUS results (Section 4.5). Management efficiency was not measured directly, but facility manager interviews indicated that issues had previously gone unreported for extended periods, sometimes weeks (Section 4.1), suggesting that structured, real-time reporting has the potential to reduce such delays. Confirming this would require a direct measure, such as issue resolution time, which is left for future work. On identifying preferred temperature ranges in open spaces (RQ3), sensor and self-reported preference data indicated a comfort range of approximately 20–24°C, consistent with the ASHRAE 55 standard, though individual preferences became less consistent above 22.5°C (Section 4.4).

6. Conclusions

This study explored how the EcoCube improves communication, satisfaction, and behavior in study spaces. It effectively helps bridge gaps between occupants and facility managers, encouraging active participation in building management. The EcoCube enables intuitive issue reporting and preference feedback, providing insights for operational enhancements. It reveals varying satisfaction levels and preferences among occupants, emphasizing the need for adaptable and data-driven space solutions. Challenges include expanding communication channels and optimizing space efficiency. Future work should focus on scaling the EcoCube's implementation across various building types, enhancing user engagement features through gamification, and integrating the EcoCube with existing IoT ecosystems and building management systems to improve data collection, interoperability, and operational efficiency. Ultimately, the EcoCube offers valuable insights for IoT-enabled social computing in building management, fostering collaboration, user satisfaction, and sustainability through its innovative design and technology.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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