

Article

Digital Twin-Stakeholder Informed Best Practice Framework for Building Management: A Case of a University Library

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Abstract

Digital twin, a technology that offers an opportunity to access dynamic and real-time data for efficient decision-making, has witnessed minimal utilization in smart facilities management. Additionally, combining stakeholders' views with a digital twin provides more efficient building management. Thus, this study aimed to combine digital twin technology and stakeholders' views to develop a best practice framework for enhancing indoor conditions of a typical university building. It analyses feedback received from building stakeholders and results from a digital twin to develop the best practice framework. This study adopted a case study approach by using a university library at Western Sydney University, Australia. It used a multi-stage approach and a series of interviews with facility management experts for the development and validation of the framework, respectively. The key findings revealed that all the monitored parameters in the digital twin system were within acceptable thresholds. However, the building occupants expressed concerns regarding excessive solar heat gain, inadequate airflow, and direct glare. It was also revealed that heat was the most disturbing environmental parameter in the library, and built-in energy efficiency measures were also not adequately maintained, contributing to the building's energy consumption. The proposed framework provides strategic measures for improving building occupants' comfort and energy consumption. Furthermore, the best practice framework aids facility managers in holistically considering key aspects of building services management in managing such buildings.

Keywords: best practice framework; digital twin; facility management; stakeholders; university library



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1. Introduction

Smart facilities management has, in the past few years, been the trending discussion regarding smart and intelligent buildings [1]. This implies that there is a need to make well-informed decisions based on real-time environmental conditions data to meet the health, well-being, and comfort of building occupants. Although several efforts have been made in the field of building/facility management, there is still a heavy reliance on human efforts for coordinating the overall activities related to building and facilities

management [2,3]. Furthermore, there is incomplete automation using the Internet of Things (IoT) in building management [4–6]. It is worth mentioning that current facilities management activities are mostly based on conditions that are pre-set without adopting dynamic and complex scenarios. In addition, these activities usually tend to be passive, reactive, and isolated [7]. Current building/facility management operations lack access to real-time and dynamic data for more efficient decision-making [8]. These predicaments of current facilities management operations and activities hinder the capability to adequately address the changing requirements and comfort of building occupants [1]. Additionally, it is also uncommon that most buildings and other facilities consume more energy in their operations than expected due to a lack of real-time and dynamic data for informed decision-making by building/facility managers. Thus, the building is unable to provide satisfactory service for its intended use [9].

Furthermore, in the application of digital technologies to tackle issues in the operation and management of buildings, the views of various stakeholders are not normally considered, although these digital technology applications are intended to improve the lives of the occupants [10,11]. Therefore, it is vital to inquire into the best practices for effectively managing buildings as well as other facilities. A key technology that can provide real-time and dynamic data for enhanced decision-making in building and facilities management activities is the digital twin (DT). As technologies are meant to aid in improving the lives of humans, it is vital to incorporate the views of the building's or facility's stakeholders to better achieve the purpose of applying these digital technologies [12,13]. It is also important to note that the use of DT technology provides a better impression of the building's indoor environmental conditions [11].

Based on these gaps, this study is aimed at advancing a best practice framework for an enhanced indoor environment in buildings using DT technology and feedback from building stakeholders. To achieve this aim, two specific objectives were set: (1) to develop a best practice framework for an enhanced indoor environment in buildings, and (2) to validate the developed best practice framework for an enhanced indoor environment in buildings. It is worth mentioning that, based on the nature of the selected educational building, the environmental condition parameters affecting thermal comfort, visual comfort, and indoor air quality were considered in this study. Acoustic comfort parameters were not considered because noise was not a significant problem in the library building. The novelty of this study lies in the development of a best practice framework considering occupant feedback and standards for achieving enhanced indoor environmental conditions when using DT technology. Additionally, this paper contributes significantly to knowledge and practice by presenting comprehensive strategies for designing, constructing, and managing existing and new buildings.

2. Digital Twin for Smart Building Management

Smart building management (SBM) has become the focus of attention in recent literature on building or facilities management practices. SBM encompasses the incorporation of several systems, processes, and technologies to improve the operation and management of facilities. The discussions on SFM have mainly centred on concepts such as intelligent buildings, smart buildings, smart homes, and ambient intelligence. Intelligent buildings and smart buildings are often used interchangeably. However, intelligent buildings involve a responsive and dynamic architecture that offers building occupants an opportunity to possess productive, cost-efficient, and improved environmental conditions through continuous interactions between the basic elements of the building [14]. While smart buildings refer to the integration of enterprises, controls, materials, and construction of the whole building to ensure adaptability and progression [15], smart homes refer to residences that

are capable of anticipating and responding to occupants' needs using technologies in the home environment and also connecting to the world beyond [16]. Finally, ambient intelligence denotes an environment that is embedded with technologies in a natural setting that senses, adapts, and responds to the presence of people and objects [17]. It is worth noting that the underlying requirements in the management of smart facilities rely on data access using technology to improve building and facility management.

Several Industry 4.0 technologies, including building information modelling (BIM), are assisting in the implementation of SFM. BIM, a process or program for extracting as well as reusing data through the development of a model with multidimensional virtual space, has limitations since the technology works on static data [18,19]. While the management of facilities and buildings using BIM provides a machine-readable, parametric, and object-oriented 3D database, the emphasis has mostly been focused on activities regarding the maintenance and operation of the building. Notwithstanding, a significant part of the activities of the facility manager concerns providing comfort to the occupants of the facility [20], and that is problematic when managing with BIM. Furthermore, the deficiencies associated with accurate as-built as well as insufficient and obsolete information on the building prevent BIM usage in the management of existing buildings [21]. Additionally, the inadequacy of the as-built BIM model data restricts its possible usage in building and facility management [22]. Thus, the inadequacies in the information related to the building produce inefficient building management, increased time and cost, and unrealistic outcomes in the management of the building. In addition, Shalabi and Turkan [23] mentioned that the collected data from facility management systems, including building management systems (BMS), are deficient in abilities concerning interoperability as well as visualization to ensure effective management.

A key technology that can provide solutions to most of the challenges encountered in building and other facilities management is the concept of DT. DT refers to a connected and synchronised digital model of physical assets that characterise both the elements and the dynamics of how systems, as well as devices, function within their environment and live throughout their lifecycle [24]. DT has the capability of coordinating many models across the system's lifecycle [25]. Additionally, the physical asset's status, character, and conditions can be simulated for numerous decision-making related to the overall management and operation of the building, as well as the comfort of occupants of the building. Within the construction industry, DT denotes a fully or partially completed structure or building's representation in real-time to reflect the status as well as the character of the structure or building [19]. To eloquently communicate this research, DT refers to a dynamic digital replica of a physical asset, facility, or building, systems, and processes through sensor devices, as well as the information feedback from the occupants [26,27].

Based on the complexities and dynamic environments associated with educational buildings, DT presents an excellent approach to managing these buildings for improved indoor conditions [28–30]. Buildings within the educational environment constantly interact with their occupants, thus possessing superior density in terms of population in comparison to residential and commercial buildings [31]. The population density in educational buildings could be as much as 3–4 times that of commercial and residential buildings. Furthermore, it is also worth mentioning that students spend much of their productive time (usually 6–8 h), constituting about 40% of their daytime in classrooms [32]. Some efforts by researchers have been geared towards the utilization of DT for managing buildings within the educational sector. For example, Desogus et al. [33] developed a DT solution for managing a pavilion at the University of Cagliari. The study highlighted the significance of DT in managing comfort and energy efficiency in buildings. Villa et al. [34] presented a fully automated framework to enhance decision-making regarding preventive

maintenance in a laboratory room at the Politecnico di Torino. The authors established the prowess of DT in enhancing decision-making in building management. Notwithstanding the efforts by researchers directed towards the utilization of DT for educational buildings, there is limited attention towards managing library buildings. Unlike classrooms that have strictly scheduled usage by students, the library has a much more constant and consistent usage throughout the day, weeks, and years. Additionally, during examination periods, the library is more densely occupied compared to other times of the year. Scoulas, Carrillo, and Naru [35] conducted a study using a library at the University of Illinois, Chicago, and found that the library was used by 90% of the students. Therefore, a considerable percentage of time as well as interactions are witnessed in library buildings, and this significantly affects the indoor condition of the building. Furthermore, the feedback of the occupants is also not integrated with the technology to improve building and other facilities management. Against this background, this research centres on the aforementioned context for developing best practices for improving building/facility management.

3. Research Methodology

3.1. Selected Case Study

This study utilized a university library at Western Sydney University in Australia as its case study. The library was chosen due to the continuous interaction between the library and its occupants. The library has six stories, with only five being accessible to occupants. The overall floor area of the library is 6700 m² and is oriented towards the north and south directions. There are several spaces for the daily operation of the library. These spaces include study spaces, collection areas, and printing areas, as well as spaces for offices. The Office of Estate and Commercial (OEC) of the university, library managers, librarians, and students serve as the critical stakeholders of the library. The OEC has the responsibility of operating and maintaining the requirements of the whole university. Additionally, the University Facility Management Team also forms part of the stakeholders and is accountable for the daily management of precise buildings, including the campus library. As a result of the vast floor area, research restrictions, and convenience, this study focused on the study spaces specifically, the level one group study rooms. Further, the group study rooms were selected based on their continuous interactions with the library occupants. The floor has six (6) group study rooms constituting an overall 86 m² floor area. The dimensions of each of the rooms are approximately 4 m × 3.5 m. It is worth mentioning that each of the rooms has a maximum capacity of 6–8 persons at any given time. The library building that was used in this research as the case study is shown in Figure 1.



Figure 1. Overview of the library building.

Figure 2 presents the floor plan of the library building, indicating the locations of the group study rooms and IoT sensors. In addition, an example of the group study room used in the research is presented in Figure 3.

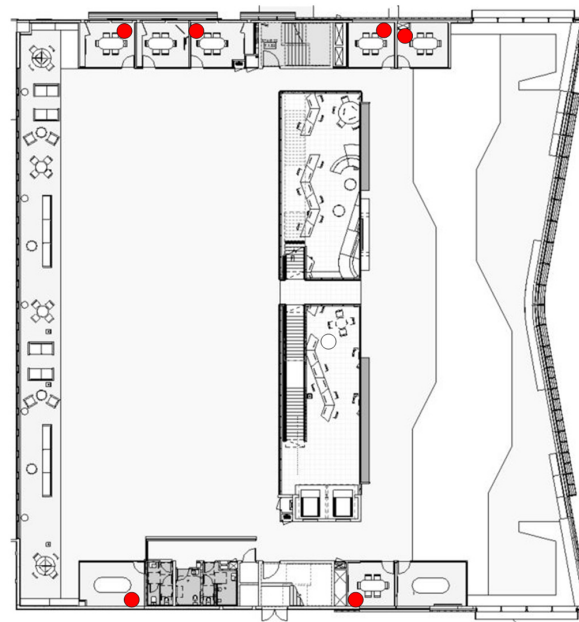


Figure 2. Deployment of IoT sensors in the group study rooms is indicated with red dots [11].

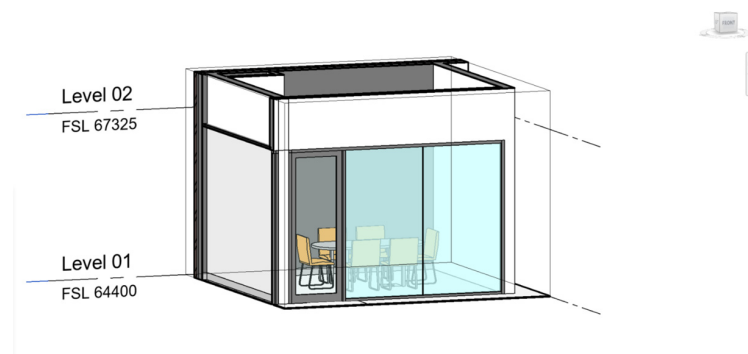


Figure 3. An illustration of the group study room [11].

3.2. Methodological Approach

This study employed a four-stage approach to develop the best practice framework for enhancing indoor environmental conditions and subsequently reducing energy consumption in buildings. In the first stage, the views of the stakeholders in the case study (i.e., the library building) were gathered in line with their level of comfort within the building. These stakeholders included the library managers, librarians, and students who normally visit the library. Using a pre-defined set of criteria that included frequent visits to the library and staying for at least two hours, specific activities/experiences in the library, and being a library staff/student, sixteen stakeholders were purposively identified for the interviews. In the second stage, a digital twin system was developed using BIM and IoT to ascertain the library's indoor environmental conditions [11]. In the third stage, a comparison was made between the measurements of the monitored indoor condition parameters and the recommended standards for a comfortable office environment, such as the library. In the last stage, the findings of the previous three stages were incorporated into the development of the framework for improving occupant comfort and subsequent energy consumption in the library. It is important to mention that the use of DT technology in developing the best

practice framework enhances the comparison processes and provides the whole image of the indoor environmental conditions in the building. The components for developing the best practice framework are illustrated in Figure 4.

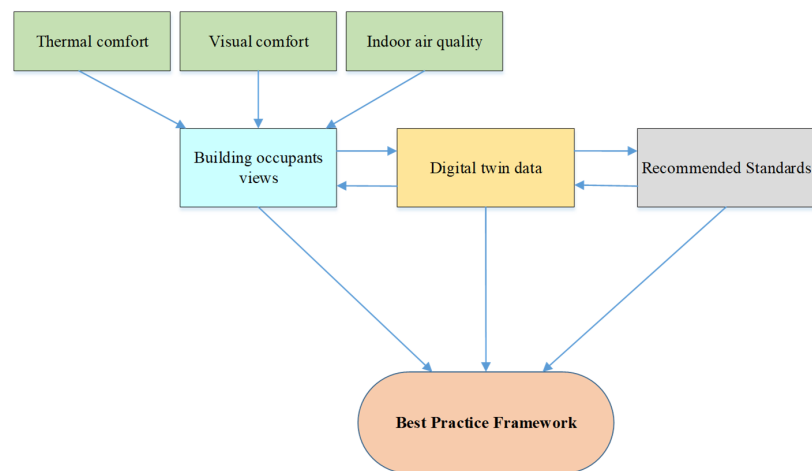


Figure 4. Components of the best practice framework.

The key contributing factors to the indoor environmental quality (IEQ) of the library space, which include thermal comfort, lighting comfort, ventilation, and pollutants, were considered in assessing the occupants' views in this study [36]. Temperature and relative humidity constituted the indicators for establishing the thermal comfort of the library stakeholders. Furthermore, the illumination of the visible light in the group study rooms under consideration also constituted the visual comfort of the library stakeholders. Finally, in terms of indoor air quality, the total volatile organic compounds (TVOC) concentration and carbon dioxide concentration (CO₂) in the chosen group study rooms were considered in the study. Other air pollutants, such as particulate matter, radon, ozone, etc., were not considered in this study due to study relevance and monitoring limitations. The process followed in developing the best practice framework is illustrated in Figure 5.

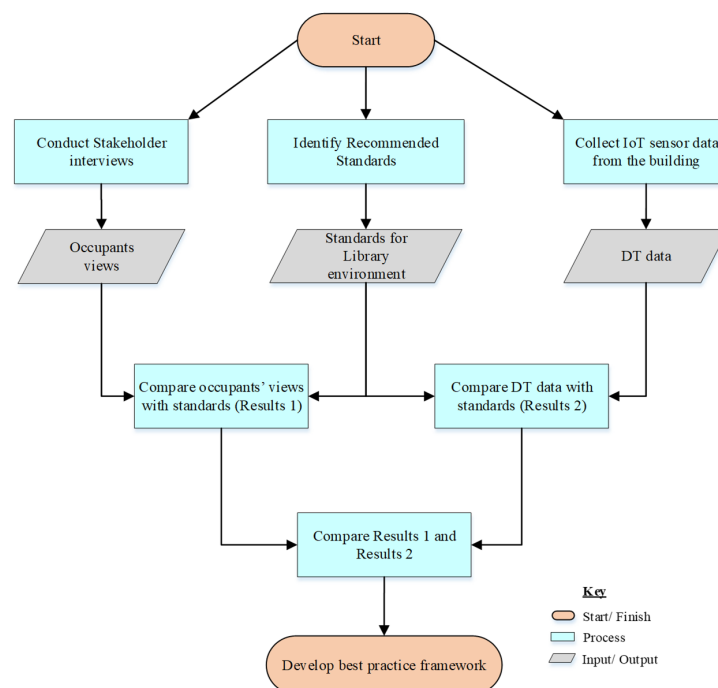


Figure 5. Process followed to develop the best practice framework.

4. Developing the Digital Twin-Based and Stakeholders-Informed Best Practice Framework

The best practices were developed considering the key contributing factors to IEQ of library spaces [37,38]. These factors include thermal comfort, lighting comfort, ventilation, and pollutants in the indoor environment [36]. To ensure comfort for occupants in the building, various actions were taken that adversely influenced how energy is used and consumed in the building. Therefore, the data from the DT system, which was developed using BIM and IoT, was compared with the recommended standard thresholds for the IEQ parameters in office buildings. These standards include ASHRAE 55-2017 for temperature and relative humidity; National Australian Built Environment Rating System (NABERS) and Australian Standard (AS 1680.1) for lighting; ASHRAE 62 for CO₂; and Leadership in Energy and Environmental Design (LEED) version 4 and NABERS for TVOC. A summary of the recommended standard thresholds for each of the monitored environmental parameters and their associated key indicators is presented in Table 1. The results were further compared with the views of the relevant stakeholders of the library in terms of their comfort in the building. These best practices were created to ensure occupant comfort and optimum energy consumption of the library building.

Table 1. Recommended thresholds for the studied parameters [11].

Parameters	Key Indicators	Recommended Thresholds	Source of Standard
Thermal environment	Temperature	21–24 °C	ASHRAE 55
	Relative humidity	40–60%	ASHRAE 55
Visual environment	Illumination	320 lux (horizontal)	NABERS
		160 lux (vertical)	AS1680
Indoor Air Quality	CO ₂	1000 ppm	ASHRAE 62
	TVOC	500 µg/m ³	LEED V4/NABERS

4.1. Digital Twin System

A DT system was developed using a 3D BIM model, IoT sensors, and actuators. The BIM model was created using Autodesk Revit 2020 software (.rvt file), and LoRa sensors were selected based on several considerations, including security protocols of the University's information technology network. In addition, the cost and other expenses associated with the use of sensors, including data transmission range capabilities, sensor configurations, and energy consumption, informed the choice of sensors used in this study. The integration of the IoT data and 3D BIM model was carried out using 'The Things Network' cloud server, C# applications, and wireless sensor networks [11,39]. This integration provided the dynamic indoor conditions in the developed DT system. To provide bidirectional communication between the developed DT system and the physical building, the library's building management system (BMS) was connected to the developed system to provide corrective actions in case of indoor environmental violations in the library building. A system architecture for developing the DT system is presented in Figure 6.

The details of the sensor used in this study are presented in Table 2. Additionally, the type of sensor is shown in Figure 7. This study used a LoRa Mulesight AM107 sensor due to its ability to capture multiple environmental indicators in a single sensor. In addition, it has a passive infrared (PIR) sensor that captures signals related to movements within 82° vertical and 94° horizontal detection areas, 5 m detection distance, and 0–65,535 output range. It is worth mentioning that, before the deployment of the sensor, humidity and temperature values were calibrated against known values in a controlled environment.

In addition, the sensor's performance was continuously tested and validated to ensure it operated within the accuracy and technical specifications of the manufacturer.

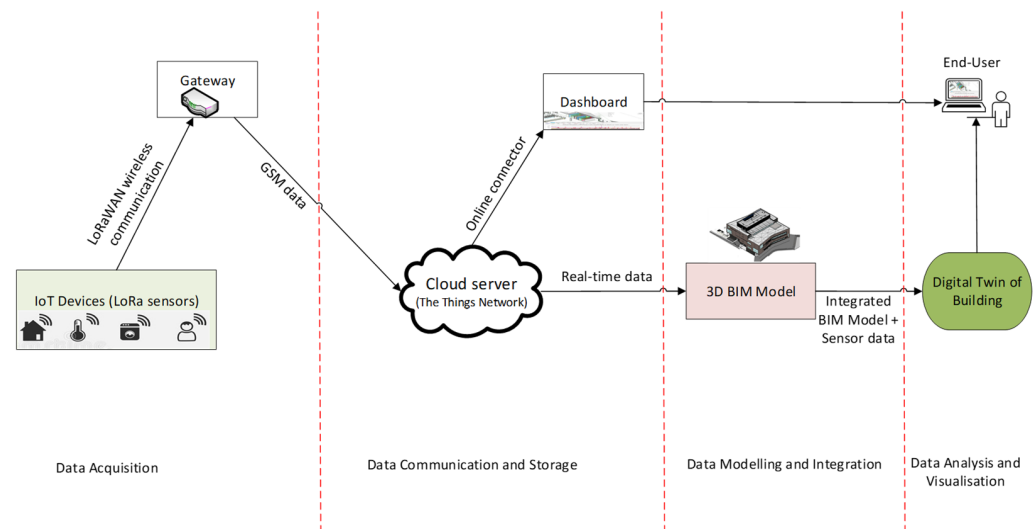


Figure 6. System architecture for developing the DT [11].

Table 2. Technical details of the LoRa Mulesight AM107 sensor.

Key Indicators	Accuracy	Measurement Range	Resolution
Temperature	$\pm 0.3\text{ }^{\circ}\text{C}$	$-20\text{ }^{\circ}\text{C}$ to $+70\text{ }^{\circ}\text{C}$	$0.1\text{ }^{\circ}\text{C}$
Relative humidity	$\pm 3\%$	0–100% RH	0.5% RH
Illumination	$\pm 30\%$	60,000 lux (visible + IR, IR)	-
CO ₂	$\pm 30\text{ ppm}$ or $\pm 3\%$	400–5000 ppm	1 ppm
TVOC	$\pm 15\%$	0–6000 ppb	1 ppb



Figure 7. LoRa Mulesight AM107 sensor [11].

The results of the monitoring of the indoor environmental conditions of the targeted group study room in the library on 7 August 2023 at 1:13 pm are presented in Figure 8. The temperature reading was $24\text{ }^{\circ}\text{C}$, and the relative humidity was 43.5%. It must be noted that the recommended threshold for temperature in a comfortable office environment, such as the library, should be between the ranges of $21\text{ }^{\circ}\text{C}$ and $24\text{ }^{\circ}\text{C}$ [40]. Similarly, the ASHRAE [40] endorses 40–60%RH for a comfortable office setting. This implies that both the temperature and relative humidity conditions in the targeted room are adequate and significantly contribute to the activities and purpose of the library. It is worth mentioning that very cold or hot working environments significantly affect the building occupants' productivity at any given time [41]. In terms of the lighting, total volatile organic compounds

(TVOC) concentrations, and carbon dioxide (CO_2), the indoor condition measurements revealed illumination (light) as 66 lux, TVOC as $168 \mu\text{g}/\text{m}^3$, and CO_2 as 826 ppm. The recommended threshold in an office space for lighting is 160 lux, whilst CO_2 is 1000 ppm. In addition, the recommended threshold for TVOC is $500 \mu\text{g}/\text{m}^3$ as mentioned earlier. The number of occupants' movements in the target room was also monitored since they affect the building's indoor conditions. There were 599 occupant movements in the target room, as depicted as 'activity' in Figures 8 and 9. It must be noted that all the measured indoor condition parameters were within the acceptable thresholds on the exact date and time of measurement. These measurements are critical and can aid the manager of the facility in making data-informed choices, especially during the post-COVID-19 era. It is also worth mentioning that in a completely functional digital twin system, the decision-making process can be automated such that signals are sent by sensors to a building management system (BMS) if violations occur. These violations can then be fixed or corrected using actuators such as heating, ventilation, and air conditioning systems (HVAC), dampers and valves, and automated windows [42]. Thus, the manager of the facility would not be required to intervene in the actions related to the correction process.

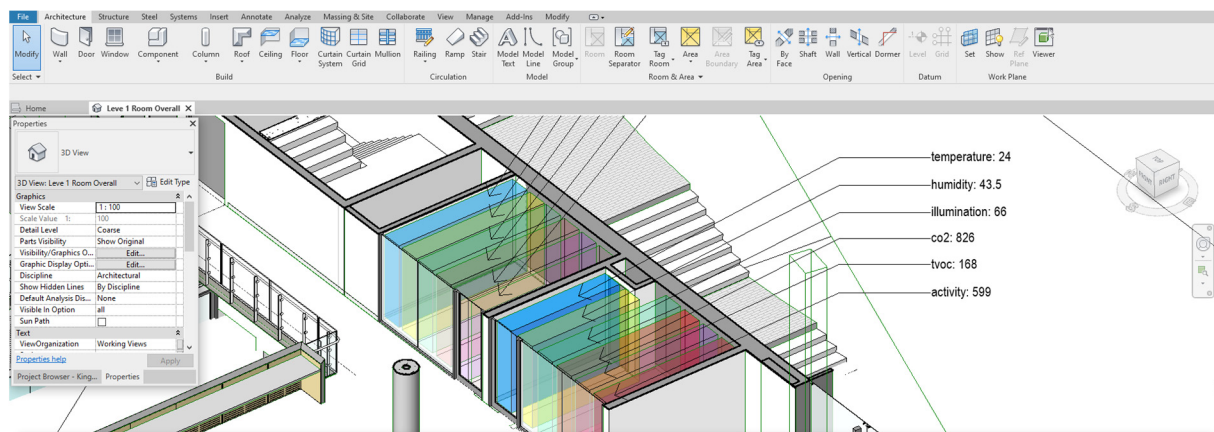


Figure 8. Screenshot of the monitoring of the DT system's indoor environmental conditions (7 August 2023).

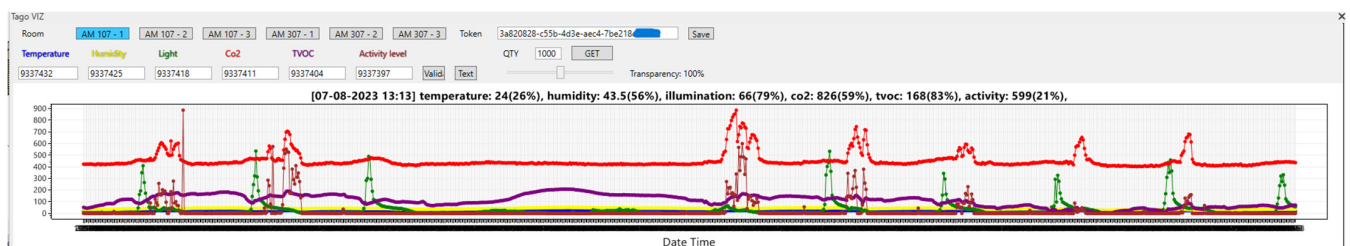


Figure 9. Screenshot of the indoor condition visualization dashboard (7 August 2023).

Additionally, to provide a better impression of the conditions of the indoor environment of the monitored group study room, an indoor condition visualization dashboard is presented in Figure 9. This dashboard assists the facility manager in comparatively determining the most influential parameters in terms of the comfort of the building occupants. It is worth mentioning that the dashboard, apart from providing a line graph for various parameters, provides the numerical values associated with all the monitored parameters for easy understanding and enhanced decision-making.

It is worth mentioning that the developed DT system provides dynamic data that supports enhanced decision-making in the management of buildings and other facilities. Thus, Figures 10 and 11 present the monitored indoor environmental conditions in the targeted group study room in the library on 8 August 2023 at 1:58 pm. The readings were

temperature 24.7 °C, relative humidity 43%, illumination (light) 533 lux, CO₂ 721 ppm, TVOC 156 µg/m³, and activity (occupant movements) 379. It was noted that most of the monitored parameters were within the recommended thresholds.

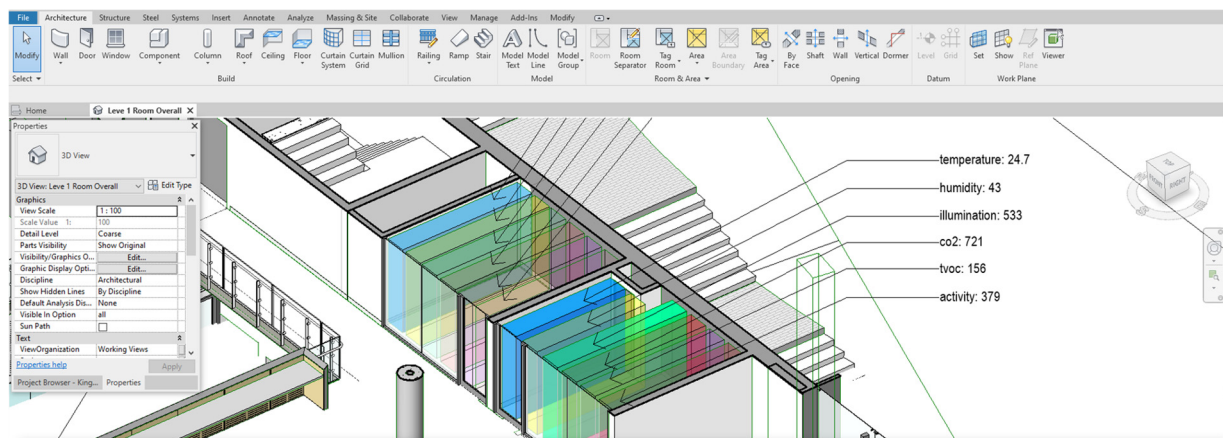


Figure 10. Screenshot of the monitoring of the DT system's indoor environmental conditions (8 August 2023).

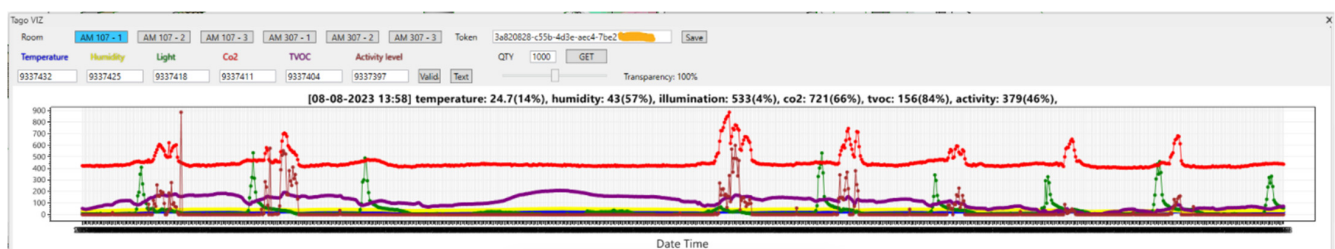


Figure 11. Screenshot of the indoor condition visualization dashboard (8 August 2023).

In addition, the monitored indoor environmental conditions on 11 August 2023 are shown in Figures 12 and 13. The results indicate that the temperature was 24.3 °C, the relative humidity was 33%, the illumination (light) was 458 lux, the CO₂ was 681 ppm, the TVOC was 84 µg/m³, and the activity (occupant movements) was 160. The results revealed that most of the monitored parameters were within acceptable thresholds.

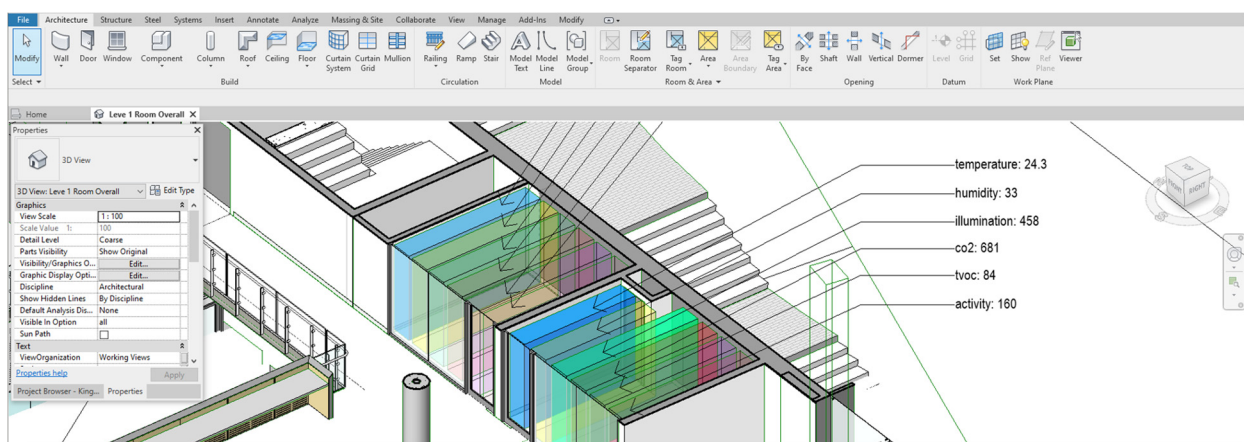


Figure 12. Screenshot of the monitoring of the DT system's indoor environmental conditions (11 August 2023).

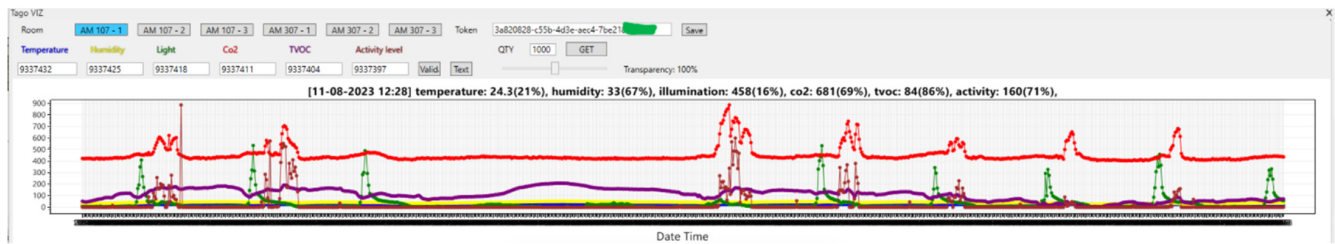


Figure 13. Screenshot of the indoor condition visualization dashboard (11 August 2023).

4.2. Library Stakeholder Interviews

The rationale of the stakeholder interviews was to complement the data ascertained from the DT system to make realistic deductions of the indoor conditions of the library. The stakeholder interviews were very significant to this study since systems and technological applications have been developed to improve the lives of humans. It was therefore prudent to ascertain the views and sentiments of the building occupants or stakeholders regarding the indoor environmental conditions and how they feel in the library building. Semi-structured interviews were conducted with library stakeholders, which include library managers, librarians, and students who frequently visit the library. A purposive sampling was used to select the stakeholders based on pre-defined criteria comprising frequent visits to the library (at least three days per week), specific activities or experiences in the library, and being a library staff or student [43]. A total of sixteen respondents were involved in the study. It must be noted that the set criteria enhanced the genuineness of responses for further analysis. A theoretical saturation point was reached after conducting twelve interviews, and conducting four more interviews did not add any new insights [44]. This implies that the current number of sixteen interviewees was adequate for the study. Table 3 presents the background information of the stakeholders. To ensure anonymity, the names of the interviewees are denoted with codes LS1–LS4 (library staff) and ST1–ST12 (students).

Table 3. Background of the interviewees.

Stakeholder	Code	Position	Frequency	Activity	Experience
1	LS1	Library Staff	6	Management role	25 years
2	LS2	Library Staff	5	Management role	30 years
3	LS3	Library Staff	6	Management role	15 years
4	LS4	Library Staff	5	Management role	17 years
5	ST1	Student	5	Studies	-
6	ST2	Student	3	Studies	-
7	ST3	Student	3	Studies	-
8	ST4	Student	3	Studies	-
9	ST5	Student	4	Studies	-
10	ST6	Student	5	Studies	-
11	ST7	Student	5	Studies	-
12	ST8	Student	4	Studies	-
13	ST9	Student	4	Studies	-
14	ST10	Student	5	Studies	-
15	ST11	Student	5	Studies	-
16	ST12	Student	4	Studies	-

It is observable from Table 3 that the stakeholders were either library staff or students who visited the library at least three times per week and had a specific activity of either managing the library or studying in the library. Further, it is noted that the library staff had more than 10 years of experience managing libraries. These details enhanced the genuineness, credibility, and authenticity of the interview responses. The key issues identified from the interviews with the stakeholders regarding the indoor environmental conditions in the library and their influence on the comfort of occupants and energy consumption are discussed as follows:

- **Heat:** It was discovered that the stakeholders were generally satisfied with the indoor conditions of the library. However, the occupants were exposed to extreme heat during the summer season. This solar heat gain was a result of the large openings in the building. Stakeholder 11 mentioned that *in the afternoons, it is almost impossible to study in the library because you get the sun coming straight at you, and it is very uncomfortable (ST7/Q7/S5)*. Stakeholder 7 highlighted that *it is difficult to work comfortably sometimes in the afternoons of summer (ST3/Q7/S3)*. These findings from the stakeholders confirm the results in the DT system, where the highest temperature is 24.8 °C, and this is seen in the targeted GSRs situated in the building's western direction. During the winter season, the library becomes too cold to ensure a comfortable working environment. The occupants do not have the opportunity to adjust the HVAC system due to its centrally controlled nature. This confirms the study by Sanni-Anibire and Hassanain [45], highlighting the relevance of occupants' ability to regulate both the HVAC system and other openings for enhanced comfort levels.
- **Indoor air quality:** The building occupants were generally satisfied with the indoor air quality in the library. However, airflow was sometimes a challenge in the autumn semester due to the non-operable nature of the windows [46].
- **Light:** The occupants were generally satisfied with the lighting levels in the library, but expressed discomfort with the amount of glare in the library. This glare resulted from the large windows and is extreme in the windows facing east and west directions. Occupants may have to keep changing positions until they find a better location. Lakhdari, Sriti, and Painter [47] highlighted that a balance between daylighting and artificial lighting ensures adequate natural light through building openings.
- **Sound:** The occupants expressed strong satisfaction with the level of noise in the library. Notwithstanding, it was discovered that a decrease in the collection may increase the level of sound in the library. In addition, it was revealed that the library becomes a bit noisy during examinations, and that affected the concentration of some occupants. However, an appropriate building design or taking necessary actions can effectively minimize indoor noise [41].
- **Overall comfort:** The building occupants were generally satisfied with the overall comfort of the library. However, it was revealed that heat was the most disturbing environmental parameter in the library.
- **Energy consumption:** Although the library is a 5-star-rated building, the stakeholders expressed concerns about the energy consumption in the building. It was discovered that the built-in energy efficiency measures have not been adequately maintained, which contributes to the energy consumption in the building.

4.3. Scope of the Framework

This study followed a similar approach to that used by Nulty et al. [48] and Crump, Sugarman, and Training [49] to prepare the best practice framework. Although the best practices are predominantly focused on the building's operation and maintenance phase, several proposals were presented to be considered in the design and construction of new

buildings. Additionally, improvement guides are provided for retrofitting existing buildings. The best practices were further categorized into energy consumption optimization and occupant comfort improvements in buildings.

4.4. Detailed Framework

Based on the comparisons between the data from the developed DT system, recommended standard thresholds for the IEQ parameters, and the views of the relevant stakeholders of the library regarding their comfort in the library, the best practices in improving occupants' comfort and subsequently optimizing energy consumption are presented in Figures 14 and 15 (see detailed explanations of the guidelines in Tables A1 and A2 in the Appendix). The best practices are based on the specific library building at Western Sydney University, Australia. Even though the practices are based on a specific library building, the findings could be adopted for improving occupants' comfort and optimizing energy consumption in other similar library buildings. Furthermore, the approach used in this study could be espoused to enhance the comfort of occupants and optimize the consumption of energy in other buildings, including residential, commercial, and industrial buildings.

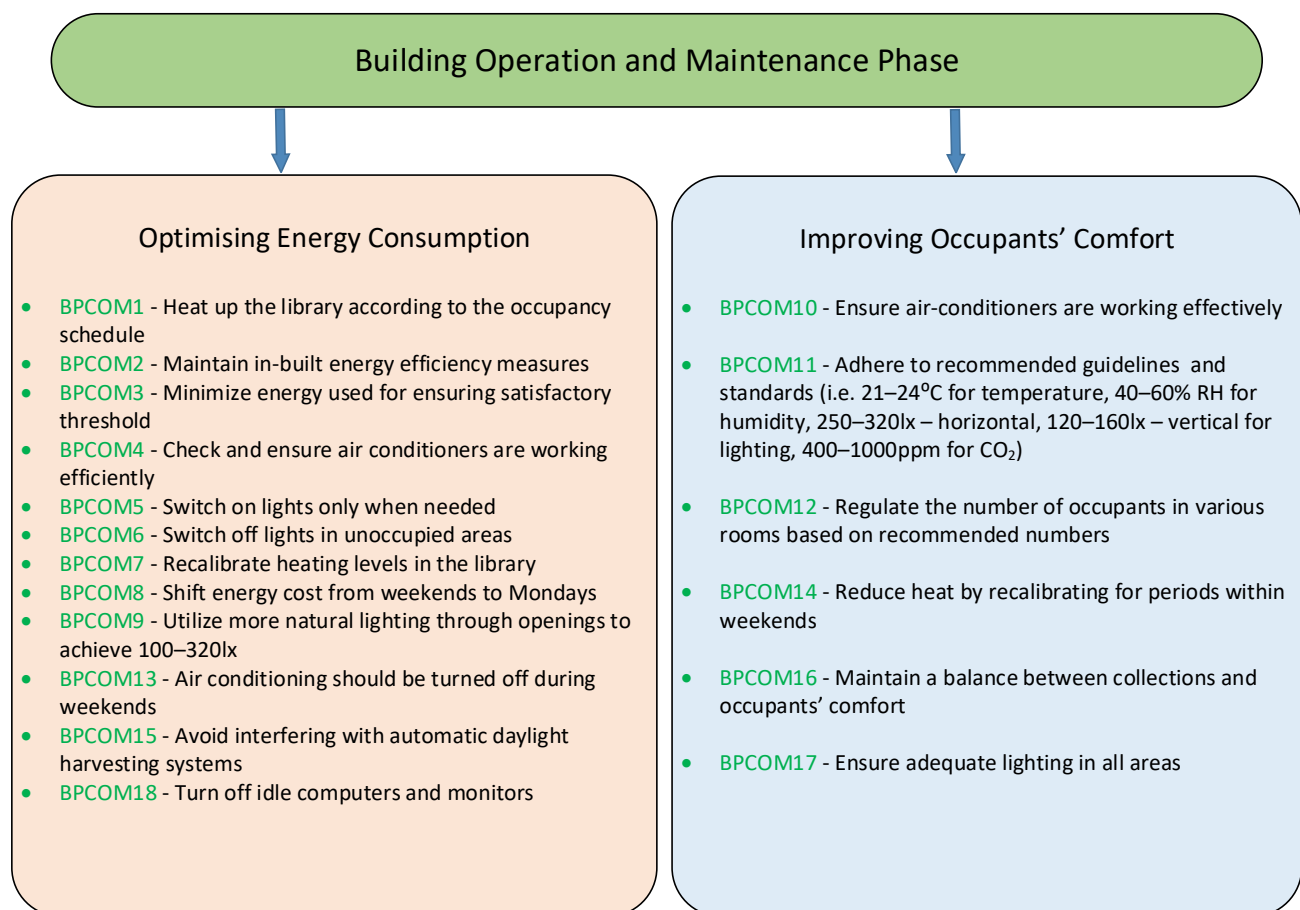


Figure 14. The first stage of the best practice framework. Note: BPCOM = Best practice code for operation and maintenance.

As presented in Figure 14, the first stage of the best practice framework consists of 18 best practices for the operation and maintenance phase of the library building: 12 for improving energy consumption and 6 for improving building occupants' comfort. More importantly, the best practices provide effective management strategies that require attention in the operation and management of the library building. In the operation and maintenance phase, facility managers need to ensure adequate implementation of these measures to

improve energy consumption and occupants' comfort. The data from the digital twin system provides a better understanding of the indoor environmental conditions in the library, and thus, a resultant framework based on the digital twin system and the views of the occupants presents much more enlightened decision-making associated with the operation and maintenance of the library building.

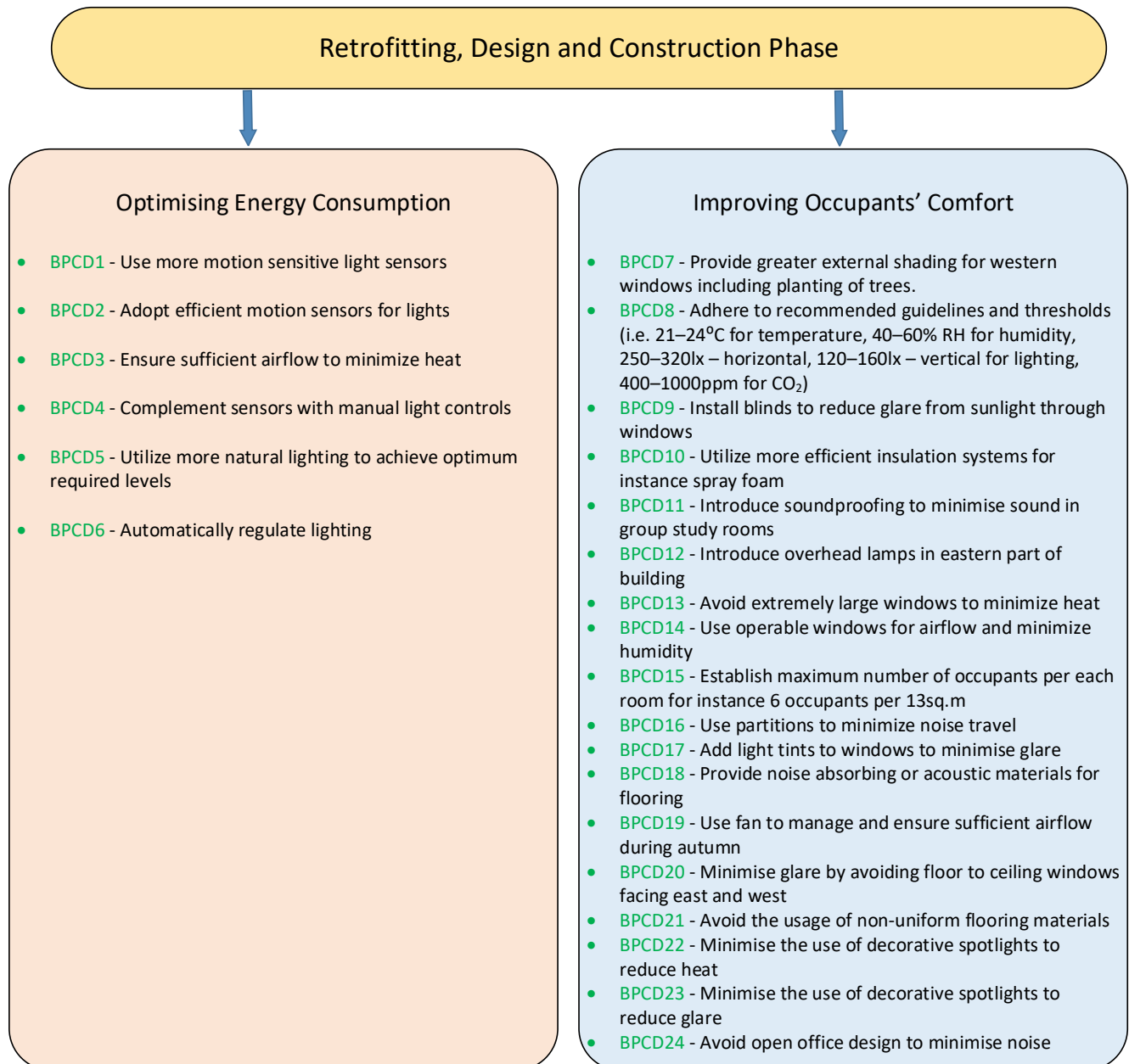


Figure 15. The second stage of the best practice framework. Note: BPCD = Best practice code for retrofitting, design, and construction.

The second stage of the framework presents the best practices for retrofitting existing library buildings and designing, as well as constructing, new library buildings. In this stage, 24 best practices are suggested. This stage encompasses 6 best practices for improving energy consumption and 18 for improving building occupants' comfort. The best practices suggested will ensure continued improvement in occupants' comfort and energy consumption. Considering the need to improve productivity and minimize energy consumption, which significantly contributes to climate change, strategies that will improve occupants'

comfort to ensure they become more productive, as well as actions that reduce the level of energy consumption in the building, are suggested. Hence, it is envisaged that this stage's best practices will improve the management of retrofitted existing library buildings as well as the design and construction of new library buildings. Figure 15 presents the best practices for retrofitting existing library buildings and designing as well as constructing new library buildings.

5. Validation of the Best Practice Framework

Research validation is considered an essential component in the final stage of any research study [50]. The validation process measures the practicality, suitability, objectivity, and reliability of the developed best practice framework [51–53]. Furthermore, the validation of any research ensures that the needs of the potential users of the research are met [54].

A qualitative approach was utilized in this research to validate the best practice framework. The approach was selected due to the difficulties in assessing the framework quantitatively [55]. Thus, a more reliable approach to this type of research is opinion-based data rather than established assessment criteria [56]. The four validation facets comprise internal validity, external validity, content validity, and construct validity.

External validity considers the generalizability of the outcomes of the study and best practices [55]. This assesses whether the framework for improving occupants' comfort and subsequently optimizing energy consumption in the library can be generalized. Internal validity evaluates the causality concept and is thoughtful of the derivability of the relationships in the data. The internal validity assesses if the developed best practice framework can be simply understood in practice [52]. Furthermore, content validity determines whether reality is accurately represented through the content of the research [57]. This validity determines whether the established best practices could guarantee a successful improvement in occupants' comfort and optimize energy consumption in buildings. Finally, construct validity evaluates the operationalization of the theoretical constructs and determines whether the research efforts measured what was set out to be measured in the objectives of the research [55]. This validity assesses the appropriateness, together with the comprehensiveness, of the developed best practice framework for improving occupants' comfort and optimizing energy consumption in buildings.

5.1. Design of the Questionnaire for Validation and Expert Interviews

To authenticate the quality as well as the credibility of the best practice framework, semi-structured interviews were conducted with experienced building/facilities management experts. The interviews comprised both internal and external experts. These experts are individuals who possess valuable knowledge in building and facility management [58]. The questionnaire for the validation comprised four sections. The first section requested the experts to provide information on their backgrounds. The second section offered the best practice framework (see Figures 5 and 6). The third section requested the opinions of the experts on the level of agreement on the ten validation questions that relate to the four aspects of validity. The degree of agreement was evaluated based on a seven-point Likert scale, where 1 = strongly disagree, 2 = disagree, 3 = somewhat disagree, 4 = neither agree or disagree, 5 = somewhat agree, 6 = agree, and 7 = strongly agree. The seven-point Likert scale was used because it provides the respondents with much wider options to make the best decision [59]. The fourth section requested the qualitative feedback of the experts on the developed best practice framework.

The experts for the validation were chosen in line with predetermined criteria, which include extensive knowledge in building or facility management, a top management role

in facility management, and more than 10 years of experience in building and facility management [60]. A purposive sampling technique was then used to select the experts for the interviews based on the predetermined criteria. This resulted in the identification of six domain experts for the interviews. The sample size for interviews is often based on reaching the theoretical saturation, where an extra few interviews will not provide new insights [44,61]. The point of theoretical saturation was achieved after conducting four interviews with the domain experts. Further conducting two more interviews did not add any new insights or provide any significant change to the results. This indicated the data saturation and therefore provided an appropriate sample size for the study. Table 4 shows the background of the experts who participated in the validation interviews.

Table 4. Details of experts who participated in the validation interviews.

Expert Code	Role	Years of Experience	Area of Expertise	Expert Category
E1	Energy and Sustainability Manager	30	Facility Management	External
E2	Campus Coordinator	15	Facility Management	Internal (User)
E3	Campus Coordinator	20	Facility Management	Internal (User)
E4	Building Manager	20	Facility Management	External
E5	Campus Coordinator	25	Facility Management	Internal (User)
E6	Infrastructure and Sustainability Manager	17	Facility Management	External

From Table 4, it is evident that all six experts have extensive experience (i.e., more than 10 years of experience) in facility management. Thus, the experts had extensive knowledge of building/facility management. Furthermore, the experts were in top management roles in facility management. In addition, the experts were external or internal (users) to the case utilized in this study, which rendered the authenticity, credibility, and genuineness of the findings.

5.2. Results of the Validation

The findings of the validation of the developed framework are provided in Table 5. It is worth mentioning that this is not a quantitative analysis of the experts' feedback. The number analysis was to get a feel for the opinions of the expert [53]. This was to determine whether the experts were predominantly in the satisfied range or dissatisfied range, or neutral [62]. Thus, the analysis does not have any statistical relevance but only achieves an in-depth understanding of the agreement of the experts on the validation questions/statements [53,63].

Table 5. Findings of the developed best practice framework validation.

S/N	Validation Statements/Questions	Responses of Experts						Mean	Mode
		E1	E2	E3	E4	E5	E6		
1	The best practice framework is relevant and easy to understand	6	7	6	5	6	7	6.12	6
2	The best practices for building operation and maintenance are appropriate	6	6	6	6	6	7	6.12	6
3	The building improvement guides for retrofitting existing buildings, and designing and constructing new buildings are appropriate	5	6	6	6	6	7	6.00	6

Table 5. Cont.

S/N	Validation Statements/Questions	Responses of Experts							
		E1	E2	E3	E4	E5	E6	Mean	Mode
4	The various best practice codes are appropriately classified	6	6	6	6	7	7	6.33	6
5	The best practices for optimizing energy consumption are comprehensive	6	6	6	6	6	7	6.12	6
6	The framework can be carefully followed to optimize the building's energy consumption	6	6	6	6	6	7	6.12	6
7	The best practices for ensuring building occupants' comfort are comprehensive	7	6	6	6	6	7	6.33	6
8	The appropriate adoption of the framework can improve building occupants' comfort	6	7	6	7	6	7	6.50	7, 6
9	The best practice framework is suitable for optimizing energy consumption and improving occupants' comfort	6	6	6	6	7	7	6.33	6
10	I would accept the best practice framework for use in buildings	6	6	6	6	6	7	6.33	6

Note: E1–E6 = Codes for the six experts.

As can be seen from Table 5, all ten validation statements regarding the developed best practice framework obtained a mean value greater than the average of the ranking scale (i.e., 4.50). Thus, the lowest mean score value was 6.00. This implies that the experts agreed that the four facets of validation (internal validity, external validity, content validity, and construct validity) of the developed best practice framework are appropriate. Furthermore, it can also be seen that the experts did not have greater variability in the responses provided regarding the developed framework.

Statements 1 and 4 were utilized to evaluate the internal validity of the best practice framework. From the results, statement 1 was rated as *agree*, which indicates that the identified best practices are relevant and easy to understand in improving occupants' comfort and optimizing energy consumption in the library building. More so, statement 4 was rated as *agree*, implying that the best practice codes were classified appropriately under those that are relevant to the operation and maintenance phase of a building, and those that are relevant to retrofitting existing buildings, and design and construction of new buildings. The construct validity was measured using statements 2, 3, 5, 7, and 9. Statement 2 was rated as *agree*, indicating that the experts hold an agreement regarding the appropriateness of the framework for managing the operation and maintenance of the building. More so, statement 3 was also rated as *agree*, implying that the experts agree that the best practices are appropriate for improving the retrofitting of existing buildings, as well as the designing and construction of new buildings. Statement 5 was rated as *agree*, signifying that the best practices for optimizing energy consumption are comprehensive and capture all the necessary aspects. Statement 7 obtained an *agree* rating, which indicates that the best practices for improving the comfort of building occupants are comprehensive. In addition, statement 9 was rated as *agree*, which means that the best practice framework is suitable for improving the occupants' comfort and optimizing the consumption of energy in the building.

In addition, the content validity was measured using statements 6 and 8. Statement 6 was rated as *agree*, indicating that the framework can be carefully followed to optimize the energy consumption in the building. Statement 8 was rated between *strongly agree* and *agree*, which means that the framework, if appropriately adopted, can improve the

comfort of the occupants of the building. Finally, statement 10 was meant to evaluate the external validity of the developed framework. Statement 10 was rated as *agree*, indicating that the developed framework is appropriate and can be accepted for use in buildings to improve occupants' comfort and optimize the consumption of energy. In total, the high scores achieved for the four validation facets of the framework indicate that the framework is appropriate, replicable, credible, objective, comprehensive, and usable for improving occupants' comfort and optimizing energy consumption in the library building.

Furthermore, the participants were requested to provide qualitative responses on the best practices regarding their usefulness to the building/facility manager. It was revealed that the best practices are very useful for improving occupants' comfort and optimizing energy consumption in the building. This was confirmed by the statement of Expert 1 that *I would say they are very useful because of the potential improvements in improving energy consumption and comfort of the occupants* (E1/Q6/S3). Expert 6 reaffirmed the usefulness of the developed best practices in that *they present very clear practices as to what can be done to improve energy consumption and occupants' comfort in the building, and the appropriate use of the framework should result in a reduction in the energy consumption* (E6/Q6/S2; E6/Q6/S3). The reduction in energy consumption in the library will then minimize energy bills and subsequently limit the carbon emissions from the building [64].

In addition, the experts indicated that the framework encompasses all the pertinent aspects for improving occupants' comfort and optimizing energy consumption in the building. Experts 1, 3, and 4 confirmed the comprehensiveness of the framework. Expert 1 mentioned that *I think you've captured every relevant area in the best practice framework* (E1/Q7/S1). Expert 3 added that *there is so much detail presented in the framework* (E3/Q7/S3). Expert 4 stated that *I am highly impressed with the level of detail in the framework and the detailed explanations document* (E4/Q7/S2), and *that's excellent* (E4/Q7/S3). The best practices were categorized to capture all the relevant aspects related to the operation and maintenance of buildings [65]. Further categorization was made for the retrofitting of existing buildings and the design and construction of new buildings [66]. These categorizations ensure that the majority of the relevant issues are captured in the developed best practices [67]. Finally, the respondents highlighted that the classification of the best practices under operation and maintenance of buildings, retrofitting of the existing buildings, and design and construction of new buildings, as well as energy optimization and improvements in occupants' comfort, makes the framework easy to understand and use. The building/facility manager can easily continue to make improvements in the building. The ease of use of the framework by the building/facility manager was confirmed by Experts 1, 6, and 5. Expert 1 highlighted that *I think the best practices are easy to follow and use* (E1/Q8/S4). Expert 6 mentioned that *they are easy to understand, so I don't see any difficulty in using these best practices* (E6/Q8/S1). Expert 5 opined that *the categorization of the practices makes them very easy to understand and apply* (E5/Q8/S2). The appropriate understanding and ease of use of the developed best practice framework would encourage and motivate the stakeholders and users to adopt and implement the framework for the management of buildings.

6. Implications for Best Practices in Building and Facility Management

The outputs of this paper provide valuable management strategies for improving occupants' comfort and subsequently optimizing energy consumption in buildings. Although this best practice framework for managing buildings is specific to the case study (i.e., the library building), it is applicable to other similar buildings. Furthermore, these best practices can also be modified to suit any other buildings where the intention is to improve occupants' comfort and subsequently optimize energy consumption. The experts pointed out that support from stakeholders and the availability of the needed resources are

essential for the application of the framework. It must be noted that the experts indicated it would be prudent to determine whether there have been improvements after the best practice framework has been applied in the building. In addition, various proposals were made by the experts for the application of the best practice framework in building/facility management. Some of the proposals include adequate and early stakeholder engagement and a well-established operational program that incorporates an assessment or rating tool for the determination of the expected outcomes from the implementation of the best practice framework.

Additionally, this study provides a roadmap for embracing the concept and technology of DT in the management of buildings/facilities. This would help in accessing real-time data for efficient and informed decision-making to enhance the overall management of the facility. Further, the integration of the stakeholders' views in the developed best practice framework would enable the facility managers to ascertain a realistic conditional appraisal since technologies are developed to improve human conditions. Essentially, the framework could be adopted and tested in the library building to assess its efficiency and effectiveness.

7. Conclusions

This study advanced a best practice framework for improving occupants' comfort and subsequently optimizing energy consumption in library buildings using a case study approach. The framework was developed based on a BIM-based and IoT-driven DT system, the recommended standards for an office setting such as the library, and the views of the library stakeholders. The key contributing factors to the indoor environmental quality (IEQ) of library spaces were considered in developing the best practice framework. These factors include thermal comfort, lighting comfort, ventilation, and pollutants in the indoor environment of the library. To safeguard the comfort of building occupants, several actions are taken, and these adversely influence how energy is utilized and consumed in buildings. Therefore, the data from the DT system was compared with the recommended standard thresholds for the IEQ parameters in the library. These results were further compared with the views of the relevant library stakeholders regarding their comfort. The key findings of the digital twin system revealed that all the monitored parameters were within acceptable thresholds; however, the building occupants expressed concerns regarding excessive solar heat gain, inadequate airflow, and direct glare. It was also revealed that heat was the most disturbing environmental parameter in the library, and built-in energy efficiency measures were also not adequately maintained, contributing to the building's energy consumption. It is worth mentioning that the best practices are predominantly focused on the operation and maintenance phase of the building, since the aim of this study is on an existing library building. Notwithstanding, several proposals were presented to be considered in the design and construction of new buildings. This study also presented improvement guides that could be considered in retrofitting existing buildings. Furthermore, the best practices were further categorized into those that are related to improving energy consumption and those that are related to improving occupants' comfort in buildings. To determine the adequacy and validity of the developed framework, six experts with extensive building/facility management experience were asked to evaluate the developed framework in four facets of validation (i.e., internal validity, external validity, content validity, and construct validity). More importantly, the experts agreed that the four aspects of validation of the developed framework are appropriate. This suggests that the framework is appropriate, credible, objective, replicable, comprehensive, and usable for improving occupants' comfort and energy consumption in the library building if carefully utilized. Thus, the framework can potentially enhance the management of the building. It is envisaged that the managers of the library building will adopt the developed best practice framework for managing the

building to ensure an enhanced improvement in the comfort of occupants and subsequently optimize energy consumption. The novelty of this research lies in the development of a best practice framework considering occupant feedback and relevant standards for achieving enhanced indoor environmental conditions when using DT technology.

Notwithstanding the contributions of this study, some limitations are worth noting. Firstly, the limitation of the study to a single case of a university library in Australia would make it difficult to generalize the findings beyond the selected library. More so, the evaluations made in the study regarding the stakeholder and expert interviews were generally subjective and may be influenced by the respondents' attitudes and experiences. Notwithstanding, the established best practices were cross-validated using both external experts and building users. This study's intent was to carry out a detailed in-depth review of an instance of a particular library to understand the intricacies and nuances of a typical library building as an exemplar case study. Thus, the findings are accurate and credible for future reference. Secondly, the developed best practice framework was not implemented in the library building to ascertain the real outcomes after its adoption. This would have provided much better evaluation outputs of the validity of the developed framework.

Considering the limitations and based on the outcomes of this research, it is suggested that future research endeavors espouse the best practice framework and test it within the context of a library building to ascertain its real impact and outcomes. In addition, the current study analyzed the opinions of stakeholders and experts in developing the best practice framework. This study has been validated, and it is comprehensive, reliable, and easy to understand and use. Future studies may use this framework as the basis for developing best practice guidelines for enhancing the internal environments of different building types.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Building operation and maintenance guidelines.

Best Practice Code	Detailed Explanations Specific to the Case Study
BPCOM1	Activate the HVAC for heating the library only on weekdays (i.e., Monday-Friday) to minimize the amount of energy used in keeping the library warm using the HVAC system.
BPCOM2	Various built-in energy efficiency measures have been built into the library. These measures should be regularly maintained to optimize the consumption of energy in the library.
BPCOM3	Although the temperature required for maintaining the collection in the library should be much lower than it is comfortable for humans. A balance should be maintained using the HVAC in ensure human comfort and maintain the collection.
BPCOM4	The air conditioning in the library should be regularly checked to ensure it is working effectively. This would minimize the amount of energy required to power the HVAC system.
BPCOM5	Lights in the library are always switched on even when nobody is around. The lights should be turned off automatically when there is nobody in the various rooms.
BPCOM6	Unoccupied areas in the library always have lights switched on. These lights should be automatically switched on only when the various areas are occupied.
BPCOM7	The calibration of the HVAC system for heating should be properly carried out to ensure the required amount of heat is produced with an optimum energy use.
BPCOM8	Instead of having the HVAC system working throughout the entire week in the library, the system could be turned off during weekends to save some energy costs.
BPCOM9	Instead of having the lights working during sunny days, optimize energy use by opening blinds to admit more daylight through windows in the library. The lighting level in the library for comfortable reading should be in the range of 100–320 lx.
BPCOM10	Ensure air-conditioners are working effectively to meet the needs and comfort of the library occupants.
BPCOM11	Adhere to recommended guidelines and standards, for instance, 21–24 °C for temperature, 40–60% RH for humidity, 260–320 lx—horizontal, 120–160 lx—vertical for lighting, 400–1000 ppm for CO ₂
BPCOM12	Regulate the number of occupants in various rooms to reduce the effects on temperature and CO ₂ in the study room.
BPCOM13	Based on the occupancy profile of the library, the air conditioning/HVAC system could be turned off during weekends to conserve energy.
BPCOM14	HVAC system should be recalibrated to the specific heat needs and comfort of the occupants based on the season (i.e., winter and summer). The temperature in winter should be in the range of 20–25 °C, and in summer it should be in the range of 23–26 °C.
BPCOM15	Avoid interfering with automatic daylight harvesting systems that have been integrated in the library.
BPCOM16	Although a lower temperature is required to maintain the collection in the library, this temperature level is not comfortable for humans. Therefore, a balance should be maintained between collections and occupants' comfort.
BPCOM17	There should be adequate lighting in all areas of the library using both natural and artificial lighting.
BPCOM18	Sometimes, idle computers and monitors are still turned on in the library. These computers and monitors that are not in use should be turned off to optimize the use of energy in the library.

Table A2. Building improvement guides.

Best Practice Codes	Detailed Explanations
BPCD1	Use more sensitive light sensors in the library to regulate the switching off and on of the lights.
BPCD2	Adopt efficient motion sensors for lights to determine where there is occupancy, so that lights are automatically switched on.
BPCD3	Ensure sufficient airflow in the library through door and window openings to minimize the amount of heat in the library at any given time. This would limit the need for cooling using the HVAC system.
BPCD4	Manual light controls should be used in the library to complement the sensors so that occupants can turn lights off if not needed at any time.
BPCD5	Utilize more natural lighting from window openings instead of constantly using artificial lighting.
BPCD6	Automatically regulate lighting in the library using smart light sensors.
BPCD7	Provide greater external shading for western windows by planting more trees.
BPCD8	Adhere to recommended guidelines for a comfortable work environment as specified by regulatory bodies.
BPCD9	Install blinds to reduce glare from direct sunlight through windows.
BPCD10	Utilize more efficient insulation systems like spray foam in buildings to minimize the transfer of heat. Spray foam insulation would have a significant impact on heating and cooling bills.
BPCD11	Introduce soundproofing to minimize sound from occupants' discussions in the group study rooms.
BPCD12	Introduce overhead lamps in the eastern part of the buildings to improve visibility.
BPCD13	Avoid extremely large windows in buildings to minimize heat gain and heat loss.
BPCD14	Use operable windows for airflow and minimize humidity in spaces.
BPCD15	Establish the maximum number of occupants per room to minimize CO ₂ concentration.
BPCD16	Use partition blocks in buildings to minimize noise travel.
BPCD17	Add light tints to windows to minimize glare.
BPCD18	Provide noise-absorbing or acoustic materials for flooring, for example, carpet instead of marble.
BPCD19	Use a fan to manage and ensure sufficient airflow during autumn.
BPCD20	Minimize glare by avoiding floor-to-ceiling windows facing the eastern and western sides of the building.
BPCD21	Avoid the usage of non-uniform flooring materials, i.e., carpet and marble together.
BPCD22	Minimize the use of decorative spotlights to reduce heat since they add to the generation of heat in the building.
BPCD23	Minimize the use of decorative spotlights to reduce glare in the building.
BPCD24	Avoid open office design to minimize noise. Partition walls serve as a barrier to the easy transfer of sound in buildings.

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