Engineering a green built environment: how buildings can support a sustainable future

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CHAPTER 4

AN INDOOR ENVIRONMENTAL QUALITY STUDY IN HIGHER EDUCATION BUILDINGS: INSIGHTS FROM POST OCCUPANCY EVALUATION AND A BIM-BASED SOLUTION

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Abstract: The Indoor Environmental Quality (IEQ) of Higher Education (HE) buildings is a critical factor that influences student comfort, health and learning experiences. Following the COVID-19 pandemic, the need to optimize IEQ in university environments has become even more pronounced. This study adopts the principles of Post-Occupancy Evaluation (POE) to assess IEQ conditions across various HE spaces through a combination of both quantitative and qualitative methods. Environmental data including temperature, noise, illuminance, CO_2 concentrations and other air quality parameters including volatile organic compounds, were analysed alongside user perceptions gathered through questionnaire surveys and insights from facility management interviews. While the findings indicate generally acceptable environmental conditions in most areas, notable identified discrepancies highlight the need for improvements to better support occupant comfort and well-being. A key challenge identified is the facility management's limited ability to manually oversee and regulate the vast, complex spaces within HE buildings which supports the necessity of dynamic and responsive IEQ management strategies. In response, this research has developed a BIM-based framework for real-time IEQ monitoring and automated environmental control. By extending BIM applications beyond static building data to dynamic IEQ management, this

study offers significant contributions to both theoretical and practical domains. Academically, it advances the state of the art by demonstrating BIM's potential in adaptive IEQ control through publications, while its practical implications support sustainability efforts and occupant well-being in HE institutions. Furthermore, the research aligns with institutional and governmental HE strategies by providing a forward-looking framework for rethinking university environments in the post-pandemic era.

Keywords: building information modelling (BIM), facility management, higher education buildings, indoor environmental quality (IEQ), post-occupancy evaluation (POE).

1. Introduction

Indoor Environmental Quality (IEQ) is a fundamental aspect of modern educational environments, influencing not only the health and well-being of students and staff but also affecting their cognitive functions and productivity (Toyinbo, 2019). It refers to the quality of a building's environment in relation to the health and well-being of those who occupy space within it. IEQ is determined by several factors, each contributing uniquely to the overall comfort, health, and productivity of occupants. These factors include thermal comfort, indoor air quality, acoustic comfort, and visual comfort, each encompassing specific elements that interact in complex ways (Wong et al., 2008; Turunen et al., 2014; Weerainghe et al., 2020; Claysen & Wyon, 2008).

The importance of IEQ research has intensified, particularly following the COVID-19 pandemic which has highlighted the necessity for improved management of indoor spaces, especially in public spaces such as higher education (HE) institutions. Unlike primary and secondary educational settings, HE buildings present unique challenges due to their diverse and complex architecture, which includes large lecture halls, laboratories with strict climate demands, and other spaces such as PC rooms. Traditional facility management methods in these environments are often manual and outdated, leading to inefficient IEQ control which are prone to delays and errors that adversely affect occupant comfort and health (Brink et al., 2021; Amaral et al., 2020). Building Information Modelling (BIM) emerges as a transformative solution providing sophisticated tools not only for detailed architectural modelling but also for managing building operations throughout their lifecycle. BIM facilitates real-time visualization and management of IEQ parameters thereby allowing facility managers to respond dynamically to the changing needs of HE settings and thus, enhance the overall health and productivity of the academic community (Hoang et al., 2020; Alavi et al., 2022; Condotta and Scanagatta, 2023; Du & Hoeft, 2020).

Building on this foundation, this research aims to study and develop a mechanism with the latest BIM technologies to monitor, control and improve the indoor environment quality in higher-education buildings. It explores how BIM can be leveraged not just for the visualization of IEQ data but also for the real-time monitoring and management of these conditions within HE buildings. By integrating sensor data directly into a BIM framework, facility managers could potentially forecast, analyze, and mitigate IEQ issues more efficiently, ultimately enhancing the comfort, health, and productivity of building occupants.

2. Research Methods

This research utilised the principles of Post Occupancy Evaluation (POE) to assess the IEQ within HE buildings with two London universities serving as the primary case studies for the empirical investigation (To satisfy ethical purposes, considerations and requirements, the Universities will be addressed in this paper as University A and B). The different types of rooms, their respective capacity as well as their ventilation type (which is a key factor that studies have shown to affect IEQ) are represented in Table 1:

Table 1 - University Data

University	Room	Capacity	Ventilation Type
A	Classroom (A)	56	Natural
	PC Room (A)	24	Natural
	Lecture Theatre (A)	191	Mechanical
	Architectural Studio (A)	30	Natural
B	Classroom (B)	41	Natural
	Lecture Hall (B)	167	Mechanical

The POE process involved: the continuous monitoring and measuring of environmental data, subjective feedback using questionnaire surveys and the interview of the facilities management (FM) team. The process of environmental data measuring involved the collection of certain IEQ parameters that are attributed to the different factors associated with IEQ. This was conducted in line with the CIBSE:TM68 – Monitoring Indoor

Environmental Quality guideline (CIBSE, 2022) for the monitoring of temperature (°C), relative humidity (%), carbon dioxide (CO_2 – PPM), total volatile organic compounds (TVOC - μg/m^3), formaldehyde (HCHO - μg/m^3), particulate matter (PM2.5 - μg/m^3), indoor ambient noise levels (IANL - dBA) and light levels (lux). It was carried out using a set of equipment based on their proven accuracy and reliability in capturing key environmental parameters. The equipment catalogue involved are illustrated in Figure 1(a-d) as Tinytag dataloggers (a-b), Temtop M2000C & LKC 1000s+ (c) and an ATP 4-in-1 environment meter (d).

a b c d

Figure 1 (a-d) - Environmental data measuring equipment

The environmental data monitoring was conducted during the winter months (November – March), a period selected due to its potential for significant variations in IEQ due to the challenges of heating and maintaining comfortable temperatures. The equipment were set to record environment data every 5 minutes following the TM68 guidelines as well as previous research and studies in the field. Furthermore, consistent with TM68 recommendations and to best represent the occupants' exposure, the equipment was placed at heights of 0.8 and 1.1 meters (Figure 2 a & b respectively), approximating the breathing zone of seated or standing individuals, depending on the typical use of each space. For lighting and acoustic measurements, spatial variability within each room was carefully considered. The Precision Gold N09AQ (ATP) 4-in-1 Environment Meter was used to assess light intensity and sound levels at multiple points across each room designed to comprehensively map the acoustic and visual environment experienced by occupants as represented in Figure 2c.

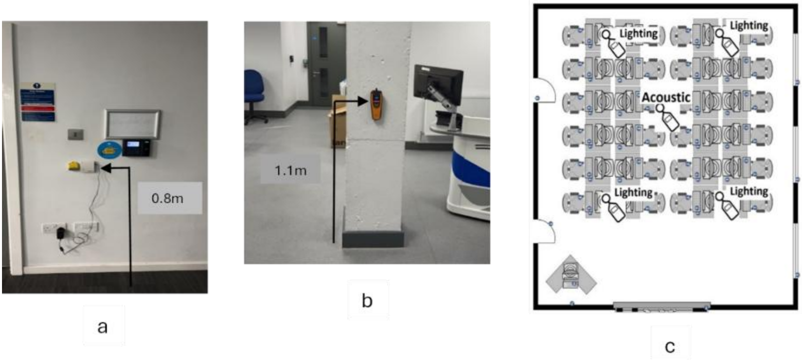

Figure 2 (a-c) - Instrumentation and Measurement Layout for IEQ Data Collection

The questionnaire survey process, conducted simultaneously with the collection of environmental data, represents the second facet of the POE process. It was conducted to effectively gauge the perception of the IEQ using students as a target group following previous studies and research as students' daily engagement with these environments places them in a unique position to offer valuable insights into how IEQ factors affect their comfort and learning experience. To assess student perceptions of IEQ factors, a web-based survey was developed using Google Forms and was shared using barcodes to ensure widespread participation. Ultimately, this POE process was conducted in two phases: the initial survey and follow-up survey which consisted of various types of questions including Likert scale, open ended and mixed type questions which were aimed to capture the immediate perceptions and responses of the respondents regarding factors like temperature, air quality, lighting, and noise levels in the classrooms.

To complement the quantitative and qualitative data gathered from environmental monitoring and student surveys, semi-structured interviews were conducted with members of the facilities management team. Each interview was conducted in person and lasted approximately 45 minutes thereby providing a substantial opportunity to delve deep into the management practices, challenges, and priorities of HE facilities. These discussions explored a range of topics critical to the operation of educational institutions, including the strategies used to maintain and enhance IEQ, energy efficiency measures, and overall sustainability practices within the HE built environment.

3. POE Results and Discussions

The environmental data measured and monitored across Universities A and B have revealed considerable variability in IEQ parameters, particularly highlighting that both carbon dioxide concentrations and temperature levels frequently reached or exceeded accepted health and comfort thresholds. Figure 3 illustrates the CO_2 data collected and it highlights the contrast between rooms characterised with either mechanical or natural ventilation. Architectural Studio (A), PC Room (A) and Classroom (A), all naturally ventilated, recorded CO_2 data which exceeded the 1500 comfort threshold provided by BB101. It was observed during the monitoring process that these rooms where characterised with high occupancy with a relative amount of airflow from the windows being open. The data suggests that the natural ventilation system alone, especially in Architectural Studio (A) and PC Room (A) which recorded CO_2 levels approaching 2500ppm, may not adequately manage air quality under high occupancy conditions. This high level of CO_2 concentration can adversely affect cognitive functions and decision-making capabilities of occupants, as elevated CO_2 levels have been linked to decreased productivity and increased discomfort (Greene et al., 2012; Satish et al., 2012). In contrast, the mechanically ventilated rooms, Lecture Theatre (A) and Lecture Hall (B), maintain lower and more stable CO_2 levels throughout the day, aligning with findings that mechanical systems can more effectively manage air quality (Seppänen et al., 1999).

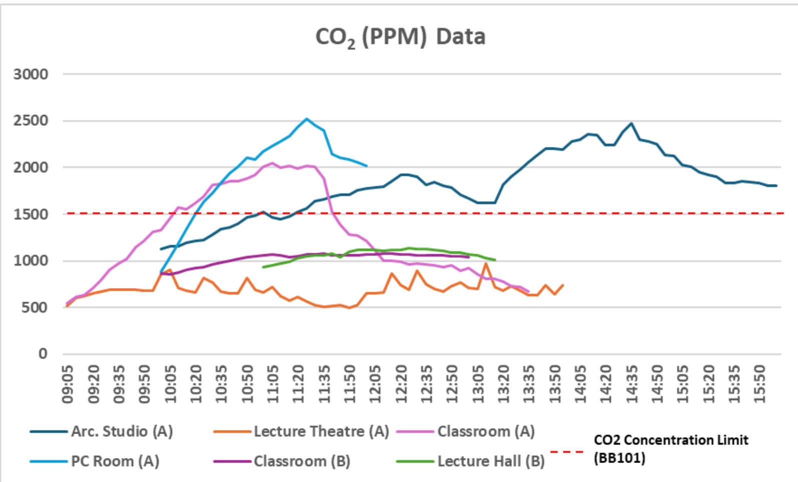

Figure 3 - CO_2 data

The temperature data is illustrated in Figure 3 across the various room with the recommended maintained temperature of 20-25°C as published by the Building Bulleting 101 (BB 101, 2018). The thermal data shows significant non-compliance with this comfort range especially in Architectural Studio (A) and Classroom (A) which recorded temperatures exceeded the upper limit. Observations indicated that the heating systems in these rooms where constantly on and while the windows were open occasionally with the outdoor air being between 3-8°C, the natural ventilation system may not suffice in maintaining thermal comfort, particularly when the internal heat gains are factored. The excessive temperatures in naturally ventilated spaces such as these, tend to compromise the learning environment thereby causing discomfort to students (Jiang *et al.,* 2018; Elnaklah et al., 2023; Geng *et al.,* 2017); evidently, it was observed that during these periods, students expressed discomforts leading to the removal of layers of clothing such as coats and jackets. On the other hand, the Lecture Theatre (A) with mechanical ventilation, maintained temperatures within a narrower range, emphasizing the effectiveness of HVAC systems in regulating indoor climates which is consistent with principles outlined by Fanger (1970, cited in Elnaklah et al., 2023) on thermal comfort.

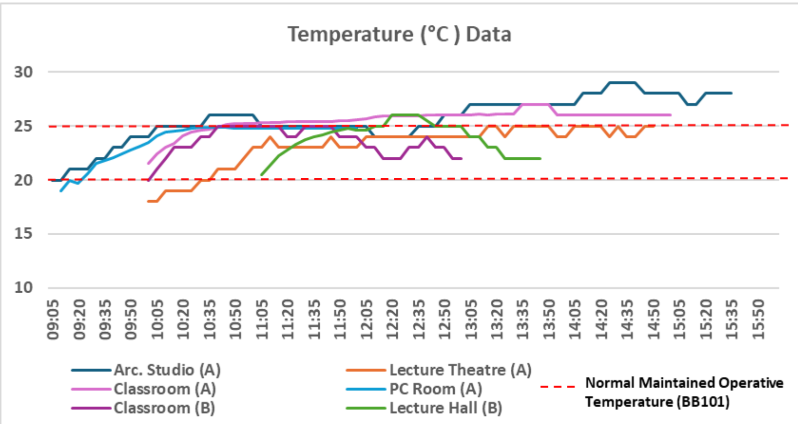

Figure 4 - Temperature Data

The indoor ambient noise levels (IANL) data recorded across University A and University B demonstrates significant compliance with the BB93 standard of 40 dBA, as shown in Figure 5. The analysis is based on $LA_{eq,2mins}$, which represents the equivalent continuous noise levels measured over a two-minute period. The data indicates that most rooms remained within the acceptable threshold, with the exception of PC Room (A) and Classroom (B), where noise levels slightly exceeded the recommended standard. Notably, mechanically ventilated rooms such as Lecture Theatre (A) and Lecture Hall (B) maintained compliance, suggesting that the background noise generated by mechanical ventilation systems remained within tolerable limits. However, the exceedance in PC Room (A) and Classroom (B) was largely attributed to open windows which allowed external noise sources, such as passing traffic, to influence acoustic conditions. Additionally, Classroom (B) recorded the highest $LA_{eq,max}$ at approximately 56 dBA, highlighting potential issues in controlling transient noise disturbances. Since BB93 guidelines emphasize the impact of excessive noise on communication and concentration, targeted measures, such as optimized scheduling to avoid peak noise periods or window management strategies, could be considered to improve acoustic performance in these spaces.

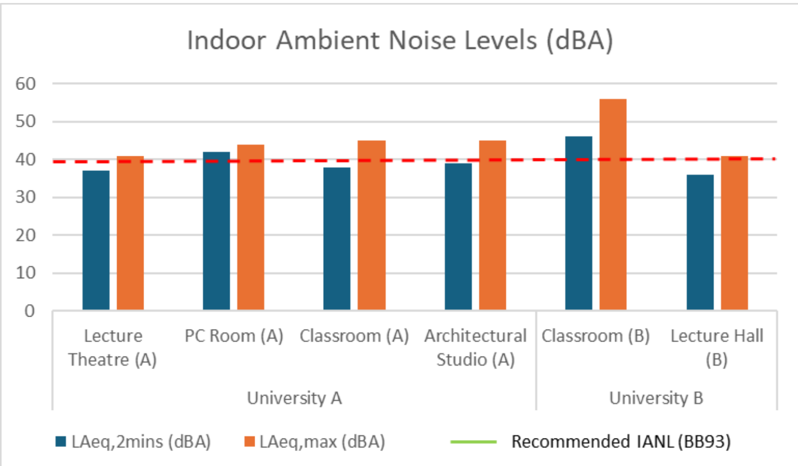

Figure 5 - IANL Data

The bar chart in Figure 6 illustrates the average illuminance levels across the monitored rooms in University A and B with the BS EN 12464-1:2021 recommended task illuminance level of 500 lux. In University A, all rooms met the recommended standard, suggesting that the lighting conditions were generally sufficient for educational activities. The occasional exceedance of the threshold, particularly in Architectural Studio (A), PC Room (A) and Classroom (A), was primarily due to the drawing up of blinds, allowing increased daylight penetration which can evidently lead to higher illuminance levels exceeding 1000 lux (Kong & Jakubiec, 2021). In contrast, Classroom (B) in University B recorded significantly lower illuminance levels, falling well below the recommended standard. This shortfall was largely attributed to the measurement period coinciding with a relatively overcast day that reduced the availability of natural daylight even when the blinds were raised. Additionally, the room's artificial lighting fixtures may have been inadequate in compensating for the lack of daylight, highlighting potential deficiencies in its lighting design. On the other hand, Lecture Hall (B), despite its lower ground-level location and lack of windows, met the required illuminance standard, solely relying on artificial lighting. This suggests that while natural daylight can enhance visual comfort, well-designed artificial lighting systems can effectively meet illuminance needs in spaces without windows. Moreover, uneven lighting distribution was observed in some rooms, where areas further from windows recorded lower illuminance levels compared to those closer to natural light sources. This highlights the need for further investigation into the uniformity of lighting conditions and potential adjustments to artificial lighting placements to ensure balanced illumination across all learning spaces.

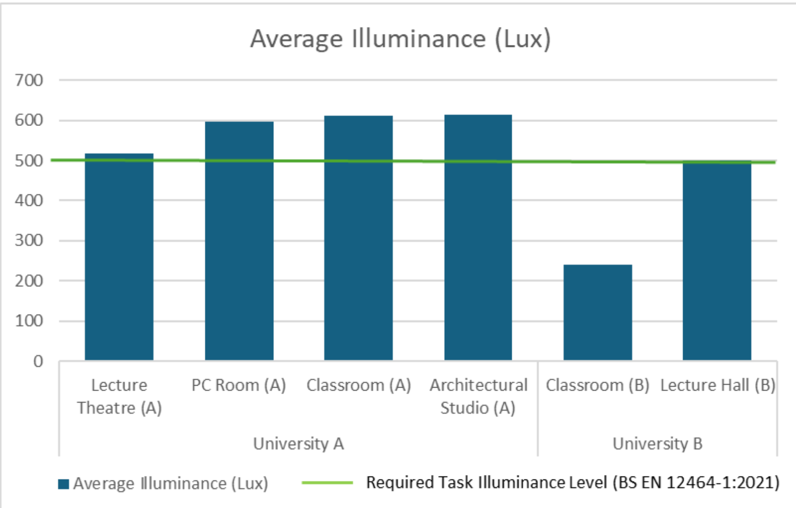

Figure 6 - Average Illuminance Data

The evaluation of the remaining environmental parameters across various rooms in University A and B demonstrated substantial compliance with established IEQ standards as outlined in Table 2. Average relative humidity levels were within the 40-70% range thus indicating suitable moisture content in the air for occupant comfort and well-being. However, the lecture hall in University B recorded a lower-than-optimal relative humidity of 35%, which may be attributed to its ventilation system or location within the building, potentially leading to dry air conditions. Concentrations of TVOCs and formaldehyde (HCHO) remained well below the thresholds of 0.3 mg/m³ and 0.1 mg/m³, respectively which indicates good air quality with regards to chemical contaminants. The only exception was the architectural studio, which recorded a TVOC level of 0.31 mg/m³, slightly exceeding the recommended limit. This may be due to off-gassing from materials such as adhesives, paints, or cleaning products, which are commonly found in creative workspaces. Although still within acceptable limits, this finding suggests that material choices and ventilation strategies should be carefully managed in such environments to mitigate prolonged exposure risks. Particulate matter (PM2.5) levels were consistently lower than the 25 µg/m³ limit, reinforcing that indoor air quality was well maintained. Despite the identified exceptions, the overall findings reflect a positive overall alignment with IEQ standards and recommendations conducive for teaching and learning.

Table 2 - Comparative Analysis of Average IEQ Parameters in University A and B

University	**Room**	**(Avg) Relative Humidity (%)**	**(Avg) TVOC (mg/m³)**	**(Avg) HCHO (mg/m³)**	**(Avg) PM2.5 (µg/m³)**
A	PC Room	46	0.15	0.06	11
A	Classroom	43	0.09	0.09	12
A	Lecture Theatre	40	0.05	0.01	12
A	Architectural Studio	40	0.31	0.08	12
B	Classroom	42	0.05	0.01	10
B	Lecture Hall	35	0.04	0.01	9
Standards		40-70% (CIBSE, 2017)	<0.3 mg/m³ (BB101, 2018)	<0.1 mg/m³ (BB101, 2018)	<25 µg/m³ (BB101, 2018)

The student feedback via the questionnaire surveys revealed a general satisfaction towards the various IEQ parameters across board. When assessing the light level in classrooms, majority of the respondents (78%) found it to be okay and within optimum levels. This was further extended to ascertaining the ability of respondents to be able to see the board/projector, with 81% affirming of their ability to do so. The feedback regarding noise levels when windows were open also indicated a general satisfaction with 68% of the respondents assessing it as usually okay. However, some discomforts were experienced by the 20% that found it to be usually severe as it was observed in some classrooms characterised with traffic noise coming in, the students seldomly closed off the windows. The feedback further highlighted a correlation between the measured environmental extremes and perceived discomfort. The survey results indicated that although a significant proportion of respondents perceived the temperature as acceptable, a considerable number reported experiencing uncomfortably high temperatures, with 4.9% describing it as 'hot' and 22% as 'warm'. These subjective experiences were consistent with actual temperature measurements in the classrooms, which frequently reached or surpassed the upper recommended limit of 25°C. Observations of students removing upper layers of clothing and opening windows to alleviate discomfort further validated these findings. The survey results also indicated that while the majority of participants were satisfied with the air quality, approximately 17% reported it as unsatisfactory. This sentiment correlates strongly with the environmental data, particularly the CO_2 measurements, which frequently exceeded the upper safety threshold of 1500ppm, notably in rooms with natural ventilation. These elevated CO_2 levels, associated with negative impacts on cognitive functions and increased perceptions of stuffiness, were reflected in the dissatisfaction expressed by respondents about air quality (Korsavi et al., 2020). Additionally, the survey affirmed the importance of IEQ factors in educational environments, with 68.3% of respondents acknowledging that elements such as temperature, air quality, and noise significantly affect their ability to concentrate, as depicted in Figure 7. This overwhelming response highlights the vital impact that conducive learning environments have on academic aspects such as concentration.

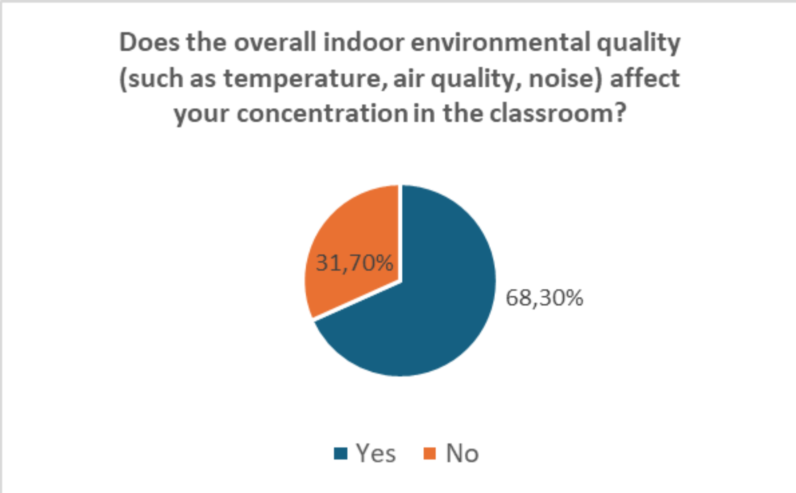

Figure 7 - IEQ impact on concentration feedback

Interviews with the facilities management team at University A revealed a strong dedication to sustainability, highlighted by the strategic objective to reach net-zero carbon emissions by 2030 across the full spectrum of emissions categories. This goal reflects the university's strong commitment to environmental responsibility and is in line with worldwide sustainability efforts. Yet, the path to achieving this objective is filled with complex challenges, especially given the varied needs of the institution's substantial community. As one manager pointed out, “We have got a population of about 14,000 people. Each person has unique needs, such as individual temperature preferences, which presents significant challenges…”. Additionally, the interviews shed light on the everyday difficulties encountered in regulating the indoor environment to enhance occupant comfort and well-being. Issues such as solar glare and inconsistent temperature control underscore the necessity for a more detailed approach to managing space and environmental conditions. An interviewee expressed this concern, stating, “And our problem, so if I think about those things that can go wrong, or affect staff and students; it's like sunlight coming through the windows getting in your eyes… rooms too hot too cold…”. These challenges are not exclusive to University A but are indicative of the complexities that FM teams in educational settings globally must navigate. The broad and ever-changing demands of such extensive facilities call for a versatile, responsive IEQ management system.

4. Bim-Based Prototype Development

The extensive POE process conducted in University A and B has yielded deep insights associated with managing IEQ in HE buildings. While the environmental monitoring uncovered cases where temperature and CO_2 levels surpassed recommended thresholds, adversely affecting student comfort and concentration, most parameters like TVOC, formaldehyde, lighting, and noise were within acceptable limits. Moreover, discussions with the FM team revealed the diverse needs of a large campus community and the challenges of manually controlling such vast and complex spaces and environments. These findings set the stage for the development of a BIM-based system, tailored to dynamically manage and optimize IEQ across university campuses with the framework illustrated in Figure 8.

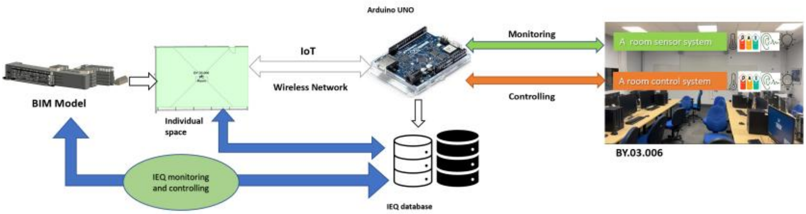

Figure 8 - BIM-based prototype framework (Source: Author's own work)

The proposed framework for the BIM-based system designed to monitor and control IEQ in HE buildings integrates cutting-edge technologies to ensure optimal environmental conditions across campus facilities. This system centres around a robust architecture that employs Arduino microcontrollers, Dynamo in Revit for BIM integration and data processing.

4.1 Key Components of the Framework

1. **Room Sensor System:** This component is equipped with a variety of environmental sensors, all connected to Arduino microcontrollers. These sensors continuously gather real-time data on critical IEQ parameters such as temperature, CO_2 levels, relative humidity, and particulates which ensures comprehensive monitoring.
2. **Integration with BIM using Dynamo:** The heart of the data processing and visualization occurs within the Dynamo environment in Revit. Dynamo facilitates the automation of data handling processes directly within the BIM model. This setup allows for an

effective synchronization between the real-time sensor data and the architectural models thereby enhancing the ability to visualize and analyse environmental data spatially across the physical layout of the buildings.

3. **Data Processing with Dynamo and Python:** Dynamo further possess the capability to process the IEQ data. It also is equipped with a python engine which also offers a powerful tool for data analysis and operations. Python's capabilities allow for the manipulation of large datasets, the execution of complex calculations necessary to maintain and optimize IEQ based on the sensor inputs and the ability to store these datasets into databases in real time.
4. **Room Control System:** The control system receives processed data and implements necessary environmental adjustments. These changes are executed through a network of actuators controlled by Arduino, which adjust various building systems like HVAC to modify the indoor conditions as required.

The integration of these technologies forms a comprehensive approach to managing the dynamic and complex environments of HE buildings. This framework not only aims to enhance occupant comfort and learning effectiveness but can also support environmental objectives such as sustainability and efficient facility management. The development of this prototype is inherently dynamic, designed to accommodate ongoing adjustments and modifications thereby ensuring that it can evolve in response to emerging insights and enhancements throughout the development process.

5. Conclusion

This research delved into assessing the IEQ in HE buildings through a comprehensive POE. The quantitative analysis of environmental IEQ parameters demonstrated that while there was general compliance with recommended standards, specific environments still fell short. These discrepancies highlighted areas within HE facilities that require enhanced management solutions to consistently meet IEQ criteria. Qualitative insights, derived from questionnaire surveys and semi-structured interviews with the FM team, highlighted the challenges of manually managing the vast and complex spaces typical of HE environments. These findings reveal a clear need for more sophisticated, automated systems to ensure optimal environmental quality across diverse and dynamic campus settings. In response to these findings, the study proposes a feasible and technically sound solution through the development of a BIM-based prototype. This prototype harnesses the power of BIM technology integrated with real-time sensor data. Processed via algorithms in Dynamo within the Revit environment, this system enables a proactive approach to managing and optimizing IEQ. By automatically adjusting to real-time environmental changes, the BIM-based prototype aims to enhance comfort, health, and productivity thereby ensuring that all campus spaces consistently meet the highest standards of IEQ.

References

Alavi, H., Bortolini, R. & Forcada, N. (2022). BIM-based decision support for building condition assessment. *Automation in Construction, 135*, 104117. https://doi.org/10.1016/j.autcon.2021.104117

Amaral, A.R., Rodrigues, E., Gaspar, A.R. & Gomes, Á (2020). A review of empirical data of sustainability initiatives in university campus operations. *Journal of Cleaner Production, 250*, 119558. https://doi.org/10.1016/j.jclepro.2019.119558

Brink, H. W., Loomans, M. G. L. C., Mobach, M. P. & Kort, H. S. M. (2021). Classrooms' indoor environmental conditions affecting the academic achievement of students and teachers in higher education: A systematic literature review. *Indoor air*, *31*(2), 405–425. https://doi.org/10.1111/ina.12745

British Standard (BS). 2021. *Light and Lighting-Lighting of Work Places* (BS EN 12464-1: 2021).

Building Bulleting (BB) 93. (2014). *Acoustic Design of Schools: Performance Standards,* Education and Skills Funding Agency. https://www.gov.uk/government/publications/bb93-acoustic-design-of-schools-performance-standards

Building Bulleting (BB) 101. (2018). *Ventilation, thermal comfort and indoor air quality of school buildings,* Education and Skills Funding Agency. https://www.gov.uk/government/publications/building-bulletin-101-ventilation-for-school-buildings

CIBSE. (2017). *Guide A – Design Guide*. Chartered Institution of Building Services Engineers, CIBSE Knowledge Series.

Condotta, M. & Scanagatta, C. (2023). BIM-based method to inform operation and maintenance phases through a simplified procedure. *Journal of Building Engineering, 65*, 105730. https://doi.org/10.1016/j.jobe.2022.105730

Claysen, G. & Wyon, D. P. (2008). The combined effects of many different indoor environmental factors on acceptability and office work performance. *HVAC & R Research*, *14*(1), 103-113. https://doi.org/10.1080/10789669.2008.10390996

Du, J., & Hoeft, M. (2020). *Use of BIM in Building Operations and Maintenance: An Approach to Identifying Sustainable Value* [Masters Dissertation, KTH Royal Institute of Technology]. KTH DiVA. https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-277036

Elnaklah, R., Ayyad, Y., Alnusairat, S., Al Waer, H., & AlShboul, A. (2023). A Comparison of Students' Thermal Comfort and Perceived Learning Performance between Two Types of University Halls: Architecture Design Studios and Ordinary Lecture Rooms during the Heating Season. *Sustainability*, *15*(2), Article 1142. https://doi.org/10.3390/su15021142

Geng, Y., Ji, W., Lin, B., & Zhu, Y. (2017). The impact of thermal environment on occupant IEQ perception and productivity. *Building and Environment, 121*, 158-167. https://doi.org/10.1016/j.buildenv.2017.05.022

Greene, R., Eftekhari, M., Clements–Croome, D., & Georgiou, G. (2012). *Measurements of CO2 levels in a classroom and its effect on the performance of the students*. CIBSE ASHRAE Technical Symposium, Imperial College, London, UK. Loughborough Institutional Repository. https://hdl.handle.net/2134/11458

Jiang, J., Wang, D., Liu, Y., Xu, Y., & Liu, J. (2018). A study on pupils' learning performance and thermal comfort of primary schools in China. *Building and Environment, 134*, 102-113. https://doi.org/10.1016/j.buildenv.2018.02.036

Kong Z, Jakubiec JA. (2021). Instantaneous lighting quality within higher educational classrooms in Singapore. *Frontiers of Architectural Research*, *10*, 787-802. https://doi.org/10.1016/j.foar.2021.05.001

Korsavi, S. S., Montazami, A., & Mumovic, D. (2020). Indoor air quality (IAQ) in naturally-ventilated primary schools in the UK: Occupant-related factors. *Building and Environment, 180*, 106992. https://doi.org/10.1016/j.buildenv.2020.106992

Hoang, G., Vu, D., Le, N. & Nguyen, T. (2020). *Benefits and challenges of BIM implementation for facility management in operation and maintenance face of buildings in Vietnam* [Conference paper]. IOP Conference Series Material Science and Engineering, Volume 869, Smart City. https://doi.org/10.1088/1757-899X/869/2/022032

Satish, U., Mendell, M. J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S., & Fisk, W. J. (2012). Is CO2 an indoor pollutant? Direct effects of low-to-moderate CO2 concentrations on human decision-making performance. *Environmental health perspectives*, *120*(12), 1671–1677. https://doi.org/10.1289/ehp.1104789

Seppänen, O. A., Fisk, W. J., & Mendell, M. J. (1999). Association of ventilation rates and CO2 concentrations with health and other responses in commercial and institutional buildings. *Indoor air*, *9*(4), 226–252. https://doi.org/10.1111/j.1600-0668.1999.00003.x

Toyinbo, O. (2019). Chapter 4 - indoor environmental quality. In V. W. Y. Tam, & K. N. Le (Eds.), *Sustainable construction technologies* (pp. 107-122). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-811749-1.00003-1

Turunen, M., Toyinbo, O., Putus, T., Nevalainen, A., Shaughnessy, R. & Haverinen-Shaughnessy, U. (2014). Indoor environmental quality in school buildings, and the health and wellbeing of students. *International journal of hygiene and environmental health, 217*(7), 733-739. https://doi.org/10.1016/j.ijheh.2014.03.002

Weerainghe, A., Rasheed, E. & Rotimi, J. (2020). *Occupant Energy Behaviours - A Review of Indoor Environmental Quality (IEQ) and Influential factors* [Conference paper]. The 54th International Conference of the Architectural Science Association (ANZAScA), AUT, Aukland. https://anzasca.net/wp-content/uploads/2021/03/83-Occupant-Energy-Behaviours-%E2%80%93-A-Review-of-Indoor-Environmental-Quality-IEQ-and-Influential-factors.pdf

Wong, L. T., Mui, K. W. & Hui, P. S. (2008). A multivariate-logistic model for acceptance of indoor environmental quality in offices. *Building and Environment*, *43*(1), 1–6. https://doi.org/10.1016/j.buildenv.2007.01.001