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Improving BIM-BEM Interoperability for Sustainable Energy Practices in Malaysia's Built Environment: A Mixed Method Analysis

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ABSTRACT

This study focuses on improving the interoperability of Building Information Modelling (BIM) and Building Energy Modelling (BEM) in Malaysia's built environment, driven by the increasing adoption of BIM under high energy consumption conditions. Recognising the challenges related to data flow in BIM-BEM interoperability, the study aimed to identify critical energy-related properties for accurate energy performance analysis, assess interoperability issues between BIM and BEM models, and propose effective strategies. Through a mixed-methods approach combining quantitative data from questionnaire surveys with qualitative insights from semi-structured interviews, the findings highlighted the importance of energy-related properties in energy performance analysis, as well as interoperability issues such as data loss, limited data feedback loops and inaccuracies in data transition that affect the analysis results. Practical strategies recommended include middleware corrective tools, visual programming, and semantic enrichment to enhance data exchange and accuracy in energy analysis. The study was confirmed by high Cronbach's alpha values ranging from 0.822 to 0.874 in reliability analysis, which ensures the credibility of the results. Ultimately, this study contributes theoretical advancements and practical guidance for industry stakeholders to promote sustainable construction practices, support the National Energy Efficiency Plan, align with the path toward Industrial Revolution 4.0, adopt global technologies, and enhance energy-saving and sustainable practices.

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1. Introduction

The built environment is a major contributor to global energy consumption and CO_2 emissions. It has been predicted that approximately 37% of worldwide CO_2 emissions related to energy will come from the built environment (Fonseca Arenas and Shafique, 2023). A trend is also seen in Malaysia, where rapid economic and technological growth, particularly in the Architecture, Engineering, Construction, and Operations (AECO) sector (Hmidah *et al*., 2023). This has resulted in significant environmental impacts, including pollution, global warming, ozone depletion, and climate change.

To mitigate these effects and in response to growing concerns about sustainability, Malaysia has implemented sustainability measures, including the use of Building Information Modelling (BIM) (Izzah Aida Badrul *et al*., 2022). With the rise of energy-efficient approaches and the popularity of green building certification, BIM has become an essential tool for assessing building energy performance and sustainability levels, aligning with the Malaysian Government's sustainability and green policy as per the 2009 National Green Technology Policy (Izzah Aida Badrul *et al*., 2022). However, traditional methods like Leadership in Energy and Environmental Design (LEED) a green building rating system, do not offer the level of details (Alhammad *et al*., 2024). Furthermore, the majority of BIM models lack multi-dimensional capabilities, which limits their ability to accurately simulate performance at detailed levels, which results in a mismatch with the data provided by LEED ratings. Building Energy Modelling (BEM), a subset of BIM, is an outstanding computational resource (Ruiji Sun and Xu, 2020). The BEM methodology supported by specific software tools will simplify the process of handling and visualising the inputs for energy prediction and analysis. The ideal situation is one where BIM-BEM interoperability imports energy-related properties of a building from the BIM model to the BEM model. interoperability between BIM and BEM could be a progressive step in lowering costs and reducing time spent on model re-creation (Bastos Porsani *et al*., 2021).

Despite several studies conducted in various areas related to BIM-BEM for energy analysis, there is a lack of quality research focusing on these areas. Previous studies have encountered data exchange issues between BIM-BEM interoperability (Gonzalez *et al*., 2021; Kamel and Memari, 2019), such as data and information loss (Durdyev *et al*., 2021), and inaccuracies of the data transition in the analysis result (Ciccozzi *et al*., 2023). Besides, Elnabawi (2020) also mentioned that data inaccessibility led to the integrity issue of the transferred data information. Other issues such as deficiency in bidirectional interoperability (Massafra and Gulli, 2023), outdated information in the model (Kamel and Memari, 2019), and data redundancy (Ruiji Sun and Xu, 2020) affect the energy performance of a building and hinder enhancement of the energy consumption prediction and efficiency in the built environment (Di Biccari *et al*., 2022).

In Malaysia, the adoption and awareness rate of BIM has significantly improved over the past three years (Izzah Aida Badrul *et al*., 2022), particularly in the energy performance of buildings in the built environment. Yet, applying BIM-BEM for energy analysis and optimisation for net-zero carbon buildings in Malaysia, especially BEM technology, or even sustainability, are still new research topics or concepts in the Malaysian built environment (Sajjad *et al*., 2024). Nevertheless, BEM, with interoperability to BIM, can greatly assist in achieving the government's policy and goals in reducing carbon emissions and targeting a more environmentally sustainable built environment. While there have been studies related to this issue, there is still potential for enhancing building energy performance analysis (Durdyev *et al*., 2021). Ciccozzi (2023) emphasised that researchers are indeed interested in this BIM-BEM interoperability, aiming at the development of new strategies for improving their interoperability between BIM and BEM. Therefore, this study aims to propose strategies for improving the BIM-BEM interoperability to enhance the building energy performance analysis in the Malaysian built environment. The objectives of this study are:

1) identify the energy-related properties for building energy performance analysis in the built environment.
2) analyse the BIM-BEM interoperability issues that hinder the building energy performance analysis.
3) propose the strategies that can be implemented in the Malaysian built environment to improve the BIM-BEM interoperability.

1.1 Theoretical Background

1.1.1 BIM-BEM Interoperability

Since the studies on building energy performance are becoming more popular, it is useful to interoperate and manage the data from BIM and BEM models as it is advantageous to the different stages of a building's lifecycle at different levels of adoption (Delgado *et al*., 2023). This is due to BIM only allows for preliminary assessment but not in-depth analysis for building energy design. Hence, interoperating with BEM software can specifically develop more in energy performance analysis.

During the building energy performance analysis, the raw data including the geometrical, material, and energy usage information will be inputted into the BIM tool for developing the model. Following the BIM model data is then transferred to the BEM tools in a readable format such as IFC and gbXML formats (Costa *et al*., 2024). However, some additional raw data for the energy model are required in the BEM model by manually inputting into the software if required. In the next stage, the visualisation and output results will be generated by the BEM model for the energy performance analysis. This effectively enhances the design choices of the energy performance analysis to increase productivity in the built environment (Ciccozzi *et al*., 2023). Furthermore, BIM-BEM interoperability allows various alternative designs in the analysis which saves time and money (Alhammad *et al*., 2024). Figure 1 shows the example of the models for BIM and BEM after the interoperability between them.

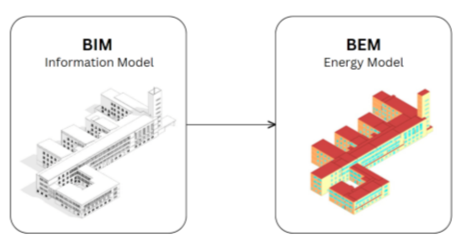

Figure 1. Example of the BIM and BEM models (Farzaneh, 2019)

1.1.2 Energy-Related Properties

Energy is a fundamental requirement for all sectors to operate efficiently and successfully (Rajeanderan, 2022). A lack of information about the energy-related properties did not permit an accurate specification hence affecting the outcome analysis result (Gonzalez *et al.*, 2021). Hence, during the energy computation, the quality of the results depends heavily on the input data (Giama *et al.*, 2022). Before BIM data are transferred to BEM analysis software for energy analysis, the required properties must be entered into the model. A review of the relevant properties is presented in Table 1.

Table 1. A literature review of energy-related properties

Energy-related properties	Description	References
Building location and orientation	A significant factor in improving overall performance and energy efficiency.	(Yaik-Wah Lim *et al.*, 2021)
	The orientation of a building's angle has varied implications for energy consumption, as it affects natural ventilation and solar radiation.	(Watfa *et al.*, 2021)
Building geometry	The shape of a building significantly influences its energy performance.	(Kistelegdi *et al.*, 2022)
	An optimised building geometry design could potentially reduce the annual energy demand.	(Ciardiello *et al.*, 2020)
Weather and climate conditions	Energy consumption data is considered during the decision-making process to upgrade the building's energy performance due to the different weather data.	(Amin and Mourshed, 2024)
Heating, Ventilation, and Air Conditioning (HVAC) system	Essential input for the energy performance model in the analysis.	(Delgado *et al.*, 2023)
	A personalised HVAC system can reduce energy consumption by minimising thermal discomfort in multi-zone buildings.	(Kwonsik Song, 2022)
Building construction materials	One of the crucial energy-related properties required for the energy performance analysis model.	(Delgado *et al.*, 2023)
	Different construction materials such as cement, metals, and concrete have respective amounts of energy consuming consumption that will bring negative impacts on the environment.	(Alvi *et al.*, 2023)
Lighting control system	Lighting technologies such as daylighting, electric lighting, and blind control were found to effectively reduce energy usage.	(Papinutto *et al.*, 2022)
Building operation	Building operation data were required to proceed with the energy analysis.	(Gunasegaran *et al.*, 2022)
Building shading	Shading parameters included shading angle, shading depth, and the number of shading slats.	(Nazari *et al.*, 2023)
	The shading design system demonstrated in the previous study showed a significant reduction in total energy demand for a building.	(Elnabawi, 2020)
Window specifications	Window specifications, including the type of glazing and size, influence a building's energy efficiency by reducing heat gains, which in turn leads to lower energy consumption.	(Watfa *et al.*, 2021)
	A building can achieve energy efficiency by reducing energy usage with a lower window-to-wall ratio.	(Chen *et al.*, 2023)

1.1.3 BIM-BEM Interoperability Issues

Despite advancements, issues with BIM-BEM interoperability continue to hinder its widespread application in the built environment (Di Biccari *et al.*, 2022). Therefore, the lack of seamless interoperability between BIM and BEM software needs to be examined and resolved by identifying and addressing the encountered issues (Delgado *et al.*, 2023).

Several researchers have identified BIM-BEM interoperability issues that affect the building energy performance precision. Kamel and Memari (2019) found data and information loss, along with the inaccessibility of BIM data for BEM models. Ciccozzi *et al.* (2023) also mentioned inaccuracies in energy simulation data affecting analysis results. Furthermore, Elnabawi (2020) highlighted data inconsistency causing unreadable results in the energy model, and noted that the limited data feedback loop does not allow changes in BEM reflect to BIM. Sanhudo *et al.* (2018) discussed outdated information hindering energy performance analysis for retrofitting solutions, while Ciccozzi *et al.* (2023) identified data redundancy issues during data transfer from BIM to BEM. Table 2 presents a benchmarking of interoperability issues relative to each energy-related property. The only consistent issue across all categories is the limited data feedback loop.

Table 2. A literature review of BIM-BEM interoperability issues for energy-related properties

Interoperability Issues	Energy properties									References
	BLO	BG	WCC	HVAC	BCM	LCS	BO	BS	WS	
Losing data and information	✓	✓		✓		✓			✓	(Asdrubali *et al.*, 2021; Kamel and Memari, 2019; Maile, 2019)
Inaccurate data transition		✓		✓	✓					(Elnabawi, 2020; Maile, 2019; Spiridigliozzi *et al.*, 2019)
Data redundancy		✓		✓		✓			✓	(Ciccozzi *et al.*, 2023; Elnabawi, 2020; Kamel and Memari, 2019)
Data inaccessibility				✓	✓	✓			✓	(Asdrubali *et al.*, 2021; Elnabawi, 2020; Spiridigliozzi *et al.*, 2019)
Outdated information			✓							(Kamel and Memari, 2019)
Inconsistent data representation			✓							(Elnabawi, 2020)
Limited data feedback loop	Data exchange between these two software systems can occur only in one direction, from BIM to BEM, with no capability for data to flow back from BEM to BIM.									(Li *et al.*, 2020)

Note: BLO: Building location and orientation; BG: Building geometry; WCC: Weather and climate conditions; HVAC: Heating, Ventilation, and Air Conditioning (HVAC) system; BCM: Building construction materials; LCC: Lighting control system; BO: Building operation; BS: Building shading; WS: Window specifications

1.1.4 Strategies to Improve BIM-BEM Interoperability

Enhancing the interoperability between BIM and BEM is essential for effective and precise energy analysis (Kamel and Memari, 2019). According to previous studies, seven strategies can enhance this improvement, which includes the application of middleware corrective tools, visual programming, Model View Definition (MVD), semantic enrichment, experimental design, standardised exchange format, and real-time connection. These approaches were observed in terms of complexity, the time needed for data transfer, use of proprietary or open-source software, capacity to minimise data loss, and the level of detail in the energy outcomes. Table 3 provides a comprehensive review of the BIM-BEM interoperability strategies.

Table 3. A literature review of BIM-BEM interoperability strategies

Strategies	Description
Middleware corrective tools	Carvalho *et al.* (2021), Ramaji *et al.* (2020), Yang *et al.* (2022) and Bracht *et al.* (2021) proposed middleware tools such as IFC Builder, BIMserver serializer, and gbXML to address errors during data transition, thereby improving BIM-BEM interoperability for energy performance analysis.
Visual programming	Several studies highlight Dynamo and Grasshopper as commonly used visual programming tools for building energy analysis (Yaik-Wah Lim *et al.*, 2021). Dynamo is widely preferred for energy analysis development, while Grasshopper integrates seamlessly with Rhino3D to optimize building energy operations (Sušnik *et al.*, 2021; Yaik-Wah Lim *et al.*, 2021).
Model View Definition (MVD)	Model View Definition (MVD) is a subset of the IFC file format designed for the exchange of data required for energy and structural analysis (Li *et al.*, 2020). It identifies relevant IFC datasets (e.g., IfcPropertySet, IfcProxy, IfcRelationship) to extend the information package within BIM, ensuring comprehensive energy model integration (Ramaji *et al.*, 2020).
Semantic enrichment	Semantic enrichment adds extended information to the BIM model to offer a meaningful representation that eases the application in energy modelling (Bloch and Tanya, 2022). More advanced semantic levels improve data flow from BIM to BEM as it provides adequate input for software that requires different information standards (Panteli *et al.*, 2020; Ramaji *et al.*, 2020).
Experimental design	Experimental design allows for the exploration of different design options to identify effective solutions for reducing data loss in projects (Gonzalez *et al.*, 2021). The experimental design begins by identifying the factors that significantly influence the experiments, then followed by optimising settings and conditions at different levels for energy performance analysis (Delgado *et al.*, 2023).

Strategies	Description
Standardised exchange formats	Standardising exchange formats is a key strategy for improving data flow and interoperability between BIM and BEM tools (Ciccozzi *et al.*, 2023). The commonly used formats for the models are IFC and gbXML.
Real-time connection	By enabling the real-time connection in the BIM model for up-to-date energy models, it can help simplify the data management in the energy model (Bastos Porsani *et al.*, 2021). According to Nagy and Ashraf (2021), the real-time connection was installed using sensors positioned within the building's interior to collect data from the built environment to reduce potential errors thereby enabling energy efficiency and thermal performance monitoring.

2. Methodology

2.1 *Description of Study Area*

This study was carried out by mixed method which consisted of 4 key phases: quantitative and qualitative approach for analysis. The flowchart for the methodology carried out for this study is shown in Figure 2.

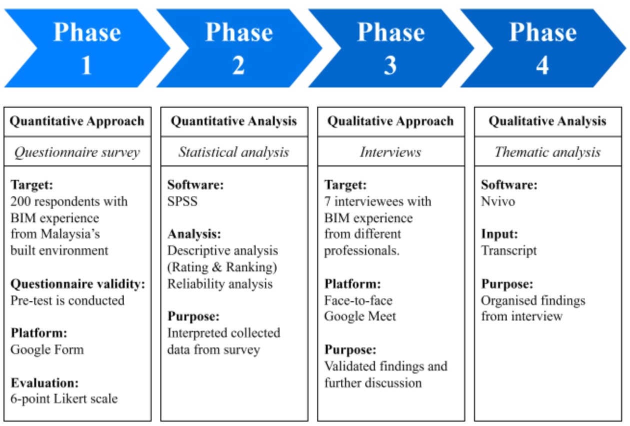

Figure 2. Research methodology flowchart in this study

2.2 *Quantitative Approach*

During phase 1, a quantitative approach was taken, starting with a structured questionnaire development using Google Forms, which was divided into four sections. The respondents will indicate their level of agreement on a 6-point Likert scale (Strongly Disagree, Disagree, Slightly Disagree, Slightly Agree, Agree, and Strongly Agree). The selection of a six-point Likert scale is to avoid a neutral midpoint, thus encouraging respondents to make a positive or negative response (Kusmaryono *et al.*, 2022). Section A aimed to collect demographic details, including the respondents' positions, roles, and their experience with BIM in energy analysis. Section B assessed the importance of energy-related properties in energy analysis while Section C collected the agreement of respondents on key interoperability issues affecting the energy analysis. Section D measured agreement levels with the strategies for improving BIM-BEM interoperability in the built environment of Malaysia.

A pilot test was conducted with 10 respondents from different BIM professional backgrounds, including educators, academics, and engineers to validate the designed questionnaire. To determine the sample size for the questionnaire, the Cochran formula (Memon *et al.*, 2020) was applied, as shown in (1):

$$n = \frac{N \cdot Z^2 \cdot p(1-p)}{(N-1)E^2 + Z^2 \cdot p(1-p)} \qquad (1)$$

where n is the required sample size, N is the population size, Z is the z-score corresponding to the desired confidence level, p is the estimated proportion of the population and E is the margin of error.

Based on the Construction Industry Development Board's (CIDB) annual report published in 2021 (CIDB, 2021), the population size was set at 418, with a focus on individuals who have received training in BIM. The assumed z-score was 95%, which is 1.96. The population proportion was estimated to be 50%. The p value was 0.5, which indicates that the maximum sample size required for a cautious estimate is required. The error margin was 5%. Thus, a sample size of 200 was determined to be used in the questionnaire survey using equation (1). The target respondents included engineers, BIM modellers, architects, contractors, project managers, and others with experience implementing BIM for building energy performance analysis.

2.3 *Quantitative Analysis*

In phase 2, data collected from the questionnaire survey were analysed using the Statistical Package for Social Sciences (SPSS). This phase included descriptive and reliability analyses. Descriptive analysis was performed on all the variables. Variables in Section B were analysed based on scale ratings to gauge respondent perspective, while Sections C and D were evaluated by ranking variables according to mean scores and standard deviations. The rankings were based on the highest mean values, followed by standard deviations. Reliability was assessed using Cronbach's alpha for these sections, ensuring alpha values exceeded 0.7 to ensure reliability (Surucu and Maslakci, 2020).

2.4 *Qualitative Approach*

Phase 3 comprised semi-structured interviews with professionals from various fields including BIM modeller and engineer, project manager, green building consultant, contractor, quantity surveyor and BIM lecturer. Seven interviewees who participated via in-person and Google Meet sessions were accepted under the successful implementation of the DEJA (Define, Explain, Justify, Apply), thereby ensuring the research findings' acceptability and validity (Mthuli *et al.*, 2021).

2.5 Qualitative Analysis

In phase 4, interviews were recorded and transcribed using NVivo software. NVivo was used to organise interview information and uncover patterns from the collected data through thematic analysis for each objective.

3. Result and Discussion

This study achieved a response rate of 28.5%, with 57 responses received from the initial target of 200 respondents. According to Wu *et al*. (2022), online surveys tend to yield lower response rates compared to in-person or phone surveys. Additionally, previous research suggested that surveys with smaller sample sizes can still produce reliable estimates with response rates ranging from 20% to 25%. Therefore, the 28.5% response rate observed in our study is deemed acceptable.

3.1 Reliability Analysis

The reliability of data from questionnaire sections B, C, and D was assessed using Cronbach's alpha, a measure where values above 0.7 are considered reliable. Section B on energy-related properties for BIM-BEM interoperability scored 0.822; Section C, covering BIM-BEM interoperability issues, achieved a Cronbach's alpha of 0.874, and section D attained 0.824, demonstrating highly reliable data for this study. Table 4 shows the reliability test for the sections.

Table 4. Reliability test's result

Section	Frequency	Cronbach's Alpha
B	9	0.822
C	7	0.874
D	7	0.824

3.2 Demographic Profile

For the quantitative approach, a questionnaire was distributed to 57 respondents within Malaysia's built environment sector. A total of 53% of respondents with engineering backgrounds responded to the survey. Out of 57 respondents, 61% have used BIM for energy analysis projects. Even though 39% of respondents lack experience, their contributions are still valuable. They may participate in future energy analysis projects, and since BEM needs to interoperate with the BIM technology, they are familiar with, they are also qualified to express their views by responding to the questions and information provided in the survey form. Figures 3 and 4 show the demographic profile of the respondents in terms of position & role and their experience in using BIM for energy analysis.

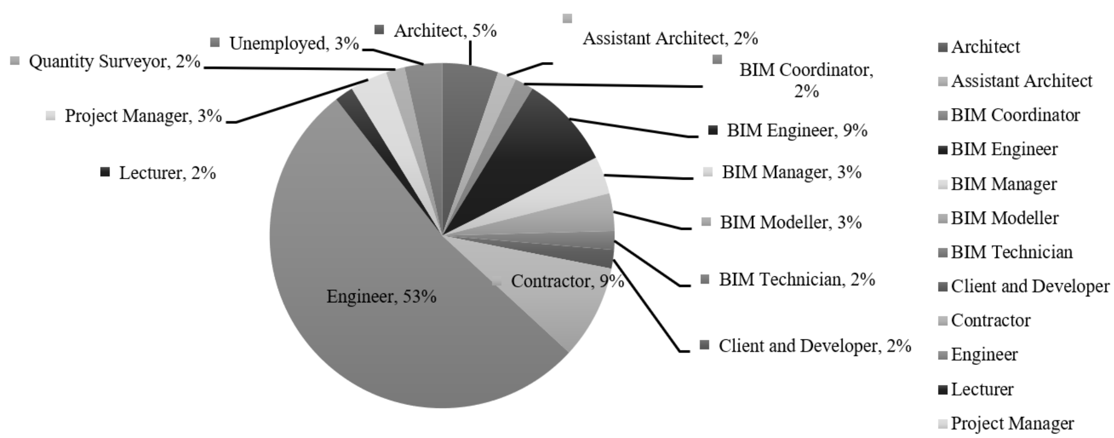

Figure 3. Position and role of respondents

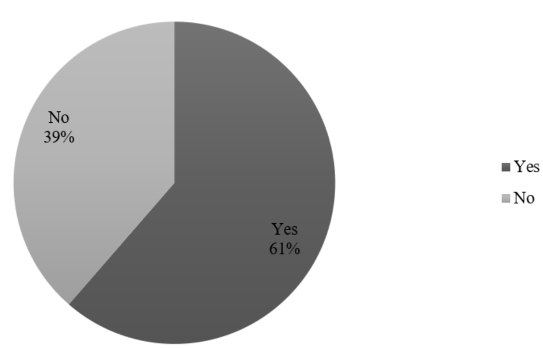

Figure 4. Experience of respondents in using BIM for energy analysis

3.3 Energy-Related Properties

Table 5 presents the percentage of agreement on energy-related properties. "*Building location and orientation*" received the highest strongly agreement rating from 42.1% of respondents, while "*Building geometry*" achieved a slight agreement of 29.8%. "Weather and climate conditions" and "*Lighting control*" were largely rated in agreement at 26.3%, with "*Lighting control*" also achieving 26.3% in strong agreement. 28.1% of respondents expressed slight agreement with building shading design, building operation and HVAC system. Interestingly, the HVAC System also garnered the highest agreement rating. Window specifications stood out with the highest "Strongly Disagree" rating at 33.3%.

As referenced in the literature review, Chen *et al*. (2023) stated that a building's window specification, such as the Window Wall Ratio (WWR), influences energy efficiency. This was proved by Watfa *et al*. (2021), which demonstrated that reducing the WWR can decrease energy consumption for a building.

Table 5. Percentage of agreement on energy-related properties

Energy-Related Properties	Percentage (%)					
	Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
Building location and orientation	10.5	3.5	3.5	26.3	14.0	42.1*
HVAC system	1.8	5.3	14.0	28.1*	28.1*	22.8
Lighting control	3.5	8.8	19.3	15.8	26.3*	26.3
Building construction materials	8.8	5.3	12.3	38.6*	22.8	12.3
Weather and climate conditions	15.8	8.8	17.5	22.8	26.3*	8.8
Building geometry	17.5	12.3	14.0	29.8*	22.8	3.5
Building operation	17.5	15.8	12.3	28.1*	19.3	7.0
Building shading design	19.3	17.5	15.8	28.1*	14.0	5.3
Window specifications	33.3*	19.3	8.8	17.5	14.0	7.0

* Optimum percentage

3.4 BIM-BEM Interoperability Issues

Table 6 presents the most significant BIM-BEM interoperability issues, with "Losing data and information" receiving the highest mean score of 4.53 and the highest standard deviation of 1.691. Following closely was "Limited data feedback loop" with a mean score of 3.95 and a standard deviation of 1.420, ranking second. "Inaccurate data transition" ranked third with a mean score of 3.65 and a standard deviation of 1.533. In contrast, "Outdated Information" received the lowest mean score of 2.75 and ranked last.

These top three rankings stand in contrast to less critical issues, such as outdated information, which can be readily addressed by simply updating to the most recent software version. Consequently, the findings presented here indicate that these problems could hinder users from accurately analysing energy performance and its widespread implementation in relevant sectors, especially in the built environment (Di Biccari *et al*., 2022). It is necessary to propose strategies to reduce errors occurring during the interoperability of BIM-BEM, as emphasised by Delgado *et al*. (2023). Therefore, to ensure the quality of energy performance analysis, it is crucial to pay attention to data and information loss, limitations in the data feedback loop, and inaccuracies in data transition.

Table 6. Ranking of BIM-BEM interoperability issues

Interoperability Issues	Mean	Std. Deviation	Rank
Losing data and information	4.53	1.691	1
Limited data feedback loop	3.95	1.420	2
Inaccurate data transition	3.65	1.553	3
Inconsistent data representation	3.42	1.523	4
Data inaccessibility	3.30	1.625	5
Data redundancy	3.21	1.532	6
Outdated information	2.75	1.683	7

3.5 BIM-BEM Interoperability Strategies

Table 7 summarises the findings. "Middleware corrective tool" scored the highest with a mean of 4.67 and a standard deviation of 1.551, followed by "Visual programming" with a mean score of 4.16 and a standard deviation of 1.251, and "Semantic enrichment" with a mean value of 3.75 and standard deviation of 1.430. The experimental design received the lowest mean score of 2.79, indicating a significant difference compared to the other strategies that were ranked higher.

Table 7. Ranking of BIM-BEM interoperability issues

Interoperability Strategies	Mean	Std. Deviation	Rank
Middleware corrective tool	4.67	1.551	1
Visual programming	4.16	1.251	2
Semantic enrichment	3.75	1.430	3
Standardised exchange formats	3.42	1.523	4
Real-time connection	3.32	1.605	5
Model view definition	3.19	1.540	6
Experimental design	2.79	1.666	7

3.6 Semi-structured Interviews

For the qualitative approach, interviews were conducted with 7 different interviewees who came across diverse professional backgrounds as shown in Table 8. The interview findings were validated through insights from different positions and roles, which are BIM modeller, architect, contractor, BIM lecturer, project manager, BIM engineer, green building consultant, and quantity surveyor involved in various stages of a building's lifecycle. These perspectives effectively reflect the current state of BIM and energy analysis in Malaysia, drawing from the interviewees' experience in using BIM for projects within the built environment.

Table 8. Background of interviewees

Interviewees	Position / Role
R1	BIM modeller and architect
R2	Contractor (Civil Engineering)
R3	BIM lecturer and architect
R4	Project manager (Civil Engineering)
R5	BIM and civil engineer
R6	Green building consultant
R7	Quantity surveyor and BIM lecturer

3.7 Thematic Analysis

From the thematic analysis in NVivo software, the findings from the interviews were summarised in Table 9. The insights provided by the interviewees were categorised into different nodes according to the themes and subthemes.

Table 9. Coding for thematic analysis

Theme	Subtheme	Codes
Energy-related properties	Window specifications	• Disagree on its highest rate on "*Strongly Disagree*" • Different perspectives from different professionals • Replace with the direct term "*Wall-Window Ratio*"
BIM-BEM interoperability issues	Losing data and information	• Frequently faced with missing data • Manually input the data
	Limited data feedback loop	• Insufficient data feedback for the predictive energy model
	Inaccurate data transition	• Time-consuming to repair data • Affect the result precision
BIM-BEM interoperability strategies	Middleware corrective tools	• Connection between BIM-BEM models • Correction on missing data and error
	Visual programming	• Customise data workflow from one to another model • Leverage existing programming expertise • Needs for specific technical skills
	Semantic enrichment	• Conceptualise the database for each energy-related property • Useful for complex characteristics buildings

3.7.1 Theme 1: Energy-Related Properties

When the interviewees were questioned about the Likert Scale ratings for each energy-related property, the majority commented in agreement. A few interviewees, namely R1, R2 and R3, shared the viewpoint that the building orientation and location of a building was crucial input for performance analysis, as it helped in reducing the heat energy from a building, by considering the direction and position of the sun.

When R4 and R5 were asked about the construction materials, they noted that different materials have different levels of energy consumption. Therefore, the energy consumed by the materials used in buildings throughout their life cycle is an important parameter in determining the energy efficiency of the building.

R4 also mentioned that building operations needed to be included in the model as they directly affect operational energy and costs. For the building geometry and weather & climate conditions, R3 commented that properties such as building geometry and weather & climate conditions needed to be inputted to simulate and analyse optimal energy performance, particularly during the initial design stage. HVAC system and lighting control were brought up, all interviewees agreed that these properties were significantly important in energy analysis.

Window specifications were a point of disagreement, receiving the most "*Strongly disagree*" scores. R6 argued that it was important as it greatly affected annual energy consumption, particularly for cooling and lighting. R3 and R7 pointed out that the ratings were tied to demographic analysis. Given that 51% of the respondents come from engineering backgrounds, R6 suggested that they would likely prioritise the structural design and technical considerations which have a more significant impact, by comparing it to other selections. R2, R4, R5 and R6 with engineering backgrounds, and expertise in this area have suggested that the term "*Wall-Window Ratio*" should be used in place of window specification, as it more precisely defines its importance in the design process of a model, and comprehensive for the understanding to the respondents.

3.7.2 Theme 2: BIM-BEM Interoperability Issues

A common viewpoint among the interviewees was their high level of agreement with the ranking. R2 commented on the issue of data loss and information, stating that 80% of the time was spent rectifying missing data manually in two different systems when using BIM.

Furthermore, R1, R3 and R5 agreed with the ranking that a limited feedback data loop hinders the simulation for energy analysis from the BEM model to the BIM model as the data is insufficient for the predictive energy model. Other interviewees, R2, R4, R5 and R7 also emphasised that the transfer of inaccurate data is a significant issue, recognised in the unreadable complex characteristics of the building, which has caused the lack of precision in the data results. Moreover, R1 mentioned his experience with inaccurate data transition, particularly with the output of location and sunlight direction. R3 emphasised that accuracy is important in informative software to ensure precise outputs.

In contrast, the lowest-ranked issue was outdated information. The interviewees, R1 and R2 shared the same view that this issue was the least critical as it could be resolved by updating the software to the latest version.

The insights collected from interviewees aligned with the findings of the questionnaire survey. These results consistently highlighted that data loss, limited data feedback loop, and inaccuracies in data transition show the significant challenges to energy analysis in the built environment, especially involving the BIM model. The agreement among interviewees suggests that addressing these critical issues is not straightforward, often requiring external assistance for resolution. These results support the findings of a great deal of the previous work by Massafra and Gulli (2023), Elnabawi (2020), Kamel and Memari (2019).

3.7.3 Theme 3: BIM-BEM Interoperability Strategies

Most interviewees expressed that middleware corrective tools are appropriate for improving BIM-BEM interoperability within the Malaysian built environment. R1 said that these tools are already in extensive use in other countries, suggesting that local BIM experts involved in energy analysis projects could adopt these overseas technologies. Furthermore, R3 highlighted the importance of "*interoperability*", or in other words, a bridge for linking data between two software systems. R2 provided further insight, explaining that different software has different file formats, hence middleware corrective tools serve as an extension between BIM-BEM which helps in data conversion to ensure readability.

R1, R2, and R6 believed that this strategy is applicable in Malaysia, given the widespread learning and application of programming languages across various industries, including the built environment. However, R3 pointed out that since visual programming requires professionals or experts in programming to adjust the interoperability flow between BIM-BEM, prioritising investment in talent and technology training development may be time-consuming.

There were some opinions on the third-ranked strategy, "*semantic enrichment*". Both R5 and R7 acknowledged that increasing the repository of energy-related characteristics for complex buildings would streamline the energy evaluation process within the software, as it aims to expand and conceptualise energy property databases to reflect a range of building characteristics, thereby addressing issues of data accuracy.

4. Conclusion

This study has successfully achieved the three objectives. Firstly, the study identified nine critical energy-related properties which are building location and orientation, HVAC system, lighting control system, building construction materials, weather and climate conditions, building geometry, building operation, building shading design, and window specifications. They are essential for building energy performance analysis throughout a building's lifecycle from design through construction, operation, and even retrofitting to ensure that energy efficiency and conservation remain a priority at every stage. This holistic approach helps in achieving sustainable building practices and reducing overall environmental impact, despite varying perspectives from different professional backgrounds on specific properties.

Secondly, the investigation into BIM-BEM interoperability revealed three major issues which are losing data and information, limited data feedback loop, and inaccurate data transition, which were identified as important barriers requiring attention to ensure precise and reliable analysis outcomes. Their presences directly impact the effectiveness, reliability, and practicality of any system or process, including in the context of building energy performance analysis using BIM-BEM interoperability.

Thirdly, the study proposed seven strategic involvements personalised for the Malaysian built environment to enhance BIM-BEM interoperability, prioritising approaches like middleware corrective tools, semantic enrichment, and visual programming to address the identified challenges effectively.

This study has several implications in practical, managerial, and social aspects. From a practical perspective, proficiency in BIM or programming within Malaysia is essential for improving energy analysis by implementing strategies that promote seamless interoperability between BIM and BEM, while also aligning with global trends like the Fourth Industrial Revolution in the construction sector. Since the success of implementation depends on human resources, processes, and technology, Malaysia could leverage its current knowledge to support the National Energy Efficiency Plan and move towards the fourth industrial revolution by adopting effective technologies from worldwide sources to enhance energy savings and sustainable practices. From a managerial perspective, industry leaders and policymakers must invest in digital transformation to equip Malaysian professionals with BIM and programming expertise. From a social perspective, this study provides actionable solutions and foundational principles to enhance BIM-BEM interoperability for professionals involved in sustainable building design and operation service in Malaysia to foster more accurate and insightful energy assessments in Malaysia's built environment.

However, the study acknowledges limitations, including low respondent rates and potential biases due to respondents lacking prior energy analysis experience. Recommendations include further research to validate the proposed strategies, by increasing the sample size of interviewees with more professionals to ensure a more balanced representation. In conclusion, this study significantly improves building energy performance analysis to achieve sustainability, energy conservation and cost-effectiveness in the built environment.

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