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Applying the BIM-LCA Method to Assess Carbon Emissions on University Campuses: A Case Study

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ABSTRACT

Building Information Modelling (BIM), as a preeminent technology aligned with digital transformation trends, is extensively used in the Architecture, Engineering, and Construction (AEC) business, consistently enhancing the representation of intelligent data. BIM has been used for energy assessments of sustainable buildings, particularly in conjunction with Life Cycle Analysis (LCA) to analyse a building's CO_2 emissions throughout its entire life cycle. Universities are using digital technologies to mitigate carbon emissions and adhere to sustainable development objectives; nevertheless, there is a deficiency of data to substantiate the efficacy of these techniques, and technical obstacles persist in their actual implementation. This research seeks to evaluate the viability of BIM-LCA in measuring CO_2 emissions on university campuses. The findings demonstrate that the implementation of BIM-LCA enhances the precision and dependability of carbon emission evaluations, and although practical obstacles exist, faith in its viability persists. Raising awareness of the sustainability benefits of BIM and providing clear guidance is expected to promote the wider adoption of BIM-LCA. This study highlights the need to establish a unified platform and standards to reduce technical glitches.

1. Introduction

Digital collaboration tools have been widely adopted across industries because intelligent data provides more accurate and comprehensive information, thereby improving facility management efficiency. Building Information Modelling (BIM) is a commonly used tool emerging from the digital trend, and its application is widespread across industries, especially in the construction sector due to the complexity of project processes [1,2]. The application of this innovative tool simulates collaboration between different teams, thereby improving profitability, reducing costs, and enhancing customer relationships [3]. Communication is crucial for ensuring smooth daily operations and avoiding rework and errors. BIM provides a unified information exchange platform and presents information in a visual way, thereby changing traditional communication methods and promoting cross-departmental communication [4]. Furthermore, the application of BIM systems has had a

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positive impact on factors such as cost, coordination, and quality [5]. With the rapid development of digital tools and technologies and the pursuit of sustainable development, the demand for BIM in the existing building sector continues to grow, and its application scope will continue to expand, with an even brighter future [6].

To better monitor and control carbon emissions throughout the entire life cycle of buildings, the application of Life Cycle Assessment (LCA) combined with BIM tools is considered an effective way to meet sustainable development requirements. LCA has evolved from a single energy analysis into a commonly used comprehensive environmental impact assessment method [7]. The goal of LCA is to identify environmental factors throughout the building's life cycle and develop reliable improvement strategies. LCA models can reveal the causal relationship between human activities and environmental consequences [8]. In construction projects, companies can use this method to assess environmental conditions and set benchmarks to comply with policy requirements. Combining BIM with life cycle assessment facilitates decision-making in early stages such as design and construction. BIM supports process collaboration among stakeholders and, when combined with environmental impact analysis based on life cycle assessment methods, can collectively improve the effectiveness of sustainability assessments, thereby providing a comprehensive overview of the project from the outset [9].

BIM tools are crucial in the initial stages of design and construction, enabling the simulation of sustainable buildings and the analysis of complex and dynamic processes using appropriate measurement models to achieve low carbon emissions [10]. Supported by visualisation technologies, the application of BIM in green building design allows management teams to assess, analyse, manage, and regulate environmental factors [11]. Mousa *et al.,* [12] further expanded the application of BIM, proposing an integrated approach that uses graphical representations of carbon emission data to assess building performance and issue alerts in the event of a crisis to minimise losses. Through the real-time collection and exchange of information, BIM can effectively support daily operations and promote sustainable development.

Liu *et al.,* [13] identify five primary areas of interest in BIM-related carbon reduction research: life cycle assessment, sustainable building materials, energy efficiency, and environmental strategies. Integration with LCA is notably prevalent in practice among these research directions, particularly in new projects, as it functions as a linking mechanism during the design phase, amalgamating building information gathered by BIM with inventory data across the entire life cycle [14]. Soust-Verdaguer *et al.,* [15] delineate the integration of BIM and LCA into three tiers: the initial tier employs BIM solely as a tool; the subsequent tier amalgamates environmental data with BIM software; and the ultimate tier leverages automated processes derived from the preceding two tiers.

Recent research has assessed the advantages of integrating BIM with LCA. A case study of an office block in Iran demonstrated a 24.92% reduction in carbon emissions with the use of a BIM-based lifecycle assessment model [16]. The implementation of the BIM-LCA framework in the Laksi Interchange project on Highway 304 achieved a 67.51% decrease in Global Warming Potential (GWP) relative to prior estimates, illustrating that real-time environmental impact assessments can significantly mitigate carbon emissions [17]. Jiang [18] demonstrated that using BIM technology in life cycle cost assessment can improve cost and energy efficiency throughout the entire process from design to maintenance. Zhao *et al.,* [19] evaluated the effectiveness of this integrated tool through a case study of an emergency building. Their findings indicated that HVAC systems are a significant source of carbon emissions, while steel and concrete are the main materials generating carbon waste [20]. Through prior simulation and assessment, companies can make more informed decisions, thereby reducing risks and achieving predetermined goals. Cheng *et al.,* [21] applied the BIM-LCA method in a museum project to enhance the functionality of a large public building. Their results showed that BIM can provide sufficient technical information to meet LCA requirements and propose feasible greenhouse gas emission reduction strategies.

Universities serve as a crucial societal benchmark for low-carbon practices and need to spearhead the implementation of successful measures. The distinctive campus setting and rising population density result in a variety of activities on university campuses, complicating energy consumption and carbon emissions, since the underlying reasons may differ based on scale [22]. Achieving low carbon emissions at universities depends on a series of measures to ensure energy sustainability. Using consensus mechanisms to define emission limits for institutions can help strengthen cooperation and thus improve the global environment [23]. Riddell *et al.,* [24] using Rowan University as an example, demonstrated that signing the American University Presidents' Climate Pledge (ACUPCC) can promote the achievement of long-term net-zero emissions goals in a cost-effective and pragmatic way. Emeakaroha *et al.,* [25] combined human psychology with technological feedback to develop a system that provides real-time energy feedback, effectively identifying challenges in various energy use behaviours and successfully reducing energy consumption, thereby improving the sustainability of university campuses.

While modern tools and related intelligent software offer technological solutions for effectively addressing the unique challenges faced by university campuses, empirical case studies are still lacking to fully elucidate the effectiveness of these applications. Furthermore, Veerendra *et al.,* [26] in their university study, pointed out that digital models may fail to accurately reflect real-world factors, thus affecting the accuracy of assessments. Human behaviour is inherently unpredictable; therefore, for more accurate assessments, the actual experiences of occupants must be considered. Digital software can simulate the energy performance of a campus, thereby identifying ways to optimise energy conservation. BIM software can discern optimal solutions and provide viable options for real applications [27]. BIM-based architectural design may use the distinct attributes of various campus structures to improve environmental performance and attain reduced carbon emissions [28]. Life cycle assessment can serve as an auxiliary tool for comprehensive analysis and prediction, thereby strengthening building management at each stage. This combination is reliable for institutions to a certain extent. However, despite BIM-LCA's versatility, applicability to various building environments, and comprehensive analysis of daily operations, making it suitable for multiple building types, there is currently insufficient evidence to demonstrate the effectiveness of BIM technology in university buildings. Like other technological tools, the implementation of BIM-LCA faces numerous challenges, and its practical feasibility has been questioned. Will users in a university setting embrace and collaborate in using the BIM-LCA model to facilitate the development of low-carbon campuses? Previous studies have often focused on technology solutions; but, in a complex environment like a campus, it is crucial to prioritise the end users, rectify its shortcomings, and promote wider application to improve its effectiveness. This study seeks to assess the feasibility of the BIM-LCA methodology for assessing carbon dioxide emissions on university campuses. This study has the following objectives:

- Understanding the functional capabilities of BIM tools and their effective use in carbon emissions evaluation
- Examining the relationship between BIM and LCA, and how BIM may improve LCA metrics over the building lifetime
- Assessing the viability of using the BIM-LCA methodology on university campuses to attain reliable improvements.

2. Methodology

2.1 Questionnaire Survey

This study employed a questionnaire survey to collect feedback from university staff and students to understand their comprehension of relevant technologies. Since the application of these technologies directly impacts them, their feedback is crucial for maintenance and future improvements [29]. Public participation has the greatest influence on the application of BIM and related technologies in the sustainable development of social buildings [30]; therefore, in this study, user opinions are considered equally important as those of professionals. A total of 101 valid questionnaires were collected, approximately 10 from facility managers and other professionals, and the remainder from other university staff.

2.2 Data Collection

This survey questionnaire will be divided into five parts, starting with the collection of basic identity information and gradually delving into understanding respondents' current understanding of the integrated application of BIM tools and LCA in CO_2 emissions. Section one of the questionnaire categorises respondents based on age, gender, occupation, and years of work or study experience. Parts two and three concentrate on assessing respondents' grasp of BIM tools and their current level of implementation, aligning with the aims of Part One. Part Two prioritises the assessment of facility managers or professionals engaged in BIM-related projects to gauge their experiences and satisfaction with digital technologies. Part three further investigates the relationship between BIM tools and CO_2 emissions to assess their efficacy and possible constraints in realising desired objectives. Part four examines the interaction between BIM and LCA in university curricula to assess their interoperability. The last section emphasises answers to current operating issues and prospective applications.

2.3 Data Analysis

In terms of data analysis, in addition to data collected through questionnaires, we can also utilise existing databases for comprehensive descriptive statistical analysis. For multiple-choice questions, we will generate general reports using Microsoft Forms for visualisation and frequency analysis. Simultaneously, we will use a digital tool called Jamovi to conduct regression and correlation analyses on issues such as BIM experience and the effectiveness of BIM-LCA integration. Jamovi is advanced statistical spreadsheet software that supports the R programming language, providing users with graphical functions for performing statistical tests and analyses, and can replace other commonly used technical tools such as SPSS and SAS.

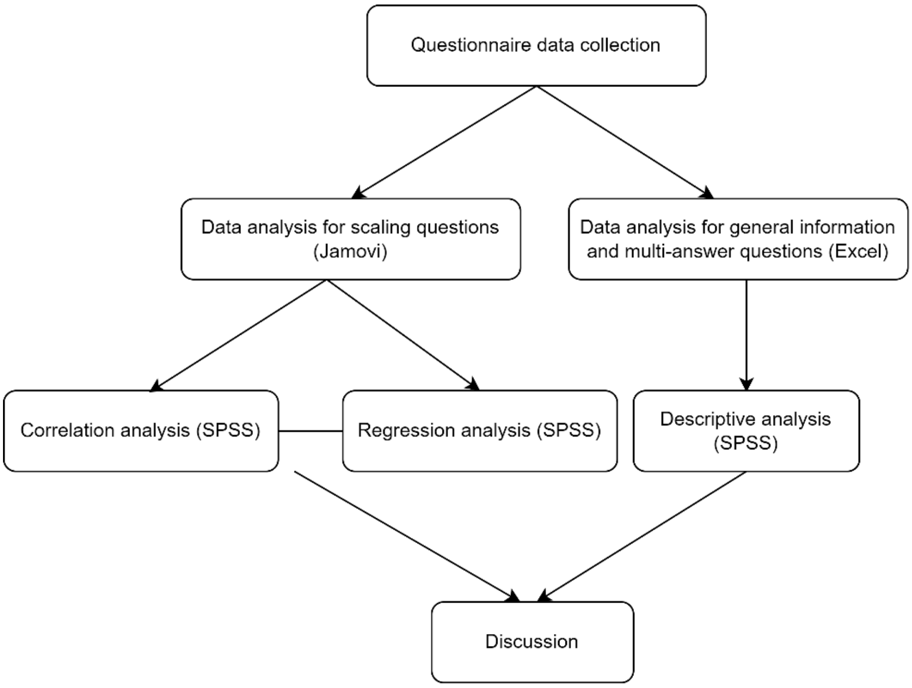

Fig. 1. The procedure of data analysis

3. Results

3.1 Demographic Information

Among the 101 valid questionnaires gathered, the gender distribution of participants was markedly unequal, with women comprising 64.4% and men 35.6% (Figure 1). The age distribution was notably concentrated, with 89.1% of participants aged 18-25, perhaps because the poll mostly targeted university students. Table 1 presents an overview of all valid questionnaires.

Table 1
Demographic information of respondents (N=101)

Gender	Number	Percentage(%)
Male	36	35.6
Female	65	64.4
Age	Number	Percentage(%)
Under 18	5	5.0
18-35	90	89.1
35-54	5	5.0
Above 55	1	0.1
Occupation	Number	Percentage(%)
Facilities/Asset manager	3	3.0
Sustainability/Environmental officer	5	4.9
Lecturer/Researcher	10	9.9
Student	83	82.2
Working duration (years)	Number	Percentage(%)
Under 5	66	65.3
5-10	30	29.7
11-20	5	5.0

A further factor potentially pertinent to Question 2 is the participants' affiliations within the university: students constituted the predominant segment at 82.2%, whereas professionals, including facilities managers and sustainability officers, represented merely 7.9% of the participants (Table 1), although this was acknowledged prior to the study. This similar rationale resulted in a somewhat concentrated range of work/study experience, with a reduced fraction of participants possessing fewer than 5 years of experience, whilst 29.7% of participants had comparatively extensive work/study experience, ranging from 6 to 10 years. Ultimately, general facts intended to comprehend the location in which their colleges were situated. The findings indicated that around 64% of participants were engaged in study or employment in London, whilst the remainder mostly lived in Scotland or the Midwest area, as seen in Figure 2.

3.2 Knowledge and Familiarity of BIM Tools and LCA

While broad information exists, proficiency and experience with BIM technologies are critical elements affecting their overall implementation on campus. The survey findings indicate that participants possess a satisfactory level of knowledge with BIM, since more than half demonstrate some comprehension of the technology (Figure 3). 42% expressed satisfaction with their user experience; however 53% maintained a neutral stance about this unique technology, which may be assessed based on the challenges they may face during its use (Figure 4). The circumstances surrounding LCA are more complex. Forty-one percent of participants indicated “moderate familiarity”, somewhat exceeding the general familiarity with BIM, thus suggesting that this trend is more pronounced in other sectors, particularly in sustainable development (Figure 5).

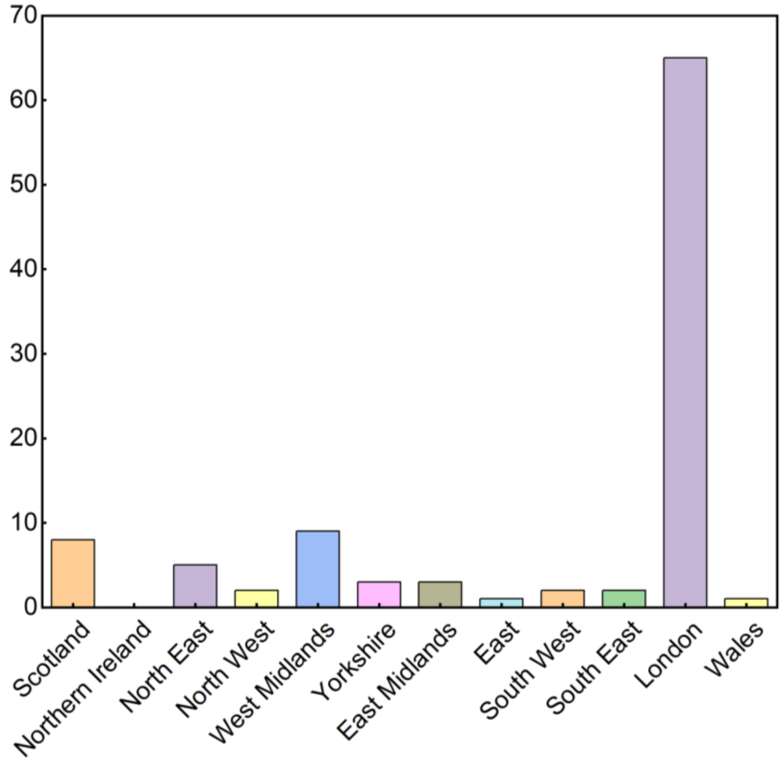

Fig. 2. Location distribution of university campus

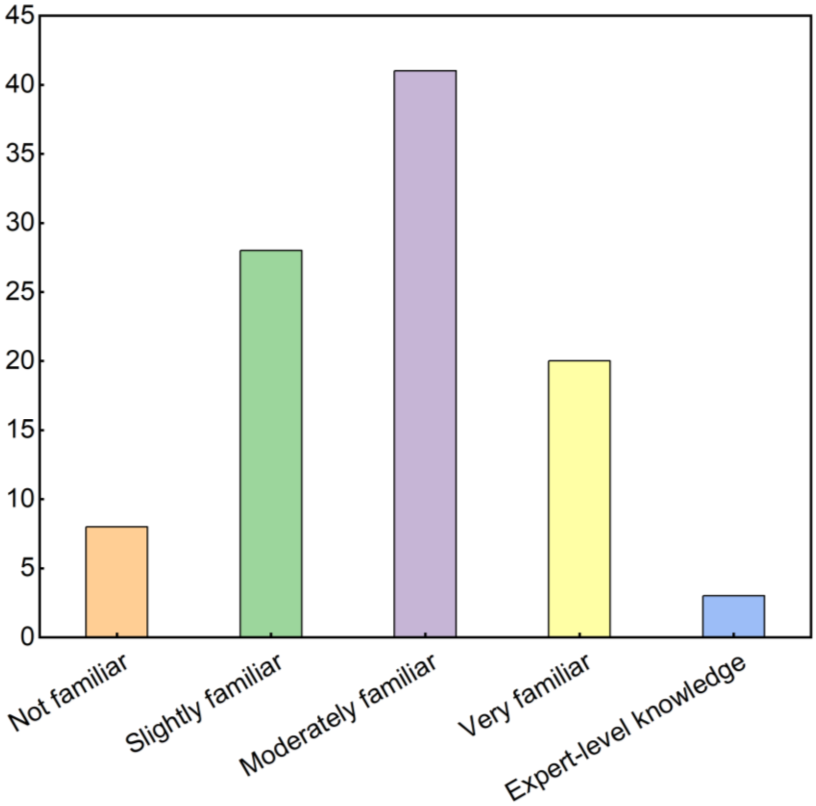

Fig. 3. Familiarity of BIM

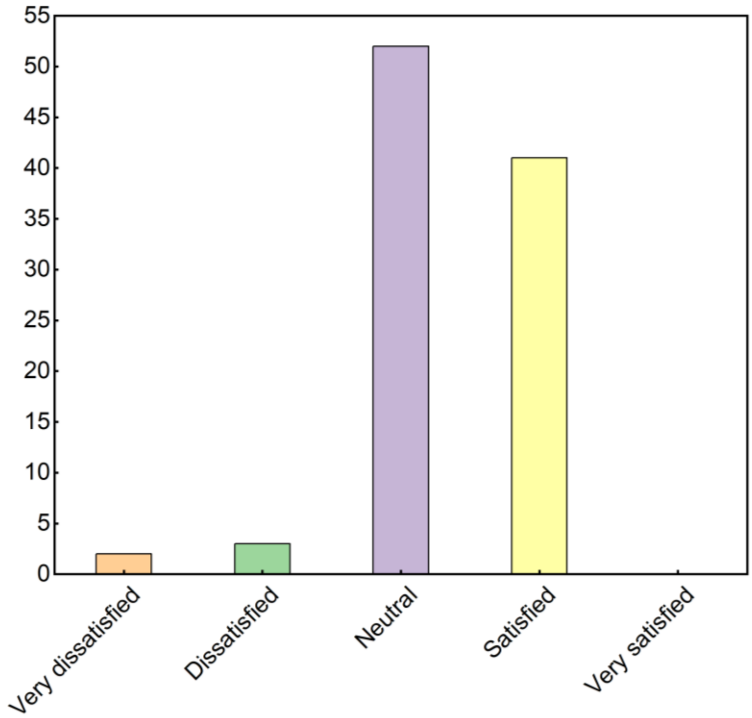

Fig. 4. Rate of satisfaction of using BIM related techniques

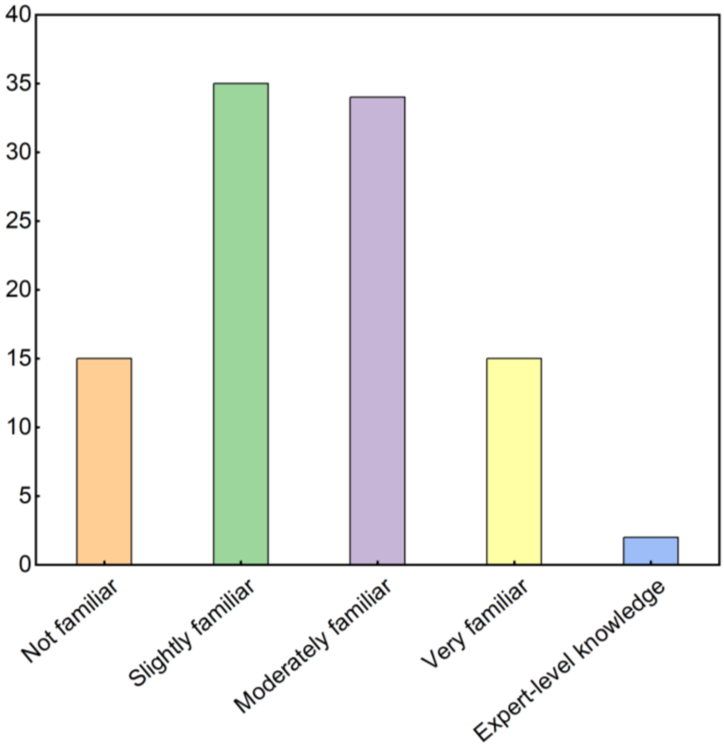

Fig. 5. Familiarity of LCA

Figure 6 illustrates the use frequency of various BIM technologies. The technologies endorsed by Autodesk seem to be more prevalent and recognisable to users. Autodesk Revit and Autodesk Insight are used more often than other technologies. Nevertheless, over one-third of the participants had no prior experience with these technologies, aligning with the earlier replies in the demographic section.

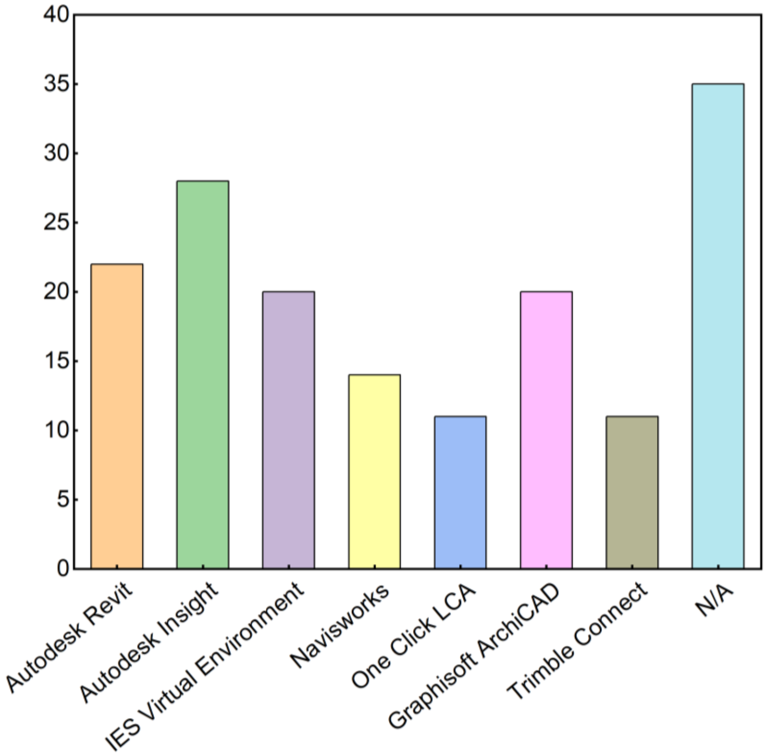

Fig. 6. The frequency of usage of different BIM tools

Figure 7 illustrates the frequency of BIM tools' contributions to significant benefits in carbon emissions. Data indicates that over fifty percent of the respondents chose rapid modelling and feedback loops, as well as comprehensive lifetime carbon monitoring from building to destruction. The question allowed participants to select up to three options. The figure showed that the distribution of each option was very even, which indicates that the public highly recognises the effectiveness of BIM or that different groups have different views on the role of BIM.

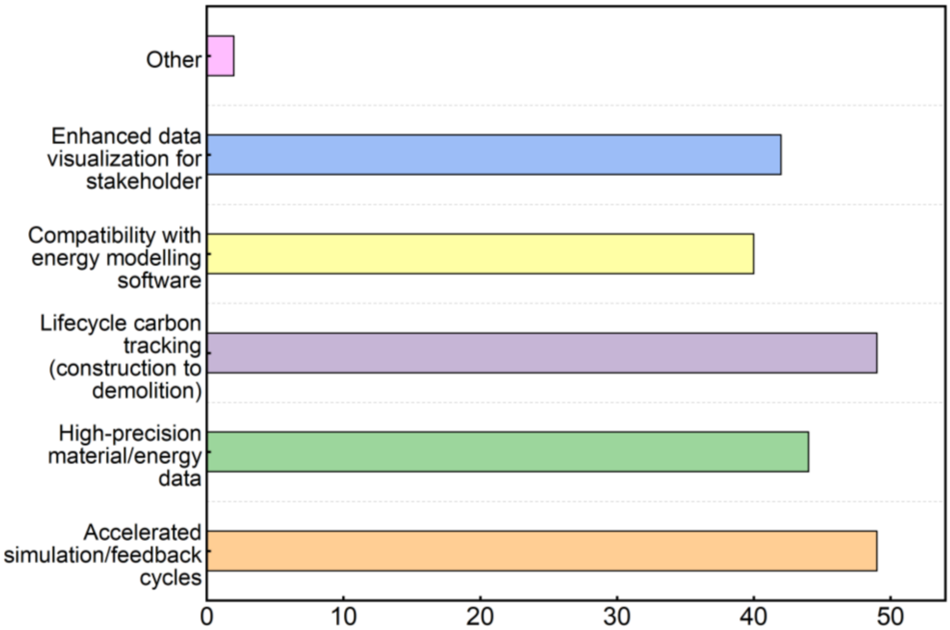

Fig. 7. The key advantages that BIM tools can offer to carbon emission

In contrast, from a critical thinking standpoint, the subsequent inquiry addressed the problems obstructing the adoption of BIM concerning carbon emissions, as seen in Figure 8. Approximately two-thirds of the participants identified two primary challenges: inadequate user training/skills and the intricacy of data administration, both of which are continually pertinent to digital transformation. Moreover, a considerable percentage also concentrated on expenses, especially the elevated costs of software and licensing.

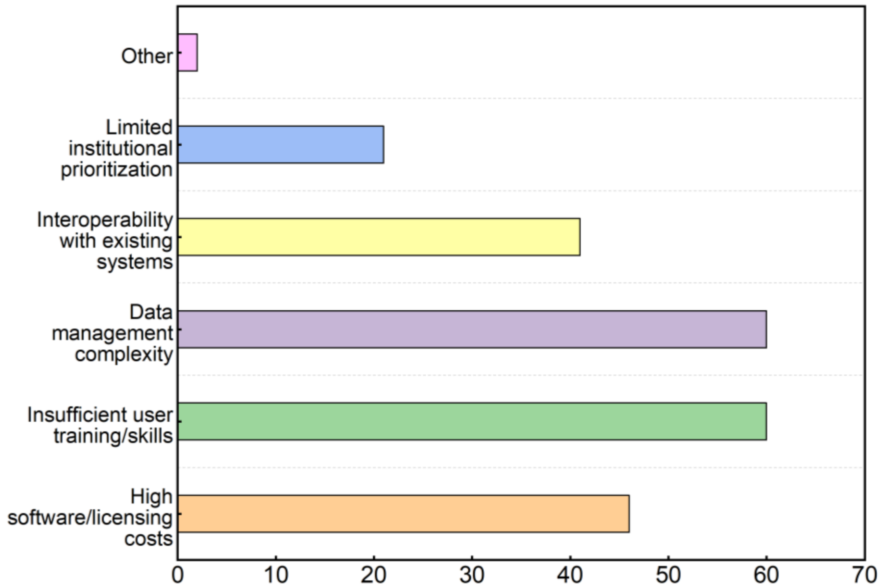

Fig. 8. The challenges that hinder BIM application for carbon emission

This research also emphasises the significance of integrating BIM with LCA to assess the objectives attainable via LCA. Figure 9 illustrates that more than fifty percent of the participants chose life cycle cost prediction and material efficiency/optimisation, both of which are intricately linked to sustainable development and long-term management. Additionally, almost 40% of the participants have shown considerable interest in trash and recycling management, as well as implicit carbon measurement.

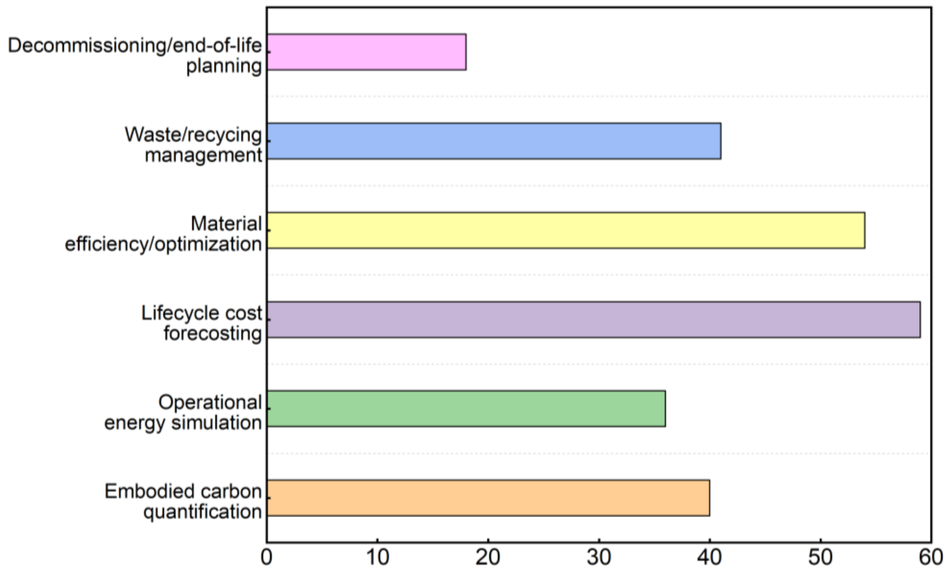

Fig. 9. The aspects of LCA that benefit most from the integration with BIM

To accomplish the primary aim of this research, we posed analogous enquiries to participants on the merits and drawbacks of integrating BIM-LCA at the present level. Figure 10 presents an overview of perspectives about barriers to BIM implementation. The findings reveal that a deficiency of proficient BIM professionals is the primary obstacle to implementation, while financial limitations and a lack of understanding of the sustainable benefits of BIM were other often cited issues (45%). Concerning aspects that facilitate BIM implementation, over 60 participants identified focused training programmes and enhanced IT infrastructure as particular solutions, along with the previously noted drawbacks (Figure 11).

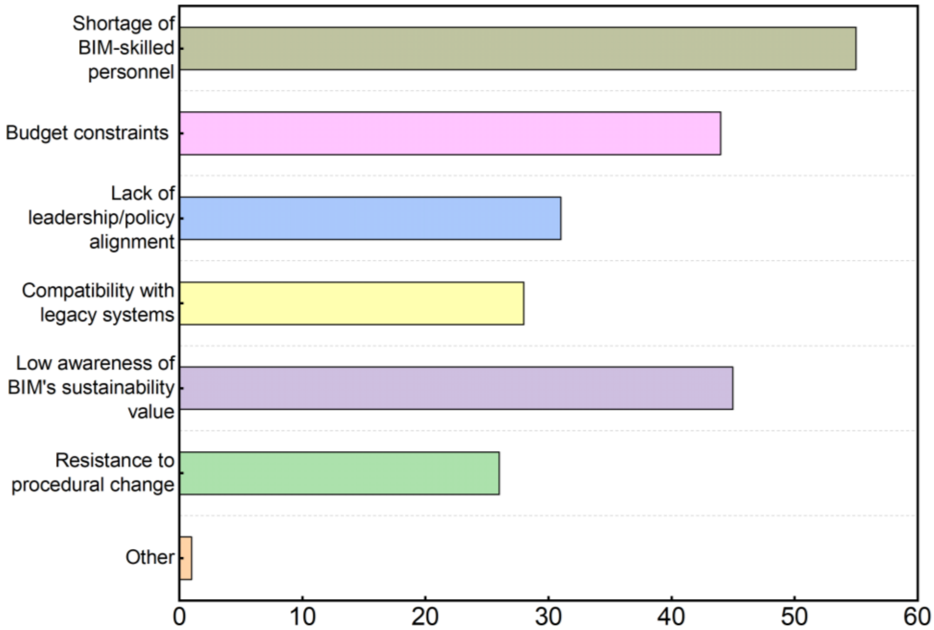

Fig. 10. The barriers that impede the BIM-LCA adoption at current stage

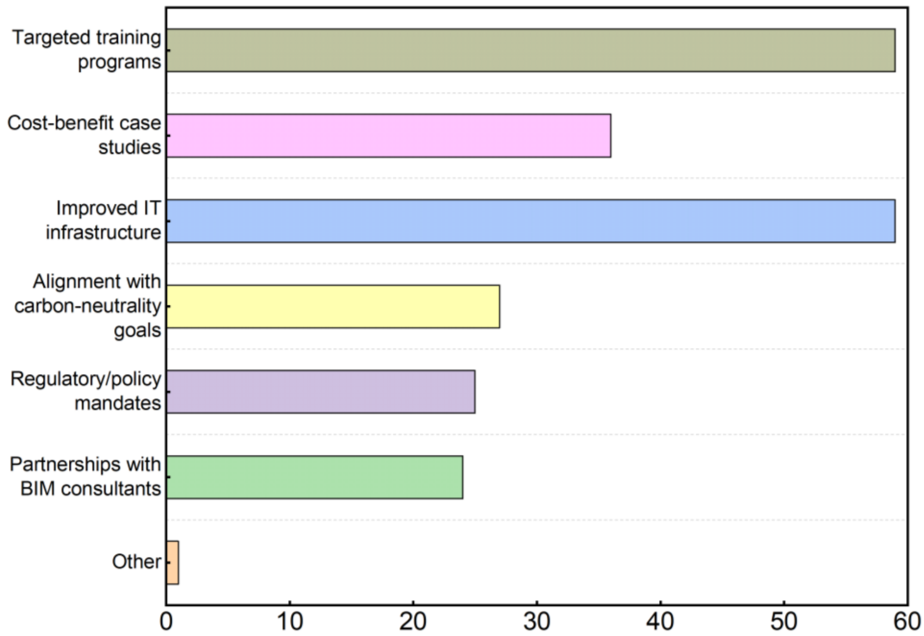

Fig. 11. The factors that can accelerate the adoption of BIM-LCA method

3.3 Correlation Analysis

Table 2 encapsulates the correlation matrix among all variables and will be positioned at the conclusion of this section. Certain factors are emphasised due to their significance.

Table 2
Correlation matrix

	BIMF	BIMS	BAT	BIME	LCAF	BIMELCA

BIMF	S	1	0.298**	0.242	0.154	0.590***	0.249*
	df	1	98	98	98	98	98
	p	1	0.003	0.015	0.127	<0.001	0.013
BIMS	S	0.298**	1	0.141	0.291**	0.235*	0.052
	df	98	1	98	98	98	98
	p	0.003	1	0.167	0.004	0.020	0.613
BAT	S	0.242	0.141	1	0.494***	0.217*	0.228*
	df	98	98	1	98	98	98
	p	0.015	0.167	1	<0.001	0.030	0.023
BIME	S	0.154	0.291**	0.494***	1	0.360***	0.294**
	df	98	98	98	1	98	98
	p	0.127	0.004	<0.001	1	<0.001	0.003
LCAF	S	0.590***	0.235*	0.217*	0.360***	1	0.288**
	df	98	98	98	98	1	98
	p	<0.001	0.020	0.030	<0.001	1	0.004
BIM ELCA	S	0.249*	0.052	0.228*	0.294**	0.288**	1
	df	98	98	98	98	98	1
	p	0.013	0.613	0.023	0.003	0.004	1
ESA	S	0.280**	0.124	0.253*	0.286**	0.238*	0.604***
	df	98	98	98	98	98	98
	p	0.005	0.222	0.011	0.004	0.017	<0.001
IIP	S	0.149	0.073	0.237*	0.358***	0.147	0.383***
	df	98	98	98	98	98	98
	p	0.140	0.479	0.018	<0.001	0.148	<0.001
CESCT	S	0.035	-0.037	0.298**	0.270**	-0.037	0.324***
	df	98	98	98	98	98	98
	p	0.732	0.714	0.003	0.007	0.712	<0.001
RBIM LCAF	S	0.112	0.120	0.324**	0.435***	0.149	0.495***
	df	98	98	98	98	98	98
	p	0.268	0.241	0.001	<0.001	0.140	<0.001
DPU	S	0.149	0.062	0.201*	0.280**	0.258**	0.201*
	df	98	98	98	98	98	98
	p	0.139	0.544	0.045	0.005	0.009	0.045
NUSI	S	0.025	0.097	0.245*	0.271**	0.101	0.339***
	df	98	98	98	98	98	98
	p	0.808	0.344	0.014	0.006	0.319	<0.001

Table 2
Continued

		ESA	IIP	CESCT	RBIMLCAF	DPU	NUSI
BIMF	S	0.280**	0.149	0.149	0.112	0.149	0.025
	df	98	98	98	98	98	98
	p	0.005	0.140	0.140	0.268	0.139	0.808
BIMS	S	0.124	0.073	-0.037	0.120	0.062	0.097
	df	98	98	98	98	98	98
	p	0.222	0.479	0.714	0.241	0.544	0.344
BAT	S	0.253*	0.237*	0.298**	0.324**	0.201*	0.245*
	df	98	98	98	98	98	98
	p	0.011	0.018	0.003	0.001	0.045	0.014
BIME	S	0.286**	0.358***	0.270**	0.435***	0.280**	0.271**
	df	98	98	98	98	98	98
	p	0.004	<0.001	0.007	<0.001	0.005	0.006
LCAF	S	0.238*	0.147	-0.037	0.149	0.258**	0.101
	df	98	98	98	98	98	98
	p	0.017	0.148	0.712	0.140	0.009	0.319
BIM ELCA	S	0.604***	0.383***	0.324***	0.495***	0.201*	0.339***
	df	98	98	98	98	98	98
	p	<0.001	<0.001	<0.001	<0.001	0.045	<0.001
ESA	S	1	0.521***	0.277**	0.465***	0.319**	0.423***
	df	1	98	98	98	98	98
	p	1	<0.001	0.005	<0.001	0.001	<0.001
IIP	S	0.521***	1	0.260**	0.385***	0.213*	0.394***
	df	98	1	98	98	98	98
	p	<0.001	1	0.009	<0.001	0.034	<0.001
CESCT	S	0.277**	0.260**	1	0.386***	0.109	0.341***
	df	98	98	1	98	98	98
	p	0.005	0.009	1	<0.001	0.279	<0.001
RBIM LCAF	S	0.465***	0.385***	0.386***	1	0.341***	0.414***
	df	98	98	98	1	98	98
	p	<0.001	<0.001	<0.001	1	<0.001	<0.001
DPU	S	0.319**	0.213*	0.109	0.341***	1	0.377***
	df	98	98	98	98	1	98
	p	0.001	0.034	0.279	<0.001	1	<0.001
NUSI	S	0.423***	0.394***	0.341***	0.414***	0.377***	1
	df	98	98	98	98	98	1
	p	<0.001	<0.001	<0.001	<0.001	<0.001	1

Note: BIMF-BIM Familiarity, BIMS-BIM Satisfaction, BAT-Belief on Advanced Technology, BIME-BIM Effectiveness, LCAF-LCA Familiarity, BIMELCA-BIM Enhancement for LCA, ESA-Early-Stage of Application, IIP-Identification of Important Phrase, CESCT-Carbon Emission Situation at Current Stage, RBIMLCAF-The Recognition of BIM-LCA Feasibility, DPU-The Difficulty of Practical Usage, NUSI-The Necessity of Unified Standard and Instruction, S-Spearman's rho, p-significance level.

The correlation matrices provide the findings of the examination of BIM familiarity and BIM effectiveness. The findings demonstrate a weak association between the two variables, as the Spearman correlation coefficient is minimal and the p-value is above 0.05, indicating that efficacy is not statistically significant and is independent of familiarity. A moderate association persists between BIM familiarity and BIM satisfaction, shown by a ρ value of 0.296, suggesting a little increasing tendency; however, it is insufficient to establish a definitive link. The p-value demonstrates that this link is statistically significant. Consequently, familiarity and user pleasure are mostly autonomous, indicating that individuals may get advantages even with little understanding of the relevant technologies.

The association between LCA familiarity and BIM implementation in LCA reveals comparable outcomes to the preceding two experiments, demonstrating a modest and statistically significant link between these variables. The link between BIM use in LCA and its early application phases is very positive. Moreover, $p < 0.001$ indicates that this association is extremely statistically significant and unlikely to result from random fluctuation. Consequently, early application planning is essential for enhancing integration efficacy. The identification of important carbon emission phases is another aspect affected by the integration of BIM and LCA. Table 2 demonstrates a modest link between the two variables; those who assert that BIM may enhance the accuracy and comprehensiveness of LCA assessments are also more inclined to think that the BIM-LCA methodology can assist in identifying important phases of carbon emissions. The p-value is constant enough to indicate the statistical significance of this association.

In terms of the feasibility of the integrated approach, the satisfaction of the current carbon emission situation has been added to the measurement of user attitude. From the result, it is clear that participants' belief of BIM-LCA application is relatively in line with the satisfaction in the current situation, as shown by the moderately positive relation between the responses. At the same time, corresponding to the strong enough effect size, the p-value suggests the statistical significance of such a relationship with the number that is smaller than 0.001. The survey also investigated users' concerns on the practical difficulty of learning the direction of improvement. According to the results presented by the matrix, even though people believe in the feasibility of the BIM-LCA and recognise that it can be applied in the university, they still worry about the technical difficulty that may be encountered through actual application, as this combination requires high-level technical support along with attendance of personnel. Such concern is in line with the responses to the previous question, and the relation is statistically significant.

It is crucial to highlight the correlation between the complexity of actual implementation and the assistance required to identify solutions. Table 2 indicates a widespread agreement that the incorporation of BIM-LCA into real operations presents significant challenges; hence, incremental guidance is essential in this regard. The Spearman correlation coefficient indicates a moderate link between the two variables. Moreover, the p-value below 0.001 further substantiates the statistical importance of this link.

3.4 Regression Analysis

This research used linear regression to ascertain pertinent factors for evaluating the feasibility of using the BIM-LCA approach at universities for carbon emissions assessment. In constructing the model, we designated awareness of BIM-LCA feasibility as the dependent variable, while the independent variables included BIM familiarity, LCA familiarity, BIM effectiveness, the augmentative impact of BIM on LCA, challenges in practical application, and the imperative for standardised specifications. All variables were transformed into continuous variables to satisfy the criteria for regression analysis.

Table 3 shows an R^2 of 0.523 and an adjusted R^2 of 0.511, indicating that the model has moderate to strong explanatory power, and the overall model test results show that the model is statistically significant ($p < 0.001$). Therefore, all listed predictors can reliably explain the differences in perceived feasibility. Table 4 analyses each predictor in detail, with BIM enhancement having the greatest impact on the feasibility of the integrated approach ($p < 0.001$, $B = 0.316$). Participants tended to believe that the benefits of the BIM-LCA combination were closely related to its successful application at the university level in CO_2 emission control. Another important predictor was the effectiveness of BIM, with an acceptable value, indicating that the practicality of BIM itself is associated with higher perceived feasibility.

Table 3
Model summary

Model	R	R^2	Adjusted R^2	F	df1	df2	p
Regression residual model	0.752	0.523	0.511	10.236	6	50	<0.001

Table 4
Linear model coefficient

Predictor	B	Std. Error	t	p
Intercept	0.869	0.393	2.211	0.030
How familiar are you with BIM?	0.030	0.052	0.582	0.562
How familiar are you with LCA?	-0.046	0.057	-0.798	0.427
To what extent do you agree: "BIM enhances the accuracy and scope of LCAs for university buildings?"	0.316	0.076	4.136	<0.001
To what extent do you agree: "BIM tools work effectively in estimating CO_2 emissions for the buildings?"	0.212	0.069	3.091	0.003
To what extent do you agree: "The combination of BIM and LCA will add technical difficulty to actual application?"	0.147	0.074	1.987	0.050
To what extent do you agree: "It is necessary to follow unified standards and step-by-step instructions when using BIM-LCA approach?"	0.116	0.073	1.526	0.130

Notes: Dependent variable: To what extent do you agree: "BIM-LCA can be feasibly applied for CO_2 analysis in university"

The difficulty of practical application showed a moderate positive correlation with B = 0.147 and p = 0.05, suggesting that although technical challenges were considered an issue, feasibility could still be viewed positively. The other three predictors—BIM familiarity, LCA familiarity, and the need for unified standards and guidelines—were not statistically significant due to p-values greater than 0.05, meaning these factors may have little impact on the practical feasibility of the model. The results indicate that the application of the BIM-LCA approach to carbon emissions can be feasible by leveraging the effectiveness of BIM tools and the benefits of such integration; however, an understanding of the technical issues is also crucial for successful implementation.

3.5 BIM Effectiveness for Carbon Emission

An examination of existing literature indicates that BIM may contribute to carbon emissions assessments. Leveraging intelligent data and the interconnectivity of various technologies, BIM can effectively facilitate real-time information sharing and data transmission, enabling early simulation of feasible carbon monitoring models. This application can help facility management meet sustainability standards at multiple stages. Based on these observations, we believe BIM can significantly improve the accuracy and reliability of energy control studies. The survey results show that BIM's main advantages lie in accelerating simulation and feedback loops and enabling full life-cycle carbon monitoring from building to demolition. These parameters are crucial for improving the accuracy and reliability of energy emission predictions and can provide appropriate solutions at each stage, thereby further optimising the overall operational efficiency of buildings.

Participants expressed concerns about potential obstacles to practical analysis, including insufficient user training/skills and the complexity of data management. As a novel tool requiring complex technological support, the potential risks of BIM are mainly reflected in cost and operation. As previously noted by Gerrish *et al.,* [31] BIM has some deficiencies, notably the absence of standardised connectors and interoperability challenges across systems. These constraints complicate precise calculations and impose more strain on personnel, who need to focus on daily operations and possess the competence to manage many challenging scenarios.

3.6 BIM-Enhanced LCA Assessment

The amalgamation of BIM with LCA is a prevalent method for energy evaluation in construction projects. They enhance one another, optimising energy efficiency and reducing costs via real-time evaluation over the full lifetime. Research conducted by Jiang [18] and Antón and Díaz [14] demonstrates that BIM enhances LCA, yielding more precise and dependable energy evaluations. Participant feedback reveals that lifespan cost estimation, material efficiency, and optimisation are the most beneficial aspects of BIM integration. Prior studies indicate that the pursuit of sustainable growth is a prevalent trend across several sectors, primarily emphasising the logical and thorough use of current resources to mitigate possible future costs. Predicting and managing supply and costs is crucial for ensuring the continued operation of projects.

The inferential analysis results differ slightly from previous findings, indicating a statistically significant, moderate positive correlation between LCA familiarity and LCA assessment. However, this correlation is relatively weak compared to other factors, which may be related to BIM familiarity. The results suggest that BIM has a significant statistically significant enhancing effect in LCA. BIM visualisation models can accurately locate key nodes in the design process and facilitate consultation and communication in LCA [32]. The BIM-LCA integrated framework delineates critical aspects affecting concealed carbon emissions during the building's lifespan and underscores the need of enhancing the LCA during the design process [33]. This discovery aligns with previous studies by Cheng *et al.,* [21]. The combination of BIM and LCA enables organisations to identify key stages in the building lifecycle and determine the optimal stages for minimising CO2 emissions, thereby promoting evidence-based decision-making.

3.7 Feasibility of Applying on University Campus

In this research, feasibility is critical to the whole examination. Prior studies have examined the carbon emissions of universities, which are now endeavouring to attain low-carbon environmental objectives in accordance with sustainable development trends and seeking to enhance environmental consciousness among university constituents to facilitate associated initiatives. According to the study of Abdul-Azeez and Ho [23], universities are using several strategies to attain reduced carbon emissions. Kim *et al.,* [34] have shown that some university projects have adopted advanced technologies such as BIM and digital twins for modelling and prediction. However, due to potential flaws in real-world projects and the unpredictable behaviour of university members, these factors may affect the evaluation results; thus, their practical application value still requires further research.

In addition to the hurdles presented by the technology tools, several widespread problems have hindered the large-scale adoption of BIM from meeting expectations. Participant input reveals that the prevailing scarcity of BIM specialists and a lack of comprehension about BIM's sustainable advantages are the primary impediments to its extensive adoption. This reflects previously acknowledged problems in BIM deployment, namely that successful execution requires sophisticated technology competencies and user proficiency. To expedite the execution of BIM LCA, participants suggested several options, including the establishment of specialist training programmes and the enhancement of IT infrastructure. The former may reinforce the concept, since the surrounding environment significantly influences people' conduct and openness to novel views; hence, thorough promotion and development are very beneficial to this process. Regression analysis explained 51.1%

of the variance in perceived feasibility, indicating that the selected parameters in the model are interconnected and together influence users' adoption of BIM-LCA. BIM efficiency and its positive influence on LCA evaluation emerged as significant predictors, indicating that the integration method is mostly dependent on the advantages of BIM technology, while LCA functions more as a supplementary tool that also derives benefits from BIM. According to the three-level integration model proposed by Soust-Verdaguer *et al.,* [15] BIM is pivotal in data collection and serves as an intermediary platform for information exchange in subsequent phases, while LCA assimilates this information, converts it into environmental impact indicators, and interprets it. Viscuso *et al.,* [35] elucidated the importance of BIM in integrating LCA and Life Cycle Cost (LCC) because it provides a visualisation platform for analysing environmental variables, thus highlighting the effectiveness of BIM as the cornerstone of the entire framework. Conversely, people tend to focus more on advantages; they want to assess the effectiveness of a technology through observable results rather than understanding its specific implementation. Therefore, proficiency in BIM and LCA is not important in the model. Previous case studies have shown that the emphasis is on the extent of energy conservation and the reduction of CO2 emissions.

Concerns about technological barriers persist; Veerendra *et al.,* [26] focused on potential errors arising from technological issues in college applications, but this does not diminish confidence in feasibility, as previous research has shown. This may stem from an insufficient understanding of the effective link between tools and outcomes; conversely, a blind reliance on innovative tools can foster the notion that challenges are insurmountable and do not lead to irreversible consequences, resulting in the perception that existing problems are solely the responsibility of professionals. Both perspectives suggest a greater focus on outcomes, impacts, and advantages than on the challenges of achieving them. Silberer *et al.,* [36] found that performance expectations remained consistent across all stages, but effort expectations only became apparent in the mid-to-late stages. Nevertheless, the instability of technology underscores the necessity of human involvement, particularly in large institutions such as universities where the likelihood of prediction failure is higher. There is insufficient awareness of the need to involve all relevant stakeholders in the process, necessitating a transition through standardised training and guidance.

4. Conclusion

This research used a questionnaire survey approach to assess the influence of the BIM-LCA tool on carbon dioxide emissions from university campuses. The research has shown that the BIM tool is proficiently applicable to carbon emission analysis because it monitors emissions during the building lifecycle through expedited simulation and feedback, hence significantly enhancing the assessment's accuracy. The results indicate that the BIM tool is adequately created to efficiently support data collection and information dissemination, hence enhancing the assessment process. This results from the sustained collaboration between BIM and energy assessment, as well as its interoperability with simulation software that enhances the effective operation of BIM.

This study illustrates that BIM improves the accuracy and comprehensiveness of LCA assessments by facilitating reliable building information collection, therefore assisting in pinpointing crucial stages for emission mitigation. The findings suggest that BIM can serve as the principal instrument facilitating the whole process and effectively perform LCA evaluations. This result can be ascribed to the first deployment phase allowing more time for the integration of the two technologies, and the interoperability between BIM and LCA fulfilling expectations.

The predictor variables in the regression model accounted for 51.1% of the variation in the dependent variable. The model suggests that improvements in BIM effectiveness and LCA evaluation are substantial predictors, highlighting a focus on benefits and outcomes rather than understanding the foundational methodologies. Moreover, there is assurance on the viability of integration, although recognising the technical difficulties of actual implementation. This trend may be attributed to a deficiency in comprehension of digital tools and early apprehensions about novel technology, issues that need resolution via focused training and standardised education.

This research addresses the need for enhancing public knowledge of BIM-LCA in relation to CO_2 emission sustainability and aims to provide standardised recommendations for practical use. Furthermore, conducting surveys and trial projects will facilitate thorough implementation, reduce complexity, and enhance confidence via experiential learning. Simultaneously, the improvement of BIM data quality must be ensured as the basis for any future simulations or predictions to extend the scope and accuracy of LCA. Therefore, many proposals for improving the feasibility and effectiveness of BIM-LCA integration for CO_2 emissions on university campuses are provided:

The limited public understanding of advanced tools impedes the connection of these technologies to practical uses; a persistent lack of awareness will intensify the difficulties of future implementation. The integrated approach of BIM emphasises the need for reliable, accurate, and consistent data support and exchange to ensure the quality of LCA investigations. The amalgamation of BIM with LCA must be implemented at every tier to augment its veracity and efficacy. Participants acknowledged the technical constraints but expressed confidence in the feasibility of this integrated approach, indicating that users stay resolute in the face of challenges. Based on this belief, providing clear and comprehensive support, including step-by-step instructions, will meet people' needs and may enhance comprehension of BIM-LCA's importance in sustainable development.

The heterogeneity among university populations hampers the forecasting of group behaviours, perhaps leading to unexpected consequences in practical applications. Consequently, it is advisable to do preliminary surveys of university users to ascertain their preferences, followed by small-scale experiments on campus to evaluate the approach's practicality. These approaches may provide a preliminary assessment of BIM-LCA, hence preventing future failures at a reduced cost. Should the tests prove successful, the insights acquired from the pilot projects will enable comprehensive implementation and bolster stakeholders' trust in the methodology.

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Conflicts of Interest

The authors declare no conflicts of interest.

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