

Article

BIM-Enabled Virtual Reality (VR) for Sustainability Life Cycle and Cost Assessment

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Abstract: Virtual Reality (VR) is receiving ever-increasing attention and is utilized by many construction companies in their current practices. This paper aims at a critical investigation of the impact of VR technology on how sustainability and cost are understood and perceived by the users in building design projects, which could lead to improving and supporting the actual building design processes. The research study focused on evaluating design alternatives using Building Information Modeling (BIM)-enabled VR technology integrated with cost and sustainability life cycle assessment (LCA) software. In doing so, the paper begins with reviewing the relevant literature in the mentioned areas. Thereafter, it adopts an experimental-qualitative-quantitative method to test the research hypothesis and analyze the effects of 360-degree VR on the users (66 participants), while distinguishing between users who have a relevant background in building/construction engineering (i.e., architect engineers and civil engineers), and those who have not (i.e., owners and clients). It is observed that despite their background, the user participants positively embrace the ideas and aspirations of sustainability, and that there is some evidence of respondents preferring the economy over sustainability. Likewise, the participants are not making an effort to measure the emissions of their design options rather than focus on the building's economic aspects.

Keywords: virtual reality (VR); 360-degree VR; Building Information Modeling (BIM); life cycle assessment (LCA); cost assessment; decision support



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1. Introduction

Building Information Modeling (BIM) is a multi-dimensional model, and information integration technology developed based on CAD technology [1]. BIM enhances work efficiency, ensuring the quality of the work by reducing errors throughout the construction of the project [2]. Applying the technology, project stakeholders can access information through the whole lifecycle of the building, including the conceptual design phase, construction phase, or even demolition phase. Cloud services associated with BIM enable stakeholders to have constant access to changes and monitor progress, reducing construction errors [3]. Advanced information technologies can be used to improve the configuration of workspaces in a construction project site plan, as well as safety procedures [4]. The industry needs to identify trends and relevant challenges, and in order to sustain, it must adapt business models to new market standards to be successful [5].

The integration of BIM with applications such as Quantity Take-Off (QTO), Scheduling tools, Life Cycle Assessment (LCA), and Virtual Reality (VR) can improve and extend the flexibility and efficiency of BIM. The three-dimensional (3D) models developed using BIM enable visualization of the prototype, whereas VR enables an immersive user experience of the finished building [6]. The immersive experience helps designers course-correct design changes proposed by the user participant and other unforeseeable changes or errors at the early design phases [7,8]. The application of VR and BIM in cost estimation and LCA analysis can diminish discrepancies at the source [9]. Cost estimation requires in-depth knowledge and experience about the construction processes and cost databases of

resources, which are generally sourced from previous or similar projects [10]. BIM-based cost estimation tools can use the 3D model to generate cost estimates depending on the model's level of detail (LOD), making the process less labor-intensive and time effective [11]. Similarly, BIM-based Life Cycle Assessment (LCA) methods can support developing and implementing an incremental sustainability assessment with the benefit of continuous documentation of LCA performance in the various design stages [12].

LCA establishes the relationship between materials and their sustainable qualities and environmental impacts [13]. The assessment helps to make an informed decision with respect to the choice of materials used for construction. Consumers of sustainable buildings would prefer solutions to be cost-effective with minimal expenditure on time and effort [14]. Hence, costs and environmental performance play a vital role in the development of sustainable buildings. However, forming an organization that deals with sustainability can be seen as a strategic initiative to influence a larger society, thereby improving sustainable development and influencing the supply chain [15,16].

In recent years, the BIM potential for extending its capabilities has been studied and addressed in many research studies (individually) related to QTO, LCA, or VR technology, but never in the combination of all these three systems. In this paper, BIM is used as a bridge between both worlds. Since there are not enough research studies that show the benefit of using BIM-enabled VR in terms of cost and carbon footprint together, a hypothesis is formulated that assumes the theory is valid. The hypothesis is developed with the assumption that there could be a link between the result and the problem.

Research on the mixing method (refer to use of BIM-based QTO/LCA + VR technology) can evaluate the use of 360-degree VR in combination with BIM, QTO, and LCA software in the development of building design solutions while balancing costs, environmental impacts, and enabling the study of user perception (i.e., in terms of esthetics, cost, and sustainability) to support decision-making and improve their understanding of complexity in the development of sustainable buildings. The present research study is conducted to explore this potential and fundamental concept to provide relevant information and guidance for AEC (Architecture, Engineering, Construction) stakeholders (i.e., designers, owners, and practitioners) during the design stages. The outcome aims to investigate the application of BIM-enabled 360-degree VR technology on how cost calculation and carbon footprint are understood (if at all) and perceived by the stakeholders during the design phases of building projects. The paper focuses on selecting façade design alternatives using BIM-enabled 360-VR technology combined with BIM-based QTO (for cost calculation) and BIM-based LCA software. In this framework, the research questions considered in the study are:

- Q1: How are BIM-enabled VR applications understood so that general users and professionals can use them to make judgments?
- Q2: How are BIM-enabled VR application outcomes for cost and sustainability assessment perceived by general and professional users?
- Q3: How effective are BIM-enabled VR applications for cost assessment?
- Q4: How effective are BIM-enabled VR applications for sustainability assessment?

This research project is organized in Section 2, the background, including a literature review of the relevant areas. Section 3 provides details of the research methodology used in the study consisting of the experimental-qualitative-quantitative method to test the research hypotheses, analyzing the effects of VR on the involved users, while distinguishing between users who have a relevant background in building/construction engineering (i.e., architect engineers and civil engineers) and those who do not (i.e., owners and clients). Section 4 presents the result from the conducted experiments, which is divided into three steps: (a) the measurement of the mean rating, (b) a presentation of the mean ranks, and (c) the analysis of the questionnaire results. Section 5 discusses the findings comparing the user participants and their relevant background together with the used technology. Finally, Section 6 presents a brief conclusion and sets out recommendations for further research.

2. Background

2.1. Building Information Modeling (BIM)

BIM models give a 3D visualization of the building, making it easier to demonstrate the design intent of cross-disciplinary professional engineers and other project participants [17]. BIM provides a convenient and highly efficient multi-professional collaboration by synchronizing the central files where various professions are able to share the same data sets and operate on a unified platform [18,19]. Even though achieving BIM's capabilities relies on effective collaboration among the team members in BIM-based construction networks, this can be challenging, as members need to collaborate [20]. The material data in BIM are inter-operable by other programs, with a constant update of changes being made throughout the process, reducing errors and re-works. Developing a database-supported VR/BIM-based communication can help with better-informed design decisions [21–23].

2.2. BIM-Enabled VR

VR technology has been advocated to facilitate design, engineering, construction, and management for the built environment [24]. The proposed BIM-based system can be programmed effectively for advanced simulation and communication, integrated with a game engine and VR technologies for construction [21]. VR can be simultaneously used to improve workspace planning related to construction activities and to share safety-related information between all partners improvising communication of the planning and safety information to all relevant partners [4]. VR programs' ability to integrate with BIM and the live sync between the BIM and the VR model enables auto-updates in real time.

2.3. BIM-Based LCA

Life Cycle Assessment (LCA) enables an assessment that facilitates tracking the possible changes associated with different stages of the cycle, which results in improvements in its environmental profile [25,26]. The integration of building systems LCA data per functional unit in the BIM platforms promotes sustainable solutions [27]. In 3D models, the ability to link the building model to various types of analysis tools provides many opportunities to improve building quality where the BIM-based LCA tools can be valuable as a decision-making method for designers as well as users in their choice of materials or design options of the project [28,29].

2.4. BIM-Based QTO

BIM-based cost estimation programs enable automatic calculation of material quantity based on the level of detail of the 3D model. However, any information on the work items related to the materials is included in the Bill of Quantity (BOQ), which is generally developed by quantity surveyors, whereas information regarding the management of construction projects can be automatically obtained from BIM [30]. QTO is a task-based on measurements of two-dimensional (2D) construction drawings and human interpretations that are usually performed after the design development phase to prepare a bill of quantity for completing the project. BIM-based QTO is the fastest and most reliable method if the model information is accurate [31]. BIM, in combination with Quantity Take-Off software such as Sigma Estimates, is an approximate estimate of the material cost that can be extended to the client in the conceptual design phase. The estimation developed in the conceptual design phase facilitates a real-time iterative model where a user participant can observe design changes and their consequences. The estimate can serve as a basis for the detailed design estimate [32].

3. Materials and Methods

The research methodology used in the current research project is a mixed method through a combination of an experimental-qualitative-quantitative approach [33]. The qualitative phase includes gathering feedback from the user experience through a questionnaire survey. The quantitative phase is done by the analysis of the quantified data from user experience sessions to examine the hypothesis.

3.1. Research Process

The experimental process's primary goal is to analyze the changes in performance, embodied energy, and costs concerning decision-making on alternative façades. The study, therefore, includes the development of different design alternatives and then the undertaking of a user survey to understand user perception of the changes made in terms of costs and carbon emission ranges. Figure 1 demonstrates the entire research process in five steps. Each step is briefly described below.

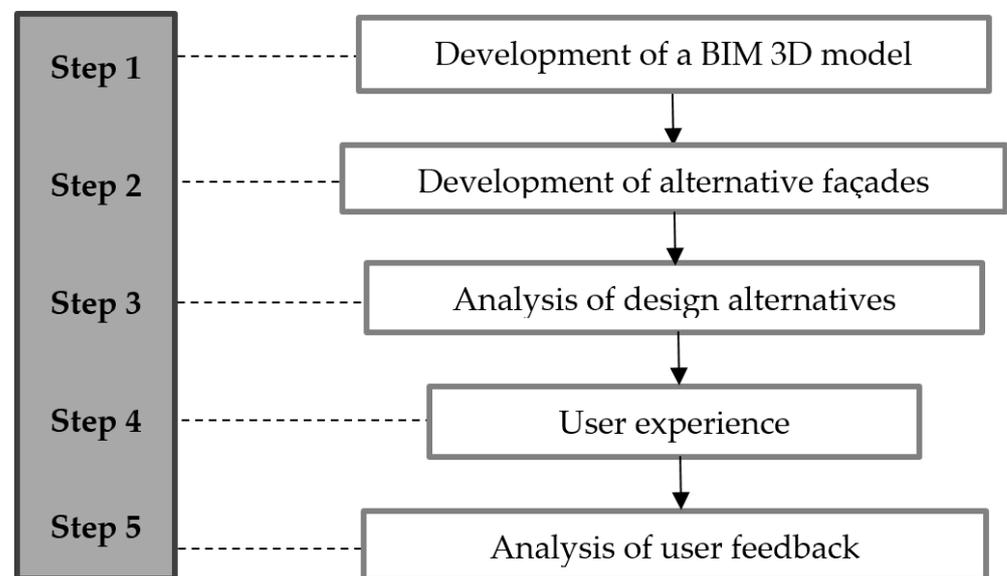


Figure 1. Research process. 3D BIM: three-dimensional Building Information Modeling.

Step 1: Development of a BIM 3D Model

The experimental study involved the interaction with an actual case study, a residential apartment located in Stavanger, Norway. Veidekke Rogaland is constructing an apartment that consists of 57 units, and the BIM 3D model of the apartment was received from the company to be used in the current research study.

Step 2: Development of façades design alternatives

The experimental analysis was conducted by creating multiple design alternatives and through multiple meetings and design iterations on the case study with the project design team together with the authors of the current paper, and resulted in the development of seven realistic alternative façade systems using Autodesk Revit [34]. Revit was used for the experiment, owing to the ease of use and availability of Autodesk Revit-based software plugins that can be used for life cycle assessment and cost assessment. Table 1 presents the façades design alternatives.

Table 1. Alternative facades.

- A - Original Facade		
- B - Brick Facade		
- C - Steel Facade		
- D - Wood Facade		
- E - Marble Facade		
- F - Travertine Facade		

Table 1. Cont.

- G -
Exposed Concrete Facade



Step 3: Analysis of the design alternatives

For the experiment, cost assessment and life cycle assessment are calculated for each design alternative. We use BIM integrated tools (Revit plugins) for this purpose. One-Click LCA [35] is used for LCA assessment and Sigma Estimates [36] for the project cost calculation. Both types of software are well known and used commonly in Denmark. The outcomes of the analysis are elaborated under Section 3.2.

Step 4: User experience

A real-time rendering and virtual reality plugin for Revit, called Enscape, is used to conduct the user experience. Comparing other VR software, Enscape enables a fully VR experience through the use of Head-Mounted Displays (HMD) [37]. Here, users experience alternative façades through the use of HMD kits. This is discussed in detail in Section 3.3.

Step 5: Analysis of user feedback

The user experience session is followed by a user feedback session where the user's feedback on the design alternatives using various themes are documented. The documented data are later analyzed to compare whether the user's perception aligns with the experimental results obtained from the analyses.

3.2. Cost and LCA Assessment

The design alternative façades are calculated for carbon footprint and cost. One-Click LCA [35] is used for LCA assessment in Kg.Co2eq (Tons), which is a metric measure used to compare the emissions from various greenhouse gases based on their GWP (global-warming potential), by converting the amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential. Likewise, Sigma Estimates [36] is used to calculate the overall Investment cost in Danish Krone (DKK). The assessments help to compare the façades and help authors and users in identifying the more efficient solution. Table 2 presents the assessment results.

Table 2. Life Cycle and Cost Assessment Results.

	Facade	Costs (Incl. Tax) (DKK)	Kg.CO ₂ eq. (Tons)
A	Original	1,842,353.08	1759
B	Brick	1,723,662.62	1511
C	Steel	2,344,431.97	1932
D	Wood	1,735,767.70	1508
E	Marble	2,067,248.72	1506
F	Travertine	1,955,400.48	1491
G	Exposed Concrete	1,652,021.26	1492

3.3. User Experience

As mentioned earlier, the experience is carried out via the application of a real-time rendering and virtual reality plugin for Revit called Enscape [38] through the use of HMD

kits due to the ease of use and better performance compared to other VR software [37,39]. The intention is to document the user experience in the feedback session on how their perception of costs and carbon footprint changed with respect to each design alternative.

Due to the COVID-19 pandemic, a nationwide lockdown was ordered by the government of Denmark. This caused an inability to access the immersive VR lab at the department of engineering, Aarhus University, in order to conduct user experience studies. Therefore, respecting the government's decision and following social distancing requirements, the experimental protocol was designed to document user experience using phone-based 360-degree VR systems with additional accessories such as Google Cardboard or slip-on VR headsets (optional). The solution was provided by the cloud rendering services from Enscape, which generates QR codes (Quick Response code) that are easily identified by the mobile phone's camera. The QR codes led to an online rendered image of each design alternative where the user participant can experience a 360° view of the design developed, as demonstrated in Figure 2. This enabled the users to experience the design alternatives and document their feedbacks at the comfort of their homes, thereby maintaining social distancing, preventing the further outbreak of the virus. The design alternatives 360° images with their relevant QR Codes are presented in Table 3.



Figure 2. User experiencing phone-based virtual reality (VR).

Table 3. Design alternatives 360-degree images with their relevant QR Codes (phone-based VR).

Design Alternatives	Images	QR Codes
<p>- A - Original Facade</p>		
<p>- B - Brick Facade</p>		
<p>- C - Steel Facade</p>		

Table 3. Cont.

- D - Wood Facade



- E -
Marble Facade



- F -
Travertine Facade



- G -
Exposed Concrete Facade



3.3.1. Preparing the Interview Questions

Following a survey that was done through an R&D project by Henrik Øien Torvund in Danish and Norwegian contexts, two types of questionnaire surveys were proposed for data collection, including (a) structured (fixed response) and (b) non-structured (a set of questions), with an additional comment section for the user participant to document their generalized views. The structured questions (as seen in Table 4) were developed through multiple meetings and iterations on the case study requirement with the project design team corresponding to the users' perception of each façade alternative in terms of costs, carbon footprint, esthetics, their willingness to be as a resident, value to cost, and maintenance themes, respectively. It is worth mentioning that the themes were selected due to the project requirements, and they can be reduced or extended in future studies. Meanwhile, the non-structured questions (as seen in Table 5) were developed to collect sufficient information comprehending the users' professional background, their knowledge on the subject area, and their needs regarding the available technologies as well as sustainable design requirements. Using the structured and the non-structured questionnaire surveys in this research study helps the authors comprehensively identify the perception changes of user participants in addition to general users and professionals can make judgments.

Table 4. User feedback for the structured (fixed response) questionnaire survey.

Facades	Costs	Carbon Footprint	Visual Style	As Resident	Value to Cost	Maintenance
Original						
Brick						
Steel						
Wood						
Travertine						
Marble						

Table 5. User feedback for the non-structured (a set of questions) questionnaire survey.

Q. No.	Factors	Score
1.	Do you use BIM for your work/projects?	
2.	Do you think cost estimation is essential in a construction project?	
3.	Do you think knowing the carbon footprint of a building is essential?	
4.	Have you used VR before?	
5.	To what extent, that you are aware of, is VR used in construction projects?	
6.	Do VR models improve your perception of costs associated with different façades alternatives?	
7.	Do VR models improve your perception of the carbon footprint associated with different façades and your decision?	
8.	After knowing the experimental results, did the 360-degree VR images affect your existing perception of costs and the carbon footprint of building façade systems?	
9.	Do you think using BIM + VR can help design efficient and sustainable buildings in the future, based on your current experience?	
10.	Do you envision a better tomorrow, where the goals of reducing global warming and making your country carbon neutral are attained?	

3.3.2. Design of the User Feedback Form

The user feedback form in Table 5 was designed to incorporate the non-structured questions developed to understand the users' depth of understanding of the experimental process, their background, and their experience of the process.

3.3.3. Experimental Protocol

The experimental protocol was developed to guide the user participants through the experimental process. Gathering feedback from the user was done using a Likert scale, as it helped to quantify the qualitative data, making analysis and interpretation simpler. Likert scales are commonly used in research that employs questionnaires and is the most widely used approach for scaling responses in survey research [40]. Thereafter, non-parametric tests were used for analyzing results obtained from the Likert scale. Non-parametric tests do not assume that the data follow a specific distribution, as the data gathered from the Likert scale is often not normally distributed; hence, non-parametric tests such as the Mann–Whitney test, Wilcoxon signed-rank test, or Kruskal–Wallis test are often used [41].

The experimental protocol is structured into three parts, i.e., intuitive, revelation, and reflection phases. The intuitive phase aims to observe the intuitive user perception of the design alternatives before knowing about their real cost and carbon footprint results. In contrast, in the reflection phase, the users are provided with the cost and carbon footprint results and then repeat the experiment the same as in the previous phase. Finally, in the reflection phase, the aim is to collect information about the users and their relevant VR experiences. For further clarification, we elaborate on each part in the following.

Part I: Intuitive phase

As the first step of the experimental process, the user participants receive an instruction manual with every developed design alternative's image and QR codes. Using the camera on the users' smartphone, the QR codes are scanned, which leads to a cloud-rendered panorama image of the design alternatives. The user participant can access two viewpoints—exterior view and interior (balcony) view. Using the viewpoints, the users can have a basic understanding of the look and feel of the design alternatives. Based on their experience, the user has to score each alternative in relation to several factors in Table 4. Here, each alternative's feedback is based entirely on the user's experience and assumptions, which are uninfluenced by any assessment data. A five-point Likert scale is used for documenting user feedback in Table 4. The scale used is as follows: (1) Poor, (2) Bad, (3) Okay, (4) Good, (5) Excellent.

Part II: Revelation phase

Here, the user participants are exposed to the assessment results (as seen in Table 2) and then repeat the experiment, contrary to the collected feedback in Part I, which is uninfluenced by the assessment results and is purely based on experience or ones' intuition. Table 4 is used in the process, and the users, once the assessment results are known, are asked to reconsider their feedback. The feedback utilizes the same Likert score rating as the previous process. This process is done to understand the change in users' perceptions towards each alternative and identify whether users are opting for a sustainable solution rather than settling down for aesthetics and other factors.

Part III: Reflection phase

Ultimately, the users are requested to undertake the questionnaire session in Table 5 to document their professional background, previous experiences, perceptions, and experiences on the experimental process. This process is done to understand the user participant's professional background and whether the users' profession hinders their overall experience. For the questionnaire, a similar five-point Likert scale, as seen in the previous phases but with a slight alteration, is used to document their feedback, as follows: (1) Strongly disagree, (2) Disagree, (3) Neutral, (4) Agree, (5) Strongly agree.

4. Results

The user participant experience included 66 participants, of which 30 participants had a relevant academic background in construction/building engineering (i.e., architect engineers and civil engineers)—hereafter referred to as CE—and those who have not (i.e., owners and clients)—hereafter referred to as N-CE (none-CE). Therefore, in the invitation for participant, the participants were primarily requested to indicate whether they have any background in the construction/building engineering field. This enabled us to compare and identify the difference in perception of cost and carbon footprint using VR in connection to the participants' background. This is important because, in any AEC type project, many expert and non-expert stakeholders are involved and have their demands and understanding of the design processes. Concerning cost and LCA assessments typically in the AEC project (particularly in Danish context today), there is a strong demand from the design team to reduce the environmental impact. On the other hand, owners' and clients' demands are focused on reducing costs. The experimental results denote how the perception of the groups are affected by the assessment results. The questionnaire from the both groups is, therefore, evaluated separately to spot differences in knowledge, values, and what the users deem essential.

The method used in the study to analyze the result from the conducted experiments is divided into three main steps, including (a) the measurement of mean rating, (b) presentation of mean ranks, and (c) analysis of the questionnaire results.

4.1. Mean Ratings for Façade Design Alternatives in All Categories

The graphs presented in Figure 3 demonstrate the mean ranks of answers obtained from the 66 participants, developed using Excel [42]. In total, there were six categories in which the participants evaluated the façade design alternatives, including cost, carbon footprint, visual style, as a resident, value to cost, and maintenance (according to Table 4).

Figure 3A presents the mean results of participants' feedback over the 'cost' category. Blue lines represent the participants' opinion of the façade cost before they had access to the assessment results by looking at the 360-degree images. The orange lines, however, represent their opinion after having access to the assessment results. This chart's high score represents a façade with a low cost, whereas the lowest score belongs to an expensive façade. Steel and exposed concrete had a major change between, before, and after access to the assessment results. The score for steel cost drops from 2.70 to 1.85 after the participants got access to the data showing steel as an expensive option. The exposed concrete score increases from 3.56 to 4.62 being promoted as an economical option. The difference in scores between the original façade and the wooden façade is evident; the original façade has a score of 0.67 higher than the wooden façade before access to the experimental data and still has a score of 0.58 higher after the information is provided.

Figure 3B illustrates the mean results of participants' feedback about the 'carbon footprint' category of the different façade alternatives. Steel and exposed concrete are the two materials with a significant change of scores before and after access to assessment results. Steel drops from a mean score of 2.55 to 1.62 after the information is exposed as the highest carbon footprint material. The mean score for exposed concrete increased from 2.86 to 4.50, which is considered to be the highest mean score across different materials despite having a carbon footprint close to travertine, marble, wood, and brick.

Figure 3C shows participants' mean result under the 'visual style' category of the façades alternatives. Original façade and travertine have received the highest scores, whereas steel and exposed concrete have received the lowest scores. The assessment results had no specific influence on visual perception.

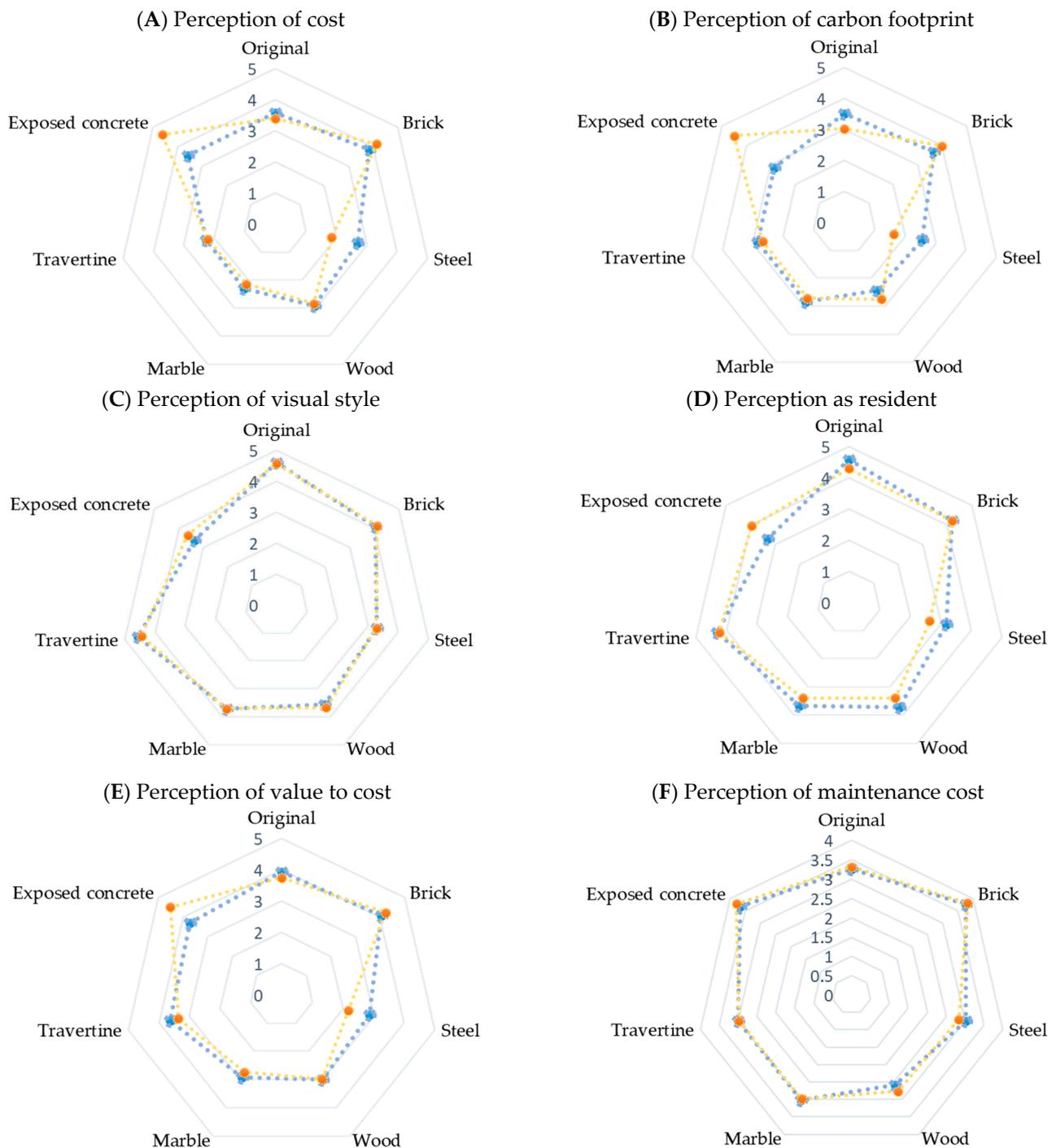


Figure 3. Radar charts demonstrating the mean ranks of answers obtained from the 66 participants for façade design alternatives (the blue line demonstrates the mean ranks before access to the experimental data, and the orange line demonstrates the mean ranks after access to the experimental data).

Figure 3D illustrates the participants' score on the 'as a resident' category on façade alternatives. A major change is observed in steel and exposed concrete, where the score for steel drops, while the exposed concrete increases. The top choices of the participants remain the same as observed in 'visual style.' This indicates that participants preferred aesthetics over cost or the carbon footprint.

The results for the 'value to cost' category are presented in Figure 3E. The participants were asked to grade the façade alternatives based on their perception of 'bang for the buck' feeling of the façade. The results obtained under this category are similar to the category

'cost' for all façade alternatives. The only façade alternative with a significant difference in score between these two categories is travertine, with high scores in the categories 'visual style' and 'as resident,' depicting that the participants value the extra cost.

The perception of façade cost is solely related to the material cost. In certain cases, it can be a cheaper solution to invest in a sturdy façade material to lower future maintenance costs. Figure 3F depicts that the participants gave the highest scores in maintenance to brick and exposed concrete while wood was given the lowest score. Changes in perception after access to assessment results are, however, minimal.

4.2. Mean Ranks Based on Education

In order to reveal the difference between the CE and N-CE groups' answers before and after access to the assessment results, box plots were used. A box plot is a standardized way of displaying the distribution of data [43]. The analysis was done using the SPSS software [44]. The reason for choosing box plots is because of its simple visual summaries and its effectiveness when drawn in groups comparing a set of cases [45]. The boxes were based on a five-number summary: minimum, first quartile (Q1), median, third quartile (Q3), and maximum. In addition to these five numbers, there might exist values outside either the minimum or the maximum referred to as outliers.

4.2.1. Comparing N-CE and CE in Relation to Façade Alternative Cost Results

The box plots for the façade cost reveals how N-CE answered differently than the CE. It gives an idea of how much each group gets influenced by the assessment results. The mean and standard deviation for each data set are presented on each box plot's right side. The standard deviation determines the variation in answers within their relevant group (N-CE or CE). The boxplots show the line for medians and some outliers, meaning that the ranges of answers from minimum to maximum are all within the median rank on the Likert scale. The answers that are different from the median value are treated as outliers.

From Figure 4, a trend where the CEs have more concurrence in the initial perception than the N-CE is observed. This can also be seen graphically in the box plot as the IQR box, and the minimum and maximum lines covered a smaller area than what could be seen for the box representing N-CE. That is evident by looking at the standard deviation data for the initial perception.

The second box for each group represents the answers after receiving access to the assessment results. The results of that part of the experiment show that N-CEs had more concurrent answers than before they had access to the results, as the box for that group covered a smaller range for all the façade alternatives in the box plot. That trend cannot be seen for the CEs, as variations were observed across design alternatives. For 'brick,' 'steel,' and 'wood,' the standard deviation increased, meaning a larger number of answers were away from the mean value. After access to assessment results, the box for wood cost covered a larger area in the box plot for the CEs than it did before.

4.2.2. Comparing N-CE and CE in Relation to Façade Carbon Footprint Results

A higher similarity between the groups in the initial perception of carbon footprint compared to façade cost is observed (see Figure 5). After the groups had access to the assessment data, the results showed a higher similarity than what was experienced in the façade alternative cost. Still, the box plots for wood, marble, and travertine showed an increase in variation in answers within the CE group. The box plots for exposed concrete show a substantial increase in score for both groups after access to the assessment results even though the data gave approximately the same score for brick, wood, marble, and travertine.

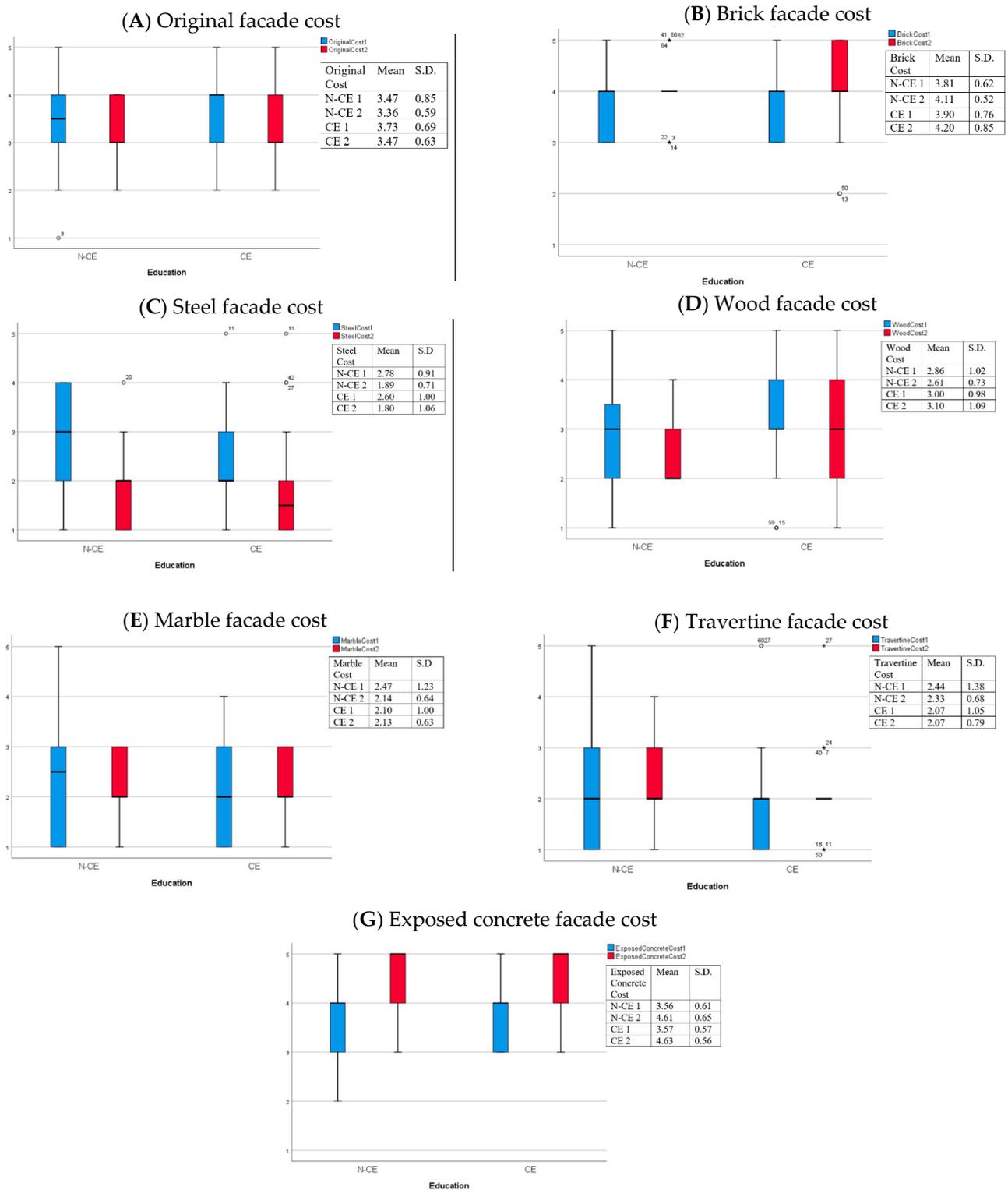


Figure 4. Box plots demonstrating mean ranks for the facade cost, comparing N-CE and CE.

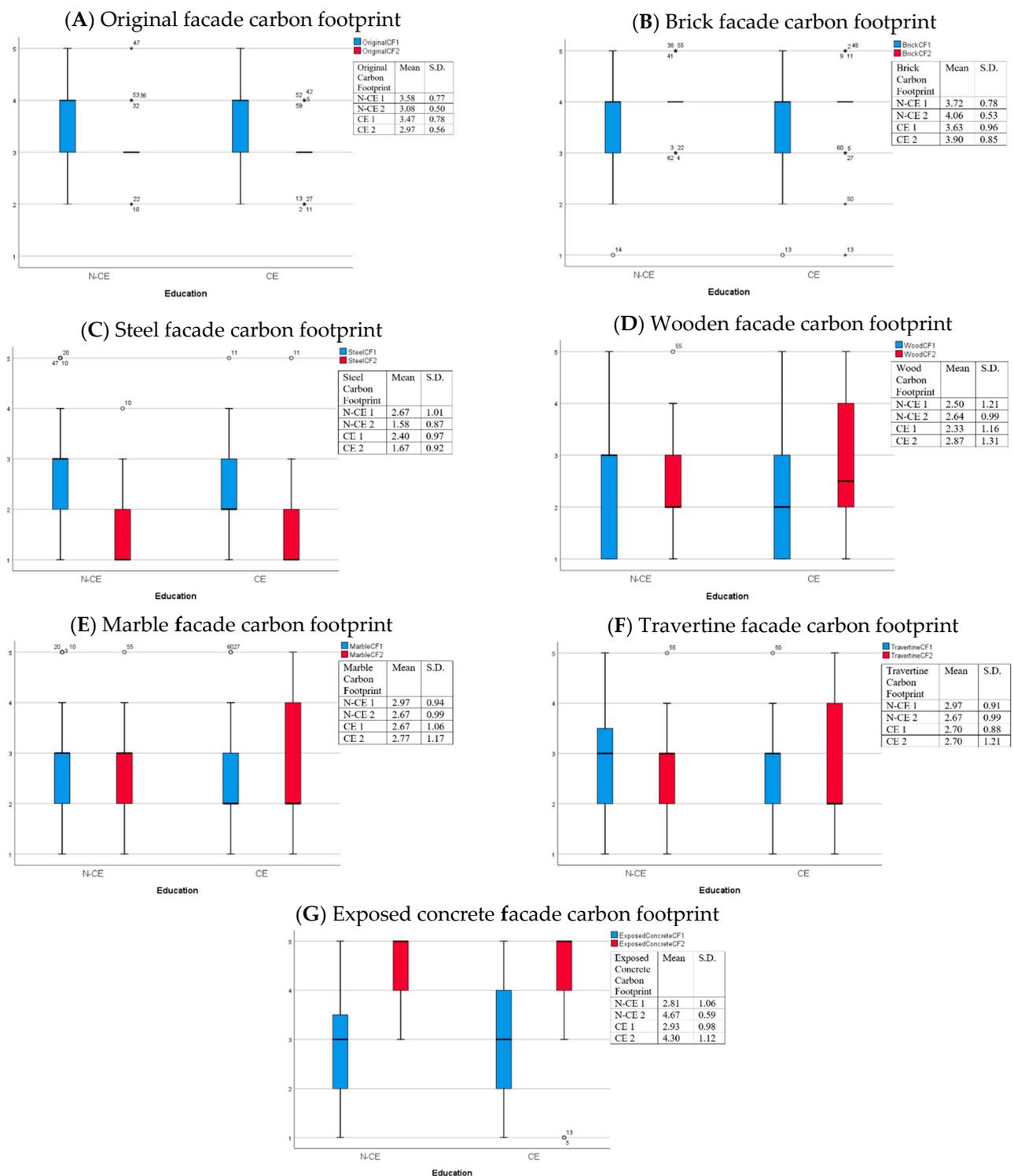


Figure 5. Box plots demonstrating mean ranks for the façade carbon footprint, comparing N-CE and CE.

4.3. Questionnaire Results

An analysis of the questionnaire was done on the two groups N-CE and CE, using SPSS. Variations in answers were expected, as the questionnaire was based on knowledge in the construction industry. It was interesting to investigate the difference in answers between the groups on how they valued cost and carbon footprint in construction projects using VR. A Mann-Whitney U test is performed to determine if there was a significant difference in

answers between these groups. The test gives a p -value, where a low p -value indicates a significant difference in the mean between the two groups. The limit chosen for the test was $\alpha = 0.05$, which means a p -value below α confirms a clear distinction between the groups [46,47].

Mann-Whitney U is a non-parametric test used to compare two independent groups when the dependent variable is not normally distributed. To use this test, four assumptions must have been made [48]. The assumptions were:

1. The dependent variable should be measured at the ordinal or continuous level, i.e., the Likert scale.
2. The independent variable should consist of two categorical, independent groups, i.e., CE and N-CE.
3. There should be independence of observations, meaning one participant cannot be presented in both groups at the same time.
4. The data should not be normally distributed.

Assumption 1 was fulfilled as the Likert scale was at an ordinal level. Assumptions 2 and 3 were fulfilled as the groups chose categorical independent groups, where one participant could not be represented in both groups. Assumption 4 needed to be tested to be confirmed. As such, a normality test was carried out to test the assumption, as seen in Table 6.

Table 6. Test of normality.

Questions	Background	Shapiro-Wilk		
		Statistic	df	Sig
1. Do you use BIM for your work/projects?	N-CE	0.610	36	0.000
	CE	0.857	30	0.001
2. Do you think cost estimation is essential in construction projects?	N-CE	0.795	36	0.000
	CE	0.577	30	0.000
3. Do you think knowing the carbon footprint of a building is essential?	N-CE	0.746	36	0.000
	CE	0.628	30	0.000
4. Have you used VR before?	N-CE	0.872	36	0.001
	CE	0.873	30	0.002
5. To what extent, that you are aware of, is VR used in construction projects?	N-CE	0.885	36	0.001
	CE	0.800	30	0.000
6. Do VR models improve your perception of costs associated with different facades?	N-CE	0.727	36	0.000
	CE	0.882	30	0.003
7. Do VR models improve your perception of the carbon footprint associated with different facades?	N-CE	0.743	36	0.000
	CE	0.830	30	0.000
8. After knowing the experimental results, did the VR models affect your perception of costs and carbon footprint of building façade systems?	N-CE	0.624	36	0.000
	CE	0.780	30	0.000
9. Do you think using BIM + VR can help design efficient and sustainable buildings in the future, based on your current experience?	N-CE	0.773	36	0.000
	CE	0.579	30	0.000
10. Do you envision a better tomorrow, where the goals of reducing global warming and making your country carbon neutral are attained?	N-CE	0.243	36	0.000
	CE	0.180	30	0.000

To test the normality for significance (sig.) value, a Shapiro-Wilk-test was used. If the value is above 0.05, it indicates that the data are normally distributed; in these results,

the sig. value is below 0.05 for all questions. Thus, the data were not normally distributed, and hence, the four assumptions for using the Mann-Whitney U test were met [48].

The Mann-Whitney U test gave a p -value called Asymp. Sig. (two-tailed). The limit chosen for the p -value in the test was $\alpha = 0.05$. A p -value below $\alpha = 0.05$ confirms that the null-hypotheses (H_0) was rejected.

The hypotheses were as follows:

Hypothesis 1 (H_0). *The means for the two groups do not have a significant difference.*

Hypothesis 1 (H_1). *The means for the two groups have a significant difference.*

As seen in Table 7, a significant difference in the answer in questions 1, 2, 5, 8, and 9 between the groups by looking at the obtained p -value was identified. A significant difference was expected in question 1 as BIM tools were mainly used by building engineers, but that just clarified the difference in experience in the technology used for the construction industry. For question 5, a substantial higher score in the CE group was expected, owing to their knowledge in the construction sector.

Table 7. Experiment questionnaire.

Questions	Mean Overall	Mean N-CE	Mean CE	p -Value	Significant Difference
1. Do you use BIM for your work/projects?	2.52	1.58	3.63	0.000	Yes
2. Do you think cost estimation is essential in construction projects?	4.39	4.14	4.70	0.003	Yes
3. Do you think knowing the carbon footprint of a building is essential?	4.44	4.28	4.63	0.062	No
4. Have you used VR before?	2.44	2.25	2.67	0.255	No
5. To what extent, that you are aware of, is VR used in construction projects?	3.12	2.47	3.90	0.000	Yes
6. Do VR-models improve your perception of costs associated with different facades?	3.79	3.92	3.63	0.494	No
7. Do VR models improve your perception of the carbon footprint associated with different facades?	3.64	3.72	3.45	0.878	No
8. After knowing the experimental results, did the VR models affect your perception of costs and the carbon footprint of building façade systems?	4.44	4.67	4.17	0.028	Yes
9. Do you think using BIM + VR can help design efficient and sustainable buildings in the future, based on your current experience?	4.39	4.19	4.63	0.002	Yes
10. Do you envision a better tomorrow, where the goals of bringing downreducing global warming and making your country carbon neutral are attained?	4.89	4.83	4.97	0.643	No

For question 2, both the groups had given a relatively high score with a mean above four and a significant difference in the answers. The CEs' scores were closer to a five on the Likert scale, showing the importance of good cost estimation is highly valued for this group. The significant difference in question 8 shows that N-CEs were more affected by the assessment results than CEs.

For question 9, the CEs gave a score significantly higher than what was answered by the N-CEs. Both scores were relatively high for the question with mean scores above 4,

but the CEs were more optimistic about the combination of BIM and VR for the design of sustainable buildings. In addition to that, comparing question 2 to question 3, it is evaluated that N-CEs found that knowing carbon footprint was more essential in general than a good cost estimation, while the opposite applied for the CEs.

In questions 6 and 7, the scores obtained from N-CEs were higher than the CEs. The mean scores for all the participants were 3.79 for VRs improvement of the perception of cost, while it was 3.64 for VRs improvement on the perception of carbon footprint. These were moderate scores, showing that the VR benefited to some degree for these purposes.

5. Discussion

In order to understand the extent of results and benefits obtained from the research, using the two types of the surveyed questionnaire, including structured (fixed response), and non-structured (a set of questions) in the previous section, the following subsections are developed to discuss the overall findings through answering the four research questions drafted in Section 1.

5.1. Comparison between the CEs and N-CEs When Using BIM-Enabled VR (Addressing Q1 in Section 1)

On the participants' views of using BIM + VR towards future design practices being built in an efficient and sustainable way, a significant difference between the groups in the Mann-Whitney U test was evident. The N-CEs had the most faith in BIM + VR as a tool for future design being efficient and sustainable, with a mean rank of 4.63. CEs had a mean rank of 4.19, which, despite being a high rank, was lower than the N-CEs.

N-CEs, in general, felt they benefited more from the perception of cost and carbon footprint using BIM-enabled VR as compared to CEs. The use of BIM-enabled VR did not influence the CEs much. Hence, the technology can be more useful for people without a large amount of previous knowledge or relevant background in the area. The results obtained from the questionnaire also showed that participants with the least experience in BIM and VR were the most impressed with the quality and functionality of the 360-degree images. Linking this to the relevant stakeholders in a construction project indicates that non-expert users such as owners or building users might be the ones with the most to benefit from the use of VR technologies.

5.2. Comparison between the Cost and Sustainability Assessments When Using BIM-Enabled VR (Addressing Q2 in Section 1)

There was mixed feedback on how the participants felt the VR images helped them evaluate the different façades in terms of cost and sustainability assessments. Some CEs with knowledge in the area reported that the VR did not provide them with any extra inputs when evaluating cost and carbon footprint. They felt that their knowledge in the area was sufficient for ranking the façade and was not affected by a visualization of the building's material. Some CEs commented that they felt the VR visualization might have a larger impact on people without prior knowledge. The N-CEs had a higher percentage of comments on how the visualization of the façade iterations gave them a better understanding of cost and carbon footprint.

Under the questionnaire's comment section, the mixed feedback can be observed due to what the participants felt was a priority. For example, some participants felt the cost of the façade was much more important than sustainability, which, from an economic standpoint, made sense, as new owners are more concerned about the initial costs of the building than expecting long-term returns. On the other hand, some participants perceived sustainability as an economic advantage due to tax incentives (based on the country), as well as increasing the building's commercial value. Despite a need for sustainable buildings, participants still preferred a solution that emphasizes the balance of cost and sustainability aspects.

5.3. Comparison between the Cost Assessments Using BIM-Enabled VR and without It (Addressing Q3 in Section 1)

The results showed a mean score between 3 (neutral) and 4 (agree) on the Likert scale for cost showing positive signs for the use of VR. N-CEs, in general, felt a higher grade of improvement in perception for cost assessment using BIM-enabled VR than CEs. N-CEs' mean rank for VR's improvement for perceiving cost was 3.92, whereas the score mean rank for CEs was 3.63. The mean overall ranking for the BIM-enabled VR influence on the perception of costs and the carbon footprint of building façade systems was between 4 (agree) and 5 (strongly agree). This depicts the improvement of cost assessment perception using BIM enabled VR than not using it based on their previous experiences.

It can be observed from the results that the N-CEs participants' decision-making is affected by having access to assessment results, with a mean rank of 4.67, which was similarly observed in the box plots. The mean rank between the two groups showed a significant difference, and the assessment result influenced the CEs to a lesser extent. The scores were still high, with a mean rank of 4.17, but were significantly lower than the N-CEs, which could be seen in the box plots, as the change was smaller, and the variation within the group increased for several occasions.

5.4. Comparison between the Sustainability Assessments Using BIM-Enabled VR and without It (Addressing Q4 in Section 1)

A mean score between 3 (neutral) and 4 (agree) on the Likert scale for sustainability assessments using BIM-enabled VR can be observed. N-CEs' mean rank for VR's improvement in perceiving sustainability was 3.72, whereas the mean score for CEs was 3.45. In general, a higher grade of improvement in perception for sustainability assessment using BIM-enabled VR was observed in N-CEs than CEs. The mean overall ranking for the BIM-enabled VR influence on the perception of costs and the carbon footprint of building façade systems was 4.44. The results depict a positive influence of BIM-enabled VR on the improvement of sustainability assessments. The results obtained in the questionnaire also showed that the participants with the least experience in BIM and VR were most impressed with the quality and functionality of the 360-degree images.

As seen in question 11 from the questionnaire, a mean overall rating between 4 (agree) and 5 (strongly agree) was obtained, depicting a positive emphasis on the use of BIM-enabled VR to design efficient and sustainable buildings in the future, based on the participants' experience. It denotes that most participants prefer to use BIM-enabled VR solutions to design better buildings as opposed to conventional methods. A common comment from CEs also mentioned the benefits of the solution involving people with no prior experience in the construction industry.

6. Conclusions and Future Work

The research in this paper proposed a hypothesis enabling a VR experience in the design decision-making of different façade alternatives, comparing the costs and carbon footprint by using BIM-enabled VR technology. The outcome of the study enabled the understanding of user perception and preferences regarding design alternatives. The research results can be used for future studies for cost and LCA analyses, exploring individual components of the building when developing sustainable solutions. In particular, they can be used for:

- (a) BIM-enabled VR applications to be extended beyond just visualization: the use of VR can be beneficial during the conceptual phase as it can eradicate cost-overruns and errors in the later stages of construction. The experiment results from the questionnaire revealed that the N-CEs participants felt the most benefited by VR, whereas the CEs had more faith in BIM + VR as a tool for future design being more efficient and sustainable.
- (b) BIM-enabled VR to be utilized in tracking carbon footprint and cost, leading to lesser emissions and costs: it was observed that VR in combination with BIM +

QTO could enable the selection of economical solution without compromising on esthetics. Based on the experiments conducted, user participants preferred economical solutions to the more expensive ones. Likewise, VR in combination with BIM + LCA could help participants make better decisions, owing to an increased concern for sustainable solutions.

- (c) Understanding of these tools (BIM, cost estimation, LCA, VR) perceived by the user participants in terms of the impact on design decisions: the software used is beneficial during the conceptual design phase, as they produce LCA and cost assessments that help designers and clients make better decisions regarding the choice of materials used in the building. Based on the survey, not every user shared the same concern for the carbon footprint, as users leaned more towards the most economical or esthetic solution. However, based on simplified cost and carbon footprint results, it was evident that the users' perception changed substantially.

It can be summarized that the user participants positively embraced the ideas and aspirations of sustainability, and there was some evidence of participants preferring cost over sustainability. This can be regulated by bringing changes through government tax incentivization for sustainable buildings to help N-CEs, such as owners, reimburse the high capital costs involved. With many cities and countries becoming carbon neutral, it is essential to raise awareness among the general population about sustainable construction benefits.

Limitation and Future Study

An important limitation of the research project on used technology and materials was the inability to access the immersive VR lab at the department of engineering, Aarhus University, due to the COVID-19 pandemic. Thus, the immersive and interactive features of VR were less explored. The unavailability of operation costs, indirect costs, and other miscellaneous costs that can influence the decision-making strategy was another limitation. Future studies could shed more light on the detailed level cost estimation of construction projects. We have also studied alternative façade systems in this project (as was highly demanded by the companies, as per the survey we performed in Danish and Norwegian contexts), which could be replaced with other building components in similar studies.

Another limitation of this research project regards the biases on the used Likert scale and analysis for data collection, such as the central tendency bias, acquiescence bias, and social desirability bias, which might be faced while using a Likert-type measurement [49]. The central tendency bias is a robust finding in data from experiments using Likert scales to elicit responses [50]. Use of a paired comparisons model, and instructions such as (a) ensuring questions (and options) are clear, (b) avoiding forcing people to provide justification for answers, and (c) ultimately not allowing respondents to give the same rating twice could be carefully monitored while conducting experiments in future research work.

While BIM 3D model data is used for planning (4D) and costing (5D) [51–55], professionals and researchers are undergoing research processes to extend BIM' dimensions to Sustainability (6D), Facility Management (7D), etc. [56]. Conducting similar research to this paper will enable BIM practitioners to move towards further n-D development of BIM, evaluating the sustainability performance of projects to enable designers towards sustainable cities and buildings, strengthening relationships with clients, construction organizations, and other key stakeholders. As such, further investigation of the effects of immersion besides additional VR tool development can be considered as potential topics for future research.

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