Integrated applications of building information modeling in project cost management: a systematic review

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Abstract

Purpose – Implementing building information modeling (BIM) in construction projects offers many benefits. However, the use of BIM in project cost management is still limited. This study aims to review the current trends in the application of BIM in project cost management.

Design/methodology/approach – This study systematically reviews the literature on the application of BIM in project cost management. A total of 46 related articles were identified and analyzed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses method.

Findings – Eighteen approaches to applying BIM in project cost management were identified. The approaches can be grouped into cost control and cost estimation. Also, BIM can be applied independently or integrated with other techniques. The integrated approaches for cost control include integration with genetic algorithms, Monte Carlo simulation, lean construction, integrated project delivery, neural network and value engineering. On the contrary, integrated approaches for cost estimation include integration with cost-plus pricing, discrepancy analysis, construction progress curves, estimation standards, algorithms, declarative mappings, life cycle sustainability assessment, ontology, Web-based frameworks and structured query language.

Originality/value – To the best of the authors' knowledge, this study is the first to systematically review prior literature on the application of BIM in project cost management. As a result, the study provides a comprehensive understanding of the current state of the art and fills the literature gap. Researchers and industry professionals can use the study findings to increase the benefits of implementing BIM in construction projects.

Keywords Building information modeling (BIM), Systematic review, Cost estimation, Cost control, Project cost management

Paper type Literature review

1. Introduction

The construction industry is facing numerous challenges in the current economic climate, including the need for timely delivery of projects within budget as well as the growing demand for accountability and transparency in project cost management (Yin *et al.*, 2019). Furthermore, with the increasing complexity of construction projects, ensuring effective project cost management is essential. Ineffective project cost management can lead to delays, overruns and disputes, negatively impacting the reputation of construction professionals, organizations and

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industry (Rajabi *et al.*, 2022). In other words, ensuring effective project cost management in the construction industry is critical. Implementing building information modeling (BIM) is an approach that can improve project cost management in construction projects (Sami Ur Rehman *et al.*, 2022). BIM implementation improves project cost management and its two underlying processes – cost estimation and cost control (Goh *et al.*, 2014). However, without adequate information, the advantages of BIM in project cost management cannot be fully realized. Hence, it is crucial to synthesize the existing information to ensure the proper implementation of BIM in project cost management.

Although BIM provides different benefits to project cost management, many construction projects still fail to realize them. Not realizing the benefits of BIM in project cost management is a missed opportunity and a significant threat to project success (Yuan *et al.*, 2019). Not realizing the benefits can risk construction projects to incur higher costs, rework and errors (Bui *et al.*, 2016). These risks can lead to project failures and negatively impact the construction industry and society (Yuan *et al.*, 2019). On the contrary, poor project cost management will lead to more design errors and delays in the construction duration (Parsamehr *et al.*, 2022). Poor project cost management can also lead to more energy consumption and a less accurate and effective flow of information during operation and maintenance. In other words, ineffective use of BIM in project cost management can result in construction projects facing different issues that can lead to project failures.

Despite the different challenges in the construction industry, there is a glimmer of hope for the future. Through the full integration of BIM in project cost management, construction projects have the potential to overcome the persistent issues of cost overruns, disputes and delays (Oraee *et al.*, 2019). Furthermore, using BIM in project cost management provides a pathway to more effective and efficient cost control and estimation, leading to improved project outcomes (Rajabi *et al.*, 2022). However, the difficulties encountered in project cost management of construction projects are often rooted in a lack of familiarity with BIM. To address that difficulty and enhance the overall efficiency of construction projects, it is essential to have a comprehensive overview of prior works on BIM in project cost management.

The lack of familiarity with BIM is a significant barrier to its effective implementation in project cost management. To overcome this challenge and provide a comprehensive overview of prior works on BIM in project cost management, this study aims to review the current trends in the application of BIM in project cost management. Specifically, this study addresses the following research questions:

RQ1. What are the current trends in BIM applications in project cost management?

RQ2. How can the integration of BIM into construction projects improve project cost management?

RQ3. What gaps exist in research related to BIM and project cost management?

The objectives of the study are to identify and analyze the current trends in BIM applications in project cost management, evaluate the potential benefits of integrating BIM into construction projects for improving project cost management and identify the gaps in existing research related to BIM and project cost management. To achieve the research aim and objectives, a systematic review of existing literature using the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) protocol and thematic analysis was conducted. This study aims to fill a gap in the literature by being the first systematic review of prior works on BIM and project cost management.

The paper is divided into several sections. Section 2 provides an overview of BIM and its significance in the construction industry. This section discusses the benefits and challenges of

implementing BIM and the integration of BIM and project management. In Section 3, the process of data collection and analysis is explained, including the identification and analysis of relevant journal articles. Next, in Section 4, the results of the bibliometric and thematic analyses are presented. Then, Section 5 of the paper addresses BIM's impact on project cost management, including cost control and estimation, and provides research recommendations. Finally, in Section 6, the paper is summarized, highlighting its implications and limitations for future research.

2. Background

2.1 Benefits of building information modeling

BIM implementation has increased over time as construction industry professionals have realized its many benefits (Liu and Zhang, 2023). First, BIM enhances on-site communication and collaboration, which ensures that all stakeholders are aligned, and potential issues are addressed promptly. Second, BIM improves visualization in the designing phase (Jin *et al.*, 2019). Project stakeholders can use BIM to plan and overview the project, which helps to minimize errors and time consumption (Darko *et al.*, 2020). Third, BIM provides benefits in design coordination; BIM can generate better results than traditional methods, leading to fewer construction errors and reducing costs. Fourth, BIM can result in better scheduling of projects. It helps to identify potential issues and delays early on, which allows for more efficient use of resources and ultimately leads to a better project schedule (Jeong *et al.*, 2016). In summary, BIM has been found to increase productivity, promote better quality, facilitate building activities, overcome design clashes, as well as improve communication, site monitoring and safety.

2.2 Challenges for implementing building information modeling

Despite the many other benefits of implementing BIM in construction projects, some issues face the adaptation of BIM in many cases. One issue is the effective management of projects using BIM. One of the challenges is creating trust among stakeholders using BIM. Farouk *et al.* (2023) highlighted the factors, challenges and strategies of trust in BIM-based construction projects in a case study in Malaysia. Different priorities of design modelers could impact the project outcome without proper planning and management (Omer *et al.*, 2022). Therefore, proper BIM management should be used to get the full benefits of BIM. Another issue facing BIM implementation is that project managers want to guarantee the cost savings of implementing BIM. This issue is more visible in low-income countries than in middle- and high-income countries, where the cost is the major issue in implementing BIM in construction. Omer *et al.* (2022) found that constructive leadership behaviors in BIM-based construction projects were often characterized by tolerance and commitment, with reliability being a common trait and style. Conversely, the study found that intolerance was a common destructive leadership behavior in BIM-based construction projects. Therefore, adopting cost-effective approaches when implementing BIM is important (Farooq *et al.*, 2020). In a step toward increasing the benefits of implementing BIM in construction, this study aims to review the current trends in the application of BIM in project cost management.

2.3 Building information modeling and project cost management

There is little literature on BIM and project cost management. The work by Sepasgozar *et al.* (2022) aimed to identify gaps in the current literature on cost analysis and management in the construction industry. The work presented the results of a systematic review and provided a detailed content review of relevant papers, identifying critical factors related to project cost management and associated risks. Another work by Vigneault *et al.* (2020) aimed to develop an innovative framework for 5D BIM solutions in project cost

management. The findings create new awareness and knowledge about 5D BIM solutions for project cost management in a digitalized work environment. In contrast, the work by Tang and Liu (2022) examined the use of BIM in construction project cost management in China. The work used computational intelligence to demonstrate the benefits of BIM and provided a detailed analysis of its application in different stages of construction projects. The work sought to improve project cost management in the construction industry and enhance its efficiency in China. On the contrary, the work by Siong (2021) explored the capabilities of BIM in aiding project cost management in the construction industry. The findings of the work provided insights into the impact of BIM on project cost management in the construction industry. There is limited literature on BIM in project cost management, and no works review the applications of BIM in project cost management. Therefore, this study aims to review the current trends in the application of BIM in project cost management.

2.4 Past review works on building information modeling

Many review works on BIM indicate the impact of BIM in the construction industry. A work by Ismail *et al.* (2016) aimed to explore the use of BIM by quantity surveyors in different countries and assess the functionalities of BIM-based cost estimating software. The objective of the work was to offer suggestions for the optimal adoption of BIM in quantity surveying firms. The aim of the work conducted by Soust-Verdaguer *et al.* (2017) was to analyze the integration of BIM and life cycle assessment (LCA) in the building sector, with a focus on examining the potential of BIM to simplify data input and optimize output data and results during the LCA application. The aim of this work by Volk *et al.* (2014) was to provide a comprehensive overview of the state-of-the-art implementation of BIM in existing buildings. The work aimed to highlight the challenges and identify opportunities for further research. The work by Abdal Noor and Yi (2018) aimed to analyze the application of BIM within the construction industry, specifically focusing on identifying gaps in the existing literature. Through this work, it was discovered that there is limited to no research on BIM and railway construction. The objective of a work conducted by Tang *et al.* (2019) was to understand the integration of BIM and Internet of Things (IoT) devices and identify common areas of application, design patterns, limitations and future research directions in this field. In summary, BIM has been the subject of different works in the construction industry with a focus on exploring its usage, identifying challenges and opportunities for further research.

3. Methodology

To achieve the study aim, a systematic literature review (SLR) was conducted. SLR is a widely accepted method for conducting SLRs. SLR allows for a more in-depth analysis of the data and the identification of themes and sub-themes within the literature (Clarke and Braun, 2014). The SLR consisted of four main stages according to PRISMA (Selçuk, 2019). The first stage of the SLR, identification of journals, involved identifying relevant journals in the field of BIM and project cost management. This was done by searching for journals in the Scopus database. The second stage, the screening process, involved reviewing the titles and abstracts of the articles found in the previous stage to determine if they were relevant to the study objectives. The third stage, eligibility check, involved reviewing the full text of the articles that passed the screening process to determine if they met the inclusion criteria. This included ensuring that the articles were published in English, peer-reviewed and relevant to the study objectives. The final stage, inclusion, involved finalizing the articles that passed the eligibility check and conducting a snowballing process to identify additional articles

relevant to the study objectives. This was done by reviewing the references and citations of the included articles and searching for additional articles not identified in the initial search. The final stage, inclusion, involved finalizing. The review process is illustrated in Figure 1.

3.1 Identification of journal articles

This study starts by identifying journal articles using the Scopus database, as it indexes more articles than other databases and is frequently used for SLRs (Farouk *et al.*, 2021a). The search was conducted using the "title/abstract/keyword" feature. The initial search consisted of articles with any version of the word: (1) BIM in the title, abstract, or keywords; and (2) cost in the keywords sections. Then the inclusion criteria were the following:

- Only journal articles were selected. On the contrary, conference proceedings, book chapters, review articles and books were excluded.
- Only English articles were included, while other languages were excluded.

The final search term was: TITLE-ABS-KEY (BIM OR "building information modeling" OR "building information modelling") AND KEY (cost) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English"). The search was conducted on December 20, 2021. The final search term revealed a total of 452 articles. Then, another filtration was conducted where journals with two or more published articles were only included, resulting in a total of 230 articles.

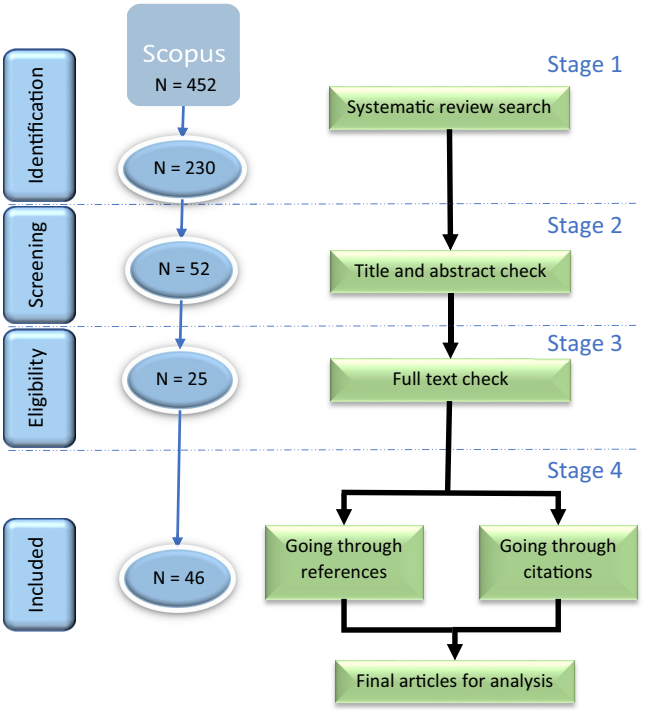

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Figure 1.
Systematic review framework

3.2 Screening process

In this stage of the study, a thorough title and abstract review were performed to identify relevant articles on BIM and project cost management. This stage is crucial as it allows for the selection of articles that are directly related to the research topic and have the most relevant information. By only considering articles that specifically focus on BIM and project cost management, the study is able to ensure that the data and insights gathered are relevant and of high quality (Rani *et al.*, 2023). The title and abstract screening resulted in a total of 49 articles, which were then carefully selected for further analysis. This stage lays the foundation for the rest of the study by providing a solid pool of relevant literature to draw from.

3.3 Eligibility check

In this stage of the study, a full-text check was performed to select the final articles that were suitable for further analysis. The full-text check is essential as it allows for a more detailed evaluation of the articles that were initially identified during the title and abstract review. This step ensures that the articles selected for further analysis meet the specific inclusion and exclusion criteria set for the study. The full-text check resulted in 25 eligible articles, which were then selected for further analysis. This stage is crucial as it allows for a more in-depth examination of the chosen articles and ensures that the data and insights gathered are of high quality and relevance to the research topic.

3.4 Snowballing

Due to the limited number of articles identified during the full-text check, forward and backward snowballing methods were used to identify additional relevant literature (Wohlin, 2014). The forward snowballing method involved searching through the citations of the identified articles, while the backward snowballing method involved searching through the references of the identified articles. Through this method, 21 additional articles were identified, bringing the total number of eligible articles to 46. This stage is important as it allows for a more comprehensive and inclusive review of the literature on BIM and project cost management. The snowballing method is commonly used in research to expand the results and ensure that the study is able to provide a thorough and reliable analysis of the current state of BIM in project cost management (Wohlin, 2014).

4. Results

4.1 The bibliometric data

This section presents an analysis of the countries, journals, author keywords and highest-impact publications related to BIM and project cost management. This information is extracted from the 46 selected articles to understand the current state of BIM in project cost management, identify patterns and trends, research gaps and most influential publications in the field.

4.1.1 Publication per year. The articles are distributed between 2005 and 2022, as shown in Figure 2. The distribution can be divided into two phases, before 2013 and after 2013 (i.e. nine years for each phase). Before 2013 (i.e. first phase), the average publication was less than one article per year. On the contrary, the average publication after 2013 (i.e. the second phase) is five articles per year. In other words, the second phase has articles five times greater than the first. The possible reason for this growth is the rapid development of technology relevant to BIM, including artificial intelligence and the IoT (Prabhakaran *et al.*, 2022).

4.1.2 Publication countries. Moving to the contributing countries, 16 countries contributed to the literature, as shown in Figure 2. China contributed the most, with nine articles, followed by Malaysia, South Korea, the UK and the USA, with five articles.

4.1.3 Keywords. The keyword network assists in adherence to the knowledge and discovering relationships between current knowledge and the intellectual organization of the work topic (Van Eck and Waltman, 2010). The analysis yielded a total of nine keywords meeting the threshold. The keyword "quantity surveying" was removed as it was unrelated. In addition, keywords with similar meanings were removed. As a result, six keywords remained, and the analysis results are shown in Figure 2.

4.1.4 Highest impact publications. As shown in Figure 2, the list of journals with the highest number of articles is presented. *Automation in Construction* has the highest number of published articles at eight. Then *Engineering, Construction, and Architectural*

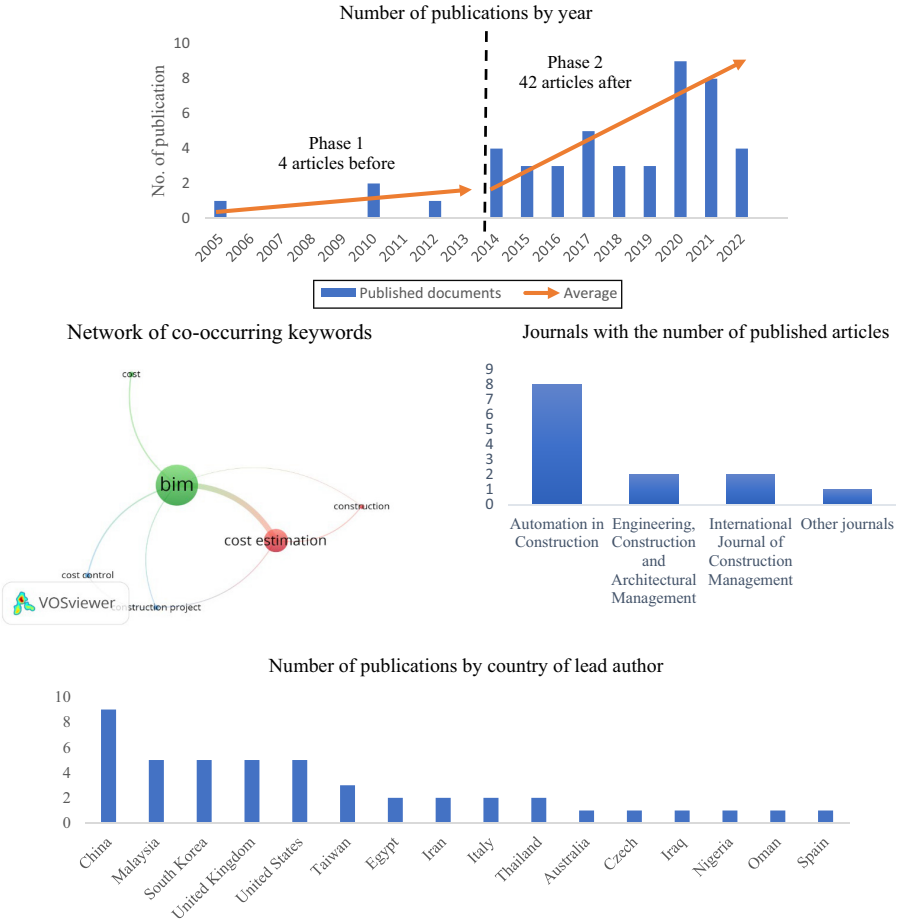

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Figure 2.
Bibliometric analysis results

Management and *International Journal of Construction Management* have two articles each. Besides those three, other journals have one article each on the topic.

4.2 Thematic analysis

Thematic analysis is a systematic method for identifying, organizing and providing insights into patterns and themes across the data set (Clarke and Braun, 2014). Thematic analysis is a common qualitative research method suitable for critically analyzing and categorizing data into themes and patterns (Farouk *et al.*, 2021b; Rani *et al.*, 2022). The analysis results revealed two main themes: cost control and cost estimation. These two themes can be divided into several sub-themes, as shown in Figure 3 with the definition of each technique in the adopted approaches.

5. Discussion

5.1 Cost control

5.1.1 Building information modeling standalone. Vitiello *et al.* (2019) proposed a framework to assess economic losses and optimize seismic retrofit operations using BIM. BIM minimizes project cost and time as well as increases output efficiency and quality by overcoming and finding solutions to common causes of delay, including estimation, clash detection and integration (Mohammed *et al.*, 2018). However, some limitations could be found due to difficulties in having a thorough contract as BIM complicates projects. Also, scheduled activities are not updated based on BIM element quantity changes (Shahhosseini and Hajarolasvadi, 2021). Feng *et al.* (2010) proposed a multi-dimensional computer-aided design (MD CAD) model as an extension of BIM. MD CAD contains and combines construction data for planning and management. The model generates a time–cost schedule for construction projects, assisting in project cost management and monitoring (Feng *et al.*, 2010). The results revealed that it has the potential to significantly reduce overhead efforts, reduce errors and improve the project.

5.1.2 Genetic algorithm and building information modeling. He *et al.* (2019) integrated GA with BIM to improve project cost management by optimizing the construction period and running costs. To achieve that, the methodology involves three steps:

(1) developing an algorithm by analyzing the characteristics that change construction periods and running costs;

(2) improving the developed algorithm and data processing processes; and

(3) integrating the improved algorithm into a BIM model.

This algorithm development methodology was proven successful and can be applied to other construction projects (He *et al.*, 2019).

5.1.3 Genetic algorithm, Monte Carlo simulation and building information modeling. Marzouk *et al.* (2018) integrated Monte Carlo simulation and GA with BIM. The integrated framework optimizes the selection of building materials and system alternatives for each cost element. GA selects the optimum alternative, while the Monte Carlo simulation assesses the selection using a fitness function (Marzouk *et al.*, 2018). The findings indicate that the framework can determine optimal building materials and systems using data on the life cycle and unpredictability cost. In addition, the proposed framework can also analyze the potential usage of green-building materials (Marzouk *et al.*, 2018). In other words, integrating BIM with GA and Monte Carlo simulation can help decision-makers choose sustainable and economical building materials and systems.

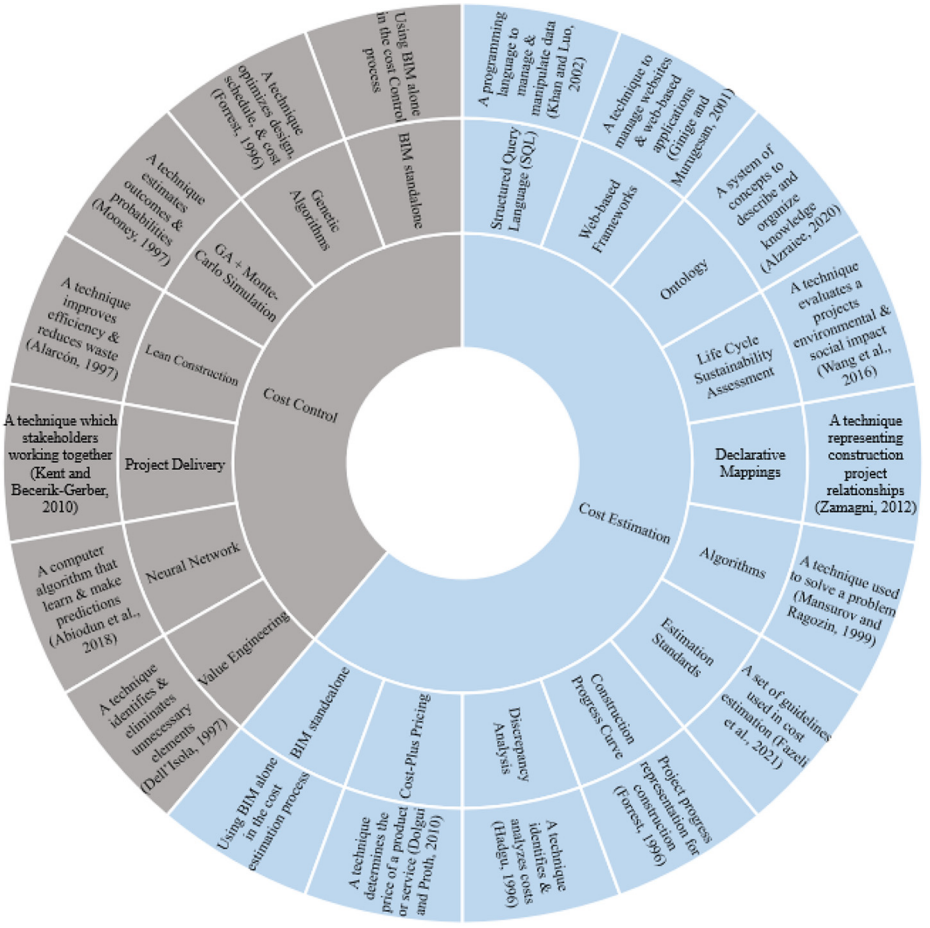

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Figure 3.
Overview of the results and related definitions

5.1.4 Lean construction theory and building information modeling. Wen (2014) integrated BIM with lean construction theory to improve project cost management. The results demonstrate that incorporating lean construction and BIM into construction projects can improve project efficiency, reduce non-value-added activities and control costs. As a result, project value and customer satisfaction are enhanced.

5.1.5 Project delivery and building information modeling. Mesa *et al.* (2016) integrated project delivery (IPD) with BIM. The research results showed the impact of IPD on the early involvement of practitioners in the design, open pricing, fair compensation and equitable allocation of responsibilities and risks. Some strategies were identified which promote project cost management:

- integrating activity-based costing and earned value management;
- integrating Monte Carlo simulation into 5D BIM to provide continuous cost estimation feedback; and

- using information and communication technology (ICT) to promote collaboration and create a strong bond among IPD members.

5.1.6 Neural network and building information modeling. Ding and Lu (2021) investigated the use of an integrated neural network comprehensive prediction model and BIM for project cost management. The results indicated that the proposed model, which combines the price advantages of ICT and BIM, can bring significant profits and effectively control costs, promoting enterprise development. This demonstrates the potential of using machine learning in conjunction with BIM in construction, including object detection and classification, quality control, quantity take-off and cost estimation. Various machine learning techniques such as linear regression, artificial neural networks, random forest, extreme gradient boosting, light gradient boosting machine, natural gradient boosting and AdaBoost can all be used in different ways within a BIM environment to achieve these capabilities (Chakraborty *et al.*, 2020; Koc *et al.*, 2021).

5.1.7 Value engineering and building information modeling. Li *et al.* (2021) proposed a framework for introducing BIM and VE to control and manage projects. The results revealed that the framework facilitates design modifications and information extraction in cost data. Another benefit of the framework is better overall quality and performance, which promotes better project cost management. As a result, the framework saves 10% in cost and time. However, the work was exclusively for a project in China, and results may differ between countries and projects. Therefore, future research can focus on real-time analysis of project schedules, safety and quality while implementing cost control changes (Li *et al.*, 2021).

5.2 Cost estimation

5.2.1 Building information modeling standalone. Lee *et al.* (2020) proposed a technique for estimating costs in BIM before the collaboration process involving making sections in the early designing phase. The results suggest that the technique allows quick review for design alternatives, resulting in reduced life cycle costs and shorter decision times. Also, Cheung *et al.* (2012) proposed incorporating cost estimation in the early design stage. The technique focuses only on representing early-stage design cost modules from the low-impact design exploration.

5.2.2 Cost-plus pricing and building information modeling. Koo *et al.* (2017) integrated the cost-plus pricing technique and BIM. Cost-plus pricing is a scheme for estimating design costs. The cost-plus technique estimated the amount of labor invested in particular design work. The technique needs a breakdown of the many types of "work items" accomplished during a project's design phases and the formalization of items to allocate person-hours to each item. The framework incorporates cost information from 54 projects. The framework was inserted into an Excel-based system, allowing the estimation of 11 different building project types. The proposed technique was verified based on comparing the cost of ten projects. Results indicated a positive 5.3% difference between the costs estimated by the system and actual costs. Therefore, the framework can accurately estimate project costs, allowing stakeholders to make better decisions.

5.2.3 Discrepancy analysis and building information modeling. Kim *et al.* (2019) showed how discrepancy analysis could be applied to observe quantity discrepancies (QDs). The objective of the work was to identify and analyze the 6%–9% QD in quantities collected from various building interior components to enhance the accuracy of cost estimation using BIM. The QD was calculated as the ratio between the target variable of each material in the individually modeled object models and the compositely modeled object models. The analysis was performed on two models: individually modeled and compositely modeled

objects. Also, project activities and materials that could affect cost estimation were identified. Moreover, the work assists in the early risk prediction caused by QD.

5.2.4 Construction progress curve and building information modeling. Wang *et al.* (2016) proposed a BIM model that creates a cost-based construction progress curve. A construction progress curve is an excellent tool for presenting project status and anticipating potential scenarios. It is extensively used to control the schedules of construction projects (Wang *et al.*, 2016). The primary objective of the technique is to deal with the precise construction schedule and multiple cost items to produce a cost-based construction progress curve. The work highlighted that the cost and unit prices must be uploaded to the proposed model. The case study illustrates four features of the model and its viability. Uploading these items is crucial in automating BIM in the cost estimations process. The work could act as a key for automating the use of BIM in cost estimations.

5.2.5 Estimation standard and building information modeling. Fazeli and Dashti (2021) presented the integration between cost estimation standards and BIM. A semi-automated BIM-based cost estimation technique enables an accurate and agile system to estimate project costs depending on design scenarios. The model was used to estimate the cost of the architectural discipline in a real construction project. The results revealed an acceptable cost estimation and could help practitioners to have an agile and accurate BIM-based cost estimation of different scenarios during the design process, as the proposed technique reduces the time of cost estimation. Moreover, it provides a practical roadmap for BIM-based cost estimation for different countries.

5.2.6 Algorithm and building information modeling. Zhao *et al.* (2019) proposed a BIM-based analysis based on the GA network. The GA model gives the prediction for the BIM cost. In the modeling process, the fitness selection operation, cross operation and mutation operation were designed in detail. A case study on 20 high-rise buildings in China revealed that the proposed technique could easily estimate the project cost (Zhao *et al.*, 2019). The advantage of the proposed technique is its ability to predict and optimize engineering costs providing a new idea for the field of building engineering. On the contrary, Tokla and Subsomboon (2020) presented an algorithm that automatically estimates building costs by exporting building component quantities from a BIM program to another program (e.g. Microsoft Excel). The algorithm creates a list of specialized work breakdown structures, construction specifications and unit costs based on the local standard. This algorithm can enhance the BIM-based quantity take-off process and cost estimation. Also, the proposed algorithm could aid estimators and decision-makers in reducing the duration and boosting the precision of the cost estimation procedure.

5.2.7 Declarative mappings and building information modeling. Lawrence *et al.* (2014) integrated declarative mapping and BIM to explore the relationship between BIM objectives and cost. In declarative mapping, rather than actual implementations, the primary goal is to express the attributes of run-time entities. The important premise is that the cost estimator will create mappings to explain the relationship between their cost estimate and BIM. The proposed system operates independently of all software systems. The key component of this strategy is that the cost estimator will produce mappings to demonstrate how their cost estimates are related to the building designs. The technique was validated through two construction projects and interviews with construction experts. The technique could decrease the time needed to update the estimated time given, generate more accurate cost estimation and provide broader expanded coverage of cost estimation.

5.2.8 Life cycle sustainability assessment and building information modeling. Soust-verdaguer *et al.* (2022) proposed a systematic way to harmonize cost estimation. It represents and validates the consistency of the "element technique" when conducting the

Life Cycle Sustainability Assessment (LCSA) in BIM. The element method is based on dividing building elements into smaller parts, referred to as elements, and counted as units of quantity (Lützkendorf, 2019). The "element technique" is a streamlined technique widely used in building design for cost estimation (Bernardino-Galeana *et al.*, 2019). In theoretical research, the "element technique" is also considered by the literature as an appropriate strategy to incorporate sustainability and cost assessment during the early design stages (Lützkendorf, 2019). This technique's consistency enables assessments of different design scenarios and reduces model checkup and quantity take-off errors. The proposed technique can help provide a transparent data structure during design, as the designer can start with a reliable data structure to support assumptions and fill in gaps.

5.2.9 Ontology and building information modeling. Lee *et al.* (2014) proposed an automated technique to search for work items suitable for building elements and materials. The technique involved three steps: extracting BIM data, including work items and retrieving relevant information. The proposed ontology can be used in realistic simulations. Abanda *et al.* (2017) also proposed an ontology-based technique involving three main steps: identifying BIM tools and software, modeling the ontology and implementing the developed ontology in an ontology engineering editor. The ontology reduces errors and increases task efficiency. The ontology-based techniques contribute to the full automation of cost estimation while increasing reliability. The proposed ontology was tested on Navisworks, and other end-users can change the ontology to match their needs.

5.2.10 Web framework and building information modeling. Niknam and Karshenas (2015) proposed a Web framework that integrates Semantic Web and Semantic Web Service technologies with BIM. The Semantic Web is an extension of the present in which information is well-defined, allowing computers and people to collaborate (Berners-Lee *et al.*, 2001). Semantic Web Service is a component of the semantic web; it uses markup that renders data machine-readable in a sophisticated manner (McIlraith *et al.*, 2001). The framework consists of three parts, creating a BIM base, creating an assembly and work item base and applying the semantic web services. To validate the framework, it was compared to another estimating program called WinEst. Compared to WinEst, the framework was 35 min faster (Niknam and Karshenas, 2015). Another benefit is its ability to submit material resource specifications to suppliers and retrieve material unit cost data for updating material cost databases.

Yousif *et al.* (2020) proposed another Web-based framework to estimate construction costs. The framework was developed using ASP.NET and C# as programming languages. The work included theoretical and practical aspects necessary for project success. The main contributions of the framework include but are not limited to automating quantity take-off, developing a Web-based framework, deploying a database management system, computing more reliable and valid calculations, offering a user-friendly interface, automating the reading and importing of construction map data and providing computation equations that are approved by experts. The framework could reduce manual work, solve quantity survey issues, reduce estimation costs and cut calculation errors (Yousif *et al.*, 2020).

5.2.11 Structured query language and building information modeling. Alzraiee (2020) proposed a BIM-based plug-in using Structured Query Language (SQL). SQL is a sophisticated tool for managing data stored in a relational database management system (Kate *et al.*, 2018). The proposed plug-in creates an interoperable information management system that transacts data to connect work items and subjective aspects of BIM elements. As a result, project stakeholders can use the plug-in to accurately estimate project costs (Alzraiee, 2020). The work's most important contribution is a plug-in that can interoperate with different BIM software.

5.3 Summary and research recommendations

This study has identified two main themes through an SLR: cost control and cost estimation. Cost control consists of seven sub-themes referred to as "approaches." The integrated cost control and BIM approaches include integration with GAs, Monte Carlo simulation, lean construction, IPD, neural network and VE. On the contrary, cost estimation consists of 11 integrated approaches with BIM. The integrated approaches include integration with cost-plus pricing, discrepancy analysis, construction progress curves, estimation standards, algorithms, declarative mappings, LCSA, ontology, Web-based frameworks and SQL. The identified approaches were critically discussed; each approach's mechanism, advantages, limitations and recommendations were presented and summarized in the following Figure 4. The following paragraphs will briefly mention a few of the critical limitations and recommendations that could be highlighted from the identified articles.

BIM standalone can improve cost control, efficiency and quality of output, but its benefits may be limited as project complexity increases. To address this, future research should explore approaches that can overcome limitations caused by project complexity (Shahhosseini and Hajarolasvadi, 2021). Integrating GAs with BIM has shown efficiency in dealing with construction cost and time, but randomness in the search procedure can cause inconsistent search results. Thus, future research should focus on addressing this limitation (He *et al.*, 2019). IPD and BIM have many features that can reduce effort errors and improve performance. However, physical constraints between building components, workspace resources and productivity can be challenging to overcome. Thus, more information and updates are needed to better integrate IPD and BIM (Elghaish *et al.*, 2020). Integrating VE and BIM has shown benefits in saving time, cost and improving project quality and performance. However, future research should focus on real-time analysis of project schedules, safety and quality while integrating VE and BIM. In addition, future research should consider different types of projects outside of China (Li *et al.*, 2021).

Using BIM alone is efficient and faster with reliable and compensative solutions compared to standard project cost estimating techniques. However, more awareness and implementation of BIM in cost estimation are recommended (Hong *et al.*, 2020). The "cost-plus pricing and BIM" framework requires more testing to validate its robustness. "Discrepancy analysis and BIM" needs future research to identify QDs on other buildings and criteria (Kim *et al.*, 2019). The "construction progress curve and BIM" approach reduces schedule cost and time by creating a cost-based progress curve. However, further investigation is needed for the s-curve in progressed projects, and the approach should be developed for different divisions (Wang *et al.*, 2016). Integrating declarative mappings and BIM can reduce the time needed in cost estimation and generate more accurate cost estimation. Future research is recommended to develop more strategies and assist in dealing with old or new mappings (Lawrence *et al.*, 2014). The "LCSA and BIM" approach is a practical method that provides a transparent data structure during the design stage. Future research is recommended to test the accuracy of the approach on other structure types and countries (Yousif *et al.*, 2020).

6. Conclusion

The use of BIM in construction projects has been on the rise in recent years due to its potential to improve construction time, cost and quality. Despite recognizing the potential benefits of BIM, the application of BIM in project cost management is still not fully realized. This study aimed to review the current trends in the application of BIM in project cost management by conducting a SLR of 46 articles to analyze the applications of BIM in project cost management. Through thematic analysis, 18 approaches to using BIM in project cost management can be grouped

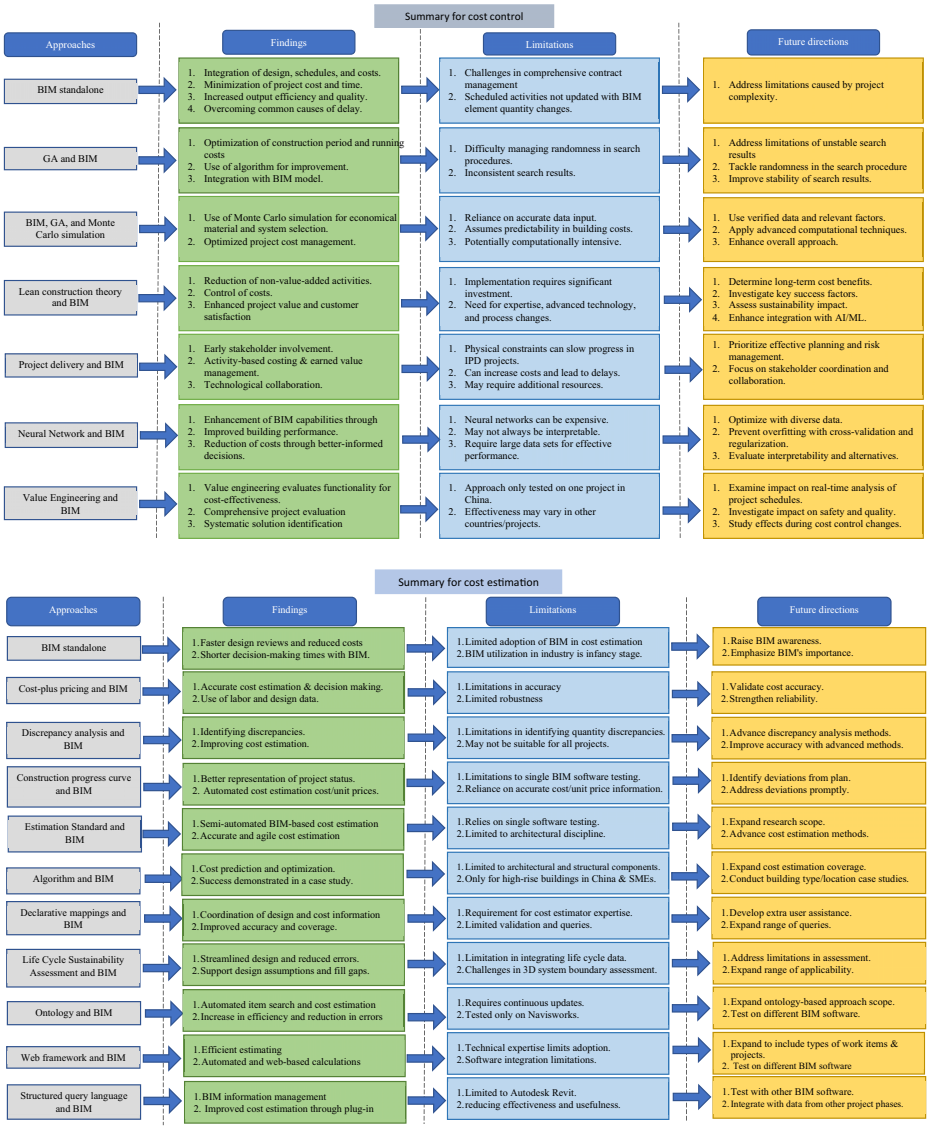

Figure 4.
Summary of the identified approaches and their related findings, limitations and future directions

Source: Author's own creation

under these two main themes (cost control and cost estimation). Also, BIM can be applied independently or integrated with other techniques. The integrated approaches for cost control include integration with GAs, Monte Carlo simulation, lean construction, IPD, neural network and value engineering. On the contrary, integrated approaches for cost estimation include integration with cost-plus

pricing, discrepancy analysis, construction progress curves, estimation standards, algorithms, declarative mappings, LCSA, ontology, Web-based frameworks and structured query language.

The study presents both theoretical and practical implications for the construction industry and researchers. The theoretical implications of this study are significant as it sheds light on the usage of BIM in project cost management. The study provides a comprehensive overview of the various approaches used to apply BIM in project cost management, thereby addressing a knowledge gap in the field. The findings serve as a reference for future research efforts, guiding researchers to focus on developing new and improved methods. The study identified two main themes, cost control and cost estimation, offering a better understanding of the areas where BIM can effectively be used. In addition, the study highlights the strengths, limitations and recommendations for each of the 18 approaches, providing a comprehensive view of the state-of-the-art. These insights can inform future research and practice in the field, leading to further advancements in the use of BIM in project cost management. In conclusion, the study provides valuable contributions to the existing body of knowledge and will likely have a lasting impact on the construction industry.

In terms of practical implications, the study is of considerable importance for policymakers and industry practitioners. It emphasizes the need to develop specific methods and processes for incorporating BIM into project cost management practices to fully realize its potential benefits. This information can be valuable for policymakers in their decision-making regarding implementing BIM in construction projects. Industry practitioners can use the list of BIM applications in project cost management to enhance the benefits of using BIM in their projects. However, they should also take into account the limitations of the list and carry out additional research to determine best practices for the effective usage of BIM in project cost management. The list of approaches' benefits, limitations and recommendations could help practitioners develop more comprehensive strategies to enhance decision-making. In summary, the study results indicate that BIM has the potential to enhance project cost management and thereby underscore the significance of conducting further research in this field. The study provides a comprehensive rundown of BIM applications in project cost management that can help researchers and construction professionals maximize the advantages of using BIM in their projects.

Although the results of the study demonstrate the potential of BIM in improving project cost management, it is important to acknowledge some limitations. Firstly, the focus of the study is limited to BIM applications in project cost management and does not encompass other aspects of construction projects. Secondly, the literature search was performed using only the Scopus database, which may result in the omission of relevant articles. Nevertheless, the authors used the snowballing method to overcome this limitation and ensure the comprehensiveness of the list, providing a more accurate representation of BIM applications in project cost management. Thirdly, the language of all reviewed articles was English. Lastly, the study does not involve primary data collection as it solely relies on reviewing published articles. Future research could conduct case studies to provide an alternative understanding of how BIM can be applied in project cost management and the potential challenges and opportunities in practice. Despite these limitations, the study objectives were adequately met as it offers a comprehensive overview of BIM applications in project cost management and underscores the need for further research to fully realize the benefits of BIM in construction projects and establish best practices for its effective use in project cost management.

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