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Review

BIM and Digital Tools for State-of-the-Art Construction Cost Management

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Abstract: Cost overrun has remained a key risk of construction projects that can be prevented by utilizing new technologies. This paper aims to identify the gap in the literature, which can potentially be addressed by using digital tools and technologies, by reviewing the current and state of the art practices. The paper presents the results of a systematic and critical content reviews on cost overruns, to address the question of what factors are affecting the cost overrun. This paper also reviews how building information modeling (BIM) in conjunction with other tools, such as the common tools in the Asia and Asia Pacific regions, are used for cost estimation and monitoring. The paper presents the results of the content review, including their contributions and limitations, which are also used to set key directions for future investigations. A total of 176 papers was identified to develop the construction cost management (CCM) dataset. The method was a mix of systematic reviews, including co-authorship network analyses, co-occurrence analytical map development covering 5671 keywords, and content analysis including theme identification and a critical review of selected papers. The paper critically reviewed 63 selected papers from CCM, which are divided into four clusters based on their scopes: BIM adoption for cost estimation and quantity surveying; BIM implementation for a bill of quantity, risk paths, and cost overruns; cost control and management; and, finally, BIM, virtual design, and value management. A trend analysis using a set of 16 themes (e.g., 3D model, BIM, Decision, Energy, and Life Cycle) for all the papers over the past ten years was developed. The content of each cluster of papers was reviewed based on the frequency of the selected themes in each cluster. The content of each cluster of papers was also reviewed critically and gaps were identified, so a set of directions for future investigations are presented.

Keywords: cost overruns; cost mitigation strategies; cost controlling; quantity surveying; revit; CostX; glodon quantity software; BIM; quantity take-off; measurement; construction cost control methods

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1. Introduction

Cost overrun is one of the most impactful risks in construction projects, and, being such a dynamic and complicated factor, it has been difficult to fully mitigate. While there are many investigations on factors affecting the project cost variations, cost overrun remains the key concern of many projects and companies in construction [1]. The main reason is that the construction industry is very resource-intensive, so many projects face resource scarcity, cost variations of materials and equipment, unexpected costs, and incidents during the construction process [2]. Cost overrun refers to any unpredicted changes in a construction project budget that may affect the project's total cost. Table 1 shows examples and evidence

on cost overrun in different contexts and years. For example, Pilger, Machado [3] suggest that road infrastructure projects are complicated and require a diverse range of materials. Due to enormous variance in construction circumstances that might occur in different sites, road construction varies from other building and manufacturing processes. The nature of construction may affect cost overruns, requiring digital tools to monitor, predict, or control the project costs.

Table 1. Evidence of cost overrun in various projects or countries.

Country Reported	Example of Cost Overrun
Ethiopia [4]	In Ethiopia, 80% to 100% of the road and railway projects experienced cost overrun. Example of road project [3].
East Asia [5]	The cost overrun of East Asia was 22.04%, while that of the whole of Asia was 26.24%.
Nigeria [6]	In Nigeria, 92.96% of Federal Capital Territory Authority Road Construction Projects suffered an average cost overrun of 54.62%.
Hong Kong [7]	Hong Kong transportation construction projects experienced 39.18% cost overrun on average.
Brazil [8]	71% of 231 Brazilian construction projects experienced cost overrun by 14%.
Malaysia [9]	A Malaysian survey in 2016 showed that 26.5% of construction projects experienced cost overrun. This survey is taken from different construction companies, including government agencies, contractors, consultants, and developer firms.
Iran [10]	Iranian construction projects faced 15.4% cost overrun.
Qatar [11]	Qatari public projects, built between 2000 and 2013, faced a 54% cost overrun while the maintenance projects were 50%.
Ghana [12]	72% of 321 Ghanaian public construction projects faced cost overruns.
Brazil [13]	72% of 145 Brazilian construction projects experienced cost overrun.
Jordan [14]	Jordanian road construction projects faced a considerable discrepancy between the initial estimated cost and final cost, which was 101%–600%, with an average of 214%.
Malaysia [15] Malaysia [16] Malaysia [17]	Over 50% of Malaysian projects experienced cost overruns. 89% of the Malaysian construction projects faced cost overruns. In particular, 46.8% of public and 37.2% of private projects did not face cost overrun.
US [18]	77% of the US highway projects saw a 50% of cost overrun.
UK [19]	The 2012 London Olympic infrastructure saw growth from $1.8 billion to $4.7 billion in cost. Boston's tunnel project experienced project costs significantly rose from $2.5 to $14.63 billion.
Australia [20]	267 Australian construction projects faced a cost overrun of 12.22%.
Netherlands [21,22]	Dutch transportation infrastructure projects saw 16.5% cost overrun on average. The Netherlands construction projects experienced cost overrun, with their figure standing at 10% to 21.7% for roads and rails.
Ethiopia [23,24]	80% of Ethiopian road projects faced the cost overrun.24 Ethiopian projects faced 80% cost overrun.
South Korea [25]	87% of road projects in South Korea faced cost overrun.
South Africa [26]	Only 35% of South African construction projects were finished within the estimated cost.
Portugal [27]	The minimum average cost overrun in Portuguese construction projects was 12%.
Canada [28]	82% of road projects in Canada faced cost overrun.
Nigeria [29]	The minimum average percentage of Nigerian construction project cost overrun was 14%.
Norway [30]	Norwegian road projects faced a cost overrun from 5.9% to 183%.
North America [31–35]	Based on the results of research on 258 European and North American Transport construction projects, the average cost overrun was 28%. With rail projects standing at 44.7% on average, followed by that of fixed-links and roads with 33.8% and 20.4%, respectively. 94% of road projects in the USA faced cost overrun.
Global [32]	The average cost overrun globally was 28%.

Table 1. *Cont.*

Country Reported	Example of Cost Overrun
UK [36]	In the UK, the projects saw an average of 47% cost overrun.
Palestine [37]	76% of Palestinian construction projects faced cost overruns.
Indonesia [38]	In Indonesia, only 51.7% of construction projects did not face cost overrun.
Indonesia and South Africa [38]	Only 20% of Indonesian and 35% of South African construction projects were finished within the estimated cost.

In the conventional project delivery, design documents are used to estimate the project cost before value engineering may be conducted for the final decisions about the design and alternatives. This process is repeated for alternatives and can be a time-consuming practice. Using new information systems and models such as 5D BIM, all the design options, including the associated costs of each design scenario, can be evaluated concurrently. However, more practice and lessons on how digital tools can efficiently be utilized are needed to enhance the process of cost estimation, which can be helpful in the financial management process. This study aims to review the current literature and identify the relevant gaps.

This paper aims to identify research gaps and develop future cost overrun directions based on a systematic search, and the selected papers are critically reviewed. This paper's objective is to discuss new potential solutions to the problem of cost overrun, which still remains a common critical issue in construction projects. The initial step in this work is to identify articles in a methodical manner, investigating cost and cost overrun in construction. Next, a content analysis is conducted to thoroughly evaluate the relevant articles and offer a thorough grasp of the current literature. Finally, the paper analyzes the gap and develops directions for future investigations.

2. Review Method

The review method is designed based on two key research questions: (1) what factors are affecting the cost overruns? and, (2) what are the new technologies, techniques, and trends that can improve cost management or prevent cost overruns? To address these research questions, a systematic review is carried out to find relevant papers and reports. This article's literature collecting and filtering technique is a wide, top-down strategy that gathers articles using broad phrases and queries first, then filters out those that may not be relevant to the research. This strategy, which comprises the three-step procedure below, has been proven to be more efficient than a constrained, bottom-up approach: (1) find and filter relevant publications; (2) classify and analyze articles for in-depth study; and (3) assess and synthesize the literature.

Various academic databases, such as Scopus and Google Scholar, are used for conducting a systematic search on the chosen topic. In addition, to ensure that relevant articles that may not have been included in a database would be identified, the references of selected articles were skimmed to find some more relevant papers to be considered in the present review.

Using a different set of keywords, articles related to cost control or management that may affect the project's total cost were searched for and reviewed, generating the most common keywords to set the final search strings for a systematic review to make sure no key articles are missed. For example, one search string that was input was "cost overrun," which resulted in over 1800 results. Since this included many irrelevant articles, more complex strings were used, such as 'cost' OR 'cost overrun', AND 'construction industry' OR 'construction project'. Furthermore, to include different spelling and grammar (e.g., visualization, visualization, and modeling), we utilized the asterisk (*) function, which enables any characters following it (see Table 2). The initial search resulted in 176 papers. Applying the filtering criteria, including scope, years from 2010 to 2020 covering the recent

decade of investigation in this field, journal articles in English, and duplicates that occurred in multiple queries, resulted in 104 records that will be used in the analysis.

Table 2. Examples of query strings in databases and results.

Selected String	Results Prior to Filtering
(TITLE-ABS-KEY (cost overrun)	1838
(TITLE-ABS-KEY (cost overrun AND construction)	704
(TITLE-ABS-KEY (cost OR "cost overrun" OR "cost estimate *" OR "quantity surveying") AND TITLE-ABS-KEY (bim OR "Building Information Model *")	2050 document results
(TITLE-ABS-KEY ("Cost control" OR "cost overrun" OR "cost estimate *" OR "quantity surveying") AND TITLE-ABS-KEY (bim OR "Building Information Model *") AND TITLE-ABS-KEY ("Construction industry" OR "Construction project"))	176
(TITLE-ABS-KEY ("Cost control" OR "cost overrun" OR "cost estimate *" OR "quantity surveying") AND TITLE-ABS-KEY (bim OR "Building Information Model *") AND TITLE-ABS-KEY ("Construction industry" OR "Construction project")) AND (EXCLUDE (PUBYEAR, 2022)) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j"))	104

Note: CCM refers to the construction cost management dataset.

Figure 1 shows the number of publications focusing on cost management from 2010 to 2021. Figure 2 also show the results of the search within Scopus, including 104 articles from different countries. Surprisingly, the selected search combination (refers to Table 2) shows that journal publications are limited to prior to 2010. However, the number of articles in the field has been increasing in recent years.

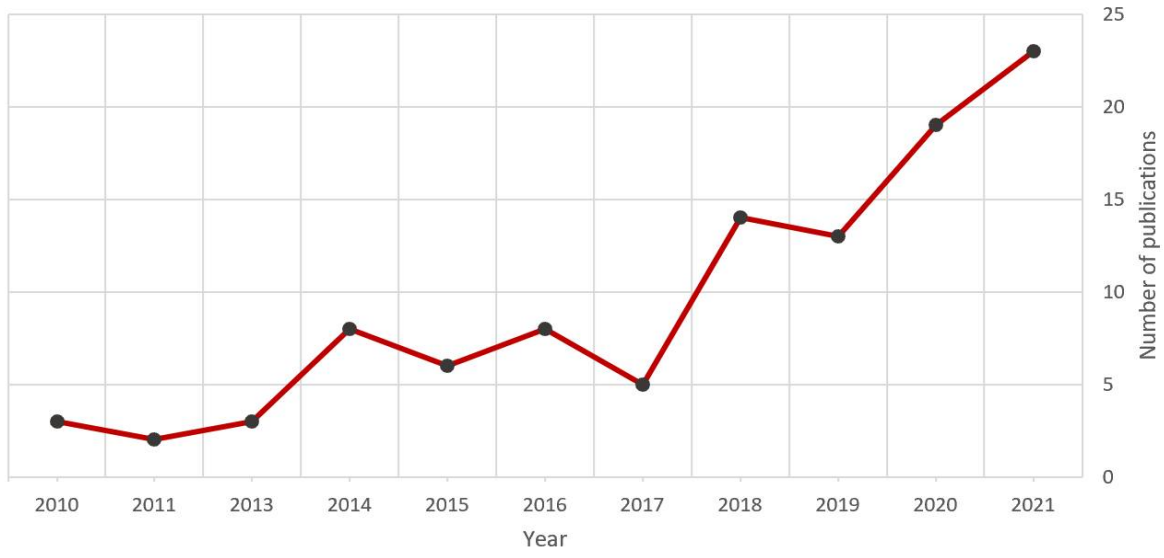


Figure 1. The number of relevant journal articles per year, based on the search results.

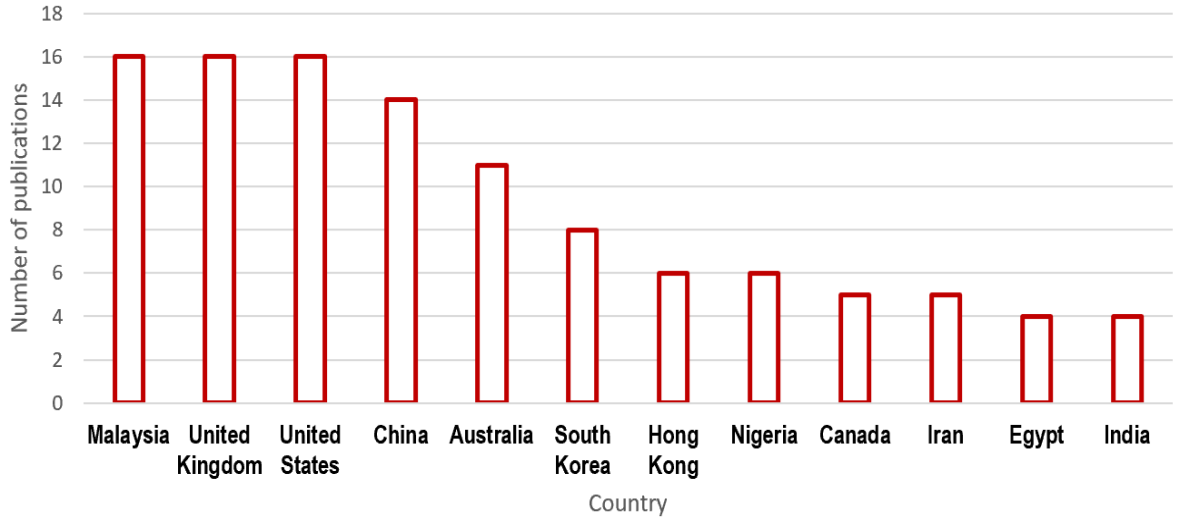


Figure 2. The distribution of the 104 journal articles by country from 2010 to 2021.

3. Bibliography Analysis

A bibliography analysis has been conducted, including co-authorship and co-citations, for determining the linkages between the construction cost management literature, based on the selected strings (refer to Table 2). The bibliography analysis, the analysis eliminates bias during the search, article selection and analysis. Based on citation records and cited references, the used bibliometric approach aids in discovering commonalities and likely patterns of research [39–41]. This helps scholars to learn from the current practice, including limitations and gaps, so that they can be filled in the future.

Figure 3 displays the outcome of a thorough counting method co-authorship analysis. An author's minimal number of papers is taken into account as 2, so 2009 authors and co-authors of 337 selected research items were included and visualized in Figure 3.

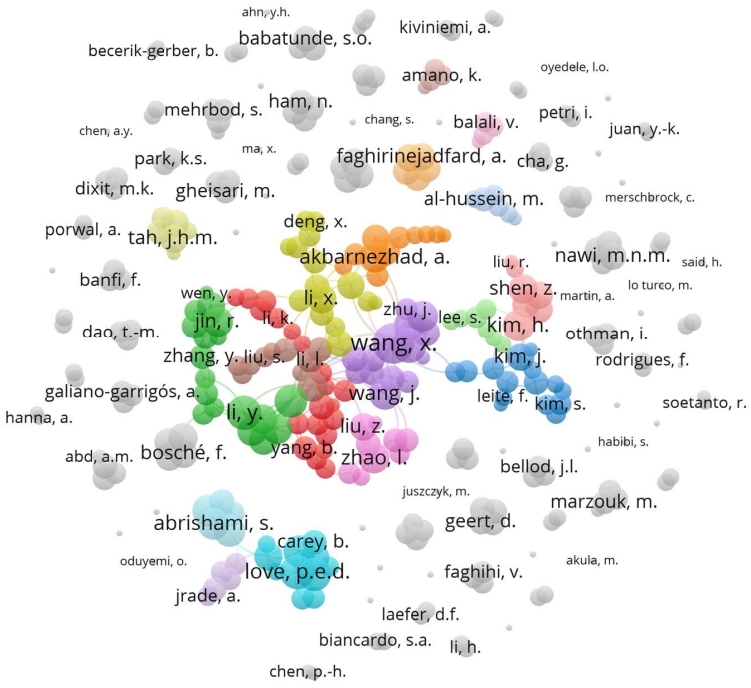


Figure 3. Visualization of co-authorship network for all 337 co-authors, out of 2009 co-authors with a minimum of two articles, using the full counting technique based on CCM, including 770 articles. Note: the total link strength was used for visualization.

The overall strength of co-authorship linkages with all authors and co-authors was determined for each of the 2009 researchers, and the strongest link strength was used to visualize Figures 2 and 3. The co-occurrence analysis map of keywords based on the initial CCM bibliographic dataset is shown in Figure 4. Figure 4 shows a total of 1151 keywords out of a total of 5671 keywords for this visualization, with a minimum number of 2 for co-occurrence visualization.

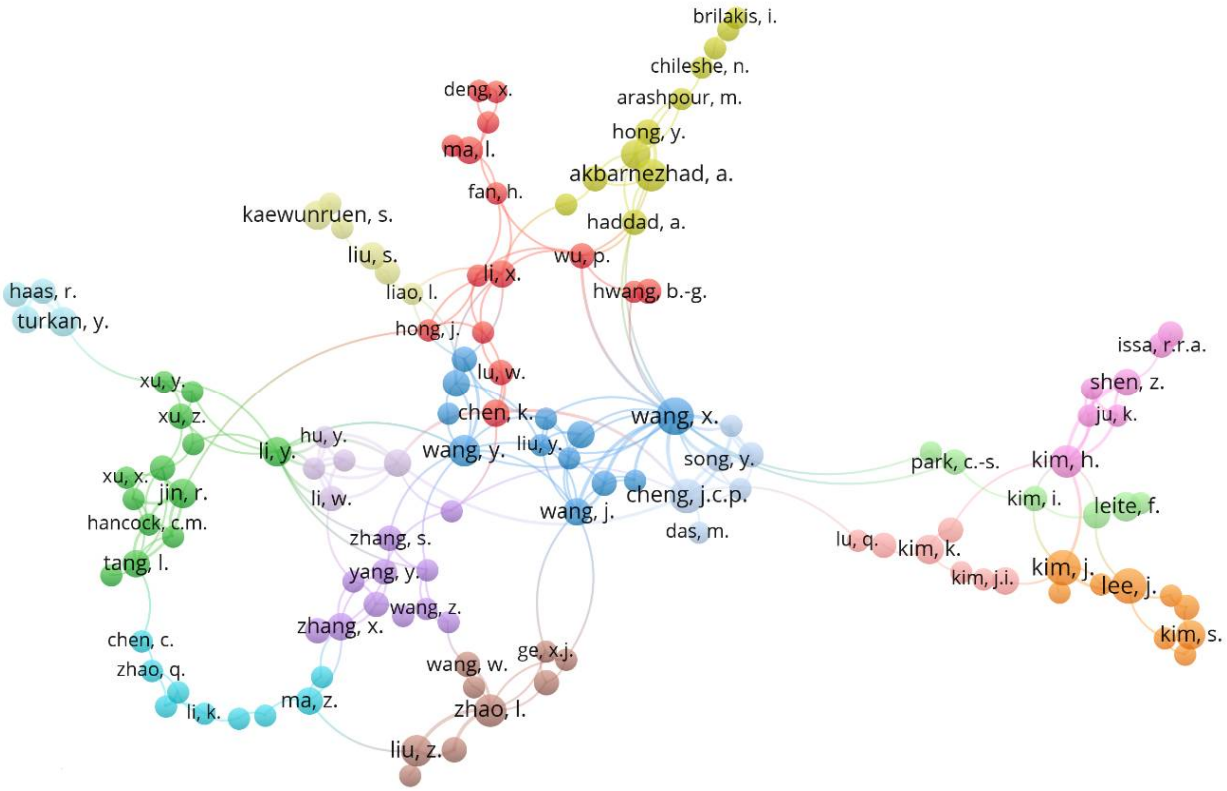


Figure 4. Visualization of co-authorship network for the only 130 connected co-authors based on the full counting techniques applied on the 770 articles of CCM.

The co-occurrence analysis map of keywords based on the initial CCM bibliographic data set is likewise shown in Figure 5, but the minimum number of co-occurrences was chosen as 2 to identify the most common themes. Figure 5 shows a total of 1151 from 5671 sample keywords.

Figure 6 shows that cost and cost-effectiveness are related to most of the high-frequency themes or keywords such as automation, BIM, construction projects, and buildings. The figure also shows that most of the keywords are repeated from 2016 onwards, which shows there might be a change in trending keywords and themes from 2010 to 2016; thus, further investigation is required. Figure 7 illustrates a co-occurrence network of keywords developed based on CCM.

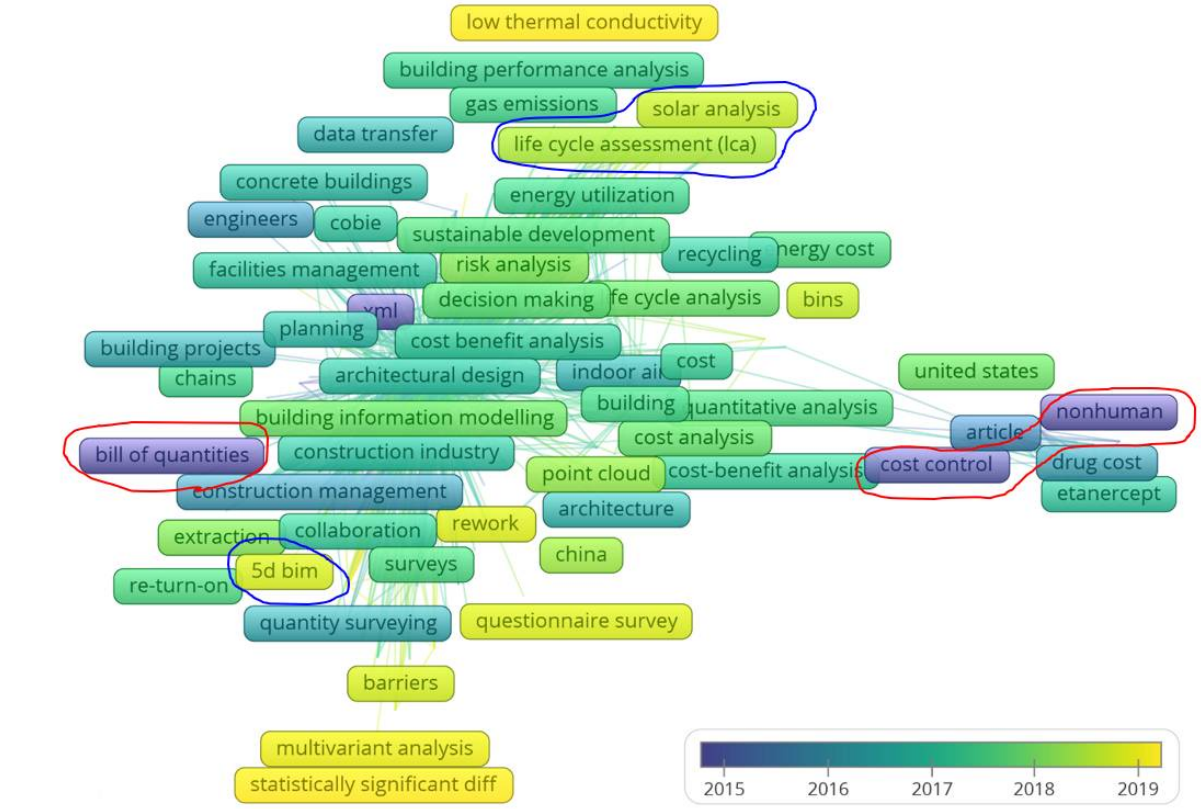


Figure 5. Co-occurrence analytical network of keywords identified from the merged CCM dataset. Note: with the minimum number of co-occurrences of 2, 1151 out of 5671 keywords are identified using the greatest total link strength.

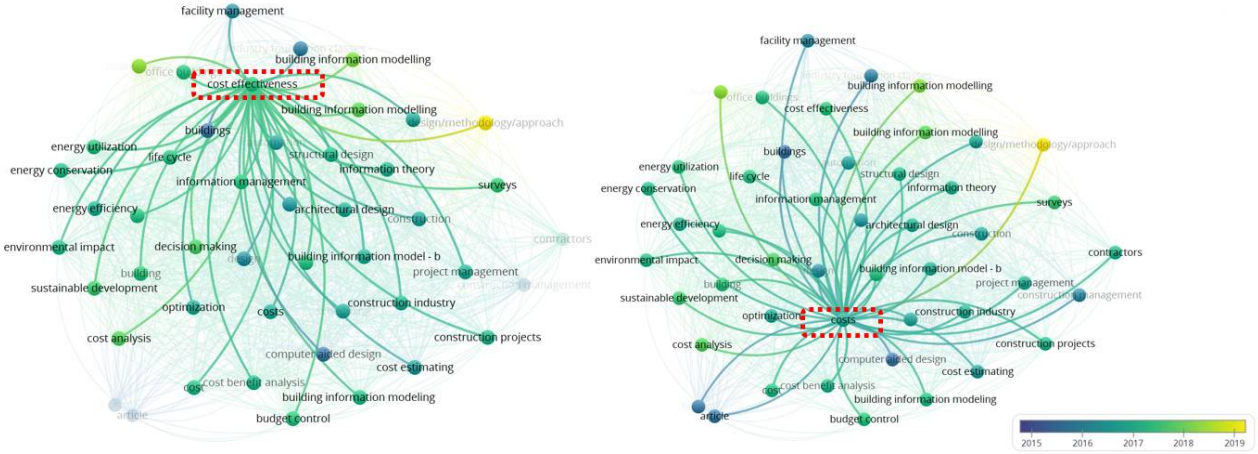


Figure 6. The cost and cost-effectiveness co-occurrence analytical maps of relevant keywords within CCM. Considering a minimum number of co-occurrences of 20, 47 keywords are identified. Note: the greatest total link strength ranging was used for selecting co-authors.

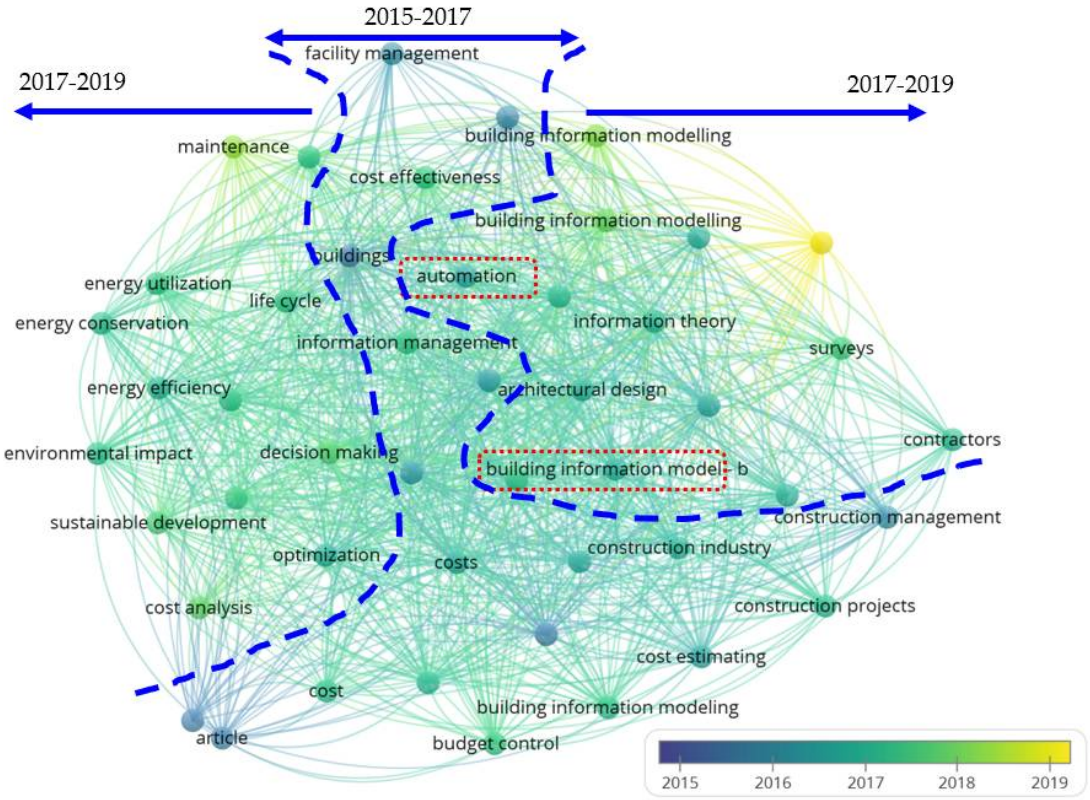


Figure 7. Co-occurrence network of themes created on CCM. Considering a minimum number of co-occurrences of 20, 47 keywords out of 5671 sample keywords are identified. Note: the greatest total link strength ranging was used for selecting co-authors.

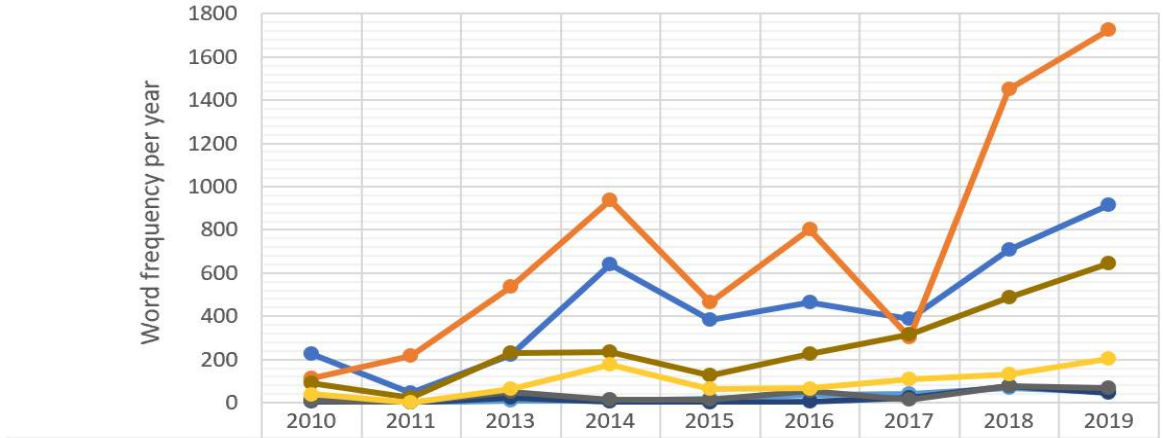
4. CCM Content Review and Systematic Analysis

This section examines the content of the CCM data set critically, focusing on the subjects, keywords, and themes. First, the entire CCM data set were grouped into four main clusters, with each cluster against a few themes such as 3D model, BIM, cost-effectiveness, design, estimator, measuring, quantity surveying, and scheduling. The CCM data set can also be classified and analyzed based on their findings. Figure 8 shows that the CCM data set's selected publications may contain at least four different types of conclusions, based on further content analysis: (i) the first cluster of papers focuses on BIM and 3D modeling for cost estimation and quantity surveying, including 22 papers; (ii) BIM implementation for developing a bill of quantity, risk paths, and cost overruns, including 13 papers; (iii) cost control and management, including 6 papers; and (iv) the fourth group investigates BIM, virtual design, and value management, including 20 papers.

Figures 8 and 9 show that some themes have received much more attention in recent years. For example, BIM and 3D models might be the core part of figures. In cost management papers of the CCM data set, energy and life cycle have received very little attention before 2015, but they have gradually been discussed in recent years. These themes are suggested to be investigated more in cost management literature. Particularly, these themes can be coupled with emerging technologies such as Blockchain, and case studies using these technologies can be useful for practitioners [42].

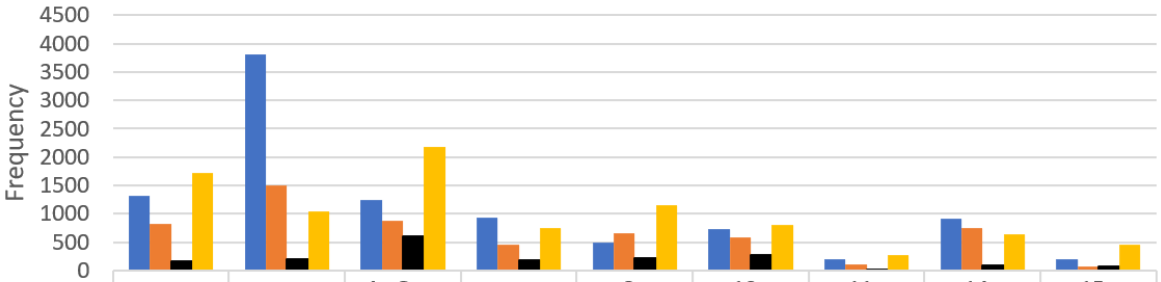
In this study, the reviewed papers are divided into four groups based on their scope: The first set of papers worked on BIM adoption for cost estimation and quantity surveying, such as [43]. The second set investigated BIM implementation for a bill of quantity, risk paths, and cost overruns, the application of new cost estimation methods such as simulation techniques or the application of BIM in construction projects; refs. [9,44] are examples, respectively. The third set includes papers on cost control and management not as the main objective but as a par. For instance, ref. [45] tended to provide a teaching method

for a web-based BIM and cost-estimating system, ref. [46] aimed at comparing the cost of buildings built with conventional and industrialized construction methods, while partly explained the cost estimation methods for two mentioned buildings, and ref. [47] found out that cost estimation can be improved by using BIM. In addition, the fourth set included papers investigating BIM, virtual design, value management, and causes of cost overrun, such as [48].



	2010	2011	2013	2014	2015	2016	2017	2018	2019
1 : 3D model	225	48	223	641	383	463	388	709	914
2 : BIM	115	218	535	936	463	800	301	1452	1727
5 : Decision	15	1	8	11	18	36	41	67	49
7 : Energy	7	1	22	4	2	7	24	77	44
9 : Life cycle	8	0	51	13	15	54	15	77	70
10 : Management	91	23	231	233	128	226	317	488	646
16 : Value	39	2	62	178	62	66	108	132	203

Figure 8. Key themes in four clusters of the CCM, including keyword analysis of BIM, cost-effectiveness, measuring, quantity surveying, and scheduling.



	1 : 3D model	2 : BIM	4 : Cost effectiveness	6 : Design	8 : Estimator(ing)	10 : Management	11 : Measuring	14 : Quantity surveying	15 : Scheduling
1	1311	3813	1250	938	487	730	195	907	205
2	816	1504	879	450	658	576	110	756	77
3	154	197	595	189	213	275	23	82	68
4	1713	1033	2178	740	1149	802	263	643	464

Figure 9. The trend of key themes is represented by word frequency over the years from 2010 to 2019.

Lawrence, Pottinger [43] focus on a case study of concrete footings take-off computation using Revit and on-screen take-off. They offer a new BIM-based estimating app named Innovaya, which recognizes design information with various formats created in Revit, AutoCAD, or Tekla. The data (e.g., dimensions of walls) are associated with dimensions

of the assembly. So, Innovaya recalls this mapping, and, in case the design is revised, the assembly quantities are recalculated or updated in a semi-automatic process, in which every managed quantity matches to a component and can be exported to a spreadsheet or joined with a chosen commercial cost database in order to do the quantity calculation. Lawrence, Pottinger [43] propose cost estimate method, which has the following functions: create views that are automatically made by BIM utilizing inquiry evaluation software; create estimate based on the input data using the Master Format standard; update BIM while the design is in process, which is considered as a reference for comparing the views; and update the estimations when the estimators get a group of estimate changes, by which they can be informed about every change and make a decision about the way the estimate must be updated. However, the efficiency and effectiveness of the method are only evaluated by 14 students with a computer science background. This method needs further assessment and validations using a larger sample of quantity surveyors, and the outcome should be cross-validated by different case studies. This type of method is critical, since the current estimation methods need to be shortened in terms of updating the estimate when either the design has changed or there are many change orders.

Wu, Wen [45] propose a web-based BIM and estimating tools for training purposes. Thus, students are able to estimate the cost in a different way. To evaluate the model, a construction case project was given to each group of students for practicing BIM and cost estimation. The system is described as follows: (1) a 3D BIM model should be built, (2) the info of the model should be developed, (3) the equipment characteristics of the model should be configured, (4) each component quantity of the model should be developed, (5) in order to integrate data and transfer to a web-based system, (6) unit price analysis should be completed as well as the cost of each component should be estimated, and (7) the total cost required to be estimated. In order to evaluate the model, 42 students and 32 experts were participated in the survey, which is designed based on TAM3. The results of this survey are then compared to the professionals' and beginners' intentions to use the proposed system by this study. The professionals have three years or more of industrial working experience and are able to estimate costs and produce design drawings of construction projects. The beginners are senior university students in the field of architectural design in Taiwan, who recently received certificates in quantity estimation and design. The variables that are studied are job relevancy, result demonstrability, self-efficacy, usefulness, and user intention to accept the system. Summaries of articles are included in Tables 3–6.

Table 3. Summary of papers focusing on BIM adoption for cost estimation and quantity surveying (Cluster 1).

Title and Reference	Cost Estimation Method, Utilized Technology, and Analyzing Method	Findings, Limitations, and Future Suggestions
Create a flexible map between cost estimation and BIM [43]	A new BIM-based estimating app named Innovaya, including Revit, AutoCAD, or Tekla software, was offered. The proposed method can generate estimations and update both BIM and estimations based on change orders and design alterations.	Shortening the estimation duration, increasing the accuracy by considering all the design conditions, and cost estimation by taking spatial and geometric relationships of design objects into account.
Establish construction progress curve by integrating schedule and cost with 3D building information model objects [49]	A BIM connected with parameters is developed. Contractual unit prices are retrieved for computing activity costs: unit prices should be saved in the quantity estimation tool. A public cost estimation tool developed in Taiwan was utilized.	Since the proposed model extracts and distributes all quantities to activities more precisely, the created curve is more reliable and precise than the original curve. The future direction should be on automating the update tasks of the project progress curve.

Table 3. *Cont.*

Title and Reference	Cost Estimation Method, Utilized Technology, and Analyzing Method	Findings, Limitations, and Future Suggestions
Explore an ontology according to New measurement rules for cost estimation [50]	Use Navisworks, select the quantification function while the standard measurement catalogs are shown to the users, import the proposed catalog opens so elements can be chosen. Finally, quantities are estimated. The ontology is evaluated semantically by six cost estimation experts. A 4D BIM modeling and the Manchester OWL syntax validator was used to validate an ontology.	The important gap identified by the literature review in this research was the fact that nearly all BIM-based estimation methods may not be according to ontologies. - Future suggestions: the proposed ontology needs to be verified by different tools. End-users should adapt or modify the proposed ontology for various requirements.
Develop cost prediction models for sports fields based on neural simulations and calculations [51]	- Simulation and opting for a large number of neural networks (called an ensemble), including various networks based on different structure or activation functions. - Developed four construction cost predictors (models) of sports fields, according to neural network ensembles. - A set of individual multilayer perceptron neural networks formed the ensembles, two of which (ENS 1 and GEN 2) were created by the set of networks that differ in their architecture and activation functions. Two ensembles (ENS 3 and GEN 4) were created using networks with similar architecture and activation functions. - a case study including cost analysis according to the BIM model of a certain sports field is evaluated, fast data extraction, and the necessary info as input for the proposed models reported.	- All four proposed models performed well in cost prediction in the conceptual estimates. - They were superior over the models based on single neural networks due to the low MAPE errors computed after testing, which was between 2.73% and 3.91%. Moreover, all prediction APE (Absolute Percentage Error) for testing cases were smaller than 10 percent, showing a satisfactory result and acceptable variation in the predictions from the real-life construction costs. - The results of the BIM-based cost analysis showed the efficiencies of the models, as APE errors were lower than 10%. A convergency in predictions was obtained, and error variation was small. The most efficient prediction of the case study was obtained by the GEN 2 ensemble.

Table 4. Summary of papers focused on BIM implementation for a bill of quantity, risk paths, and cost overruns, the application of new cost estimation methods such as simulation techniques, or BIM applications in construction projects (Cluster 2).

Title and Reference	Cost Estimation Method, Utilized Technology, and Analyzing Method	Findings, Limitations, and Future Suggestions
Discover the use of simulation methods for cost estimation and control and to evaluate their impact on cost performance of projects in Malaysia [9]	- In order to reach the target, which is degerming the usage of simulation methods in construction, a survey questionnaire including government agencies and consultant/contractor firms in Kuala Lumpur, Malaysia, was conducted. - Total of 83 questionnaires was completed, among which 45 contractors, 21 consultants, 12 developers, and 5 government agencies were the respondents.	Nearly 95% of companies use contingency cost estimation, calculated by means of traditional techniques, 3.6% use Monte Carlo simulation, and 6% using 4D simulation. A small number of companies use Innovaya (1.2%), Bentley ConstructSim (2.4%), Oracle Crystal Ball (6%), Buildsoft, Cost-X, BIM, Autodesk Navisworks, and SKALA (9.6%). Barriers are software price, low awareness, low level of skills, sophistication, suitable software for a specific purpose, and time-consuming.

Table 4. *Cont.*

Title and Reference	Cost Estimation Method, Utilized Technology, and Analyzing Method	Findings, Limitations, and Future Suggestions
Determine the application of BIM-based detailed cost estimating software and evaluate the drivers to BIM acceptance in Nigeria by quantity surveying consulting companies [44]	A questionnaire survey was conducted by the participation of quantity surveying firms from the Nigerian Institute of Quantity Surveying (NIQS). 21 drivers of BIM implementation for quantity surveying were identified, including quantities automation, time-saving in the process of quantities preparation, improved decision-making quality, data coordination, and enhanced design quality.	49.32% of participants were aware of BIM but not using it for cost estimating or were not aware of cost applications. Participants ranked the software they used for cost estimation: (1) Microsoft Excel alongside 3D software, (2) Autodesk QTO, (3) Navisworks, (4) Innovaya Composer, and (5) CostX. This study was restricted to quantity surveying consultation companies; a larger sample size, including clients and contractors, is suggested.
5D BIM in KL University, Vijayawada, Andhra Pradesh state, India [52]	The case study is a 10-story car parking using two-dimensional (2D) drawings. 4D model scheduling is used for interactivity, graphical representation, detailed planning of the project, and dynamic interaction.	Integrate Primavera and Revit in order to develop 5D applications that improve the visualization of the construction progress.

Table 5. Summary of papers focused on cost control and management as a part of their work (Cluster 3).

Title and Reference	Cost Estimation Method, Utilized Technology, and Analyzing Method	Findings, Limitations, and Future Suggestions
Provide a learning model by integrating BIM and cost estimating, and evaluate the technology acceptance among experts [45]	Used two groups of students and a real construction project was given to each group for practicing in examining the technology acceptance model.	The students accepted the proposed learning model in this study. Students need to practice before they can become familiar with the new tool completely.
Compare the BIM-based cost estimation of a construction project with Industrialized Building System (IBS) or Conventional Building System (CBS) [46]	CBS: the 3D models are imported into Navisworks, while all building materials are defined in detail connected to Resource Catalog components. The materials are allocated to the related groups (e.g., rebar, wood form, and concrete for footing the foundation). IBS: To estimate quantity, the work breakdown structure was made in Navisworks. Needed construction activities for each part of the building were collected according to their preference and kind of relationships with previous and next activities.	The quantity take-off is conducted for all building parts that were created on the 3D model. There is a considerable difference between the CBS and IBS methods for construction cost (the total figure for the project built conventionally was $62,392, whereas that of the industrialized one was $88,012).
Recognize and evaluate the advantages and blockers of BIM adoption in Hong Kong [47]	A survey was conducted in Hong Kong. - 44 questionnaires from 62 were analyzed by utilizing basic statistical analyses.	Some construction stakeholders resist technology adoption. Suitable use of BIM assures that the cost is estimated more efficient plus decrease the probability of under-budget or over-budget, so can eliminate the cost overruns in construction projects.

Table 6. Summary of key papers related to digital modeling and cost management.

Title and Reference	Cost Estimation Method, Utilized Technology, and Analyzing Method	Findings, Limitations, and Future Suggestions
BIM education in quantity surveying, case of Malaysia [53]	- This work proposed a framework to improve the QS students' knowledge and skills to answer the demand of industry for BIM graduates.	- Future work: developing the curriculum to increase the students' and lecturers' perception and extending it for higher graduate courses are recommended.
Ontological Inference, BIM Data [54]	- An ontological inference of work items that activates search (automated) of the most suitable work items and their connected unit costs are presented. - The approach is evaluated by a case study.	- Finding: the proposed work can perform in real situations. The approach used for building cost estimation can help engineers in using BIM info from IFC XML more easily and can be useful in the entire estimation process automation.
Utilize Semantic Web and Semantic Web Service tools [55]	- This research presents a novel method of cost estimation, by utilization of semantic web technology. - The estimating method proposed in this work depends on BIM, knowledge of estimation, and the data of construction material that is shown in a web ontology language. - The estimating app is evaluated by being compared with WinEst.	- Findings: (1) The evaluation findings show that the approach can increase the estimators' efficiency. (2) Material resources and updating the estimating material cost databases should happen before new estimations.
Features of building services standard, Malaysia [56]	- This research is aimed to investigate the need for creating a BSSMM, which is able to manage building services. - To this aim, a questionnaire is designed and filled by experts in Malaysia.	- The questionnaire results in 23 key features of measurement, which are categorized into three groups and are ranked. - Limitations: More investigation on the rules of the BSSMM is needed.
State of practice of BIM in the mechanical construction industry [57]	- This research examines the application of BIM in the mechanical construction industry. - It is based on an extensive survey and interview of 27 questions. Most of the respondents (68%) are American, and the rest (32%) are Canadian.	- Findings: (1) 58% of mechanical contractors had experienced BIM for less than three years, (2) The BIM implementation cost was lower than two percent of total cost, and (3) Above 70% of participants confirmed this approcah decreases conflicts and improves coordinations.
Lean construction and BIM [58]	- This research integrates BIM with the lean concept, both of which can play an important role in cost control of the construction projects. - A case analysis is used to show the use of the mentioned idea in the construction projects.	- the findings indicates that the integration of lean construction and BIM technology is able to control cost-efficiently, decrease the activities that are non-value-added, and eventually increase the project value and meet the clients' requirement.
Implement earned value management using bridge information modeling [59]	- This research proposes the application of BIM in bridges. The application combines BIM and the concept of Earned Value (EV) in order to investigate the project state at special dates.	- Findings and limitations: Even though the presented cost estimation modules help the cost estimation, it is restricted to direct costs related to only: materials, labor, and equipment. The module does not consider indirect costs such as overheads, taxes, bonds, insurances, and contingency.
A technical review of BIM-based cost estimation in UK quantity surveying practice, standards, and tools [60]	- This research investigates the cost estimating practice and method in the UK and the effect of the BIM application. - This paper in addition, reviews the existing BIM-based tools of cost estimation in the UK quantity surveying.	- Findings: The review indicates that most of the tools cannot support the UK practice in an automatic manner, and more works are needed to use them in projects. While every tool has its own special ability to help the quantity surveyor in using BIM technology.

Table 6. *Cont.*

Title and Reference	Cost Estimation Method, Utilized Technology, and Analyzing Method	Findings, Limitations, and Future Suggestions
BIM-assisted cost estimation [61]	- This research develops a quantitative approach to examine the effects of BIM-Assisted Detailed Estimating (BADE). In addition, it examines the effect of visualization factor and its compound effect and aggregated calculation factor on the building cost so as to understand the estimator's cognitive details. - A group of case studies with various amounts of estimate complexity is created and evaluated on entry-level estimators by means of both conventional estimating and BADE approaches.	- Findings: (1) The BIM-assisted estimation outperforms the conventional estimation methods. The visualization and aggregation performances of the BADE tool have a considerable effect on the function of the detailed estimate. (2) The more complex the estimation tasks become, the clearer the benefits obtained from applying BADE tools instead of conventional estimation methods. - Future work: More research on industry-level cases and subjects in need.

The research by Lawrence, Pottinger [43] aims at creating and maintaining a cost estimate taking advantage of flexible operation that associates each element of BIM with elements of cost estimation. Performance 1 (CP1) and CP2 are obtained as two detailed cost estimates (due to the changes in design, CP2 is prepared 16 weeks after CP1) and cost analysis features such as code, unit of measure, unit rates, and total quantity. The article explains a process of concrete footings as an example of a detailed take-off, by which reaches a conclusion that: the aggregating process of the mentioned various quantities for every cost item needs a large amount of time and effort. The interviews revealed that when changes in design happen, each revision leads to a big deal of manual work to review the new drawings with new changes, which also to update the On-Screen Take-off quantities. Based on both the mentioned weak points and how BIM-based estimating apps are able to address many drawbacks of the methods depending on 2D paper or digital drawings, the research then evaluates a new BIM-based estimating app named Innovaya, which is explained more in the table. The paper concluded Innovaya is useful for take-offs because the model relies on how categories are organized in the BIM. In particular, the cost items that are used by the cost estimator should be matched to the category of building components in the BIM. Specific mapping types are emphasized in order to coordinate and update the cost estimate: (1) proxies, (2) aggregated conditions, and (3) spatial conditions. Proxies, which are mapping features, can be useful for cost estimators in order to connect a design to a cost estimate so that the estimator can utilize relevant building elements as proxies in the early stages of a project when exact specifics are lacking. Aggregated conditions are responsible for characterizing categories of building elements beyond BIM components to change a component whenever items of another component group are changed. The spatial conditions and geometric configurations of building components significantly affect the cost and design constructability. Moreover, the greater number of changes that happen in an item feature results in less repetitive work, ultimately decreasing productivity. Therefore, the estimator should be informed of any special configuration change in every revision. The proposed cost estimate method by this study is as follows: (1) Making project mappings by a data modeler who is a professional cost estimator, plus a professional person familiar with BIM to formulate inquiries. (2) Creating views, which are values for mappings, automatically made by BIM utilizing inquiry evaluation software based on the mapping definitions. (3) Making an estimate, when the cost estimator makes the project estimate. The input data is formed based on the Master Format standard. The views made in the previous stage play the role of a controller for the estimator in making the cost estimate. (4) Updating BIM while the design is in the process by the party (or the Architect), which is considered as a reference for comparisons. (5) Comparing the views, in which a new group of views is created by evaluating the inquiries in the mappings. Moreover, (6) updating the estimate, when the estimators get a group of estimate changes,

by which they can be informed about every change and make a decision about the way the estimate must be updated. Sometimes, without estimators' intervention, the estimate can be updated in an automatic manner, although without the estimators' control, this kind of automation may lead to incorrect action. Therefore, the proposed system informs the estimator about the change and provides the estimator important data to accept the suggested changes or make more refinements if necessary. Thus, this process can sometimes be called semi-automatic.

Wang, Wang [49] propose a BIM model for cost estimation. The Public Construction Cost Estimation System (PCCES) is adopted because it is a common system in Taiwan. In future works, the modelling processes should be conducted frequently to update the progress curve as the project proceeds in order to add more automation to the suggested model, and this application needs to be examined. Faghirinejadfard, Mahdiyar [46] calculate and compare the cost of two similar buildings using the IBS and CBS methods. The following comes to the cost estimation methods utilized by this research for two buildings. In the CBS method, the 3D models are first imported into Navisworks Manage, while all building materials are defined in detail connected to Resource Catalog components. Next, the mentioned materials are allocated to the related groups. Lastly, quantity take-off is taken in an automatic way for all building parts that are created on the 3D model. The required construction activities for each part of the building are collected according to their preference and kind of relationships with previous and next activities. In addition, every activity unit price is taken from the Malaysian Public Work Department (JKR) price list, including resources such as machinery, labor, and materials. This research framework is as follows: (1) data collection, from Malaysian rules and market conditions, and the price list of the Malaysian Public Work Department (JKR); (2) modeling a case project located at Universiti Teknologi Malaysia that has different plans (on a plan for IBS and another for CBS methods) by means of Revit including foundation, beams, exterior and interior walls, columns, etc.; (3) exporting the 3D models to Navisworks Manage, calculating the construction cost of each building, doing quantity take-off; (4) estimating 5D and 4D according to the data from the previous step by presenting the project WBS made in the Navisworks Manage; (5) extracting different advantages of prefabrication method from the previous research that affect the process of onsite construction and contribute to a decline in some costs; and (6) using Microsoft Excel and the visual graph, analyzing the influence of time on a comparison of two building techniques according to the Break-Even Point (BEP) analysis, Return on Investment (ROI), and each project value. The findings show that there is a considerable difference between the CBS and IBS methods for construction cost (the total figure for the project built conventionally was $62,392, whereas that of the industrialized one was $88,012).

Abanda, Kamsu-Foguem [50] illustrate a graph of the process of cost estimate in a BIM cost estimating software. This research also reviews the literature about intelligent cost estimation methods and provides information about: (1) the previous works in terms of cost estimation to some extent, (2) BIM-based construction cost estimate, and (3) BIM-based cost estimate tools and measurement rules. The ontology is evaluated semantically by six participants. In order to check the ontology syntactically, the Manchester OWL syntax validator is used. Then, this study takes advantage of Navisworks for a building that is used for ontology validation. Since the proposed ontology is only validated in Navisworks, it is recommended to be tested on other tools such as Autodesk Quantity Take-offs (QTO). End-users can also adapt or modify the proposed ontology so as to meet their different requirements.

The paper by Babatunde, Perera [44] suggests that BIM applications should be developed for quantity surveying and cost estimating. They reviewed the literature, pilot studies, and a questionnaire survey of both BIM users and non-users who are practitioners in Nigeria. They conduct a survey using 73 participants, including 31 users and 42 non-users. However, this investigation was restricted to quantity surveying companies, so it suggested

collecting the survey from the standpoints of clients and contractors with a comparison with other countries with similar conditions.

The study by Juszczyk, Zima [51] conducts a simulation and develops a large number of neural networks (called an ensemble). Taking advantage of a model with a number of networks instead of a model using one network is the main difference between this study's approach and the traditional use of neural networks. According to neural network ensembles, this research develops four construction cost predictors (models) of sports fields. The model's variables, nature, and their values are related to the characteristics of sports fields as special facilities and their construction costs. A set of individual multilayer perceptron neural networks forms the ensembles, two of which (ENS 1 and GEN 2) are created by the set of networks that differ in their architecture and activation functions, while the rest two ensembles (ENS 3 and GEN 4) are created with the networks of similar architecture and activation functions. In this investigation, the cost analysis process takes advantage of the BIM model availability in terms of fast data extraction and the necessary info as input for the proposed models. This study shows that: (1) all four proposed models perform well in cost prediction in the conceptual estimates. (2) they are superior to the models based on single neural networks due to the low MAPE errors computed after testing, which is between 2.73% and 3.91%; and (3) the results of the BIM-based cost estimation show the efficiencies of the models, as Absolute Percentage Error (APEs) errors are lower than 10%. A convergence in predictions is obtained, and error variation is small. The GEN 2 ensemble obtains the most efficient prediction of the case study. The predictions are created for the cost values updated for only a special year, which is the limitation of this work, and this matter is suggested to be investigated carefully in future research. Also, all predicted APEs for testing cases are smaller than 10%. This shows a satisfactory result and acceptable variation in the predictions from the real-life construction costs.

A study by Alrashed and Kantamaneni [62] develops and evaluates 5D BIM for housing projects to evaluate the perception of participants in the Kingdom of Saudi Arabia (KSA) housing types. Alrashed and Kantamaneni [62] adopted two-path analysis methodology: (1) Path One: survey analysis to learn participants' opinions about the case house styles. (2) Path Two: create a 5D BIM as well as a construction costs estimation. In this paper, firstly, 3D CAD models of mid-terrace houses are made in ArchiCAD. Secondly, the created models are exported to Vico software. Thirdly, 3Ds are activated, and material codes are stored as a library that includes the unit rate of materials. Fourthly, they are transferred into Excel in order to calculate the precise model quantities automatically, in case any change in design or recalculation will be needed, so that the final bill of quantities (BOQ) of the mid-terrace houses of this study can be created. It is shown that: (1) The traditional methods of cost estimation use simple tools and software (such as Excel for calculating project unit prices and historical data), in comparison with new methods including various techniques such as the ones used in this research leading to a more accurate cost estimate. (2) The proposed 5D BIM declines the costs considerably by reducing material waste and time clashes.

The work by Ali, Mustaffa [53] proposes a framework to improve the Quantity Surveying (QS) knowledge and skills to answer the demand of industry for BIM graduates. The proposed framework is aimed to support the Malaysian industry and government initiatives to BIM implementation. It also encourages the utilization of BIM for higher education, and professional training. Developing the curriculum to increase the students' and lecturers' perception and extending it for higher graduate courses are recommended for future works.

A study by Lee, Kim [54] presents an ontological inference of work items that activates search (automated) of the most suitable work items and their connected unit costs. It includes semantic data for work items and conditions, also a semantic reasoning rule, which enables the ontology. A case study evaluation by this study showed that the proposed work could perform in real situations. The proposed approach used for building cost

estimation can help engineers more easily use BIM info from IFC XML and can be useful in the automation of the entire estimation process.

Niknam and Karshenas [55] present a novel technique for quantification, which uses semantic web tools using a machine-processable data modeling that allows data sharing via online tools. The estimating method proposed in this work depends on BIM, knowledge of estimation, and the data of construction material in a web ontology language. An estimating app is presented in this work, which combines distributed information given various stakeholders to prepare cost estimates. This paper intended to simplify the process by decreasing people's involvement in repetitive activities of cost estimating. The estimating app is examined in a comparison with the WinEst tool. The findings show that the approach can increase the estimators' efficiency substantially. It shows that, although the estimating databases have many resources and material databases should be updated before each cost calculation, this method may substantially increase the estimating efficiency.

Amuda-Yusuf and Mohamed [56] investigate the need for creating a Building Service Standard Method of Measurement (BSSMM), which allows quantity surveyors to manage the cost of building operation and services. A questionnaire was designed and the outcome of the survey identified 23 items of the chosen standard; they were categorized into three groups and are ranked. Boktor, Hanna [57] conducted another survey and examined an application of BIM in the mechanical construction industry. It is based on an extensive survey and interview of 27 questions including: (1) organization background, (2) current BIM applications, and (3) BIM application in the future. The majority of the respondents (68%) are American, and the rest (32%) are Canadian. It is shown that: (1) 58% of mechanical contractors had experienced BIM for less than three years. (2) The implementation cost of BIM was reported as less than two percent of the total project cost. (3) Above 70% of participants confessed that BIM decreases conflicts and improves coordination of the project.

Wen [58] suggests that the construction projects should integrate BIM with the lean construction concept, both of which can play an important role in the cost control of the construction projects. The findings of a case project examination indicated that the integration of lean construction and BIM is able to control cost-efficiently, decrease the activities that are non-value-added, and eventually increase the project value and meet the clients' requirements.

Marzouk and Hisham [59] propose BIM applications in bridge projects in terms of cost and time analysis and management. The cost estimation application is able to do with an approximate or detailed cost estimate. It is designed flexibly to be used with either default or defined values. Various acting measurement indexes are used to control the project cost and schedule over the implementation phase of construction. The application combines BIM and the concept of Earned Value (EV) in order to investigate the project state at special dates. A case study is then used to show the application of the presented modules. The findings indicate that, even though the presented cost estimation modules help the cost estimation of bridges, it is restricted to direct costs that are related to only materials, labor, and equipment. The module does not consider indirect costs such as overheads, taxes, bonds, insurances, and contingency.

Wu, Wood [60] investigate the cost calculation practices and methods in the UK, including the effect of the application of BIM. Several important problems have been identified related to information exchange, model quality, and UK standards. This paper reviews the current BIM tools of cost estimation in the UK context, so that the ability of the current BIM functions for supporting the UK quantity surveying can be examined. The four most famous reviewed tools in the UK are the Solibri model checker, Autodesk QTO, CostX, and Causeway BIM measure. The results of the review indicate that most of the tools cannot support the UK practice in an automatic manner, and more investigations are needed to use them in the UK projects. As an example, Solibri is capable of checking models, CostX is capable of visualizing the models, and CATO is able to be integrated into the BIM measure.

The study by Jrade and Jalaei [63] integrates building management systems, Life Cycle Assessment (LCA) tools, and a database of sustainable construction project designs. Integrating BIM (3D), an LCA, a certification, and a cost module was considered and aimed to make the sustainable designs easier. A real construction project is provided to show the effectiveness and abilities of the mentioned model. The proposed model is easy to use because it needs fewer user inputs and provides error prediction. Its benefits include decreased time, quicker calculations, and reliable output reports. However, it contains the following limitations: (1) the model cannot be used during construction; (2) the database was developed based on limited BIM files with limited components; and (3) the model does not work fully automatic.

Popov, Juocevicius [64] analyzes the use of BIM, computer-assisted tools, and simulation methods of building process according to the idea of Virtual Project Development. A cost estimation based on a Computer-Aided Evaluation System (CAES) in the BIM environment is summarized in the following figure by this paper. It is shown that the application of BIM on the 5D concept over the whole project lifecycle leads to some merits such as (1) supporting visualization and information; (2) simplifying the creation and sharing the data related to design, building, and keeping the buildings during their whole lifecycle; and (3) a computer-aided examination tool in construction, according to BIM, makes a link between structural design, cost estimation, and scheduling. According to Migilinskas and Ustinovichius [65] and Popov, Mikalauskas [66], the computer-aided evaluation system (CAES) can enhance the time efficiency of the project up to 40%, which may be required for design and the estimation.

Shen and Issa [61] develop a quantitative estimation for evaluating the effects of BIM-Assisted Detailed Estimating (BADE). In addition, it examines the effect of visualization factor and its compound effect and aggregated calculation factor on the building cost so as to understand the estimator's cognitive details. Two BADE tools are examined to distinguish the influence of the visualization component on estimate from the combined effect of both the visualization and aggregation functions on estimation. A set of case studies with varying levels of estimate complexity are produced and tested using entry-level estimators using both traditional and BADE methodologies. The evaluation results show that the BIM-assisted estimation outperforms the conventional estimation methods. The visualization and aggregation performances of the BADE tool have a considerable effect on the function of the detailed estimate. The research depicts that the more complicated the estimation become, the fairer the benefits obtained from applying BADE tools instead of conventional estimation methods. It is also mentioned that, in order to get more conclusive results, more research on industry-level cases and subjects is needed. Table 7 includes summaries of papers related to digital modeling and cost management.

Table 7. Glodon Quantity Software–GCL and Glodon Cost estimating software—GBQ (model visualization can only be done in GCL) and SMC.

Factor	Glodon Quantity Software (GCL); Glodon Cost Estimating Software (GBQ)	SMC
Information exchange	GCL supports GFC, IGMS, and IFC formats. GFC is preferable. If the building material of the BIM model components cannot be found in the built-in tool of GCL, such as section steel, this may cause a loss of information.	SMC support DWG and IFC format. IFC can merge most BIM information in one file. The conversion needs to be done carefully.
Visualization	Similar to Revit, GCL supports visualization of the BIM model effectively. Possible to provide a view of the quantity of certain selected elements' and show or hide any specific elements.	SMC supports the visualization of the BIM models effectively.
Quantification process	Using the built-in classifications, GCL provides the flexibility of making modifications to its standard, and some components can be allocated to the desired category.	SMC supports changes to its classifications. The components can be to any category, such as NRM, to extract accurate information extracted.

Table 7. *Cont.*

Factor	Glodon Quantity Software (GCL); Glodon Cost Estimating Software (GBQ)	SMC
Reliability of information	Possible to select from the predefined range of parameters, rules, or standards in the application to validate the model or adapt the rules according to the project's goals. The results can be communicated by the designers for changing details of the design.	Similar to GCL, possible to predefine parameters and communicate with designers for required changes.
Customization of built-in categories	GCL can generate a standard estimating format quickly and supports BIM.	SMC enables manual classifications and to generate a standard estimating format quickly.
Report generation and exporting	The bidirectional connections between Revit and other tools might be difficult to manage. Alteration of the model that was amended in Revit can be identified and located.	SMC can automatically identify and locate alterations of the model that revised in BIM authoring software.
Change or revision management	GCL enables the export of taking off results into spreadsheets, and GBQ, can generate cost reports according to built-in or input rates.	SMC allows exporting of outcomes of take-offs into Excel files adding rates to Excel, and generating cost reports.

5. Project Cost from Project Management Methodology Perspectives

The Project Management Body of Knowledge (PMBOK) [67] defines cost management as estimating, budgeting, monitoring, and controlling costs. Moreover, it is about managing the daily costs of a project. This term is different from the term financial management, which refers to revenue resources for financing and its profit on investment, cash flow, and investment payback analysis.

Construction estimations can be categorized from simple estimates to complex ones, and it includes direct and indirect costs. The costs that are directly caused by specific scope of work and include costs of equipment are direct ones, while indirect costs may not be related to a special scope of a task and might be relevant to several scopes of the project.

The cost of the required resources is established in cost management, including operation costs and project life cycle costs. The plan needs to be customized to the requirements of the client, while also considering the other project stakeholders' requirements. Cost management planning needs to be managed through the process of design to improve the possibility of estimating from the design phase and indicate the way the bill of materials (BOM) will be prepared.

To save time and cost, increase project performance and quality, and improve the performance of a design-to-cost facility, life cycle costing, value engineering, and constructability analysis are essential aspects used in the earliest planning processes on construction projects and enhance the decision-making process. Cost planning starts with estimating and the process of changing into budgeting. The terms bill of materials (BOM) and material take-offs (MTOs) refer to measure material quantity. Bill of quantities (BOQ) is another term referring to a database or spreadsheet that lists quantities of various items such as materials, equipment, and labor.

Estimation accuracy depends on the quality of the scope definition. The accuracy also increases as the project progresses within its life cycle.

A list of key factors needed to be considered in construction cost estimating is as follows:

- Condition of site;
- Availability of labor source, type, and wage rates;
- Limitations of site access;
- Limited working hours;
- Distance to available facilities;
- Equipment and material logistical needs;
- Weather;
- Effects of local people and social group;

- Health, safety, and environmental rules;
- Geotechnical information.

Many estimations rely on the same project basis or on published rates of projects implemented by the government, in which the forecast is based on an inflation index or escalation rate. The Basis of Estimate (BOE) is defined as an imperative document that assists estimating accurately.

Most organizations do have a defined schedule for recording the real cost at the end of work on a weekly, fortnightly, or monthly basis based on the activity or project. Throughout the process, the project accounting system captures the actual labor, material, equipment, and subcontractor expenses. The project team reviews and analyzes the accounting report in terms of completeness and accuracy. Large project teams find it difficult to record real costs for the same work duration since each part might use various cut-off dates. So, for such projects, an accrual method can be used to record revenue and costs as Work in Progress (WIP).

Forecasts are created, modified, and repeated using information gathered throughout the project's implementation. Estimate at Completion (EAC) is often based on actual costs for finished work, as well as an Estimate to Complete (ETC) for work that remains to be done. Based on previous experience, the project team must foresee what it would confront when conducting the ETC. ETC may be estimated based on the leftover amounts when real quantity measurements are available. A manual, bottom-up summary by the project manager and project team is the most common EAC forecasting goal. To record the three EVM dimensions Present Value (PV), Earned Value (EV), and Actual Cost (AC), to present graphical trends, and to estimate a range of likely final project results, project management software is always employed. Cost control collects more accurate data that may be used, lowered, raised, or eliminated as the project progresses. The change control procedure is used to acquire clearance to transmit the relevant management sources to the cost baseline, when the number of changes requiring the usage of management reserves grows.

6. Example of Cost Estimation Using a Digital Tool Compatible with 3D Modeling

Different cost estimation tools are commonly used for cost estimation and take-off analysis by many quantity surveyors in Asian countries. Figure 10 shows a basic flowchart for importing the model and estimating the cost for a 3D building model using a set of selected tools.

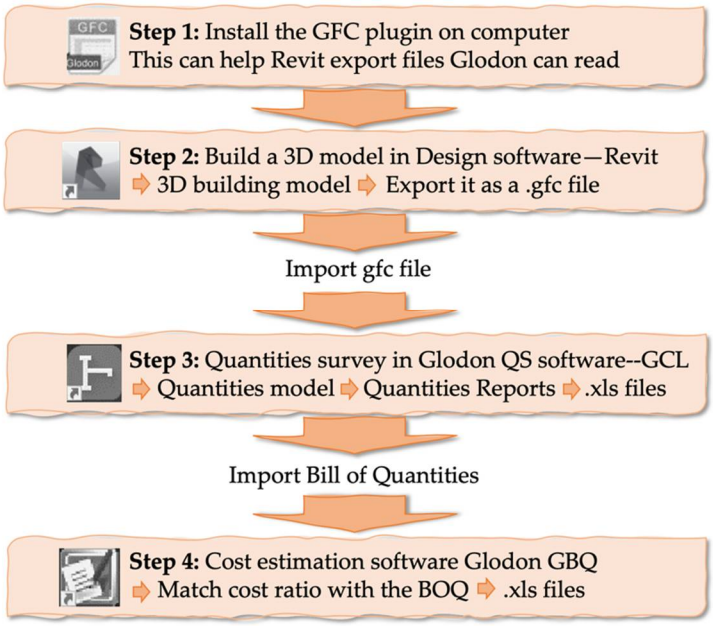


Figure 10. A technical workflow showing the cost estimation process using selected tools.

In the second step, after installing the GFC plugin, an additional function of 'Glodon BIM quantities surveying' will show up on the functional menu, and the quantities take-off function will appear in a Dropbox. There should be two other types of quantities take-off function, namely MEP quantities surveying and decoration quantities surveying. They are supported by the GFC plugins different from that of housing buildings. These two types of quantities surveying options only can be seen after installing the corresponding GFC plugin, which can coexist with housing buildings quantities surveying in Revit.

The confirmation of information is required when exporting .gfc file to ensure the 3D model file is appropriately read by the Glodon QS software and to avoid matching the wrong layer number with its elevation. The built-in quantities surveying measurement rules in Glodon are different from the design rules of Revit, so primitives cannot be connected (i.e., Cancel connecting the primitive). Using non-standard components' names and inappropriate connection of different elements against Glodon QS software measurement rules can result in errors.

Glodon is used for creating new quantities surveying projects, and it is compatible with the local needs in China, so it possesses all the provincial built-in quantities surveying rules and costs evaluating codes in the application. Usually, in the software, the selection of the cost ratio is according to the provincial location of that project. The cost evaluators can adjust the parameter according to the cost standard in their company, which is adjustable. The software allows two types of quantity codes in China, namely the bill of quantities-based cost estimating method and cost ratio-based cost estimating. These two methods are similar to "top-down estimating" and "bottom-up estimating," respectively. This increases the adoption rate for this software in China, and the lack of local rules hinders adopting other globally accepted tools.

In order to create a QS project in Glodon, the quantities measurement rules should be selected or defined. Then, a database should be selected, and relevant information should be inserted. Next, the 3D model should be imported into QS software. In the main interface of the QS software, there is also a BIM function menu that allows importing the Revit interoperate file in a dropbox. Three file formats are supported, the .gfc, .ifc, and .igm extensions.

Similar to other tools, one of the investigators experienced some challenges were importing from Revit to GCL. For large-sized models, the transmission process from Revit to GCL might be challenging. In this case, the model should be imported layer by layer. Some components are missed when importing a Revit model file into QS software because the original BIM file includes extremely complicated details for the decoration elements and cannot be read by GC as a cost quantity software. Missing a few components will result in errors and a certain degree of inaccuracy in quantities surveying. To solve this problem, these missed components should be re-built in QS software. Figure 11 shows a canopy as an example that is missed once importing the 3D model into GCL. Then, different substitute material is used to draw this canopy in GCL. Even though the content is different from the original canopy in Revit, the volume and quantities are similar, and this will not exert a significant influence on the ultimate quantities result.

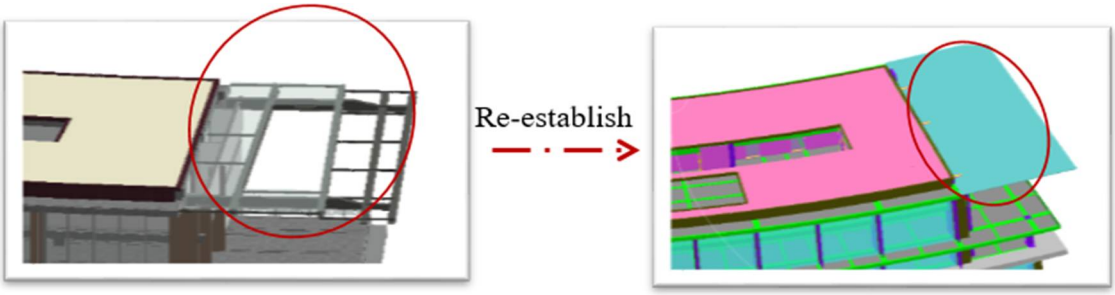


Figure 11. Example of a missing canopy and the need for solving the missing element.

As Glodon operates the QS and cost estimation in two specialized tools, the comparison of the related function of Glodon with other tools is presented as follows. It should be noted that tools and software packages are evolving and upgrading over time and/or their efficiency would vary in various simple or complex projects. Table 7 shows a summary of comparisons between GCL/GBQ and SMC.

7. Discussion and Future Directions

The content analysis shows that four main sub-topics have been investigated in the literature. First, some papers examined different cost estimation methods, such as Lawrence, Pottinger [43], Wang, Wang [49], Abanda, Kamsu-Foguem [50], and Juszczyk, Zima [51]. Second, other papers investigated applying new cost estimation methods such as simulation techniques [9] or the application of BIM in construction projects [44]. However, recent studies report that most of the quantity surveyors use Microsoft Excel alongside one type of 3D software tool. For example, Babatunde, Perera [44] report that over 49.32% of quantity surveyors in Nigeria are not using BIM-based cost estimating tools. Thus, other studies suggested some improvements using BIM applications for quantity surveying in the curriculum for undergraduate students [68].

The third set includes papers that worked on cost estimation not as the primary objective but as a part. For instance, Wu, Wen [45] provide a teaching method for a web-based BIM and cost estimating system, or ref. [46] aims at comparing the cost of buildings built with conventional and industrialized construction methods, while partly explained the cost estimation methods for the two mentioned buildings. Chan, Olawumi [47] identify that cost estimation can be improved by using BIM. In addition, the fourth group included papers investigating causes of cost overrun, such as [48].

One of the key sub-topics suggested for future studies is exploring or developing digital applications for quantity surveying. This requires some selected case studies using these applications demonstrating how the technology can be implemented and the associated advantages and benefits of the digital tools. Some countries have low awareness of digital technology applications for cost analysis. At least, there is a lack of practices to utilize these technologies, such as Monte Carlo Simulation or using 4D and 5D BIM [9]. Alashwal and Chew [9] show that some of the construction companies have not implemented simulation methods to estimate contingency costs. For example, the Monte Carlo simulation is used by only 3.6% of Malaysian companies. Moreover, the figure for 4D simulation is 6%, which indicates the low application of simulation methods in contingency cost estimation [9]. Table 8 shows directions for the future and some examples of key factors and limitations.

Having knowledge about the causes of time and cost overruns on such buildings can aid clients to make better decisions, as well as help consultants and contractors, decreasing the risk of facing the mentioned overruns [48]. The clients' or the consultants' speed and accuracy in making decisions for the project are also important and will not let the contractor or other parties make baseless claims or time overruns that can lead to cost growth [48]. They also suggest that different consultations should be made with the skilled parties, with sufficient time allowed to prepare the needed documents. Serious care in the preparation phase is also imperative to avoid mistakes that would be costly in the future.

The paper presents the results of the content review and presents a set of key directions for future investigations. Additionally, literature has been reviewed in four groups based on their scope: cost estimation methods, the application of new cost estimation methods such as simulation techniques or application of BIM in construction projects, implications in different contexts, and, finally, papers focusing on causes of cost overrun.

Table 8. Future directions based on deficiencies of the current cost management in response to industry 4.0 trends.

Key Factors or Tools	Examples or Limitations	Directions for Future Studies
Usefulness and functionality of the digital tools; conceptual models can be developed based on TAM [69] or technology adoption models [70,71]	• Limited sample sizes in conducted surveys (questionnaires) [9,44], particularly for technology acceptance (TAM3) [45], less information from Quantity Surveyors (QSs) perspectives [72] (see Table 6) • Accurate EV estimation considering indirect costs such as overheads, taxes, bonds, insurances, and contingency [59] • Life cycle assessment [73] (refer back to Figures 5 and 8)	• Increase the adoption rate for Monte Carlo Simulation or using 4D/5D BIM [52,60], CAES [64], web-based BIM [45], Innovaya 5D Estimation [43] (see Table 4) • Evaluate case studies using different QS tools (e.g., Cost X, Vicosoftware, GCL, QTO and GBQ, Causeway BIM measure, Solibri model checker [60], WinEst [55]) • Prevent information missing while using plug-ins and tools [72], interoperability issues, and challenges of collaboration between BIM managers and QSs [72]
Risk analysis [74,75], cost monitoring and control	• Questionnaires are based on similar factors that frequently were asked [74–76] • Resist changing [47] • Limited practice for automating simulation optimization using context-aware computing or risks [77]	• How to save material waste and construction project time [62] in an automated manner • Explore risk management applications of BIM, GIS, RFID, photogrammetry, mixed reality, and cloud computing [77] • Improve curriculums by considering the application of new technologies [68]
Develop automated systems using Blockchain [42], intelligent contracts [78], and laser technologies for measurement [79]	• Blockchain in construction contract management for a wide range of construction projects, see [42] • Lack of fully automated systems to be integrated into BIM. Automation and BIM are emerging topics in the literature (refer back to Figure 7)	• Integration of the selected QS tool with intelligent contact systems • Adopting blockchain technology [80] • Using blockchain for quantifying the cost [81], asset information modeling and management [82], embodied carbon estimation, and emission trading [83] • Track the design commands change orders and actions considering a certain level of transparency and security using BIM or collaborative platforms [84]

8. Conclusions

The present review conducted a systematic review, and content analysis resulted in identifying four main sub-topics that have been investigated in the CCM literature: (1) papers examined different cost estimation methods; (2) papers investigated applying new cost estimation methods such as simulation techniques or the application of BIM in construction projects; (3) papers investigated cost estimation and training methods for web-based BIM; and (4) causes of cost overrun.

The paper used a mixed method of bibliographic analysis and content review to identify deficiencies in the current literature, compare various available technologies for cost management, and analyze the literature trends over a decade. The paper provides a detailed content review of the literature established in one decade on cost analysis and management. The paper presents the results of a systematic review in the selected databases. In addition, the content of relevant papers was reviewed, and a set of key factors related to cost management and associated risks were identified.

Various applications for quantity surveying, such as GCL and Cost X, were reviewed. Based on the review, a set of topics for future studies are presented, which can help scholars to build on their future studies. The paper also suggested a set of directions for the future: usefulness and functionality of the digital tools; developing conceptual models based on TAM (or technology adoption models); utilizing risk analysis cost monitoring and control; developing automated systems using Blockchain and intelligent contracts; and utilizing laser technologies for measurement.

The review suggests investigations to enhance the awareness of quantity surveyors about the application of emerging technologies, by demonstrating case studies and benchmarks. The CCM dataset shows a lack of practices to utilize these technologies, such as Monte Carlo Simulation or using 4D and 5D BIM implementation in complex projects, blockchain implementation, laser applications for measurements, fully automated systems for QS purposes integrated with smart contracts, and many other intelligent solutions. The paper is limited to reviewing the CCM database, so future studies are suggested to present details of technology implementation processes.

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Abbreviations

Acronyms	Full Words of a Compound Term
3D	Three-Dimensional
4D	Four-Dimensional
5D	Five-Dimensional
AC	Actual Cost
APE	Absolute Percentage Error
BADE	BIM-Assisted Detailed Estimating
BEP	Break-Even Point
BIM	Building Information Modeling
BOE	Basis of Estimate
BOM	Bill of Materials
BOQ	Bill of Quantities
BSSMM	Building Service Standard Method of Measurement
CAD	Computer Aided Design
CAES	Computer-Aided Evaluation System
CATO	Corporate Accessibility Technology Office
CBS	Conventional Building System
CP	Cost Performance
EAC	Estimate at Completion
EBSCO	Elton B. Stephens CO (company)
ENS	Ensemble
ETC	Estimate to Completion
EV	Earned Value
EVM	Earned Value Management
GBQ	Glodon Cost Estimating Software
GEN	Gigabit Ethernet Networking
GIS	Geographic Information System
GQS	Glodon Quantity Software
IBS	Industrialized Building System
ICE	Independent Cost Estimate
ID	Identity Document
IFC	Industry Foundation Classes
IGM	Irregular Grid Models
JKR	Malaysian Public Work Department
KSA	the Kingdom of Saudi Arabia
LCA	Life Cycle Assessment
MAPE	Mean Absolute Percentage Error
MTO	Material Take-offs

NIQS	Nigerian Institute of Quantity Surveying
NRM	New Rules of Measurement
NRM	New Rules of Measurement
PCCES	Public Construction Cost Estimation System
PCCES	Public Construction Cost Estimation System
PMBOK	Project Management Body of Knowledge
PV	Present Value
QS	Quantity Surveying
QS	Quantity Surveyors
QTO	Quantity Take-offs
ROI	Return on Investment
TAM3	Technology Acceptance Model 3
WIN	Work in Progress

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