Recent Advances in 5D BIM Cost Control: A Novel Ontological Approach

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Abstract

Cost overruns have been a major source of concern to project clients and other project stakeholders for decades. Consequences of cost overruns include reduced profit margins for the contractor and numerous other issues for all stakeholders, including inefficient allocation of scarce resources, delays, contractual disputes, as well as project failure or abandonment. 5D Building information modelling is a viable solution to the aforementioned problems, but despite proliferation of 5D BIM applications, studies report slow application of these software in the construction industry. This has largely been due to issues relating to inadequate information, lack of standardization, and interoperability challenges. Interoperability issues can be addressed by merging BIM and ontology to improve cost management. However, research efforts merging BIM and ontology have focused more on the cost estimating and cost budgeting, with little research focusing on cost control. This paper proposes a conceptual framework for 5D BIM-based construction cost control that provides a formal description of entities and relationships based on ontology-based knowledge representation. The underlying principle of the framework is based on utilising 5D BIM technology in the process of cost planning, cashflow management and cost reporting to keep expenditure within a specified budget.

Keywords

Construction cost management, Cost control, BIM, Ontology

1. Introduction

The cost performance of a construction project is essential to determining its overall success (Ingle & Mahesh, 2022). However, cost overruns continue to be a prevalent problem in project management. Inadequate planning and scheduling, inaccuracy of time and cost estimation, erroneous quantity take-off (QTO) and bills of quantities, flawed cash flow projections for the project and the general deficiency in cost management (Memon et al., 2014; Rostami & Oduoza, 2017) are significant factors affecting cost performance. Interestingly, the use of the fifth dimension (5D) of building information modelling (BIM) emerges as a possible way to address these issues and is seen as a system that can improve cost management by making it more effective and efficient (Abdel-Hamid & Abdelhaleem, 2021; Mitchell, 2012). BIM has been widely applied in the construction industry due to its numerous advantages, which include a reduction in project execution time, construction cost reduction, the integration of tasks and professions, enhanced efficiency through clash identification and avoidance, and a reduction in risk (Abanda et al., 2020; Buhammood et al., 2020). Regarding cost management, 5D BIM incorporates cost element related to objects and object assemblies in the BIM model (Abanda et al., 2015). This can be accomplished either by incorporating cost information into the objects of the BIM model or by connecting to software tools for estimating in real-time (Stanley & Thurnell, 2014). This, in turn, makes it possible to extract exhaustive, accurate and precise data from the model, which can then be directly utilized for determining costs (Eastman et al., 2011).

Regardless of the potential and promises of BIM to improve construction processes, the application of BIM in cost management and specifically cost control is fraught with challenges (Kim & Grobler, 2013; Sepasgozar et al., 2022). There are some challenges that still need to be overcome such as lack of understanding BIM workflow, identification of essential information to be provided during the pre-contract and post-contract phases, identification of the methods for integrating as-built data into the designed models, lack of interoperability between BIM technology and cost management systems and absence of collaboration between stakeholders.

Recently, efforts by researchers (Abanda et al., 2013; Kebede et al., 2022; Pauwels et al., 2017; Ren et al., 2021; Sobhkhiz et al., 2021; Venugopal et al., 2015) demonstrated a possibility for enhancing several construction activities, including cost management, by merging BIM and Semantic Web to address the interoperability issues. The ontology used to explicitly express the knowledge and rules of a domain is essential to the semantic web (Abanda et al., 2017). BIM and ontology are widely studied areas, as BIM allows for standardized data and information for various calculations and analyses, while ontology aids in the representation and reuse of domain-specific concepts and reasoning rules (Ma & Liu, 2018). Ontology technology offers value to BIM by allowing for information integration and the ability to perform complicated queries across multiple information sources (Pauwels et al., 2017). As a result, the implementation of BIM, due to its ability to provide reasoning support, has proven advantageous in numerous domains of construction (Abanda et al., 2017; Abdullahi et al., 2019; Li et al., 2022; Ren et al., 2021; Zhou et al., 2023). More so, research have focused more on the cost estimating and cost budgeting, with little to no research focusing on cost control. This research therefore provides a novel approach for an ontological based framework for BIM-based construction cost control.

2. Literature Review

2.1 Overview of construction cost management

As stated in the Project Management Body of Knowledge (PMBoK) (Project Management Institute (PMI), 2016) "project cost management entails the planning, estimating, budgeting, financing, funding, managing, and controlling of costs in order for projects to be completed within budget". In the construction sector, cost management encompasses all cost-related activities. from project inception to effective occupancy and utilisation of a structure (Ashworth, 2013). Kelly and Male (2003) defined construction cost management as a service that focuses primarily on cost reduction or substitution. The term is also used to describe a multidisciplinary service which combines conventional quantity surveying techniques with systematic cost reduction or substitute processes. Prior to the commencement of construction, cost management prioritises cost planning and cost estimation processes. The purpose of the estimated cost is to generate a realistic and proper budget for the project while maximising the client's value for money (Lu et al., 2018). Cost planning seeks to arrive at an agreeable cost framework in the most economic manner, while considering aesthetics and technical feasibility (Royal Institution of Chartered Surveyors, 2013). After construction has commenced, the focus changes to cost control and making sure expenditures remain well within the predetermined budget and cost framework.

2.2 Building Information Modelling

BIM has transformed the construction industry away from conventional paper-based information management processes and toward automated information management methods fuelled by complex innovation, which brings various inclinations in terms of time, cost, and quality (Wu et al., 2014). By enabling users to input very specific property data into 3D building models, it has attracted a lot of attention in the AEC industry (Eastman et al., 2011). BIM has vast potential for automating the time-consuming tasks of quantity surveyors by providing a mechanism for direct, automated extraction of quantities from three-dimensional parametric digital models (Matthews, 2011). Several BIM-based estimating and quantity take-off applications have been created, including Navisworks, Assemble, CATO Suite, iTWO CostX, Solibri Model Checker, Vico Office, Innovaya Suite and Glodon etc. and have shown tremendous success (Moses & Hampton, 2017; Sepasgozar et al., 2022; Vigneault et al., 2020).

In BIM, the fifth dimension (5D) reflects the incorporation of the cost factor, which is acknowledged as a competitive cost management strategy for many firms (Smith, 2014). 5D BIM is gaining traction, and cost management organisations concentrating more on it as a result of its numerous benefits (Alrashed & Kantamaneni, 2018). Despite the many benefits of BIM, its adoption in the AEC industry is hindered by interoperability issues (Abanda et al., 2017; Abbasnejad & Moud, 2013; Azhar et al., 2008). BIM interoperability refers to the ability of BIM applications to share, transfer, collect, and handle data utilizing consistent standards and protocols (Grilo & Jardim-Goncalves, 2010). This is often cited as a major barrier to BIM adoption and can lead to significant costs during facility operation and maintenance (Pishdad-Bozorgi et al., 2018).

2.3 Semantic web and BIM

Since the emergence of BIM in the AEC industry, the number of areas in which it is being applied has grown substantially. Presently, BIM applications are not restricted to buildings alone; they also encompass bridges, tunnels, and roadways or any artefact in the built environment (Sobhkhiz et al., 2021). BIM has had a significant impact on the AEC sector, leading to the development and widespread use of BIM authoring and application tools like Autodesk Revit Architecture, Nemetschek Allplan, Autodesk Green Building Studio, Graphisoft ArchiCAD, Autodesk Revit Structure, Autodesk Navisworks, Vico Office Suite, Autodesk BIM 360, Autodesk FormIt (Farghaly, 2020; Nguyen et al., 2019). This developing trend has resulted in a paradigm shift in how industries define, customise, and utilise the semantics of geometry-intensive product models (Pauwels et al., 2017). Consequently, industry sectors and software developers have been increasingly interested in collecting and exchanging a building's "semantics." This interest encompasses not just design and construction, but also building engineering, HVAC design, facility management (FM), simulation, renovation, operational building management and demolition (Pauwels et al., 2017).

Multiple studies have investigated the potential use of semantic web technologies with BIM in the AEC industry and after several ontologies were proposed for BIM, more practical studies have emerged. For instance, by converting the EXPRESS IFC schema to OWL, Pauwels and Terkaj (2016) presented the ifcOWL ontology, which is an IFC-based ontology. This builds on the previous work of Beetz et al. (2009) that aimed to provide access to the IFC file format as RDF graphs, permitting it to connect to other RDF data sources. Additionally, Costa and Madrazo (2015) also contributed to this trend by creating an online catalogue for construction products that is compatible with BIM technology and allows access to acquire product information from within a BIM application by designers.

In construction safety domain, Wang and Boukamp (2011) created an ontological framework for outlining concepts and semantic connections linked to construction works, job stages, and risk origins with the goal of assisting in safety risk assessment. Similarly, Lu et al. (2015) created the construction safety checking ontology (CSCOntology) that includes five key concepts: "line of work," "task," "precursor," "hazard," and "solution."

In sustainable development, Jiang et al. (2018) in an effort to facilitate the green building evaluation processes proposed integrating BIM and semantic web. In a different study, Xiao et al. (2019) developed a semantic web and BIM-based technique for building energy management information retrieval. Similarly, a framework was created by Sobhkhiz et al. (2021) leveraging the capabilities of the semantic web to address the data management challenges of BIM-LCA (life cycle assessment) applications.

In cost management related domain, (Abanda et al., 2011) created an ontology for building labour cost estimation. Cheung et al. (2012) utilized a knowledge-based tool for defining and evaluating early-stage expenses called the low-impact design explorer to generate schematic BIM models. Lee et al. (2014) developed a method for inferring ontological structures to automate the search for the most appropriate work items for cost estimation, taking into account working conditions and efficiency. Liu et al. (2016) proposed an ontology-based semantic method for obtaining quantity take-off data from a BIM design model. Abanda et al. (2017) also examined the prospect of creating a cost estimating ontology based on the New Rules of Measurement (NRM) for use in tendering stages.

Similarly, Abdullahi et al. (2019) created an ontology for detailed measurement of building construction in Nigeria. Ren et al. (2021) presented an approach for retrieving information from the BIM environment with the ontological knowledge base to enhance automation and reasoning for more efficient value for money (VfM) assessments that facilitate decision-making.

In conclusion, various studies on ontology and BIM have been conducted in the construction industry during the past decade. Some studies explored the utilisation of ontologies for product modelling, while others focused on conceptualisation of construction domain knowledge. In cost management domain, which involve cost estimating, cost budgeting and cost control. The efforts range from development of ontologies to improve the accuracy of BIM-based quantity take-off/ cost estimation to automating reasoning in construction cost estimation. However, there seem to have been no studies specifically on the creation and utilization of ontology to automate the process of construction cost control. This research proposes a novel approach for an ontological based framework for BIM-based construction cost control.

3. Methodology

Taking a similar approach to applying design science research (DSR) approach to conceptual framework development (Barth et al., 2020; Nguyen et al., 2019), and following others such as Hevner et al. (2004), Vaishnavi and Kuechler (2004) and Weigand et al. (2021), this study adopted a DSR approach and three primary research methods are used to achieve its objectives. DSR is a methodology for conducting research that aims to create new, useful artifacts or systems (Vaishnavi & Kuechler, 2004). The goal of DSR in ontology development is to create a new ontology that is both useful and usable, and that can be applied in a specific domain or context. The ontology development process using DSR is characterized using a formal and structured methodology, rigorous evaluation and testing, and a focus on practical relevance and applicability.

To accomplish the objectives of this research, a comprehensive analysis of existing literature relevant to the topic was conducted. This literature review was focused specifically on the field of construction cost management, as well as two related areas of study: 5D BIM and semantic web technology. The data gathered for this study were extracted from several Royal Institute of Chartered Surveyors (RICS) guidance notes (BIM for cost managers: requirements from the BIM model (D. Smith et al., 2015), cost reporting (RICS, 2015), overview of a 5D BIM project (RICS, 2014), new rules of measurement 1: order of cost estimating and cost planning for capital building works (RICS, 2013), cashflow forecasting (RICS, 2011).

Based on literature review findings, BIM-based construction cost control process was established. Thereafter, ontology engineering was utilised to develop conceptual knowledge structure for BIM-based construction cost control. Ontological framework development involves creating a structured representation of a particular domain of knowledge, typically using formal logic or a controlled vocabulary (Singh & Anand, 2013; Slimani, 2015). This representation, known as an ontology, can be used to facilitate knowledge representation and reasoning tasks, such as information retrieval and semantic web applications. The development process typically includes tasks such as identifying the key concepts and relationships in the domain, defining the vocabulary and formal representation of the ontology, and validating the ontology through testing and evaluation (Noy & McGuinness, 2001; Suárez-Figueroa et al., 2011)

Finally, the developed ontological framework was validated. This is the process of ensuring that an ontology, or a formal representation of a set of concepts and their relationships, adheres to certain rules and principles. It includes checking for consistency, completeness, and accuracy of the ontology, as well as verifying that it conforms to established standards and guidelines for ontology development. The goal of ontology validation is to ensure that the ontology can be used effectively for knowledge representation and reasoning tasks. Various tools and techniques can be used for ontology validation (Baader et al., 2003; Brank et al., 2005; Gómez - Pérez, 2001), and many ontology development methodologies include evaluation as a part of the process. The frame of reference for ontology validation can include requirements specifications, competency questions, and real-world scenarios. This study utilised the requirements specifications as provided in the RICS guidance notes and semi structured questionnaire survey for the validation on the developed knowledge-based framework for BIM-based construction cost control.

4. Conceptual Ontological Framework for 5D BIM Cost Control

4.1 Concept of 5D BIM construction cost control

The paper presents an ontological framework for construction cost control using 5D BIM technology. The paper reviewed relevant studies about 5D BIM applications and ontology development for the research. As shown in Figure 1, the preparation of a 5D BIM model requires four primary processes. (1) BIM model development, (2) Quantity take-off (QTO), (3) Creating 4D BIM (i.e., integration of schedule information and QTO list), and (4) Creating 5D BIM (i.e., integration of cost information and schedule-loaded QTO list).

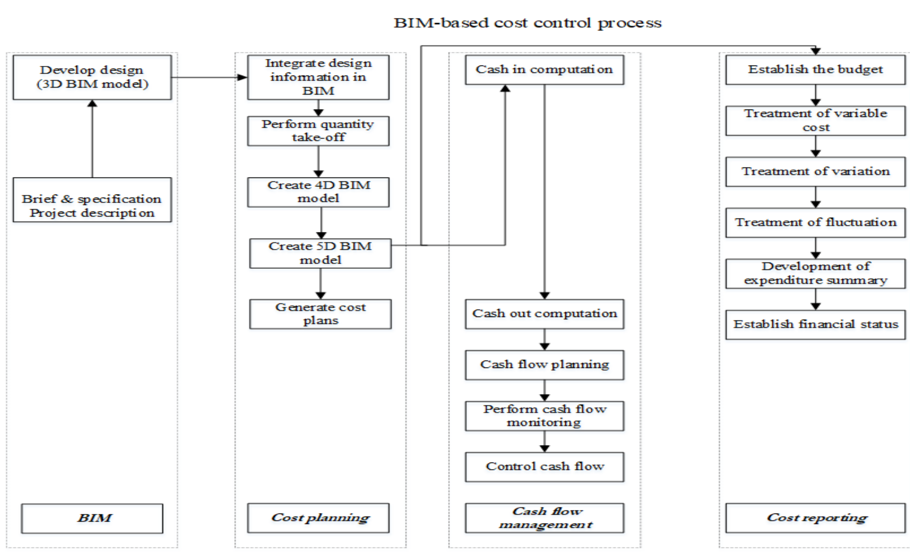

Figure 1: BIM-based construction cost control process.

During the cost planning phase, a building information model that comprises comprehensive geometric and semantic information can be incorporated into a 5D software system to produce a QTO list. By linking the QTO list with an external schedule database, a schedule-loaded QTO list is generated. By fusing this schedule-loaded QTO list with an external cost database, it is feasible to produce a cost-loaded project schedule, or cost-loaded timeline. This cost-loaded timeline file can then be imported into the 5D platform to generate a 5D BIM model, which can be utilized for conducting 5D simulations and creating cost plans.

In cashflow management phase, cash-in computation activity transforms the cost-schedule loaded information into project cash-in flows in the form of periodic payments, profits, retention amount and mobilization payment. This activity is governed by contractual conditions such as contract type, agreed-upon payment period, certification period, profit margin, retention percentage and period, and risk considerations associated with forecasting. Using 5D-BIM software tools such as Autodesk Navisworks and Causeway CATO suite, the computations are performed. The cash-out computation activity transforms the cost-schedule loaded information into cash-out flows for the project. It is governed by the various payment patterns agreed upon by contract parties and the forecasting risks affecting cash flows. Additionally, the computations are performed utilising 5D BIM software tools. The cashflow planning activity entails utilising several cash flow management techniques based on the organisation's cash flow policies to determine the most suitable strategy for planning the analysed cash flows. The cashflow monitoring activity determines the status and performance of the project's cash flow by comparing actual cash flow to projected cash flow. The final activity in the cashflow management process, control cashflows, leverages the output from the cashflow monitoring activity and current cashflow management strategies to correct the discovered deviations.

In cost reporting phase, which is the last phase of the construction cost control process. Using the established budget from the 5D BIM model, the first activity involves the treatment of variable costs like the provisional sums. The QS includes the full cost of each provisional sum in the outturn cost report at the outset of the construction contract. As work is completed and the costs are determined for each provisional sum, the quantity surveyor adjusts each provisional sum's outturn cost projection to reflect the actual costs incurred. The next step is to handle variations such as contract instructions. These must be valued according to the terms of the contract and included in the cost report. Once the value of a contract instruction has been agreed upon with the contractor, the cost report should reflect this. If the value has not been agreed upon, it should be identified separately in the cost report. If the contract allows for adjustments to the contract price due to fluctuations, the quantity surveyor must include the amount of the adjustment in the cost report, but only the amount of change that is applicable to the amount of the work completed to date, and the report should indicate that no provision for potential cost fluctuations has been made. Finally, the expenditure summary should be developed to provide the client with the financial status. In this way, the quantity surveyor enables the client to take steps to avoid cost increases or take advantage of any cost savings.

4.2 BIM-based cost control ontology

The ontology is designed to achieve standardisation and formalisation of BIM-based construction cost control domain knowledge in order to assist stakeholders in implementing highly efficient construction cost control (CCC). The concepts of this ontology cover construction cost control processes (cost planning, cashflow management, cost reporting), cost planning components (work breakdown structure, cost breakdown structure) cashflow management processes (cashflow forecasting, cashflow planning, cashflow monitoring & control), cost reporting components (treatment of variable cost, treatment of variations, treatment of fluctuations, expenditure summary). Concepts, sub concepts and relationships are depicted in the ontology as shown in the next sections. Concerning standards and technical manuals, five guidance notes are referenced in this research as summarized in Table 1.

Table 1. Knowledge Sources of CCC-Onto

Knowledge source	Type
BIM for cost managers: requirements from the BIM model	RICS guidance note
Cost reporting	RICS guidance note
Overview of a 5D BIM project	RICS information paper
New rules of measurement 1: order of cost estimating and cost planning for capital building works	RICS guidance note
Cashflow forecasting	RICS guidance note

4.3 Class and the class hierarchy

Cost planning

“Cost planning” is a subclass of “construction cost control” class, it comprises breaking down the building(s)' cost limit into specific into specific cost goals for each component of the building. It describes the methodology by which the design team wants to allocate the finances available among the constituent components of the building(s) and provides a framework for creating the design while keeping costs under control. “Cost planning” has other sub classes as “labour cost, material cost, plant and equipment cost, service cost, contingency cost, facility cost, cost of project insurance”. These components are provided as subclasses in the form of a "work breakdown structure (WBS)" and a "cost breakdown structure (CBS)," that can be used to organize the elements of construction work into packages for procurement. These subclasses are derived from the "5D BIM model".

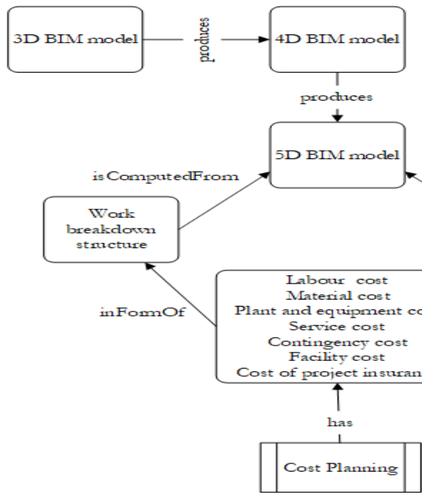

Figure 2: Cost planning class in the CCC-onto.

Cashflow management

“Cashflow management” is also a subclass of “construction cost control” class, it entails the subclasses of “cashflow forecasting”, “cashflow planning” and “cashflow monitoring and control”. It is described as a holistic process that involves the forecasting, planning, monitoring, and controlling of cash receipts and payments. “Cashflow forecasting” also has subclasses of “cash in” and “cash out”. “Cash in” class includes the computation of “profit, periodic payment mobilisation payment and retention payment” to arrive at a figure for the total cash receipts forecast. However, the “cash out” class includes the computation of “labour cost, materials cost, plants cost, subcontractors and suppliers’ payment, other fees” as forecasted payments.

In “cashflow planning” subclass, it entails either “frontend loading” or “backend loading”. “Frontend loading” is a strategy in which a bill's early items carry a larger margin than its later ones, while “backend loading” is a strategy in which the bill's latter items carry a higher margin than its earlier ones.

In cashflow monitoring and control” subclass, it is achieved by monitoring cash flow performance and applying corrective measures where deviations are spotted. It is done using variance and performance indices such as cost variance; schedule variance; cost performance index and schedule performance indices are computed to determine the status and performance of the project cash flow. “Cashflow performance” subclass is established by computing the “variance indices” based on “cost and schedule variance and “performance indices” based on “cost and schedule performance”.

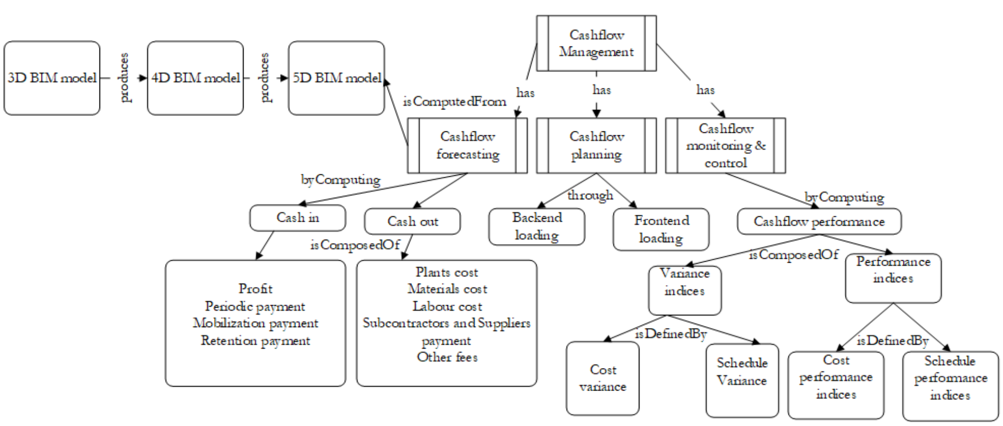

Figure 3: Cashflow management class in the CCC-onto.

Cost reporting

"Cost reporting" is also a subclass of "construction cost control" class. This entails:

all costs that have been incurred as of the report date and can be accurately valued according to the contract terms,

all costs that have been incurred as of the report date and can be reasonably estimated according to the contract terms,

an estimate of future costs that can be reasonably anticipated at the report date and estimated according to the contract terms, and necessary risk allowances that can be reasonably anticipated at the report date.

"Cost reporting" has subclasses of "treatment of variable cost, treatment of variations, treatment of fluctuations, expenditure summary and financial status".

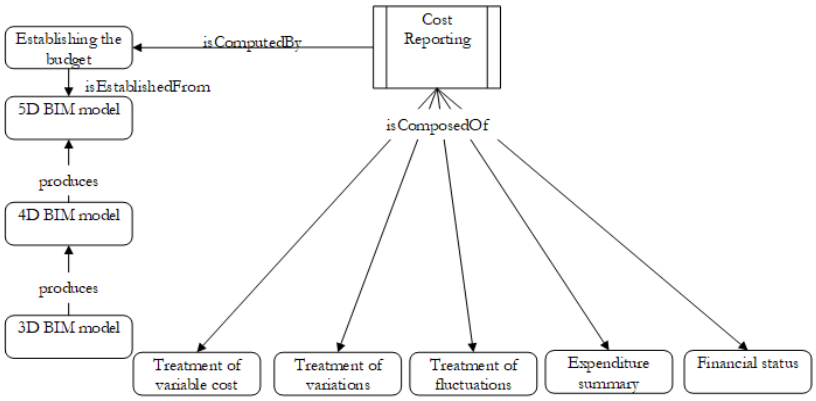

Figure 4: Cost reporting class in the CCC-onto.

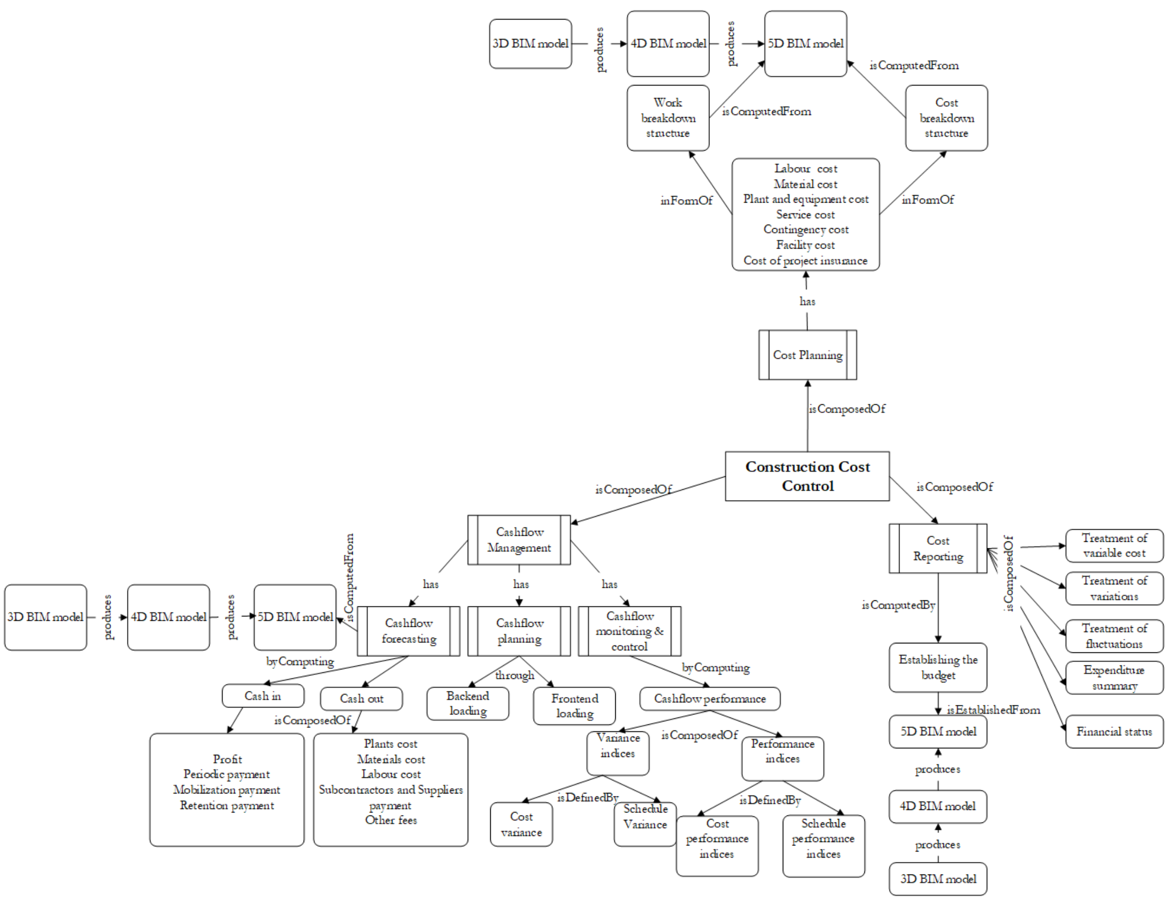

Figure 5: BIM-based CCC-onto.

4.4 Framework validation

The proposed framework as shown in Figure 5 was validated by utilising the requirements specifications as provided in the RICS guidance notes for each process of cost planning, cashflow management and cost reporting. This was adopted from (Lovrencic & Cubrilo, 2008) to determine the consistency, completeness, conciseness, expandability and sensitiveness of the developed knowledge-based framework. In addition, a semi-structured questionnaire survey was sent to the experts who had been involved in the previous ontology evaluation to evaluate the developed framework. As indicated in Table 2, the experts were required to respond to five questions using a 5-point Likert scale, where 1 represents disagreement and 5 complete agreement. Each question had an average score over 4, indicating that the constructed framework that integrates semantic web technology and BIM in construction cost control gained relatively high confirmation.

Table 2: Description analysis of questionnaire survey results

No.	Questions	Min	Max	SD	Avg.
1	The constructed framework facilitates the reuse of construction cost control knowledge	4	5	0.39	4.82
2	The constructed framework facilitates consistent and effective knowledge representation by formalizing the concepts and relationships of BIM-based construction cost control	4	5	0.49	4.65
3	The constructed framework promotes the integration of heterogeneous knowledge of processes in BIM-based construction cost control	3	5	0.64	4.18
4	The constructed framework provides computable information requirements for better semantic interoperability	4	5	0.44	4.76

5. Conclusion

This study began with a comprehensive literature review that led to an understanding of construction cost control and 5D BIM. Moreover, implementation obstacles for 5D BIM were identified and discussed. Interoperability, where there is no knowledge-based framework for BIM-based construction cost control, was a fundamental issue. The goal of the proposed conceptual ontological-based framework is to promote a shared comprehension of BIM-based construction cost control, establish the theoretical foundations of the concept and to provide practitioners with a thorough knowledge of the intrinsic structural aspects of construction cost control. To achieve this, the conceptual model should be designed in a way that is easily understandable for its users. When implemented correctly, the conceptual model should meet four essential goals (Kung & Soelvberg, 1986).

- Enhance understanding of the represented system.

The developed conceptual framework improves comprehension of the relationship and scope of BIM-based construction cost control by providing a comprehensive, integrated and thorough systematisation of the process.

- Support effective communication of contextual information among relevant stakeholders.

By utilising an ontological conceptual framework as a basis for BIM-based construction cost control, software developers can develop a common language and use the framework visually to facilitate the exchange of system information.

- Provide software developers with a frame of reference for to extracting system specifications.

This study provides software developers with a deep understanding of the underlying architecture of BIM-based construction cost control.

- System documentation for future reference and collaboration support

The proposed ontological framework assists practitioners and scholars organise and structure BIM-based construction cost control processes and communicate them to various stakeholders.

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