A comprehensive literature review of 5D building information modelling using latent Dirichlet allocation analysis

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Jacopo Cassandro, Claudio Mirarchi and Alberto Pavan
Department of Architecture, Built Environment and Construction Engineering, Polytechnic of Milan, Milan, Italy

Abstract

Purpose – This research evaluates the current state of 5D building information modelling (BIM) in cost estimation and management within the architecture, engineering and construction/FM industry. It identifies key areas of interest, synthesizes industry needs and highlights research gaps by analysing a large corpus of academic articles.

Design/methodology/approach – A quantitative approach using latent Dirichlet allocation (LDA) analysed articles from Scopus and Web of Science. The methodology involved querying these databases for relevant articles on 5D BIM and cost estimation, applying LDA to identify and analyse emerging themes and synthesizing the findings for a comprehensive overview of the research landscape.

Findings – The LDA analysis reveals themes in 5D BIM for cost estimation and management, including integration with cost tools, implementation challenges and practical case studies. It also highlights technological advancements, software innovations and educational needs for effective BIM adoption. Research gaps are noted in standardization, interoperability and the long-term impacts of 5D BIM on project lifecycle costs.

Research limitations/implications – This study's reliance on abstracts may miss key terms in full texts, though full-text analysis could introduce noise. Despite this, the findings offer valuable insights into trends and opportunities in 5D BIM research, guiding future studies and highlighting underexplored areas.

Originality/value – This study provides novel insights by using LDA to analyse a large volume of 5D BIM research articles systematically. Unlike traditional reviews, LDA enables the objective identification of latent themes across over a thousand abstracts, reducing bias and ensuring scalability. By integrating natural language processing with domain-specific expertise, the study reveals critical issues in the construction industry by identifying research gaps.

Keywords BIM, Cost estimation, Cost management, 5D BIM, Latent Dirichlet allocation, NLP

Paper type Literature review

Introduction

Several articles have been published discussing recent trends and research themes in building information modelling (BIM), along with their implications (Biswas *et al.*, 2024). BIM uses digital tools and technologies to support business processes that generate shared digital representations of built assets through the design, construction and operation phases. BIM enables the production and management of information and improves communication across the entire construction life cycle (Eastman *et al.*, 2011; Sacks *et al.*,2018). To achieve its full

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potential, BIM extends beyond geometric representation in a 3D environment (Charef *et al.*, 2018). The third dimension (3D) provides graphical and non-graphical information within a digital model of a construction project. The fourth dimension (4D) integrates scheduling data to visualize and control project development during the construction phase. The fifth dimension (5D) manages and links cost information to the 3D model and project schedule. Nowadays, there is an increasing interest in domains linked to the geometric world of construction (3D BIM). This study focuses on BIM-based cost management (5D BIM).

The implementation of 5D BIM significantly enhances the management of design change (Harrison and Thurnell, 2015), improves the exchange of information among stakeholders and reduces errors and delays (Grilo and Jardim-Goncalves, 2010; Sattineni and Macdonald, 2014). It also facilitates the inclusion of relevant data for monitoring and managing project costs (Mesároš *et al.*, 2019).

Before the advent of 5D BIM, cost management relied on traditional methods based on manual processes. Estimators calculated costs based on their experience and knowledge, starting from project drawings and specifications (Fazeli *et al.*, 2021), performing quantity take-offs (QTOs) manually from 2D drawings. This process was time-consuming and error-prone.

Furthermore, cost scenario analysis using spreadsheets was challenging and inefficient. Any project changes require recalculating estimates from scratch, often resulting in outdated figures. This approach often led to delays and increased the risk of cost overruns. The accuracy of cost estimates heavily depended on the estimator's expertise, frequently leading to inconsistencies, inconsistencies and human error (Fazeli *et al.*, 2021; Elghaish *et al.*,2020).

In response to these limitations, the concept of "5D CAD" emerged in the early 2000s, extending traditional CAD models by incorporating time and cost dimensions (O'Brien, 2000). These systems enabled the simulation of construction sequences alongside cost implications, offering visual and quantitative support to decision-making. By associating components with unit costs and scheduling data, 5D CAD anticipated many of the functions now embedded within BIM platforms (Popov *et al.*, 2010; Smith, 2014). Although less interoperable than current solutions, 5D CAD laid the foundation for integrated design-to-cost workflows that define contemporary digital construction practices.

The methodological principles introduced by 5D CAD, such as linking quantities to the cost elements of the construction process, remain central to current 5D BIM approaches. As such, the transition from 5D CAD to 5D BIM reflects a broader shift from standalone design applications to semantically rich, interoperable environments supporting lifecycle cost management (Lu *et al.*, 2016). Recognising this evolution helps to contextualize 5D BIM as the result of progressive technological integration, rather than a completely new paradigm.

The concept of 5D BIM was formally introduced in 2010 (Charef *et al.*, 2018; Popov *et al.*,2010). Since then, numerous studies have examined its potential benefits and implementation challenges (Stanley and Thurnell, 2014), as well as its adoption in real-world construction projects (Stanley and Thurnell, 2014; Lu *et al.*, 2016). 5D BIM is now widely regarded as a promising solution to enhance the efficiency and reliability of cost management processes throughout the project lifecycle (Lu *et al.*, 2016; Smith, 2014).

On the other hand, doubts remain regarding the actual performance improvements brought by 5D BIM adoption (Wahab and Wang, 2022). Key challenges include software security, investment in staff training and software purchase and software accessibility standards (Mesároš *et al.*, 2019). Another major constraint is the level of information need (Sattineni and Macdonald, 2014; Aibinu and Venkatesh, 2014).

This paper aims to examine and evaluate recent literature related to cost management in BIM. This study identifies current practices and potential research gaps to guide future research investigations in the construction sector. Literature was sourced from two major scientific databases: Scopus and Web of Science.

The main purpose of this document is to answer the two questions that follow:

Q1. What are the current applications and research related to the cost domain in BIM?

Q2. What are the emerging issues in the published literature related to the cost domain in BIM, and what are the "grey areas" of current research?

The analysis shows that some areas remain underexplored. This research contributes to existing knowledge by synthesizing the critical needs of the BIM sector in the field of cost estimation and cost management. It also highlights current research gaps through a statistical meta-analysis of the literature. To achieve this, due to the increased number of articles, a statistical meta-analysis of literature was conducted using latent Dirichlet allocation (LDA). This method enables objective identification of latent themes across over a thousand abstracts while reducing bias and ensuring scalability.

This paper is structured as follows. Section "Method of Research" illustrates the research design method used in this paper. The first step is to give an overview of the method used: the statistical meta-analysis used to evaluate the published literature. Thereafter, the section "Results and Findings" presents the findings of the quantitative analysis conducted. Subsequently, the section "Discussion" discusses the findings by quantitative results while presenting critical issues in current research. In the final section, "Conclusion and Future Work", the limitations of this study, the implications for future research and the contributions made in this article are outlined.

Research methods

This study aims to synthesize the pressing issues related to the dimension of the cost linked to the BIM world in the architecture, engineering and construction (AEC) industry, to support BIM implementation and consolidate existing domain knowledge, thus identifying future research directions. To address these objectives, a quantitative statistical analysis of a large data set of published literature was conducted using LDA to illuminate the established 5D BIM knowledge domain. This analysis allows a complete view for validation purposes. Unlike traditional reviews, LDA enables the objective identification of latent themes across more than a thousand abstracts, reducing bias and ensuring scalability. By integrating natural language processing with domain-specific expertise, the study uncovers critical themes such as cost data management, interoperability challenges and technological integration. Furthermore, the findings address significant research gaps, offering practical pathways for the application of 5D BIM in cost estimation and project lifecycle management. This innovative use of LDA not only advances meta-analytical approaches in BIM research but also aligns academic insights with industry needs, making it a valuable contribution to the field.

The use of multiple data sources to study the same phenomenon allows researchers to detect critical issues and consistent relationships between variables. All research methods have inherent strengths and limitations; therefore, quantitative analysis allows for a broader and more objective exploration of data patterns.

The methodology used consists of a three-step process, aligned with the structure illustrated in Figure 1, and described in the following sections:

(1) data collection;

(2) data analysis and topic identification; and

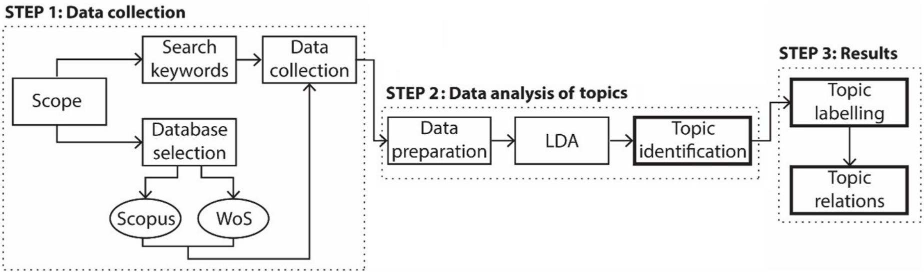

Figure 1. Workflow of the methodology adopted
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(3) topic labelling and validation.

Statistical meta-analysis consists of data collection (Step 1) and data analysis (Step 2). The entire data set collected was analysed using the LDA method. Step 3 presents topic labelling and topic relations.

Data collection (Step 1)

Data collection began with the collection of abstracts from academic journals and conference articles using two databases: Scopus and Web of Science (WoS). Scopus contains over 27,500 peer-reviewed journals, 11.6 million conference papers, and over 90 million records (Scopus, 2023). The WoS database covers over 12,000 peer-reviewed journals and more than 160,000 conference proceedings (Clarivate, 2023).

The initial query aimed to identify current research on 5D BIM. A predefined set of keywords, operators and nesting combinations was applied to both databases (Table 1). Starting from articles published since 2013, a total of 1,865 abstracts were collected in June 2024. A comparative review showed a balanced distribution of articles between the two databases.

The collected data were stored in text files and contained the following information: authors, titles, year, type of publication, abstracts and keywords. Since the analysis is based on abstracts, any entries without one were excluded. In total, three text files were removed from the database. In addition, 507 duplicate articles were eliminated. The final cleaned data set comprised 1,281 unique abstracts used for the analysis.

Data analysis and topic identification (Step 2)

Considering the large volume of extracted articles, a statistical meta-method was selected to identify the dominant knowledge domains in the BIM cost area.

Several statistical meta methods currently exist, such as the term frequency–inverse document frequency scheme (Salton and McGill, 1986), latent semantic indexing (Deerwester *et al.*, 1990) and probabilistic latent semantic analysis (Hofmann, 1999) and LDA (Blei *et al.*, 2001).

LDA was chosen for its ability to model the co-occurrence of words across large corpora, allowing efficient extraction of underlying topics. Compared to other methods, LDA is less prone to overfitting and enables an objective evaluation of extensive textual data (Blei *et al.*, 2001). While bibliometric analyses often rely on subjective selection criteria, LDA reduces such bias by using unsupervised learning techniques. LDA is a topic modelling technique

Table 1. Overview of data extracted from research studies in Scopus and Web of Science (WoS)

Keywords	Number of articles Scopus	Number of articles WoS
"5D BIM" OR "5D Building Information Modeling" OR "5D Building Information Modelling" OR "5D Building Information Model"	109	52
"Cost estimation" AND "5D BIM" OR "5D Building Information Modeling" OR "5D Building Information Modelling" OR "5D Building Information Model"	27	20
"Cost estimation" AND "BIM" OR "Building Information Modeling" OR "Building Information Modelling" OR "Building Information Model"	244	177
IFC OR "industry foundation class" OR "industry foundation classes" AND "5D BIM" OR "5D Building Information Modeling" OR "5D Building Information Modelling" OR "5D Building Information Model"	6	2
IFC OR "industry foundation class" OR "industry foundation classes" AND "cost"	333	232
IFC OR "industry foundation class" OR "industry foundation classes" AND "qto" OR "quantity take off" OR "quantity-take-off"	14	12
"BIM" OR "Building Information Modeling" OR "Building Information Modelling" OR "Building Information Model" AND "qto" OR "quantity take off" OR "quantity-take-off"	123	73
ifcowl	48	70
"cost" AND "BIM" OR "Building Information Modeling" OR "Building Information Modelling" OR "Building Information Model" AND IFC OR "industry foundation class" OR "industry foundation classes"	198	120
"cost" AND "ifcOWL"	2	3
TOTAL per database	1,104	761
TOTAL	*1,865*	
TOTAL without abstract	3	
TOTAL without duplicate and abstract	*1,284*	

Source(s): Created by author

developed in the fields of natural language processing, machine learning and computer science to retrieve and query bodies of large data (Blei *et al.*, 2001). It defines "corpus" as a collection of "M" documents, "document" as a sequence of "N" words and "word" as the basic unit of the data (Blei *et al.*, 2001). It uses documents as representations of themes, where each topic comprises a collection of keywords represented in a certain proportion. LDA provides an automated procedure for sorting the contents of a corpus of text data into a set of meaningful "topics". The algorithm automatically groups terms into a meaningful set of topics with minimal human intervention.

The analysis was implemented using Python 3.10, a widely used object-oriented programming language. Python was selected due to several advantages:

- It provided quick development and test activities as Python can be executed directly without the need to compile an executable format – the script was executed using Jupyter Notebook to optimize the execution of the algorithm of analysis (Project Jupyter, 2023) or using Visual Studio Code, installing the available extensions to execute the code;
- It offers several dedicated packages for the development of natural language processing [e.g. the Natural Language Toolkit package (Bird *et al.*, 2008)], and topic modelling applications [e.g. the Gensim package (Rehurek and Sojka, 2010)]; and

- It allows easy reading and code transparency for dissemination, verification and re-use in future research.

Data preparation. Before applying the LDA, the data set was pre-processed to improve the reliability of topic extraction. These steps included:

- tokenizing abstracts into a "bag of words";
- converting all letters to lowercase;
- removing all stop words (e.g. "so", "and" and "or") using the English stop word dictionary provided by the Natural Language Toolkit (NLTK) package for Python;
- eliminating all forms of punctuation;
- excluding words with fewer than three characters due to their irrelevant significance in the text; and
- removing numerical characters and overly common domain-specific terms that appeared across all topics.

A personalised set of words was defined by the authors and removed from the corpus following a series of iterations of the algorithm on the available data [1]. This has led to the elimination of even terms that are predominant transversally on all topics and therefore do not characterize them.

After pre-processing, a stemming algorithm technique (Hotho *et al.*, 2005) was applied to consolidate words with the same roots [2]. The identification of *n*-grams was included to identify possible correlations because LDA does not evaluate the sequencing of words in texts analysed. An n-gram is an aggregation of single words processed during the tokenization of a set of words, where *n* identifies the number of words considered in the aggregation. For example, the bi-gram "cost-estimation" reflects the joint significance of both terms. Based on findings in previous research (Yalcinkaya and Singh, 2015), the inclusion of bi-grams improved topic coherence. The use of three grams in this research did not provide significant improvements to the data analysis.

Latent Dirichlet allocation. After that, the cleaned data were applied to the vector representation process, in which each document was represented as a set of words occurring across the corpus. A unique ID was assigned to each word, thereby creating a "dictionary". Consequently, documents were represented as numerical arrays, where each number corresponded to a specific word. The algorithm then counted the frequency of each word in each document and linked it to its corresponding ID. As a result, each document was encoded as a sparse vector, suitable for input into the LDA transformation model.

LDA requires a predefined number of topics as input data. The algorithm's performance was evaluated through a quality assessment procedure, which determined the optimal number of topics based on thematic clarity and model output quality. This assessment relied on the UCI coherence score, a quantitative metric that measures how well the identified topics represent the underlying corpus (Röder *et al.*, 2015). To this end, the LDA model was tested using four configurations: 5, 10, 15 and 20 topics. The coherence score remained high (approximately 0.63) for both the 5- and 10-topic models but dropped to around 0.60 for 15 and 20 topics. Based on the comparative results, the authors selected the five-topic model as the most effective solution, noting that the 10-topic model contained significant thematic overlap between topics.

Topics identification. Once the LDA model was finalized, each document was associated with a probability distribution across topics. Based on this distribution, a dominant topic was assigned to each document, effectively clustering them into thematic groups. It is important to note that emerging topics may not include all existing research areas, as the model tends to highlight only the most prevalent themes based on their statistical relevance and frequency within the data set. Topics with fewer occurrences, corresponding to underrepresented areas in the literature, may fall below the detection threshold and thus be omitted. These represent so-called "grey areas" or emerging fields in the academic discourse. For instance, in Topic 0, the frequency of the top 10 keywords ranged between 1.0% and 4.5%, while any keyword appearing in less than 1.0% of documents was excluded by the algorithm.

To ensure robustness and consistency, the topic modelling process was iterated ten times for each configuration (i.e. 5, 10, 15 and 20 topics). This approach aimed to verify the stability of the most significant keywords and confirm their dominance relative to other terms. Given the probabilistic nature of the method, the keywords identified may vary slightly across runs. Therefore, a consistency score was calculated for each output. Ultimately, the version with the highest consistency score (closest to 1) was selected for the final analysis.

Topic labelling and validation (Step 3)

Step 3 comprised topic labelling and the identification of thematic relationships. Three authors and three external experts in the field independently interpreted the LDA results and proposed topic labels. Subsequently, they convened to discuss and consolidate their interpretations, ensuring consistency and alignment. In this phase, the first author collected the results of the LDA analysis in an Excel spreadsheet. This file was then distributed to the other two authors and three external experts, including a representative from a construction company and two professional engineers. Each participant independently reviewed the data and proposed labels for each data cluster.

The individual assessments were then collected and compared. A collaborative meeting was held to discuss discrepancies and refine the topic definitions. This process ensured a comprehensive and multidisciplinary evaluation, enhancing both the robustness and validity of the identified topics while minimizing individual bias.

The final set of topics resulting from this procedure is presented in the section "Results of the Statistical Analysis".

Results and findings

Results of the statistical analysis

The results are based on the quantitative analysis, which presented topics related to 5D BIM research identified in existing literature. The synthesis of quantitative results offers an interpretative framework for understanding key arguments to inform future 5D BIM research (Creswell and Creswell, 2017). The main research areas have been clearly identified, and the outcome of the Quantitative analysis [3] is presented in Table 2. This table shows, in percentage terms, the frequency of keywords identified across the Topic clusters through the statistical process. These keywords, derived from the iterative LDA procedure, were considered optimal for representing the primary research domains in the field.

The research identified 5 different macro areas, Topic 0-1-2-3-4 (Table 2), in which to divide the current research. Table 3 summarizes the main research areas divided by the Topic clusters identified through the analysis performed according to the methodology described in the section "Method of Research". The five topics identified are:

(1) technology and methods for cost data;
(2) cost estimation management methods;
(3) cost and estimation data management;

Table 2. Quantitative analysis results

Topic		K0	K1	K2	K3	K4	K5	K6	K7	K8	K9
Topic 0	%	0.005	0.005	0.005	0.004	0.004	0.003	0.003	0.003	0.003	0.003
	key	construct	data	cost	process	estim	project	use	method	system	work
Topic 1	%	0.014	0.010	0.009	0.008	0.007	0.006	0.004	0.004	0.004	0.003
	key	cost	construct	estim	data	project	cost_estim	method	process	manag	system
Topic 2	%	0.009	0.009	0.009	0.007	0.005	0.005	0.004	0.004	0.003	0.003
	key	project	cost	construct	data	manag	process	estim	method	use	industri
Topic 3	%	0.008	0.006	0.005	0.004	0.004	0.003	0.003	0.003	0.003	0.002
	key	construct	cost	project	process	system	use	energi	data	manag	industri
Topic 4	%	0.006	0.005	0.004	0.004	0.004	0.003	0.002	0.002	0.002	0.002
	key	construct	cost	project	data	system	process	semant	use	ontolog	manag

Source(s): Created by author

Table 3. Main topics analysis

Topic	Topic label	No. of paper	%
0	Technology and methods for cost data	219	17.06
1	Cost estimation data management and methods	334	26.01
2	Project cost data processes, methods and management	362	28.19
3	Energy design and use cost management	210	16.36
4	Cost data ontology	159	12.38

Source(s): Created by author

(4) energy design and use costs management; and

(5) cost data ontology.

Each topic is listed with the corresponding number of articles and percentage of total articles analysed (1,284 abstracts). The key topics of the 5D BIM dimension, underlying the idea of better and more efficient cost management and estimation (Elghaish *et al.*, 2020), appear in each topic, and this confirms what is initially defined by the search keys.

5D BIM trends in research

The analysis has identified five key topics illustrating the different applications of 5D BIM in research. These topics highlight the significance and advancements BIM brings to the construction industry in the field of cost.

Topic 0: technology and methods for cost data. This topic emphasizes leveraging technological advancements and methodological approaches for effective cost data management in construction projects. BIM and automation enhance data accuracy and project efficiency.

Topic 1: cost estimation data management and methods. Efficient cost estimation and data management are crucial for successful project planning and execution. This section examines how BIM-enabled strategies and methodologies ensure accurate cost estimation from the early design phases, facilitating precise financial forecasting and better resource allocation throughout the project.

Topic 2: project cost data processes, methods and management. Streamlined cost management processes are critical for keeping projects on schedule and within budget. This section explores how BIM enhances the management and optimization of cost data throughout the entire project lifecycle, from initial planning to execution, improving overall project outcomes by integrating efficient cost control methods.

Topic 3: energy design and use cost management. Managing costs related to energy-efficient design and usage is vital for sustainable construction. BIM helps optimize energy performance, evaluate lifecycle costs and reduce operational expenses.

Topic 4: cost data ontology. Cost data ontology is a structured approach that categorizes and correlates cost information, enhancing interoperability and data integration. This section discusses the development and application of cost data ontologies in BIM.

Overall, the trend of research results for the five topics identified, in Figure 2, provides a comprehensive overview of 5D BIM trends and shows an increasing interest in this field in recent years. Current trends indicate that this sector will continue to play a significant role in construction management. The observed decline in 2024 is attributable to the analysis only considering publications from the first half of the year. By projecting a uniform distribution of publications for the entire year and thus doubling the number of articles identified in the first half of 2024, using dashed lines in Figure 2, it is possible to observe how the year-end estimate confirms the growth and interest in the topics analysed for all five identified subjects.

In addition, Figure 3 shows the total number of 5D BIM publications since 2013 in each Topic.

Discussion

The analysis of topics has shown that 5D BIM is currently being used across various research fields. These topics delve into strategies, tools and challenges related to managing cost data from the initial design stages. The importance of organising and managing costs in project networks is therefore crucial.

The five topics identified by the statistical analysis are described and analysed below.

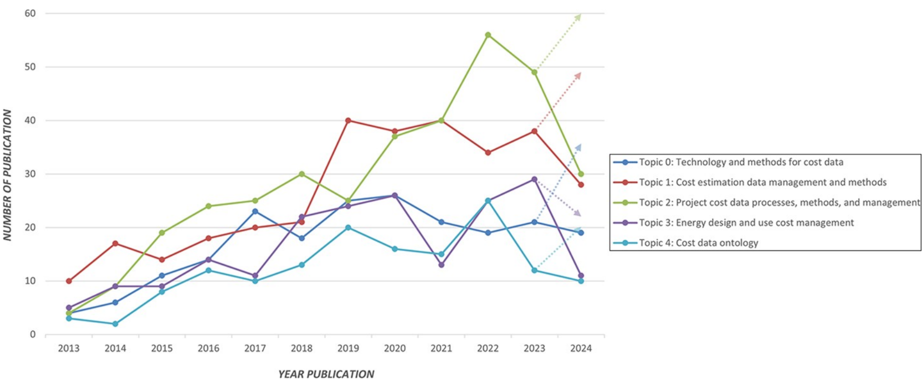

Figure 2. Temporal evolution of publications across identified topics (2013–2024)
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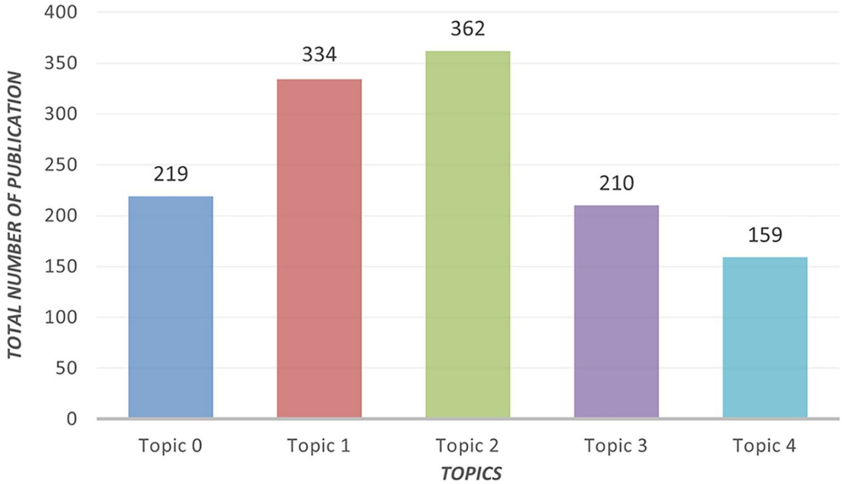

Figure 3. Total number of publications per identified topic (2013–2024)
Source: Created by author

Technology and methods for cost data

The first topic, "Technology and Methods for Cost Data", emphasizes the role of technological advancements and methodologies, particularly BIM, in shaping cost data management. The integration of tools like BIM and automation of QTO has been acknowledged in both research and industry for their potential benefits (Rouhanizadeh *et al.*, 2021; Gohil *et al.*,2022; Valinejadshoubi *et al.*, 2024). However, despite this recognition, the economic advantages of BIM are often seen as intangible and unclear, posing a barrier to its widespread adoption (Barlish and Sullivan, 2012; Jin *et al.*,2017; Zhang *et al.*, 2018; Cezar *et al.*, 2023; Jafary *et al.*, 2024). Consequently, these perceived economic benefits are frequently regarded as a significant barrier to the widespread adoption of BIM, as indicated by the research conducted by Papadonikolaki and Aibinu (2017) and Tan *et al.* (2019).

Furthermore, accurate cost feedback is essential for early design decision-making, but it is challenging for cost estimators to provide precise estimates when the project is evolving and incomplete (Sepasgozar *et al.*, 2022). The adoption of 5D BIM technologies aims to address this issue by reducing manual workloads and enhancing precision and timeliness (Mesároš *et al.*, 2019; Forgues *et al.*,2012). Traditional cost estimation methods, which often involve outdated workflows and non-digital processes, are prone to errors and inefficiencies (Agostinelli *et al.*, 2019). This makes cost estimates less reliable, yet there is growing interest in BIM as a solution to these challenges, driven by the realization that traditional standards no longer align with BIM-based systems (Banihashemi *et al.*, 2022). BIM offers a structured approach to aligning cost and quantity data, facilitating a seamless workflow and improving project document updates. By addressing cost and delay issues, BIM's automated monitoring capabilities are vital in the AEC sector (ElQasaby *et al.*, 2023).

The 5D BIM methodology enables more efficient information exchange, reduces errors and offers a clear budget and construction progress to stakeholders (Grilo and Jardim-Goncalves, 2010; Sattineni and Macdonald, 2014; Mesároš *et al.*, 2019). In addition, it provides faster cost feedback, leading to improved customer satisfaction (Pasquire *et al.*, 2011). The 5D model's ability to directly associate unit costs with specific quantities enhances safety and optimizes cost management throughout the project (Abdel-Hamid and Abdelhaleem, 2023). A study by Abdel-Hamid and Abdelhaleem (2023) demonstrated that the gap between planned and actual costs decreased from 12% to 5% with 5D BIM (Abdel-Hamid and Abdelhaleem, 2023).

Various BIM-based software applications facilitate the integration of BIM into cost estimation (Abanda *et al.*, 2017; Toan *et al.*, 2023). These tools, such as Autodesk Revit (Autodesk, 2023), offer fundamental modelling capabilities and essential features for calculating user costs associated with building components. In addition, there are specialized cost-measurement software solutions like CostX (Exactal, 2023), Vico Estimator (Trimble, 2023) and Innovaya Visual Estimating (Innovaya, 2023).

However, interoperability issues persist, particularly between 3D, 4D and 5D modelling, preventing full realization of BIM's potential (Moshtaghian and Noorzai, 2023; Ramaji *et al.*, 2018; Yoon and Pishdad-Bozorgi, 2022). There are still several doubts about the actual improvement given by the application of 5D BIM methodology (Wahab and Wang, 2022; Moses *et al.*,2020). It is worth noting that the extent of 5D BIM implementation varies among different countries (Mesároš *et al.*, 2019).

From this need emerged numerous studies have developed automated systems to improve cost estimation accuracy through tools like quantity extraction and open standards such as Industry Foundation Classes (IFC) (Fazeli *et al.*, 2021; Rouhanizadeh *et al.*, 2021; Le *et al.*, 2021; Liu *et al.*, 2014; Alzraiee, 2022; Ma *et al.*, 2013; Gökçe *et al.*, 2013). These systems promise quicker, more accurate processes for cost management (Yao *et al.*, 2020; Sherafat *et al.*,2022; Han *et al.*, 2017). Agostinelli *et al.* (2019) proposed a framework for cost planning that automatically updates quantities as models change (Agostinelli *et al.*, 2019). Other studies, like those by Le *et al.* (2021) and Akanbi and Zhang (2017), focus on BIM-database integration for more precise cost estimation (Le *et al.*, 2021; Akanbi and Zhang, 2017). Stransky and Dlask (2018) focused on a semi-automatic process to identify and link work items between BIM models and cost estimating software (Stransky and Dlask, 2018).

While several software solutions exist for 5D BIM (Mesároš *et al.*, 2019; Smetanková *et al.*, 2018; Vigneault *et al.*, 2020), issues remain. Using various software necessitates additional effort to synchronize all data about cost, schedule and quantities (Suarez *et al.*, 2020). The need for manual inputs to complete cost estimation processes is a significant weakness in the automation of construction cost estimation. Several studies introduced NLP techniques to address this gap, automating the alignment of BIM elements with cost items (Akanbi *et al.*, 2019; Akanbi and Zhang, 2020; Nabavi *et al.*, 2023; Shahinmoghadam *et al.*, 2024; Yin *et al.*, 2023).

Similarly, integrating BIM with virtual reality (VR) offers a way to automatically compute costs when project changes occur (Wang and Tung, 2023; Lee *et al.*,2022).

Cost estimation data management and methods

Data management and cost estimation methods are crucial for the success of construction projects in the AEC sector. The process of construction cost estimation is inherently labour-intensive and requires accurate data collection, management and analysis of materials, labour and costs (Lee *et al.*, 2022; Ma and Liu, 2014; Herdyana and Suroso, 2023). Accurate cost estimation is essential for budgeting and tendering in construction projects, involving direct costs like materials, labour and professional services (Samphaongoen, 2010; Olatunji *et al.*, 2010).

Cost estimation is a dynamic and knowledge-intensive process, comprising two components: quantities of design elements (e.g. concrete columns) and process quantities related to construction tasks (e.g. labour hours for concrete casting) (Marzouk *et al.*, 2018). Engineers typically rely on design plans, specifications and available cost data to calculate material quantities and assign unit costs, often based on their judgment (Xu *et al.*, 2015a, 2015b). BIM tools, particularly 5D BIM, help automate these calculations, reducing manual work and improving data accuracy (Elghaish *et al.*, 2020; Alsamarraie and Ghazali, 2023).

The integration of BIM with QTO functionality offers a higher degree of precision in cost estimation, directly linking extracted quantities with cost databases (Azhar, 2011; Bryde *et al.*, 2013). This process reduces the time engineers spend on manual quantity measurement (Choi *et al.*, 2015). The most common method involves associating digital object codes with price items from cost databases (Pavan *et al.*, 2017). In addition, BIM-based clash detection has been shown to lead to significant cost savings by refining processes and improving detection accuracy (Chahrour, 2021).

Despite these advantages, research on BIM adoption in QTO remains fragmented (Mesároš *et al.*, 2019; Alzraiee, 2022; Zhao and Wang, 2014), with significant gaps in functionality. Traditional BIM models often lack essential information for QTO, and the calculations may not align with prescribed rules in standard methods of measurement, compromising the accuracy of cost estimation (Han *et al.*, 2017; Liu *et al.*, 2021; Yang *et al.*, 2022). Furthermore, engineers must still manually verify work items and assign costs, a process complicated by low-level development (LOD) of BIM models [Sattineni and Macdonald, 2014; Aibinu and Venkatesh, 2014; International Organization for Standardization (ISO), 2023, Issues like differences in layer dimensions for elements such as architectural walls, or overlapping structural elements in low LOD models, hinder cost estimation accuracy (Khosakitchalert *et al.*, 2018; Lee *et al.*, 2015).

While the potential of BIM to enhance cost control is widely acknowledged, the exploration of its full capabilities is ongoing. Several studies are investigating how BIM can improve cost estimation accuracy, surpassing traditional manual methods (Haider *et al.*, 2020; Clark, 2019; Matejka and Vitasek, 2018). Research by Zhao and Wang (2014) and Khaleel and Naimi (2022) has shown that BIM technologies like Revit can significantly improve the accuracy of cost estimates compared to manual methods (Zhao and Wang, 2014; Khaleel and Naimi, 2022; Shen and Issa, 2010).

Project cost data processes, methods and management

In construction projects, cost, schedule and quality targets are critical parameters for determining project success (Silva and Warnakulasooriya, 2017; Hui *et al.*,2023; Abdel-Hamid and Abdelhaleem, 2023). Assessing economic viability at an early stage is essential for informed decision-making and project realization (Bender and Stoy, 2021; Nsimbe and Di, 2024). However, managing project cost data goes beyond initial cost estimation and encompasses the entire project lifecycle (Wan Abdul Basir *et al.*, 2023; Inzerillo *et al.*, 2024). Effective management of cost data is crucial for accurate planning, monitoring and control throughout the project (Chen, 2023).

Managing cost data requires robust processes, methods and strategies to ensure accurate tracking and control. Achieving this goal demands more than just estimating costs; it involves comprehensive data management practices. One of the primary challenges is ensuring efficient data exchange, not only within the cost domain but also across different domains and disciplines. Efforts in the architecture, engineering, construction and owner industry have focused on improving data interoperability across various software systems. BIM serves as a strong foundation for collaborative data management, supporting efficient monitoring and control of processes like design, planning, cost control, construction and maintenance (Ruano-Ruiz *et al.*, 2022).

While modern methodologies offer real-time data accessibility and integration, traditional construction project management approaches are often linear and fragmented, hindering seamless data exchange and resulting in project delays and budget overruns (Chen *et al.*, 2021). The use of diverse BIM software tools by different stakeholders can also lead to inconsistencies, data gaps and reduced operational efficiency (Ren *et al.*, 2022; Leicht *et al.*, 2020; Keerthana and Gunarani, 2019).

To address these challenges, buildingSMART has introduced IFC, a standardized schema to enhance data interoperability across different software applications. This schema helps ensure data consistency, improving collaboration within the industry (Cheng and Wu, 2013).

The integration of cost models within BIM is an evolving field. New standards, such as ISO 16739 (IFC4), have introduced additional entities and properties to expand BIM's capabilities [International Organization for Standardization (ISO), 2018]. While the representation of process-based cost information through IFC4 objects shows promise, further development is needed to fully realize this potential (Isatto, 2021). IFC data structures hold significant potential for improving information integration and interoperability, providing a standardized platform for various BIM software, reducing complexity and lowering project costs (Ramaji and Memari, 2015).

Energy design and use costs management

Sustainable practices, particularly energy efficiency, have gained significant attention in the construction industry. Managing energy-related costs in construction projects is crucial for maximizing energy-efficient building components, evaluating life-cycle costs and reducing long-term operating expenses. Effectively managing energy design and use costs is vital for constructing environmentally friendly and cost-effective buildings.

Recent research highlights key themes and challenges in energy design and use cost management, particularly the use of 5D BIM models. These models provide comprehensive insights into all costs associated with building projects, enabling better decision-making regarding energy-efficient components (Pučko *et al.*, 2020; Wasim *et al.*, 2023).

In addition, the analysis of building envelope shape, especially for amorphous buildings, using IFC has improved the reliability of design proposals and cost prediction by incorporating building performance at the initial design stage (Choi and Lee, 2023; Choi and Lee, 2023).

Interoperability between BIM and building energy models has also been a key focus, especially regarding the structured data for material properties, which enhances the efficiency of the mapping process (Turkyilmaz, 2013; Porsani *et al.*, 2021; Ahn *et al.*, 2014; Santos *et al.*, 2017). However, despite the existence of dedicated databases, the lack of a common property set for building materials complicates the mapping process, hindering the integration of energy performance data with cost estimation models (Fenz *et al.*, 2021).

A significant challenge in economic analysis is obtaining cost data based on energy performance, particularly in the early design phases. This often results in postponing quantitative economic analyses until later stages, when making changes becomes more costly and difficult (Rafati Sokhangoo *et al.*, 2019).

The management of energy design and use costs is a dynamic and evolving field, with significant potential to improve sustainability and cost-effectiveness. BIM and IFC technologies are crucial in addressing the complexities of energy-efficient building design and management, yet challenges remain in fully integrating energy performance data with cost analysis tools.

Cost data ontology

The construction industry is increasingly adopting ontologies and semantic technologies to improve the management and utilization of cost data. This theme explores the development and implementation of cost data ontologies, which provide a standardized, structured representation of cost-related information. These ontologies facilitate seamless data exchange and interoperability among stakeholders, contributing to the evolution of more efficient and interconnected cost data management systems.

The integration of ontologies with BIM has become a significant trend, enhancing the organization and use of cost-related data (Santos *et al.*, 2017; Xu *et al.*, 2013). Cost data ontologies enable a structured representation of information, standardizing data exchange across stakeholders (Abanda *et al.*, 2017; Choi and Lee, 2023).

Notably, the integration of BIM with ontological inference has shown promise in improving cost estimation and work item classification, with BIM automating the search for suitable work items, such as in tiling methods. Ontologies also play a key role in standardizing measurement methodologies, such as the new rules of measurement (NRM), which improves the precision of cost estimation during the tendering phase (Ma *et al.*, 2013). Lee *et al.* (2014) introduced an ontological approach to automate work item selection, enhancing consistency and reducing subjectivity, thereby supporting BIM-centric construction management practices (Lee *et al.*, 2014). Abanda *et al.* (2017) further explored the automation of cost estimation using BIM and an ontology based on NRM (Abanda *et al.*, 2017).

However, a critical need remains for ontology-based platforms that can quickly create BIM applications with reasoning support, addressing challenges in cost estimation and overall interoperability. The combination of BIM and ontological technologies has demonstrated potential in automating cost management, compliance checking and green building evaluation (Narlawar *et al.*, 2019). Jia *et al.* (2022) proposed an approach to automatically generate finite element models from BIM using OpenBIM and IFC to streamline cost management processes (Jia *et al.*, 2022). Guo *et al.* (2020) introduced a technique for automatically generating SPARQL queries to facilitate data extraction (Guo *et al.*, 2020).

In the AEC/FM industry, ontologies like ifcOWL are widely used to improve data exchange and cost estimation through enhanced interoperability (Gökçe *et al.*, 2013; Ren *et al.*,2021; Vakaj *et al.*, 2020; Pauwels and Terkaj, 2016; Terkaj and Šojić, 2015; Beetz *et al.*, 2009). This ontological approach enables more accurate evaluations of design alternatives, further optimizing the cost estimation process (Xu *et al.*, 2013). Xu *et al.* (2016) and Liu *et al.* (2016) proposed semantic web-based ontologies for cost item generation and QTO from BIM models, respectively (Xu *et al.*, 2016; Liu *et al.*,2016). Lawrence *et al.* (2014) proposed an approach to cost estimation by mapping the BIM objects to cost information (Lawrence *et al.*, 2014). Abanda *et al.* (2015) introduced an ontology-based approach utilizing the UK standard method of measurement for cost estimation (Abanda *et al.*, 2015). Ma *et al.* (2016) developed a methodology that uses ontology to formalize specifications for construction cost estimation in China (Ma *et al.*, 2016). In addition, Abanda *et al.* (2016) and Abanda *et al.* (2014) developed an ontology based on NRM to enhance QTO and cost estimation processes during the tendering phase of construction projects (Abanda *et al.*, 2016; Abanda *et al.*, 2014). Fürstenberg *et al.* (2021) investigated the use of semantic web technology to facilitate BIM-based automated cost estimation linked to an IFC property set (Fürstenberg *et al.*, 2021).

Despite these advancements, the challenges in the construction sector remain substantial. The successful integration of BIM and ontological approaches requires deep knowledge of cost estimation processes and the extension of pricing data (Biolek *et al.*, 2019).

As technology continues to evolve, the construction industry must adapt to improve cost estimation efficiency and accuracy, paving the way for better decision-making and streamlined processes. By integrating BIM, ontologies and advanced reasoning support tools, the future of construction cost management holds great promise, ultimately reducing errors and enhancing cost efficiency (Xiao *et al.*, 2022).

Research gaps, challenges and future directions

In the field of construction cost management, many advances have been made, particularly with the integration of technologies such as 5D BIM. However, several research gaps and challenges remain, which prevent the full implementation of these technologies in the cost estimation, management and decision-making processes. Summarized general research gaps for all the topics:

- *Technology and methods for cost data:* Despite advancements in BIM and automation tools, the integration and interoperability between BIM models and cost estimation software remain key challenges. Manual data input continues to hinder seamless alignment, preventing the full realization of BIM's potential in cost management (Inzerillo *et al.*, 2024; Chen, 2023).
- *Cost estimation data management and methods:* BIM models often lack the necessary granularity for accurate QTO and manual verification of cost items remains common, leading to inconsistencies and errors that limit BIM's ability to streamline and automate cost estimation [International Organization for Standardization (ISO), 2018; Ahn *et al.*, 2014].
- *Project cost data processes, methods and management:* BIM and IFC provide a strong foundation for cost data management, but further advancements are needed to fully integrate process-based cost information. Current integration between BIM and cost estimation tools is fragmented, requiring more sophisticated methods for handling cost data across different software systems (Wan Abdul Basir *et al.*, 2023; Ren *et al.*, 2022).
- *Energy design and use costs management:* The lack of standardized property sets for material data and the late-stage consideration of energy performance cost data hinder the integration of energy-efficient design and cost optimization within BIM, particularly during early design phases [International Organization for Standardization (ISO), 2018; Porsani *et al.*, 2021].
- *Cost data ontology:* Despite progress, challenges remain in extending pricing data and integrating ontology-based platforms with BIM. A standardized ontology that encompasses all aspects of cost data, including pricing and material properties, is still lacking and requires further development (ElQasaby *et al.*, 2023; Fenz *et al.*, 2021).

Table 4 presents a comprehensive overview of the main research gaps, challenges and future directions, specifically focusing on the five identified topics within BIM in the construction sector. These topics represent a balanced spectrum of research opportunities, ranging from areas with substantial existing literature to those still underexplored. By highlighting these gaps, the table aims to guide future research efforts and facilitate a clearer understanding of where innovation and further investigation are most needed.

Conclusion

The primary significance of this article lies in its quantitative analysis of the current state of the art in 5D BIM. This analysis has enabled researchers to focus on critical industry needs while simultaneously contextualizing ongoing 5D BIM research within the framework of industry experience. Moreover, it serves the essential function of directing future research

Table 4. Research gaps, challenges and future directions in 5D BIM

Topic	Research gaps	Challenges	Future directions
0. Technology and methods for cost data	Integration and interoperability between BIM models and cost estimation tools remain significant barriers. The alignment between BIM elements and cost items is not fully realized	Fragmentation of BIM systems and cost estimation tools requires manual intervention. Lack of standardized methods for full automation	Development of standardized protocols for integrating BIM models with cost estimation tools. Creation of unified systems to reduce manual data input
1. Cost estimation data management and methods	BIM models often lack sufficient detail to support accurate cost estimation. Manual verification of cost items is still required	Inconsistency in data provided by BIM models and reliance on manual verification lead to inaccuracies	Enhancing the granularity of BIM models and automating data verification. Development of sophisticated tools to ensure data consistency
2. Project cost data processes, methods and management	Need for cost models that integrate process-based information. Interoperability across different software systems is still insufficient	Fragmented data management systems hinder data sharing across different software platforms. Lack of comprehensive cost models in BIM	Development of advanced cost models that integrate process-based information and ensure smooth interoperability between software systems
3. Energy design and use costs management	Lack of standardized property sets for material data. Energy-related costs are considered too late in the design process	Difficulty in integrating energy performance data. Delays in considering energy costs during the early design stages	Development of standardized property sets for materials and improved integration of energy data in BIM models Incorporating energy costs earlier in the design process
4. Cost data ontology	Lack of standardized ontologies covering all aspects of cost data. Incomplete integration of ontologies into existing construction workflows	Incomplete ontologies for cost data hinder automation of cost estimation. Existing platforms need improvement to support real-time reasoning	Development of comprehensive ontologies that cover all aspects of cost data. Creation of ontology-based platforms to automate cost estimation and enhance interoperability

Source(s): Created by author

endeavours. In this context, LDA was used to analyse a large corpus of published literature, offering several methodological and practical advantages. From a methodological perspective, LDA enables the objective identification of latent themes in large-scale literature data sets, reducing human bias typically associated with manual thematic coding. It supports scalability and reproducibility, which are essential in growing research fields such as 5D BIM. Practically, LDA-based topic clustering can inform academic curricula by highlighting underexplored areas, guide funding priorities by identifying research gaps and support industry stakeholders in tracking the evolution of cost-related BIM research.

However, LDA also presents certain limitations. Firstly, it relies on the statistical co-occurrence of words and does not account for deeper semantic meaning or contextual nuances. Secondly, the granularity of topic interpretation is influenced by parameter tuning and subjective labelling, which, despite expert validation, may affect consistency across studies. Thirdly, the analysis is based solely on abstracts, which may exclude important terms present in the full text.

Despite these limitations, the integration of LDA into systematic literature reviews represents a robust and efficient approach that bridges theory and practice. It contributes to the body of knowledge by offering a replicable methodology for mapping complex research domains and has the potential to influence both academic research directions and applied innovation in the AEC sector.

In this review, five topics related to 5D BIM were presented and analysed starting from the data of the LDA analysis:

(1) technology and methods for cost data;
(2) cost estimation data management and methods;
(3) project cost data processes, methods and management;
(4) energy design and use costs management; and
(5) cost data ontology.

From this analysis, it has emerged that the management of cost data in the construction field is undergoing a transformation due to the integration of BIM, ontologies and advanced technologies. This evolution improves cost estimation accuracy, data exchange and interoperability, leading to more efficient and sustainable construction practices. However, key barriers persist. These include interoperability challenges between cost estimation tools and BIM platforms, the lack of standardized property sets for building material data and the need for manual data inputs in cost estimation workflows. Overcoming these issues is essential to fully unlock the potential of 5D BIM in promoting cost-effective and sustainable construction.

Overall, this article establishes an objective and empirical foundation for analysing the state of research in the 5D BIM domain. The research areas and themes identified highlight current trends and future opportunities that can benefit both industry and academia. The findings help current BIM researchers position their work within a broader thematic framework and assist emerging scholars in identifying relevant directions for future inquiry.

The gaps identified in this study can be addressed by practitioners and researchers who may use this work as a roadmap. By leveraging the detailed analysis of existing challenges, future research can focus on overcoming barriers in interoperability, automation and standardization, accelerating the adoption of advanced 5D BIM methodologies.

This article significantly contributes to the field by outlining the current research landscape in 5D BIM and suggesting pathways for future exploration. However, it has limitations, notably the exclusive reliance on abstracts, which may omit nuanced content present in full-text articles. While full text analysis could provide additional depth, it may introduce noise. Despite this, the study examined a substantial number of abstracts, identifying trends, albeit not exhaustively. To address gaps, keywords related to interoperability, cost and other dimensions were closely examined. The statistical method employed possible variation due to randomness in document clustering. To mitigate bias, the labelling phase involved six independent reviewers, leading to convergent and validated results.

In conclusion, this study used LDA as the primary analytical method. However, other statistical approaches could be explored in future research to validate or complement these findings. As a potential extension, this methodology could be applied to other BIM dimensions, such as 4D BIM, to evaluate cross-dimensional relationships and thematic consistency.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Notes

[1.] Delete list used in the algorithm: [‘abstract: ‘, ‘ab ‘, “.\n”, ‘elsevier’, ‘bridg’, ‘queri’, ‘algorithm’, ‘network’, ‘function’, ‘propos’, ‘oper’, ‘cell’, ‘develop’, ‘approach’, ‘stage’, ‘check’, ‘applic’, ‘evac’, ‘qualiti’, ‘compon’, ‘layout’, ‘ation’, ‘patient’, ‘waste’, ‘commun’, ‘gener’, ‘image’, ‘social’, ‘rural’, ‘review’, ‘predict’, ‘china’, ‘firm’, ‘relev’, ‘repres’, ‘build’, ‘building’, ‘inform’, ‘model’, ‘also’, ‘paper’, ‘research’, ‘mine’, ‘need’, ‘needs’, ‘finding’, ‘findings’, ‘purpose’, ‘result’, ‘results’, ‘present’, ‘presents’, ‘provide’, ‘provides’, ‘include’, ‘includes’, ‘require’, ‘requires’, ‘improve’, ‘life’, ‘base’, ‘current’, ‘output’, ‘outputs’, ‘switch’, ‘path’, ‘increase’, ‘decrease’, ‘cover’, ‘covers’, ‘differ’, ‘differs’, ‘high’, ‘year’, ‘years’, ‘feature’, ‘features’, ‘extract’, ‘compare’, ‘compares’, ‘show’, ‘shows’, ‘sign’, ‘signs’, ‘dose’, ‘do’, ‘breack’, ‘breacks’, ‘perceive’, ‘perceives’, ‘potential’, ‘mg/kg’, ‘initial’, ‘print’, ‘cool’, ‘breast’, ‘studies’, ‘study’, ‘use’, ‘uses’, ‘ment’, ‘used’, ‘useful’, ‘integrat’, ‘plan’, ‘structur’, ‘detect’, ‘quantiti’, ‘technology’, ‘industri’, ‘decision’, ‘tradit’, ‘reliabl’, ‘ent’, ‘evaluation’]

[2.] The stemming dictionary used in the code: http://snowball.tartarus.org/algorithms/english/diffs.txt

[3.] The results report the frequency (expressed in % terms), of the keywords derived from the quantitative analysis of the corpus of the main topics.

Keywords&Frequency (K) keywords and relative frequency (%) in the main topics.

Topics: Topic 0: Technology and methods for cost data; Topic 1: Cost estimation data management and methods; Topic 2: Project cost data processes, methods and management; Topic 3: Energy design and use costs management; Topic 4: Cost data ontology.

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Corresponding author
Jacopo Cassandro can be contacted at: jacopo.cassandro@polimi.it