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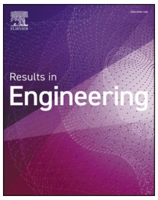

Quantifying the influence of BIM adoption: An in-depth methodology and practical case studies in construction

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ABSTRACT

This research presents a comprehensive framework for quantifying the benefits of Building Information Modelling in construction. Through industry insights and surveys, the study validates formulated equations and integrates case studies from the Swedish construction sector. Results reveal increased costs in the design phase but indicate time and cost savings during design and construction. Operational benefits, notably in maintenance planning and energy efficiency, constitute a substantial portion of the total estimated benefits. The study introduces a unified quantification methodology, demonstrating an investment rate of 16.1 % and 10.17 % for cases A and B, respectively. This research contributes to the ongoing discourse on BIM adoption, offering valuable insights and methodological advancements for industry practitioners.

1. Introduction

Evaluating the financial performance of Building Information Modelling (BIM) is a crucial task, particularly at the project's completion (Abdelbary et al., 2020; [1]). The adoption of BIM involves a significant investment, and decision-makers must validate whether the monetary returns outweigh the associated costs [2]. Currently, large corporations and industry analysts are actively conducting economic evaluations of BIM, each utilizing unique methodologies such as pilot projects, workflow analysis and benchmarking [3,4]. However, an ongoing debate questions the feasibility of it [5]. This discourse highlights the complexity of gauging BIM's economic value and underscores the need for a comprehensive understanding of its monetary implications to help decision-makers assess the technology's viability in relation to financial outcomes [6,7] (see Table 8).

BIM adoption in the construction industry faces several significant challenges, particularly concerning cost and the uncertainty surrounding its financial impact [5]. One of the primary issues is the high initial investment required for BIM implementation, including software, training, and process restructuring, which can be prohibitive for many firms [8]. Additionally, there is often a lack of clarity on the return on investment (ROI) for BIM, as its benefits, such as improved collaboration and reduced rework, can be difficult to quantify [9]. The variability in reported savings and costs across different projects further adds to the uncertainty, making it challenging for stakeholders to predict the financial outcomes reliably. These challenges underscore the necessity for a comprehensive and standardized framework to evaluate BIM's financial performance accurately, which our research aims to address.

Despite ongoing efforts, accurately translating BIM effects into numerical values faces several limitations such as the complexity of projects data, availability of data, and the lack of time and resources to conduct such studies inhouse [10,11]. The measurement of BIM effects relies on numerous assumptions compared to scenarios without BIM implementation [12]. These assumptions serve to bridge gaps necessary for conducting the study, which are challenging for the project team to obtain directly, such as market conditions, data availability, and consistent project conditions [8].

Reviewing previous studies that aimed to quantify BIM benefits reveals a significant discrepancy in reported estimates. For instance, several studies attempted to calculate the ROI of BIM, with reported values ranging widely from 16 % to 1654 % [13]. Similarly, this disparity in reported values is evident in studies measuring other BIM benefits. For example, the ability of BIM to reduce delays was reported with values between 7 % [14] and 67 % [15], while its capacity to enhance coordination and reduce changes ranged from 6 % to 47 % (Abdelbary et al., 2020). This discrepancy emphasizes the necessity for a

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more transparent and standardized approach to evaluating and reporting the quantitative impact of BIM to enhance credibility and understanding of its financial implications.

A thorough comprehension of the business benefits associated with BIM is crucial for organizations to make informed decisions about adopting BIM technology and ensuring its effective implementation [16,17]. This understanding empowers organizations to assess the potential ROI and balance the benefits against the costs, highlighting specific advantages such as cost savings, increased productivity, and error reduction [16,18,19]. Additionally, a nuanced understanding of BIM's business benefits aids in formulating a well-defined implementation strategy, enabling organizations to maximize the utility of BIM [9].

This study addresses the necessity of quantifying BIM benefits, emphasizing the lack of established methodologies. It endeavours to create a comprehensive framework by engaging industry practitioners, focusing on comparing scenarios of activities using BIM against a likely counterfactual scenario without BIM. The primary goal is to equip organizations and decision-makers with a tool to assess the feasibility of BIM in their specific contexts. The research methodology entails an extensive literature review to identify relevant metrics, followed by a survey to validate and refine these metrics based on industry insights. The subsequent proposal of quantification methods and equations will undergo validation by experts in the construction industry, leading to the development of a robust BIM benefits quantification framework. This proposed framework will be tested on two real-world case studies from construction companies in Sweden.

1.1. Related studies

Previous literature has widely acknowledged that investment in BIM offers both tangible and intangible benefits and costs. This study comprehensively examines all pertinent research endeavours aimed at quantifying or elucidating the value associated with these tangible and intangible metrics. Thus, a critical analysis of the research methodologies employed to investigate the investment value of BIM becomes imperative to discern past research trends. It is noteworthy that this study builds upon a thorough literature review conducted in earlier phases and serves as a continuation of that effort [20]. The literature review scrutinized 75 articles specifically focused on quantifying the effects of BIM.

The primary focus of this literature review was to compile quantified benefits BIM from previous studies and the methods used to quantify those benefits. One commonly suggested method for assessing the investment in BIM is the ROI [14,21,22]. This methodology quantifies the profit, gains, and losses resulting from an investment, represented as a percentage of the invested amount, and adjusted for contributions and withdrawals [23]. The calculation of ROI in the context of BIM technology aims to elucidate the purpose behind the expenditure and the anticipated outcomes [14].

Cost-Benefit Analysis (CBA) is another approach employed to evaluate the economic feasibility of adopting BIM technology in the construction industry [24,25]. BIM's economic viability is determined by comparing the costs and benefits associated with its implementation and utilization [26]. The implementation of BIM involves acquiring hardware and software, providing employee training, and modifying existing workflows [14]. Potential benefits encompass enhanced collaboration, reduced rework, and improved project outcomes [27,28]. The objective of CBA is to ascertain whether the benefits derived from adopting BIM outweigh the associated costs and whether investing in BIM technology is economically feasible [29].

Reviewing previous research that employed ROI or cost benefits analysis solely revealed the complexity and challenges associated with calculating ROI and CBA for BIM implementation across the entire construction lifecycle [20]. This complexity often leads to oversimplified evaluations or a narrow focus on specific project aspects [10]. Additionally, a wide range of numerical values reported for BIM benefits in different studies highlights discrepancies and inconsistencies in measurement approaches and assumptions.

To gain a comprehensive understanding of prior research endeavours, the literature review categorized selected sources based on various dimensions, including their relation to the project lifecycle and the impact of BIM on different stakeholders [28,30]. Some studies covered the entire project lifecycle, while others specifically analysed distinct phases [27]. For instance, there were examinations of BIM benefits for consultants, facility managers, asset owners, and manufacturers, each providing unique insights into the impact of BIM on these stakeholders [6,31]. This approach allowed for a nuanced exploration of the diverse dimensions and stakeholders affected by BIM implementation.

The literature review identified a prominent research trend, with a significant emphasis on quantifying specific BIM benefits, often associated with distinct functions or project phases [32,33]. Primarily, research concentrated on the design stage, exploring the impacts of design optimization, error reduction, clash detection, and stakeholder coordination [1,17]. Approximately 24 % of the articles focused on the integration of design and construction, delving into topics like quantifying change order costs and assessing how BIM enhances opportunities for prefabrication and offsite construction [34,35].

Post-construction effects of BIM were examined in 12 % of the analysed articles, evaluating the investment value for operators and facility managers [36,37]. Additionally, a substantial number of studies addressed sustainability and optimized energy consumption during building operations [38].

The literature on quantifying and assessing BIM benefits reveals several gaps and limitations. Firstly, there is a lack of standardization in methodologies, resulting in inconsistencies in measurement and reporting [20]. Additionally, many studies provide incomplete descriptions of their methodologies, hindering the assessment of their accuracy and reliability [21,23]. Moreover, a wide range of numerical values are reported for BIM benefits across different studies (Table 1.), highlighting discrepancies and inconsistencies in measurement approaches and assumptions. Furthermore, some studies focus solely on tangible benefits, overlooking the intangible effects of BIM, such as improved collaboration and decision-making [10]. Assessing the full lifecycle benefits of BIM poses challenges due to limited data availability and complexities in measurement.

Furthermore, most studies are confined to single-project assessments, neglecting the long-term value proposition of BIM investment and its cumulative benefits over multiple projects [41]. Lastly, calculating ROI and CBA for BIM implementation across the construction lifecycle is complex and challenging, often leading to oversimplified evaluations or a narrow focus on specific project aspects [29].

In addition to the aforementioned limitations, it is noteworthy that very few articles in the literature involve industry cases. This indicates a significant gap between research and industry practice, suggesting that the industry still lacks its own quantification methodology for BIM benefits. The scarcity of industry cases in research underscores the need for closer collaboration between academia and industry practitioners to develop robust methodologies that accurately capture the value of BIM implementation in real-world scenarios.

The forthcoming stages of this research will extend from the foundation laid by previous research efforts. The initial step involves the validation and customization of the measured attributes extracted from the literature through a comprehensive survey study. The outcomes of the survey will yield specific metric values for each identified quantifiable BIM benefit, subsequently replacing a variable in each formulated equation. The overall quantification methodology will undergo testing using two real-world case studies from the Swedish construction industry.

2. Methodology

This study endeavours to establish a systematic methodology for

Table 1
Extracted quantified attributed from the literature review.

	Measured Attribute Reported values
ROI	Giel and Issa [13] ROI of BIM varied greatly from 16 to 1,654 %, Conde et al. [16] ROI of 34.5 %, Kim et al. [3] ROI of 145 % & 350 %, Lee et al. (2012) A BIM ROI of 22–97 % was derived by converting 709 design errors detected by BIM into rework cost savings, Lee and Lee [8] The integrated BIM ROI to consider the overall effect of applying BIM was about 476.72 %, McGraw-Hill [12] 62 % of the targeted sample reported a positive ROI, Stowe et al. [22] ROI of 1.8 %–10.5 %, Ham et al. [1] ROI of 94.41 %, Won and Lee [39] BIM ROI of 27 %–400 %,
Productivity	Abdelbary et al. [40] 50 % reduction in labour works, Conde et al. [16] productivity improvement exceeding 27 %, Poirier et al. (2015) increase in productivity ranging from 75 % to 240 %, Qian (2012) Productivity Loss for Company ~2 Months Downtime, Rafael Sacks (2005) 2.3 % improved work productivity, Reizgevičius et al. [7] productivity gain after staff training 31 %, Sacks and Barak (2008) productivity gain for drawing production of 21%–61 %, Succar et al. (2012) productivity gains of 15 % and 41 %,
Prefabrication opportunities	Banihashemi et al. (2018) 50 % increased possibilities for prefabrication, Khanzode et al. (2008) 100 % pre-fabrication for the plumbing contractor, Kuprenas and Mock (2009) shop fabrication of $25,000, McGraw-Hill [12] BIM increased prefabrication by 22 %,
Change orders and design errors	Abdelbary et al. [40] BIM resulting in rework cost reduction of 49 percent, A total saving of 10 %, generated by BIM clash detection and 32 % reduction of change orders, Barlish; and Sullivan [15]; 42 % reduction in change orders, Giel and Issa [13] change orders was reduced by 40, 48, and 37 %, Ham et al. [1] rework due to design errors 5–20 % in the total contract amount reduced by 47 %, Honnappa and Padala [2] 8.16 % cost saving due to less changes, Lee et al. [4] BIM impact on preventing rework $314,000, Lopez [17] design errors were revealed to be 6.85 and 7.36 % of contract value, Love et al. [14] 10 % saving in contract value through clash detection. 40 % elimination of unbudgeted change, Williams (2011) changes reduced by 47 %,
RFI's	Abdelbary et al. (2020) approximate reduction of 90 % of RFI's, Barlish; and Sullivan [15]; 30 % in RFI's, Conde et al. [16] reduced by 25 %, Giel and Issa [13] RFI's was reduced by 34 %, 68 %, 43 %,
Schedule	Abdelbary et al. (2020) schedule reduction of 57, Barlish; and Sullivan [15]; 67 % less delays, Honnappa and Padala [2] 11.52 % time saving, Khanzode et al. (2008) 6 months' savings on the schedule, Kuprenas and Mock (2009) savings of time value of $10,000, Love et al. [14] 7 % reduction in schedule, Paneru et al. [9] reduce the time to complete a project by 7 %, PWC [6] Time savings in design 6.3 % and 36 %, Time savings in build and commission 15.3 %, Time savings in handover (12.5 %), Sacks and Barak (2008) An overall reduction of between 15 % and 41 % of the hours required for a project,
Environmental, sustainability, energy performance and waste management	Banihashemi et al. (2018) reduction of waste by 2 %, Ferreira et al. (2023) 2–5% savings in energy consumption, Hasanain and Nawari (2022) design optimization 20%–60 % less water consumption, Hussain et al. (2023) Carbon emissions are reduced by 32.94 %, 14.92 %, 28.40 %, and 6.52 % during the production, construction, operation, and demolition stages, Kamel and Kazemian (2023) 26 % lower energy use, Motalebi et al. [18] 24%–58.2 % reduction in energy consumption, Tu et al. (2023) construction waste source reduction of 67 %, 48 %, and 4.6 %, Won et al. (2016) BIM-based design validation prevented 4.3–15.2 % of waste on sites,
Facility management and operations	Love et al. [14] cost of not using BIM is $680,000 over an asset's operating life, PWC [6] Cost savings in asset maintenance (60.7 %), Tsantili et al. [33] reducing yearly energy usage by 43.75 %,
Project outcomes	Abdelbary et al. (2020) A total saving of 10 % ($10 million), generated by BIM, Barlish; and Sullivan [15]; 5 % savings n contractors' costs, Conde et al. [16] 20 % reduction in costs per project, Kim et al. [11] BIM has contributed to identifying and/or resolving issues whose contractual values are as much as 15.92 % of the total direct cost of the project, Kuprenas and Mock (2009) clash detection savings of $25,000, Love et al. [14] 80 % reduction in the time taken to generate a cost estimate with cost estimation accuracy within 3 %, Paneru et al. [9] decrease the time needed to generate a cost estimate by up to 80 %, PWC [6] 3.0 % savings in total Cost savings in clash detection (1.8 %), Wong et al. (2018) cost of drafting reduced by 80%–84 % using BIM.
Investment cost	Barlish; and Sullivan [15]; design costs: 31 % increase, 29 % increase in 3D background model creator costs: 34 % increase, Qian (2012) Investments for BIM Costs (per staff) of ~S$18,000 to S$30,000, Reizgevičius et al. [7] Expected productivity loss after starting to use BIM software 34 %,

quantifying the benefits of BIM in construction projects, addressing gaps identified in prior research. The research will unfold in a sequential manner, commencing with a thorough literature review. Subsequently, insights will be validated through a survey within the Swedish construction industry. The outcome will involve the development of metrics and calculations within a comprehensive framework, assessing tangible BIM benefits while considering associated costs. The framework's validity will be gauged through evaluation by a panel of industry experts, ensuring the sufficiency of the formulated calculations and providing a foundation for feasibility determinations. The framework is then tested using two actual case studies from Swedish construction projects. The research methodology is visually depicted in Fig. 1.

2.1. *Attributes identification*

The methodology's initial phase sought to identify quantifiable indicators representing tangible benefits of BIM. This involved a comprehensive literature review, examining industry reports to compile and aggregate quantified values corresponding to these indicators. Table 1 compiles quantified attributes extracted from the literature review, categorized based on the measured benefits. This categorization

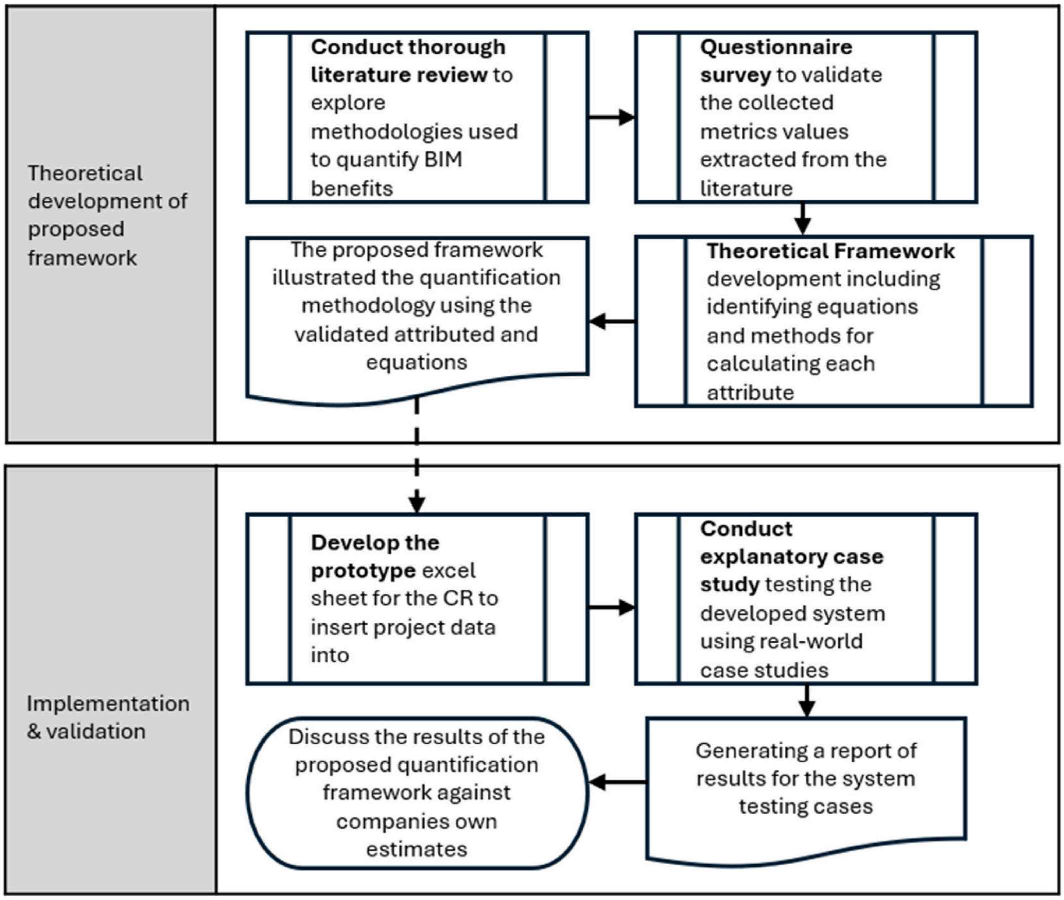

Fig. 1. Research methodology.

provides a comprehensive overview of the diverse aspects of BIM benefits explored in the reviewed literature.

Table 1: Quantified attributes extracted from the literature review.

2.2. Questionnaire survey

The survey was designed to validate findings from prior research and bridge the gap in research specific to the Swedish construction industry. Acknowledging the diverse landscape of the Swedish construction sector, the questionnaire survey method was chosen to efficiently gather insights from a broad spectrum of industry practitioners. This method was aligned with the research objectives, enabling a thorough exploration of professionals' perspectives on BIM benefits in construction. Through a meticulously developed online questionnaire, precision and reliability were ensured, with mandatory questions implemented to reduce the risk of incomplete or missing data. Covering demographic information and evaluating perceived benefits using 12 predefined items (shown in Table 2.), participants were asked to select intervals reflecting the impact of each benefit on project costs based on their project-specific data.

The questionnaire, produced with the assistance of a professional survey design platform, adopted a web-based format for seamless distribution and response collection, enhancing response accuracy and validity. Targeting diverse stakeholders within the Swedish construction industry, including clients, consultants, designers, manufacturers, suppliers, contractors, facility managers, and building operators, the survey was disseminated electronically via a web-based platform. Recipients were chosen through a combination of purposive and convenience sampling methods, focusing on individuals with experience in BIM utilization within the Swedish construction industry. This approach yielded a sample of 128 respondents. The sample size collected for this research is sufficient for several reasons. First, the study targets BIM practitioners in Sweden, a specialized population where a smaller, relevant sample is appropriate. Second, practical challenges like low response rates and limited access to participants must be acknowledged. Finally, the population's homogeneity, given the focus on BIM applications in construction processes, suggests that a larger sample would not yield significantly more insights. Evaluation of the research variables' reliability using Cronbach's alpha yielded a value of 0.870, surpassing the 0.70 threshold and indicating acceptable reliability.

2.3. Establishing quantification methodology

Each benefit was quantified using a tailored approach, involving the derivation of specific equations. The development of the equations involved a synthesis of insights from several previous research studies [8,13,14,21,22], incorporating their proposed quantification methodologies and insights gained from industry initiatives [6,12]. Additionally, the equations were subjected to adjustments and reformulations to align with the proposed methodology of this study. This adaptation was essential to cater to the specific data collected from various companies, ensuring the relevance and applicability of the equations within the context of this research.

2.4. Validating the framework

After formulating the framework for quantifying BIM benefits, it became crucial to validate the established equations and techniques for each attribute. The validation process involved presenting the framework to a panel of industry practitioners. Through discussions for each

Table 2
Benefits measurement criteria.

	Indicator	Measurability and metrics
Design (D)	Assumed efficiency saving to internal management costs (D1)	BIM implementation targets enhanced project efficiency, reduced delays, and minimized resource requirements for public bodies. Achieved through improved cost predictability and stakeholder engagement via 3D modelling, this leads to time savings for the internal management team, entailing assumed cost savings in the project's design phase. Equation (1) was utilized to calculate internal management costs. In the equation, "in-house costs" signify the monthly expense for overseeing the design phase, while "design and construction durations" represent the project's duration in months—both being specific to the case. The "efficiency" is a validated percentage derived from prior research and the survey, reflecting the reduced management efforts attributed to BIM implementation $D1 = \textit{Inhouse costx Efficiency savingsx Design \& construction duration}$
Construction (C)	This benefit will reduce associated contractor's prelim costs (C1)	BIM has the potential to generate time and cost savings in project scheduling and duration by improving the project schedule, increasing pre-fabrication and design for manufacturing and assembly, optimizing construction equipment, enhancing subcontractor briefings, and mitigating design risks. These advantages result in a reduction in the contractor's preliminary costs, calculated using the following equation (2). In the equation, "construction value" denotes the total tender price upon which the contractor bases the preliminary costs, while "reduction percentage" indicates the assumed reduction in preliminary costs attributed to BIM implementation. $C1 = \textit{Construction valuex prelims }\%\textit{x Reduction }\%$
	Assumed reduction of the program and leading to reduced inflation costs (C2)	BIM can enhance project efficiency by streamlining design and construction processes, leading to quicker project approvals, enhanced cost predictability, and a decreased risk of delays and cost overruns, ultimately lowering overall project costs. This benefit assumes that BIM reduces project duration, thereby preventing additional inflationary costs. The equation for this calculation is as follows (3): In the equation, the "reduction percentage" aligns with the variable described in (C1), and "project duration" is expressed in years. $C2 = \textit{Project durationx construction valuex Annual inflation }\%\textit{x Reduction }\%$
	Assumed efficiency saving to contractors pricing levels (C3)	A model-based approach to procurement, facilitating digital quantity take-offs and a thorough understanding of project scope and risks, instils greater confidence in commercial costs, design, and scope. This, in turn, leads to more competitive tender prices. The savings arising from enhanced pricing accuracy are calculated as follows: The reduction in tender prices attributed to BIM implementation is a variable established through prior research and validated through the survey. $C3 = \textit{Reduction in tender prices assumed }\%\textit{ x construction cost}$ (4)
	Assumed efficiency saving to construction risk provisions (C4)	The BIM model will mitigate uncoordinated design issues through collaborative modelling, resulting in a decrease in the necessary contract risk sum during the construction phase. The reduction, attributed to risk mitigation, is calculated as follows: The reduction in contract risk attributed to BIM implementation is a variable established through prior research and validated through the survey. $C4 = \textit{Reduction in contract risk assumed }\%\textit{ x construction cost}$
	Assumed reduction in client held risk (C5)	Improved stakeholder engagement, enhanced design coordination, and greater cost predictability lead to fewer project changes, reducing the client's contingency allowance for risk during project development. The savings from mitigating uncertainties and lowering risks are calculated as follows: The reduction in client risk due to BIM implementation is a variable that has been established through previous research and confirmed through the survey. $C5 = \textit{Reduction in client risk assumed }\%\textit{ x construction cost}$
	Assumed efficiency saving to cost of BWIC (C6)	A fully coordinated BIM model ensures cost predictability for Builders Work in Connection (BWIC) requirements with detailed modelling and a fully defined BWIC schedule. BIM's impact leads to reduced BWIC provisions, achieved by decreasing provisional sums or utilizing offsite manufacturing and assembly. The cost savings related to BWIC efficiency are calculated as follows: In the equation, "M&E works" signifies the total electrical and mechanical components of the construction, "BWIC %" is the percentage of builders work in connection, and the "assumed saving %" is a variable established through prior research and confirmed through the survey. $C6 = \textit{assumed saving to BWIC }\%\textit{ x }\%\textit{ of M\&E worksx BWIC}\%\textit{ x construction value}$
	Assumed efficiency saving to management of changes during construction (C7)	Implementing a model-based procurement approach enables precise digital quantity take-offs and a comprehensive understanding of project scope and risks. This leads to improved cost predictability and ultimately results in more competitive tender prices. The assumed cost savings for the management of design during construction are calculated as follows: In the equation, the "number of changes in the project" and the "cost of managing each change" are case-specific variables provided by the user. The "percentage of reduction in changes" is a variable established through prior research and confirmed through the survey. $C7 = \textit{cost of mamaging one change x reduction in change events }\%\textit{ x Nr. changes}$
Operations (O)	Assumed efficiency saving to transfer data at completion (O1)	Creating a Project Information Model (PIM) that integrates smoothly with the Asset Information Model (Wang et al.) and aligns with operational facilities management systems reduces the cost of transferring data upon project completion. The assumed cost savings for data transfer at completion are calculated as follows: Where the time is the number of hours required by the existing resources to transfer data. $O1 = \textit{Time in Hrs. x hourly rate}$
	Assumed efficiency saving per annum of enhanced data management (O2)	A comprehensive asset information model facilitates easy sourcing, access, and sharing of information, eliminating the necessity to create new data for each maintenance event. BIM usage is assumed to generate annual savings in data management costs over the operational period of the facility, calculated as follows: In the equation, "time saving" is expressed in hours, the "operational period" is in years, and the "number of requests" is calculated within a one-year timeframe. $O2 = \textit{time saving per request x hourly rate xNr. of requests x operational period.}$
	Assumed efficiency saving per annum to energy costs (O3)	BIM facilitates enhanced modelling of the energy performance of the proposed solution and enables more effective testing of materials and construction techniques, resulting in improved energy efficiency. When offsite manufacturing is employed, it enhances the building's air tightness, subsequently reducing energy costs during the operational stage. The assumed yearly savings in energy costs are calculated as follows: In the equation, the variables for "energy use" and the "area of the building" are specific to the case, while the "efficiency enhancement percentage" is a variable established through prior research and validated through the survey. $O3 = \textit{efficiency enhancement }\%\textit{ x Area x energy use x rate of KWh x operational period.}$
	Assumed saving time and resources for each maintenance event during the operational stage (O4)	During the facility's operational stage, automatic generation of product parts, health and safety information, access details, and work methodology from the asset information system reduces resource costs for each maintenance event. The savings in time and resources due to BIM can be calculated as follows: The variables in the equation are all case

(*continued on next page*)

Table 2 (*continued*)

Indicator	Measurability and metrics
	related, in exception to the assumed savings in efficiency of handling maintenance due to BIM, which is a variable established through previous research and confirmed through the survey. *O4 = Time saved per event x cost rate of labor x Nr. of maintenance events x efficincy* %
Assumed savings due to combined maintenance tasks (O5)	Utilizing an asset information model allows for a strategic view of medium-term maintenance activities across a portfolio of projects/assets. The structured asset data enables bundling procurement works for goods and services, resulting in improved value for money. The combined maintenance tasks are anticipated to yield savings, calculated using the following equation: In the equation, "LCC" represents Life Cycle Costs achieved through proactive and strategic procurement of lifecycle works, specific to the case. The "assumed savings in efficiency of handling maintenance due to BIM" is a variable established through prior research and validated through the survey. *O5 = LCC rate x gross internal area xo perational period x efficincy* %

attribute, feedback and considerations from the panel were thoughtfully incorporated into the final version of the framework.

2.4.1. *Case studies*

The validated framework was empirically tested by analysing genuine construction projects within the Swedish construction industry. This involved scrutinizing actual construction projects, providing researchers with the opportunity to witness the implementation of BIM and its real-world impact on various project aspects. This practical application offers insights beyond theoretical assumptions [42]. The inclusion of case studies also facilitates direct engagement with industry practitioners, enabling researchers to collect valuable feedback, insights, and perspectives from those actively involved in BIM implementation. This iterative feedback process enhances the research by integrating the practical experiences of professionals working in the field [15].

The selection of case studies was contingent upon various factors, with a primary emphasis on the willingness and availability of companies to participate in the study. This consideration was pivotal, given that the study necessitated the provision of sensitive project information by the participating companies. Additionally, the selection of cases prioritized projects exhibiting a high degree of BIM implementation throughout the project life cycle. This approach aimed to authentically capture and compare the tangible benefits derived from BIM implementation in contrast to conventional methods.

2.5. *Theoretical framework development*

Each benefit calculation underwent thorough individual examination. The attributes identified for these calculations required two types of variables: metrics converting assumed BIM benefits into cost values (validated through research and questionnaires) and case-specific variables (project-specific figures). Fig. 2 illustrates the theoretical framework development after identifying the measurement criteria of the identified tangible benefits.

In Table 2, details of the calculation for benefit measurement of each indicator are provided with clarification of equations development.

2.6. *Assumed BIM investment associated costs (I)*

The costs linked to BIM investment and implementation are methodically quantified and incorporated into the overall BIM benefits assessment methodology. These costs, consistent across various BIM environments, encompass expenses like establishing a common data environment (CDE), BIM management costs, training-related expenses, Employer Information Requirement, Organization Information Requirements (OIRs), updating facilities management systems as mandated by the procuring authority, and maintaining the BIM model.

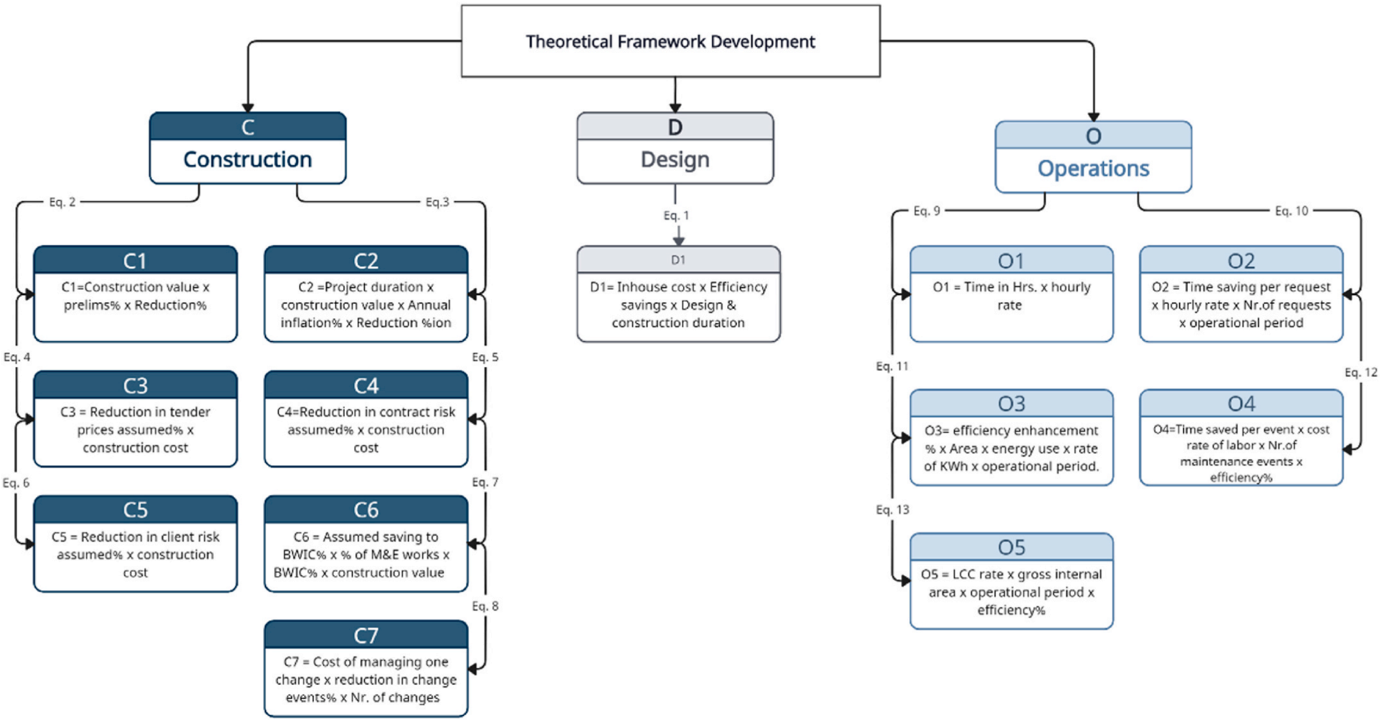

Fig. 2. Theoretical framework development.

2.7. *Verification of assumed metrics*

The developed equations for each item incorporate two essential types of variables to quantify the impact of BIM. The first type consists of case-related variables, specific to the project or company, tailoring the results to the specific context under study. The second type comprises metrics derived from various research efforts and case analyses within the industry, where BIM benefits have been quantified to a certain level of confidence. These variables were collected, evaluated, and validated through the questionnaire survey conducted in this research.

Table 3 presents the extracted metrics derived from the analysis of survey data. Participants selected the most accurate estimate of the BIM effect based on their own experiences and projects. It is important to note that the provided answers are grounded in previous research results to maintain accurate estimations within reasonable intervals. For each item, the answer with the higher frequency was considered.

The overall equation for the assessment methodology, incorporating all costs and benefits and calibrated using the qualitative assessment, can be expressed as follows:

$$\textit{Implementation of BIM benefits total} = \left\{ \left(\sum_{i=0}^{n} D + \sum_{i=0}^{n} C + \sum_{i=0}^{n} O \right) \times l \right\} - \sum_{i=0}^{n} I$$

2.7.1. *Illustrative case studies*

The quantification methodology framework underwent validation through the examination of multiple case studies, conducted in collaboration with industry practitioners. The primary aim was twofold: firstly, to assess the framework's efficacy, and secondly, to scrutinize the outcomes of the analysis. These outcomes specifically unveiled the discernible benefits attributable to BIM implementation within the projects subjected to evaluation.

2.8. *Pre-processing phase*

Following outreach to several companies meeting the selection criteria, the initiation of the process commenced with those expressing an interest in participating in the study. Each designated case representative (CR) received an Excel sheet outlining the requisite inputs for the case to facilitate the implementation of the quantification methodology. After the collection of necessary data and the identification of a pertinent case within their project database, a series of meetings and iterations ensued to ensure the accurate application of the quantification methodology.

Table 4 illustrates a summary of the cases (see Table 4).

Case A: Health care clinics, Karlstad, Sweden.

Table 3
BIM benefits variables as extracted from the survey analysis.

BIM related item	Estimation of impact
BIM can reduce the project duration during the design by:	21–40 %
BIM can enhance the efficiency of the design by:	41–60 %
BIM can reduce tender (Contract/BOQ) prices by:	6–10 %
BIM can reduce changes during the construction by:	21–40 %
BIM can reduce the project delivery duration during the construction by:	1–20 %
BIM can increase safety on site during the construction by:	1–20 %
BIM can reduce requests for information on site during the construction by:	21–30 %
BIM can reduce Builders Work in Connection (BWIC) costs by:	1–20 %
BIM can increase possibilities for prefabrication by:	>50 %
BIM can facilitate the creation of As-built models by:	1–30 %
BIM can reduce energy consumption for new projects during operation by:	8–10 %
BIM can facilitate maintenance works by:	21–40 %

Table 4
Summary of cases details.

	Case A	Case B
Building function	Healthcare Clinic	Education Centre
Gross Internal Area of Building (m2)	39,484	21,900
Scope	Full construction	Full construction
Delivery method	Integrated Project Delivery (Design-Build/Fast Track development)	General contract
Construction Cost $	104,319,793	39,800,000
Case representative	Designer and Project manager	Construction main contractor
Design & construction period (months)	38	28

The project scope is constructing a new healthcare clinic, the project underwent comprehensive modelling and documentation using various BIM environments. This encompassed the creation of 12 Revit models and the incorporation of over 29,000 pieces of equipment. The entire equipment inventory was meticulously modelled and monitored throughout the phases of design and implementation. The case data were obtained through the architectural company, which served as both the project manager and overseer of project delivery.

The utilization of the Integrated Project Delivery process using BIM facilitated simultaneous collaboration among all project stakeholders on the model. The architect utilized Autodesk Revit for the construction and documentation of the model, which was subsequently shared on a cloud server to foster collaboration with clients, consultants, and contractors. This enabled all stakeholders to monitor real-time changes to the model and make necessary adjustments to design and cost on their respective ends. Additionally, the BIM-IPD process promoted enhanced collaboration among construction trades, allowing them to work seamlessly in the field without disrupting each other's system layouts, as most clashes were pre-emptively detected in the model prior to the construction phase. Fig. 3 illustrates the stakeholder relationship diagram as described by the case representative.

2.9. *Qualitative assessment*

According to the project representative, the utilization of the Integrated Project Delivery (IPD) process, employing the Hybrid Collaborative Delivery Team, proved highly advantageous for this project, particularly given its modelling through BIM software. Significantly, the project operated on a fast-track schedule, characterized by several unresolved design elements at the onset of construction. The design team dynamically refined the BIM model by accommodating client-driven change requests and adjustments prompted by on-site conditions during the construction phase.

Facilitated by the IPD process, stakeholders, including architects, consultants, and contractors, concurrently collaborated on the model. Autodesk Revit served as the primary tool for constructing and

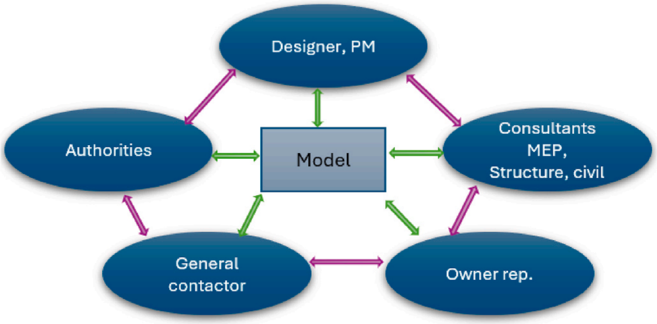

Fig. 3. Case A stakeholders relationship diagram.

documenting the model, which was subsequently shared on a cloud server for seamless collaboration. This collaborative approach enabled stakeholders to monitor real-time changes to the model, allowing for prompt adjustments to design and cost considerations.

Furthermore, the BIM-IPD process fostered enhanced collaboration among construction trades. The ability to harmoniously work in the field was facilitated by the pre-detection of clashes in the model, mitigating interference with each other's system layouts during construction. This integration of BIM and the IPD process contributed to a streamlined and collaborative project delivery approach, particularly beneficial for addressing evolving design requirements and maintaining efficient coordination among diverse project stakeholders.

The qualitative assessment of the case indicates a high level of BIM implementation within the project, with a corresponding high likelihood of achieving associated benefits. The case representative, however, underscored certain concerns that potentially influenced the project's performance. Notably, governmental review cycles extended beyond anticipated timelines, primarily due to limitations in accepting various file formats by the authorities' infrastructure, necessitating multiple points for data storage.

Furthermore, the CR identified a need for improved synchronization between the design and construction teams during model updates. Instances arose where construction activities outpaced documentation, leading to confusion for building inspectors who concurrently served as plan reviewers on the project. Addressing these challenges is crucial for optimizing the potential benefits of BIM implementation and enhancing the overall efficiency of the project delivery process.

2.10. Quantitative assessment

The quantitative assessment adhered to the prescribed quantification framework, with input pertaining to project details, costs, operations, and other relevant factors supplied by the CR following consultations with pertinent internal departments. In instances where obtaining precise estimates proved challenging, certain assumptions were made to facilitate the quantification process. The following table delineates the outcomes derived from the application of the quantification methodology to the case data, with benefits and costs allocated across distinct project phases.

The results indicate that this is a projected assessment when contrasting BIM adoption with traditional project delivery methods. The estimation demonstrates that the adoption of BIM for this project yields substantial benefits throughout the project life cycle. According to the assessment, BIM adoption could potentially lead to a time savings of up to 16 weeks in the project delivery stage. The analysis further reveals that BIM implementation incurs costs primarily during the design and brief stages, with the most significant value accruing during the operations phase.

2.11. Case B: Education centre, Stockholm, Sweden

The College aimed to enhance its current allied health and science facility and introduce a new musical centre for public service. The facility boasts a sophisticated architectural design that harmonizes with an efficient technology infrastructure, projecting an anticipated energy savings of up to 31 percent compared to a traditional educational centre, as envisioned by its designers. The building incorporates a range of distinctive energy-saving features, emphasizing daylighting elements and placing significant emphasis on acoustics, aligning with its educational campus context and functional purpose.

All members of the design team were extensively familiar and at ease with the strategies employed for this project, having collaborated closely on numerous occasions. This mutual familiarity and collaboration proved pivotal in attaining their objectives. The effective implementation of strategies necessitated distinctive qualities from the design team, including robust leadership from both the client and design team, the mechanical engineer's confidence, a lighting designer well-versed in integrated daylighting strategies, and consultant's adept at detailed daylighting, all comfortable with the concept of "integrated design."

Furthermore, the project team extended beyond the conventional group of engineers, incorporating a separate MEP firm tasked with conducting an energy study and an academic research organization. One notable strength, as highlighted by the CR, was the extensive experience of the main stakeholders working together for over 13 years. This longstanding collaboration played a crucial role in cultivating the collective expertise essential for realizing the project's ambitious goals.

2.12. Qualitative assessment

The project team formulated sustainable project goals and strategies, garnering support from the college administration for low-energy strategies and targets. At the heart of the project approach was the emphasis on integrated design, a concept central to avoiding cost premiums when fully embraced. However, it represents a paradigm shift that necessitates knowledge and confidence from the design team, robust leadership from the architect, and the trust of the client. The synergies within both the design and client teams were manifest in an integrated design approach, resulting in a synergistic building.

The collaborative involvement of administration, facilities, and building occupants at the project's inception was instrumental in establishing goals and fostering a high level of confidence. In the integrated design approach, where every building component contributes to broader energy and user comfort objectives, understanding constraints becomes paramount. The primary goal of achieving energy efficiency without compromising performance was carefully considered from the outset, requiring the development of BIM models for rigorous energy analysis.

The qualitative assessment highlighted a pronounced focus on the benefits of BIM during the operations phase, underscoring the project team's commitment to sustainability and efficiency throughout the building's life cycle.

2.13. Quantitative assessment

The following table illustrates the results obtained through the application of the quantification methodology to the case data. It presents a breakdown of benefits and costs allocated across different project phases.

3. Discussion

The assessment results were deliberated with the case representatives to gain their perspective on the quantified benefits. This discussion aimed to compare the identified benefits with those realized by the case representatives or whether they had previously conducted an internal assessment of BIM feasibility in-house.

4. Case A discussion

The assessment of Case A unveiled a substantial positive impact of BIM on the overall project life cycle, surpassing the case representative's initial estimates regarding BIM benefits for this project. Examining the estimated costs for the design stage, the CR found them to be highly reasonable. They remarked that a significant portion of design input occurred earlier in the project compared to the traditional Design-Bid-Build process with two-dimensional (2D) drawings.

The early involvement of code officials in the process proved instrumental in averting costly changes for the design and construction team. Despite the time and resource investment required for developing the model at an early stage, the benefits were notable. This was particularly evident as it marked the first comprehensive review of the 3D model, revealing that incorporating relevant data into the model significantly expedited the review process.

The estimate also revealed cost savings throughout the construction stage. The CR noted that having an open dialogue with code officials conferred a significant advantage to the project's design and construction team. Engineers, architects, and contractors engaged in discussions about regulatory issues with code officials well in advance within a virtual environment, facilitating early decision-making on conflicting items.

The utilization of the BIM model during construction proved instrumental in cost reduction by minimizing rework in the field. Problems were identified at an early stage, thanks to the construction team running clash detection on the building systems using the BIM model. This approach allowed for a swift and coordinated installation of systems by the construction crew. The team could execute their work independently of other trades' schedules, exemplified by the predetermined placement of electrical conduits and plumbing pipes based on the BIM model. This not only streamlined the installation process but also contributed to reduced labour costs.

In addition, the team leveraged the BIM model to generate highly detailed files suitable for fabrication. This facilitated the prefabrication of building elements, resulting in a substantial reduction in construction costs. BIM modelling enabled the breakdown of systems into sections that could be efficiently constructed in a controlled off-site environment, leading to higher productivity and enhanced quality. These prefabricated components were subsequently assembled on-site, contributing to increased efficiency in the construction process.

When questioned about the company's exploration of BIM feasibility, the CR disclosed that they had undertaken a partial assessment of the benefits of BIM implementation for this project. This evaluation was conducted as part of their business development team's broader effort to assess project success factors and disseminate organizational lessons learned. Their internal estimate regarding the BIM-IPD process indicated a notable reduction of 90–120 days in the overall time required for permitting and inspections, inclusive of the processing of model updates. This contrasted with the 16-week estimate resulting from the applied quantification methodology.

Furthermore, the company's cost estimate reflected substantial savings, encompassing both the early completion of the project, and reduced permitting and inspection fees through the use of BIM-IPD. The projected savings, when compared to the conventional process, were estimated to surpass $3 million. However, it was acknowledged that the internal estimate lacked the detailed quantification of project-specific details and internal savings that the applied framework successfully addressed. Consequently, the framework's estimate was deemed more detailed and comprehensive in comparison to the in-house assessment.

5. Case B discussion

The owners embarked on the construction of their education centre with precise sustainability goals in mind, and the amalgamation of energy-efficient design principles with a focus on long-term Return on Investment became progressively apparent throughout the construction process. Upon evaluating the costs and benefits of the implemented energy-efficient strategies, a notable impact of BIM on the operations phase emerged.

As per the CR, considerable lessons were gathered from a project management perspective, particularly concerning the integration of internal/owner project teams and external contractors. While the formation of an integrated team stood out as one of the project's positive aspects, the procurement and bidding process, unfortunately, hindered the participation of several contracting parties, including electrical and mechanical personnel. Due to the owners' active involvement in the technical aspects of the preliminary design process, many of these teams had to be enlisted after the initial project plans had been finalized and agreed upon. This posed a notable challenge during the bidding process for the contractors involved.

The collaboration of all design disciplines and the construction manager working on a shared BIM model played a crucial role in facilitating integration and coordination. This collaborative approach proved particularly beneficial for realizing the design's sustainability aspirations and the desired open, exposed layout. The CR clarified that their in-house project performance study indicated the construction of the project proceeded without any cost overruns. However, the initial estimate failed to fully capture the actual savings derived from the elevated level of BIM coordination among stakeholders. Similar to Case A, a significant portion of the costs was shifted to the upfront of the cost curve, predominantly in the design phase.

The CR presented the outcomes of the survey measuring occupants' satisfaction conducted one year after the project's completion. An Indoor Environmental Quality (IEQ) assessment indicated that low-energy buildings can achieve elevated levels of productivity and comfort. The survey gauged occupant satisfaction with thermal comfort, air quality, and lighting, and the results surpassed comparable benchmark values. This is particularly noteworthy given that the building relies on natural ventilation and daylighting. The natural ventilation system of the project delivers thermal conditions similar to mechanical cooling but with 70–90 % less energy consumption for conditioning.

During the discussion of BIMs benefits in the operations phase using the quantification method, a calculated yearly savings of almost $100,000 over the assumed operational period of 40 years was revealed. The CR explained that they successfully demonstrated to the client that the building's construction cost would be on par with a conventional design, yet it would yield nearly $50,000 in annual operational cost savings. This outcome surpassed their initial calculations, highlighting that their estimate had not accounted for additional aspects of BIM benefits, including savings in maintenance activities and operational costs (see Table 5).

6. Discussion of inhouse assessments of potential benefits

A discussion was conducted with both CR regarding their perceptions of BIM benefits, particularly addressing key assumptions related to BIM cost and time savings. The focus was on benefits that stakeholders often recognize intuitively, even without an official attempt to quantify them. The discussion involved comparing their BIM activities against a counterfactual scenario where BIM was not utilized. Table 6provides a summary of the results of this comparison from the stakeholders' perspective (see Table 7).

6.1. Case analysis results compared to similar research from the literature

Table 6 provides a summary of the case analysis highlights and presents similar findings from prior research that attempted to quantify the same attributes using alternative methodologies.

Both cases noted an escalation in costs associated with adopting BIM, with this expenditure being front-loaded to the design and briefing phase of the project. The increased costs were attributed to heightened efforts required for early-stage model development and more detailed design work compared to conventional methods. Case B reported a greater increase in costs, justified by the client's stringent standards aiming for sustainability goals and energy calculations. In comparison to analogous studies from the literature, higher percentages of cost increase were reported [7,15]; however, both results are relatively dated. It is important to note that recent advancements in technology and more sophisticated software have made BIM implementation less costly for companies. Many companies are gradually taking steps to incorporate BIM, reflecting a positive trend in the industry.

Similarly, both cases reported time savings despite requiring additional efforts at the project's outset for BIM implementation. Notably, time savings in project schedules during the design and construction phases were observed. These findings align with similar results reported in previous literature. The time savings observed in both cases can also

Table 5
Quantitative assessment of case A.

Type	Item	Total $
ENGINEERING & DESIGN		
Benefit	Reduce internal management costs that can be allocated to other projects.	19,000
Benefit	Reduced printing costs.	3,990
Cost	CDE Investment	−260,799
Cost	Information Manager Role	−260,799
Cost	BIM Training	−20,000
Cost	EIR Development	−10,000
Cost	OIR & AIR Development	−15,000
Cost saving during Engineering & Design stage		**−543,608**
PROCURE & CONSTRUCT		
Type	**Item**	**Total**
Benefit	Reduce prelim costs on site	563,327
Benefit	Reduce time and inflation costs	991,038
Benefit	Improved tender prices	521,599
Benefit	Reduce construction risk	3,129,594
Benefit	Reduce client held risk	3,129,594
Benefit	Reduce costs for BWIC	521,599
Benefit	Reduce cost to manage change	80,000
Cost	Investment in Facilities Management Systems	−5,000
Cost saving during Procure & Construct stage		**8,931,751**
OPERATION		
Type	**Item**	**Total**
Benefit	Robust data transfer at completion	6,000
Benefit	Efficient data management	800,000
Benefit	Improved energy performance	5,545,800
Benefit	Efficient maintenance events	240,000
Benefit	Bundling of maintenance events	1,422,000
Cost	Maintenance of AIM during Operations	−416,000
Cost saving during Operation stage		**7,597,800**
Cost saving for project lifecycle		**15,985,943**

Table 6
Quantitative assessment of case B.

Type	Item	Total $
ENGINEERING & DESIGN		
Benefit	Reduce internal management costs that can be allocated to other projects.	2,800
Benefit	Reduced printing costs.	1,400
Cost	CDE Investment	−119,400
Cost	Information Manager Role	−99,500
Cost	BIM Training	−10,000
Cost	EIR Development	−4,000
Cost	OIR & AIR Development	−20,000
Cost saving during Engineering & Design stage		**−248,700**
PROCURE & CONSTRUCT		
Type	**Item**	**Total**
Benefit	Reduce prelim costs on site	53,730
Benefit	Reduce time and inflation costs	83,580
Benefit	Improved tender prices	199,000
Benefit	Reduce construction risk	796,000
Benefit	Reduce client held risk	796,000
Benefit	Reduce costs for BWIC	99,500
Benefit	Reduce cost to manage change	25,000
Cost	Investment in Facilities Management Systems	−10,000
Cost saving during Procure & Construct stage		**2,042,810**
OPERATION		
Type	**Item**	**Total**
Benefit	Robust data transfer at completion	4,000
Benefit	Efficient data management	480,000
Benefit	Improved energy performance	2,562,300
Benefit	Efficient maintenance events	152,000
Benefit	Bundling of maintenance events	1,261,440
Cost	Maintenance of AIM during Operations	−320,000
Cost saving during Operation stage		**4,139,740**
Cost saving for project lifecycle		**5,933,850**

be translated into cost savings, adding to the overall BIM benefits calculated using the established equations. Both cases experienced cost savings in the overall design and execution phases of the project. These outcomes are consistent with similar literature focused on quantifying the impact of BIM on project costs.

The predominant share of estimated potential benefits in operations is evident in both cases, constituting 48 % of the total estimated benefits for Case A and a substantial 70 % for Case B. Within the operations phase, the most significant source of benefit in both cases lies in maintenance planning and execution, and in energy efficiency of building operations. It’s noteworthy that the quantified estimate of anticipated maintenance savings for Case A encompasses an additional saving attributed to using BIM for optimizing maintenance expenditure throughout the asset’s design life. The substantial emphasis on operations-phase benefits is attributed to the nature of infrastructure operations extending over several years. The estimates of total savings in maintenance spend, therefore, encapsulate annual savings projected across approximately 40 years for both cases.

While the Return on Investment (ROI) method has been commonly employed in the literature to assess BIM benefits, the previous studies exhibit significant variations in their results, lacking a unified calculation method for ROI. The outcomes of the case analysis using the established quantification methodology revealed an ROI of 16.1 % and 10.17 % for cases A and B, respectively.

7. Conclusion

There is a lack of a standardized methodology readily available for government construction clients and asset owners to consistently measure and evaluate the benefits of BIM. Numerous case studies have been conducted globally to showcase the advantages of BIM, contributing significantly to the evidence pool. However, a considerable number of these studies lack transparency in explaining the methodology used to estimate benefits, especially if they provide quantified or monetized figures. It’s frequently unclear against what benchmark or counterfactual scenario these reported benefits are measured or claimed. Additionally, many research efforts lack practical applications through case studies, relying more on assumptions and theoretical frameworks.

In conclusion, this research endeavors to address the crucial need for a comprehensive framework to quantify the benefits of BIM in the construction industry. Grounded in a thorough literature review, this study categorizes and compiles quantified BIM benefits, spanning various project phases and stakeholder perspectives. The formulated equations, derived from industry insights and validated through a survey, provide a robust foundation for assessing the tangible impacts of BIM on project costs.

The research method carefully integrates case studies from the Swedish construction industry to validate and refine the developed framework. Through comparing BIM activities against a counterfactual scenario without BIM, stakeholders’ perspectives contribute valuable insights, highlighting the challenges and benefits. The analysis of real-world projects accentuates that BIM implementation involves initial costs, particularly in the design and brief stages, yet these costs are becoming less significant with technological advancements.

Importantly, the research addresses the limitations inherent in the diverse application of BIM and variations across projects. Stakeholders’ difficulty in providing precise scale judgments and the scarcity of commercially sensitive data underscore the challenges in uniformly measuring BIM benefits. Despite these limitations, the study significantly contributes to the understanding of BIM’s impact on project costs,

Table 7
Summary of stakeholder's perspective.

The use of BIM scenario		Realization?		In house estimate
Benefit	Assumption	A	B	CR comments
Time savings in design: • Client review and stakeholder consultation • Design reviews. • Design coordination and management	Using 3D modelling in diverse design activities decreases the time required for design execution.	No	No	Neither Case A nor Case B could verify time savings during the design stage. Case A's CR highlighted prolonged approval procedures due to the requirement for 2D drawings. In Case B, additional efforts were invested in model development, particularly due to the emphasis on sustainable design goals.
Time savings in build and commission: • Design reviews. • Design coordination. • Site layout and logistics planning • Construction planning	The utilization of 3D modelling throughout various design and construction activities reduces the time required for construction and commissioning.	Yes	Yes	The design, construction, and commissioning processes were carried out simultaneously, leading to a modest timesaving for the construction team in schedule planning. Case A specifically highlighted efficiency gains during the fabrication phase.
Cost savings from better clash detection: • Design coordination and management. Cost savings from fewer changes	Clashes are identified virtually through a model rather than during on-site activities, resulting in reduced wastage of time and materials, leading to cost savings.	Yes	Yes	The design team stakeholders estimated a potential 5 % efficiency savings across the design process. They highlighted that the application of BIM resulted in cost savings in clash detection. The use of the 3D model enabled the identification of clashes digitally, preventing any clash-related issues on the construction site.
Time savings in handover: • Test assets. • Train asset owners/ managers in use • Handover asset and associated information to client.	The digital transfer of accurate as-built asset information, coupled with the use of the Asset Information Model (Wang et al.) for testing and training, contributes to time savings during the handover phase.	yes	yes	Stakeholders suggested the potential for time savings in training asset owners on the use of the asset. BIM has decreased the time needed to coordinate and manage responses to queries, enhancing the ability to respond effectively.

Table 8
Cases findings vs. literature findings.

	Case A	Case B	Literature findings
Increase in design cost due to BIM investment	7 %	13 %	31 % [15] 34 % [7]
Time savings during design and construction	11 %	4 %	11.5 % [2] 7 % [14] 6.3–36 % [6]
Overall cost savings in design and construction	8 %	5 %	10 % (Abdelbary et al., 2020) 20 % [16]
Calculated ROI	16.10 %	10.17 %	34.5 % [16] 1.8%–10.5 % [22] 27 % [39] 94.4 % [1]

with a particular emphasis on maintenance planning and execution.

The findings underscore the multifaceted nature of BIM benefits, with time savings, cost reductions, Return on Investment (ROI), and the significant impact of maintenance planning and execution. In both cases, the largest source of benefit is in maintenance planning and execution, making up 48 % and 70 % of total estimated benefits for Cases A and B, respectively. These estimates include annual savings over approximately 40 years, emphasizing the enduring nature of benefits in the operations phase.

This research not only quantifies BIM benefits but also offers a methodological contribution to the ongoing discourse on measuring the impact of BIM. The insights gained can inform strategic decision-making, further encouraging the gradual yet impactful integration of BIM practices in the construction industry.

8. Limitations

Limitations of this research include the difficulty faced by stakeholders in assessing the impact of BIM across various projects due to differences in its application. While stakeholders could confirm the existence of benefits, determining the scale of these benefits was challenging in some cases. Constraints in time and the willingness of companies to participate also posed limitations. Additionally, the nature of data requested, including commercially sensitive information, limited detailed analysis in some instances, relying on high-level estimates. The case analysis is further constrained by assumptions, such as inflation rates and operational periods, which were challenging to obtain or decide upon by the case representatives.

Another limitation of the framework pertains to its scope, which focuses solely on the quantification of tangible benefits and costs associated with BIM. While this approach enables the estimation of measurable impacts, it does not account for intangible effects. Although intangible effects are also significant, the framework provides companies with estimates of quantifiable benefits and costs. This ensures that the results generated by the framework offer a clear understanding of what can be measured with certainty, despite potential limitations in capturing intangible impacts.

To further advance the understanding of BIM benefits and implementation, future research could focus on several key areas. Firstly, conducting longitudinal studies across various regions and project types could provide deeper insights into the long-term impacts and cost-benefit dynamics of BIM. Additionally, exploring the integration of emerging technologies such as AI and IoT with BIM could uncover new efficiencies and value propositions. Comparative studies examining BIM adoption in different industry sectors beyond construction, such as infrastructure and facilities management, would also be valuable. Finally, developing standardized metrics and methodologies for quantifying both tangible and intangible BIM benefits would enhance consistency and reliability in future research. By building on the findings of this study, researchers can contribute to a more comprehensive and nuanced understanding of BIM's role in enhancing project outcomes and industry practices.

CRediT authorship contribution statement

Lina Gharaibeh: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Sandra Matarneh:** Writing – review & editing, Visualization. **Bjorn Lantz:**

Writing – review & editing, Supervision. **Kristina Eriksson:** Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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