Exploring the Challenges in Building Information Modeling (BIM) During the Design Phase: Evidence From Cross-Country Studies

Tássia Farssura Lima da Silva, Darli Rodrigues Vieira, and Marly Monteiro de Carvalho

Abstract—**Building information modeling (BIM) is transforming the construction life cycle. Nonetheless, there is a notable gap in research regarding the key challenges associated with BIM. This study aims to investigate the primary challenges in the design phase and their implications for project success. To address these objectives, cross-country case studies were conducted in four large engineering companies from the USA, Canada, Brazil, and United Arab Emirates. Data were collected through 23 semi-structured interviews with managers, engineers and directors, and content analysis was performed using NVIVO software. The resulting coding structure revealed the following categories: organizational and cultural issues, professional and knowledge issues, technological and operational issues, cost issues, BIM specific issues, design issues, data issues, and information and communication issues. The findings highlighted the most significant challenge as the lack of BIM knowledge or expertise. Additionally, an important enabler in the design phase is the accuracy of data provided by BIM, which enhances project management analysis. Finally, the BIM challenges and enablers influence various benefits dimensions, particularly on the efficiency.**

Index Terms—**Building information modeling (BIM) enablers, challenges, design phase, risk management, success dimensions.**

I. Introduction

Engineering projects involve the collaboration of a multidisciplinary team, including technical disciplines, subcontractors, consultants, material, and equipment suppliers. This project environment introduces challenges due to the extensive quantity of information that needs to be exchanged among these various professionals, and the use of information technology facilitates collaboration throughout this process [1] to ensure better project success and results.

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Digital technologies, notably building information modelling (BIM), have been recognized for their significant value in enhancing project efficiency. Moreover, advanced applications of BIM, automation, the Internet of Things, and drone technology represent examples of digital technologies that propel the transformation of the built environment, thereby delivering enhancements in efficiency and quality [2]. Indeed, the effective management of collaborative information exchange represents a fundamental element for attaining the desired objectives in the design phase [3]. BIM can also provide opportunities to reduce project threats and support risk management [4]. A previous study identified the most significant challenges in the design phase and explored BIM-based solutions [5]. While BIM can enhance risk management, its adoption introduces substantial challenges related to changes in process, technology, and people, whose interactions are complementary and highly challenging [1]. Scholars have focused their attention on the integration of BIM and risk management [6], [7], [8], [9], [10], [11], [12]. Most studies are related to the safety context in construction, presenting limited research concerning practice in the design phase of engineering projects.

Ghaffarianhoseini et al. [13] report a weak implementation related to challenges hindering its effectiveness. Consequently, BIM poses substantial challenges for companies throughout the implementation process in the design phase. Collaboration problems emerge across stakeholders [14], [15], while economic [16], managerial [9], and technological obstacles [1], [17] also arise. Nevertheless, it is crucial to mobilize initiatives regarding the success factors that guide both professional and academic domains.

In this context, numerous authors have identified enablers that exert influence on the success of BIM adoption. The BIM literature has thus distinguished a comprehensive set of challenges and enablers to support professionals toward successful BIM implementation strategies. However, there is still a lack of consensus regarding the most significant enablers and the list varies significantly across studies, such as those conducted in Singapore [18], Hong Kong [19], and Canada [20] highlighting the need for more context-dependent research [21]. Furthermore, various perspectives are employed, such as the incorporation of BIM technologies with lean construction approaches [22], BIM collaboration process [20], BIM implementation [23], and BIM execution [24]. Despite this, research on BIM adoption during the design phase in engineering projects remains limited.

To address this research gap, this study aims to identify the challenges and enablers in the design phase. Additionally, it seeks to understand the relationship between challenges and the successful use of BIM by companies. The following research questions (RQs) thus emerged.

RQ1: What are the benefits achieved by the companies with the use of BIM?
RQ2: What are the main BIM-related challenges in practice?
RQ3: Which are the main enablers in the design phase in practice?
RQ4: How BIM-related challenges influence achieve benefits in practice?

To address these research questions, we adopted a case study research method with content analysis supported by NVIVO software. As suggested by Ariono et al. [21], BIM drives barriers, and enablers differ between developed and developing countries. Therefore, we selected four engineering companies from different countries, including developed ones such as the USA and Canada, as well as a developing country such as the United Arab Emirates and Brazil. Data were collected based on 23 semi-structured interviews with managers, engineers, and directors.

This study contributes to theory in three folds. First, it shows the lack of professionals with BIM knowledge or expertise. Second, the results indicate that anticipating and mitigating BIM challenges positively affect various success dimensions, particularly enhancing project efficiency. Third, an enabler that stood out in the design phase is data accuracy provided by BIM. Finally, by including both developed and developing countries, our study provides a diverse perspective on the challenges and enablers in BIM across different economic contexts.

The rest of this article is structured as follows. First, Section II presents the main theme concepts in the literature review. Second, Section III describes the case study method. Third, Section IV presents the main findings from the research and their discussion. Finally, Section V concludes this article.

II. Literature Review

A. BIM Challenges

Notwithstanding its numerous advantages, BIM adoption still presents numerous challenges to its use and implementation [25]. These challenges linked to BIM encompass a broad range of difficulties and obstacles encountered during the design phase of BIM implementation including technical, organizational, economic, and environmental aspects, explored in this section. Besides, BIM faces specific risks and uncertainties that could potentially impacts on project outcomes, such as financial losses, delays, or failures in meeting project objectives.

The investigative research by Almarri et al. [26] has identified the primary challenges emerging from BIM adoption, including lack of experienced and skilled personnel, lack of collaborative work processes, and lack of understanding BIM processes. There are also economic obstacles to the application of BIM in the design phase relate to cost, shortage of professionals, and changes to workflow processes [16].

Liao and Ai Lin Teo [27] revealed lack of stakeholders' involvement to work collaboratively from early design and unwillingness to change. Besides, problems emerge from the uneven distribution of BIM developmental and operational costs among stakeholders, which requirement changes in contracts to foster collaboration across stakeholders [14], [15].

Othman and Alamoudy [9] acknowledged that its implementation can be a time-consuming process, demanding full commitment from all project participants for its success execution. This includes the organization's assistance and investment in training, skilled professionals, and technological infrastructure.

Furthermore, professionals expressed concerns related to technology issues, more specifically, software functionally, technology immature, and compatibility [1]. Meng et al. [17] reinforce as technical challenges data interoperability, technology integration, and data management.

There are limited initiatives in the literature to integrate BIM platforms and risk analysis models to enhance the benefits derived from this relationship [28]. Inadequate relevant knowledge and experience, interoperability issues, and cultural resistance were the top-ranking of a prioritization list regarding the main risks associated with BIM identified by Viana and Carvalho [29].

Although Ahmad et al. [6] suggested the concept of automated risk management using BIM in construction projects, the current state of its use still requires manual risk selection and relies on opinion-based probability input. They have recommended that BIM software developers should assume the responsibility of coding the proposed framework. Yasser et al. [30] proposed a model based on a specific program and the authors suggest developing other methods to facilitate and speed up the linking process between risk management and BIM. Despite Moshtaghian and Noorzai [31] created a framework to integrate risk management on BIM, the results show some obstacles like, time-consuming and the users faced challenges using the application.

B. BIM Benefits and Enablers

Project success is linked to benefits, delivering results that align with the desired functionality and performance, including schedule and budget compliance [32]. Othman and Alamoudy [9] proposed a framework to optimize project performance during the design phase, while Carvalho and Rabechini Junior [33] assess success in seven dimensions (project management, project product/service, impact on team, present and future impact on business, impact on the customer and sustainability). Brunet and Forgues [34] propose certain measures for achieving optimal project management success, including the use of BIM. The authors state that the BIM approach has the potential to become a catalyst, enhancing synergy and project performance.

BIM integrates multidisciplinary and structural data to create a virtual model throughout the project life cycle. BIM adoption drives organizational and technical innovation enabling the development capabilities and opportunities [2].

When effectively implemented, BIM enhances project performance across several aspects, including project quality and value, team performance and project management efficiency. BIM provides an integrated design and construction process, leading to improve quality at reduced costs and project duration [35]. BIM has been regarded as a technological innovation that has strengthened risk management [6]. It allows professionals to create an accurate three-dimensional digital model [36], to track potential conflicts and clashes at the design phase, reducing errors, thereby eliminating the need for numerous requests for information [18], and supporting designers to verify the quality of BIM models according to clients and regulations requirements [37]. BIM also presents an opportunity to integrate sustainability analysis into the design process and provides potential support for minimizing construction waste during the design phase [38].

Furthermore, the advantages of BIM extend to an organizational context, including its influence on both clients and businesses. The capability to apply BIM to different management processes and analyses results in achieving high project performance [39]. A case study conducted by Rockart [40] emphasized that BIM enables the extension of services to clients, the acquisition of a competitive market, and the adoption of modern technology to enhance business process. The authors also recognized the efficient reuse of information through a knowledge database, leading to enhanced client satisfaction. Similarly, Olawumi and Chan [41] disclosed the following benefits: improved resource planning and management, compliance with the project delivery schedule, and enhanced collaboration among stakeholders.

Indeed, while the literature highlights numerous advantages associated with BIM utilization, which can contribute to project success, a more comprehensive understanding of the BIM enablers is necessary. This knowledge is essential to effectively address the challenges so far in its implementation. According to Rockart [42], BIM enablers could be defined as essential factors for a project's success. Thus, BIM enablers are the most significant to enhance project performance and ensure success in construction projects [43]. However, despite increasing academic attention, a thorough and well-established analysis of BIM enablers is still lacking [44].

The adoption of BIM in design firms is still not well understood, which leads to difficulties for firms when implementing this technology [2]. As noted by Fakhimi et al. [45], BIM successful results have not yet been reported by engineers in specific industrial sectors, due to a lack of comprehensives studies. Furthermore, Evans et al. [22] emphasize the necessity of exploring BIM enablers to enhance its application from the early design stage, since the decisions made at this phase of the project have the highest potential to influence the subsequent phases [46]. By implementing appropriate control measures early on, many foreseeable challenges can be mitigated, minimizing the likelihood of issues emerging in later phases [47]. Indeed, design stage have a significant role in managing the risks during the project's lifecycle [3]. Furthermore, the design phase is exposed to numerous challenges that have the potential to result in errors, project failure, unsatisfied clients, cost overruns, and other adverse consequences [9].

The literature review recognized the value of BIM, yet several research gaps persist. BIM implementation presents significant challenges related to process changes, technology integration, and stakeholder interactions that remain insufficiently explored. Most existing studies focus on the stage of construction execution, exploring safety contexts, with limited attention given to BIM's role in the design phase of engineering projects. Furthermore, there is no consensus on the most crucial enablers of BIM adoption, and findings vary considerably across different contexts. Thus, our study helps to narrow these gaps, through context-specific research, providing a deeper investigation into BIM adoption during the design phase. We focus on understanding BIM's challenges and their influence on project success.

III. Research Method

This section outlines the methodology employed to address the research questions. Initially, a preliminary literature review is conducted to identify gaps and relevant topics related to this study. Afterward, exploratory case-based research is proposed involving four case studies undertaken by interviews and analyses of documents provided by the companies. Case study research incorporates study questions, propositions and criteria for interpreting findings [48]. The selection of the case study method in this study is justified by its capacity to analyze the investigated topic in practice, identify new variables and hypotheses, and assess inferences through a combination of within-case and cross-case analyses [49].

A. Sample Characterization and Data Collection

We applied a theoretical sampling process with careful case selection, choosing cases where the similarities and differences are likely to enhance theory building [50]. Data collection was conducted across companies in four countries, including two developed countries and two developing countries. The meticulous selection process is based on the following criteria:

1) have a well-defined management structure;
2) have risk management practices within their management processes;
3) actively engaging in projects utilizing BIM;
4) organizations must operate within the domain of engineering projects;
5) granting access to specific internal documents and stakeholders, essential for both data collection and interview sessions.

Semi-structured interviews were conducted with key stakeholders including directors, project managers, field managers, and engineers. Each interview session was documented through recording and subsequent transcription. In accordance with the recommendations of Voss et al. [51], field notes were taken during the interviews to capture nuanced insights. Although the authors also recommend interviews with multiple respondents per case study, the determination of participant numbers hinges on the research's nature and data quality. The possibility of a smaller sample is acknowledged, if results are strengthened by complementary data collection methods alongside interviews [52]. This study, in alignment with these considerations, incorporated a review of archival data. The primary documents analyzed comprehended policies, procedures, work instructions,

TABLE I
COMPANIES AND AREAS INTERVIEWED

Company	Sector	Country	Number of professionals interviewed	Number of interviews	ID Code	Areas interviewed	Experience (in years)	Job position
A	Consulting, engineering, digitalization, management and integration	Brazil	8	8	ARM APM1 / APM2 ACE1 / ACE2 ACM ADE AQSE	Risk Management Project Management Civil Engineering Construction Management Digital Engineering Quality, Safety and Environment	21 20 / 23 19 / 10 18 29 27	Director - PMO and Strategic Planning Project Manager / Planning Manager Civil Engineering Manager / Project Coordinator Project Director Digital Engineering Leader Project Director
B	Consulting, engineering, construction, operation, maintenance, intelligent networks	Canada	4	6	BRM1 / BRM2 BMEE BOP	Corporate Risk management Mechanical and Electrical Engineering Operational Intelligence	28 / 29 25 12	Vice-President Risk Management Vice-President Mechanical and Electrical Engineering Data-Centric Engineering Expert
C	Engineering and construction	United Arab Emirates	2	6	CRPM CDD	Risk and Project management Digitalization & Development	22 12	Managing Director Bids Development / Digitalization
D	Engineering and construction	EUA	2	3	DPM DVDC	Project management Virtual Design and Construction	18 14	Project Director Regional VDC Director

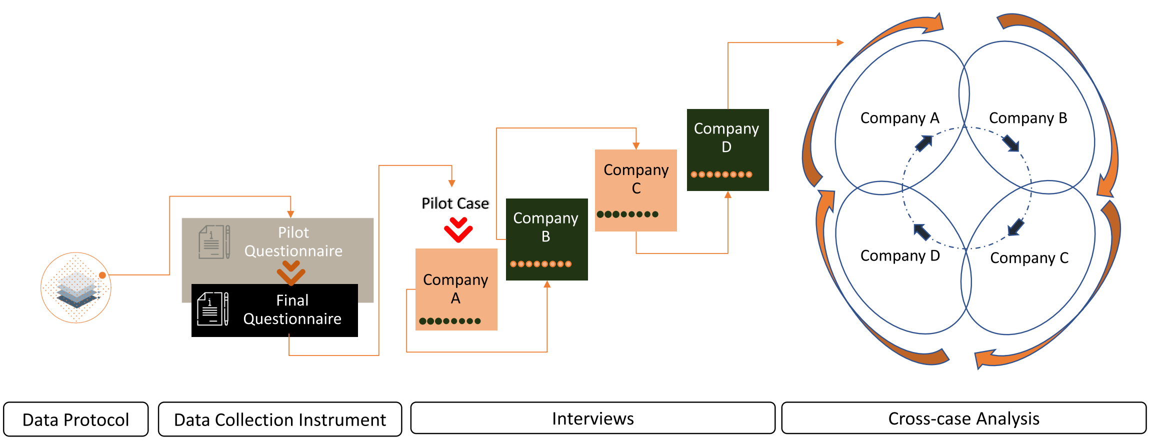

Fig. 1. Research design.

internal standards, organizational charts, and technical documents related to risk management and BIM. A total of 16 professionals were interviewed, either face-to-face or in virtual meeting rooms. Each interview lasted approximately 1 h, with a variation of plus or minus 20 min. Four professionals were interviewed twice, and one was interviewed three times as they were involved in different areas related to the research topics, and to clarify some issues identified in the data collected.

For information and data collection, a research protocol was developed, guided by both the literature review (previous research which included a bibliometric and content analysis), and the researcher's prior expertise. This protocol includes an introduction and details about the company, the project, and the interviewees. It then outlines thematic areas within the questionnaire, addressing the following.

1) BIM challenges in the company's organizational context, focusing on stakeholders actively involved in BIM implementation and risk management.
2) BIM in the design phase, targeting stakeholders engaged in the project's design phase.
3) The relationship between BIM challenges and project success, directed at stakeholders with access to project performance reports utilizing BIM.

The questions were designed to offer a comprehensive understanding of the BIM implementation in the interviewed companies. Additionally, they explore the motivations behind the adoption, the primary challenges faced, and the benefits identified through BIM implementation. A pilot case was formulated to enhance the research quality by referring to data collection and the delineation of procedures, following the guidance of [53]. After reviewing feedback from both practitioners and researchers, minor adjustments were implemented to mitigate the potential for misinterpretation. Table I provides detailed characteristics associated with the four exploratory case studies.

B. Data Analysis

Aligned with the research questions, we adopted a multicase approach. Our data analysis aimed to investigate both similarities and differences across cases to inform theoretical generalizations [54]. The cross-case analysis focused on two key aspects aligned with our research objectives: the challenges of BIM and the benefits most commonly associated with its implementation. We conducted a qualitative analysis of interviews using NVIVO software. This involved classifying data into first and second-order codes, or "nodes," based on main constructs and organizing them into a code tree structure in accordance with established literature guidelines [55], [56]. This stage produced a project coding book, as exemplified in Appendix A. Emergent codes were continuously compared with relevant literature constructs, as discussed in the previous section. We then engaged in axial coding to explore the relationships between first-order codes, aiming to develop second-order themes and refine emerging themes. This process suggested aggregate dimensions that could help explain the observed phenomena [57].

A visual representation of the research design is summarized in Fig. 1.

IV. Results and Discussion

This section delineates and scrutinizes the primary evidence collected in the case studies in addressing the research questions outlined in Section I.

A. BIM Benefits

The data analysis revealed the identification of success dimensions proposed by [33], signifying that the interviewed professionals acknowledge positive project performance through the utilization of BIM. To exemplify these aspects, statements are provided in Table II.

The case studies indicate that, despite the inherent challenges associated with the technology, emergent opportunities and positive outcomes are apparent. Consistent with existing literature, the adoption of BIM has yielded enhanced budget and schedule adherence, along with improved project quality [2], [35], [58], [59], [60]. Companies highlighted improvements in both the product/service dimension and team capabilities. According to Company D (ID interviewee DVDC), "BIM has increased the accuracy and reliability of design data, especially when we can involve trade partners early." Similarly, the interviewees mentioned that the BIM learning environment enhanced team capabilities and skills, thereby improving project performance.

This investment in skill development not only facilitated the collaboration but also enabled team members to leverage BIM tools and methodologies more effectively. As a result, teams were better equipped to address project challenges, coordinate, and deliver high-quality outcomes. The professional's skill development enhances their ability to effectively engage in collaborative BIM projects, ultimately contributing to improved project outcomes and performance [61]. Additionally, companies indicated a positive impact on business, particularly in terms of project value for the organization, data accuracy, the adoption and integration of new technologies as drones and digital twins, all contributing to client satisfaction. For instance, Company A (ID interviewee ACE1), mentioned "Recently we made a proposal, and we made a video using the model, and we sent it to the client. So, we added more value to the proposal, before BIM we would never do this."

A prior study conducted by da Silva et al. [62] identified project management efficiency as the most frequently discussed success dimension in the literature. Additionally, the study brought to light emerging themes such as safety and social impact. In practice, companies indicated that that discussions around these topics remain limited. Despite presenting actions and strategies to facilitate BIM adoption supporting sustainable approaches (see Table II); companies acknowledged encountering numerous challenges in achieving this level. Company B (ID interviewee BMEE) remarked "I see a lot of people interested in this topic, but honestly, only a few are using it."

Certain initiatives have been observed to enhance project performance concerning social and environmental considerations. Nevertheless, companies encounter challenges in working in a collaborative and integrative environment, largely attributed to the entrenched design culture within the sector. The developmental stage of BIM is deemed to be at a primitive stage [63], potentially lacking the requisite information and conditions necessary to reach sustainability benefits [64]. Studies indicate that limitations and challenges, stemming from both technological constraints and a lack of knowledge among professionals, hinder progress toward this objective. Despite the expansion of academic research on BIM and sustainability, there are lack or no studies addressing the practical application of these concepts in the industry [65]. The synergy between BIM and sustainability has the potential to enhance the economic, social, and environmental performance of engineering projects. However, preliminary measures toward achieving sustainability require a comprehensive understanding and categorization of BIM uses and environmental indicators from the early stages of design [64]. Olawumi and Chan [66] emphasized that for the achieving any sustainable smart initiative, there must be a proper integration of the knowledge and skills among stakeholders and an increase in their involvement, acknowledging the limited experience of some of them in BIM.

The research conducted by Lu et al. [38] recognized benefits arising from the integration of sustainability and BIM. However, the authors identified challenges including, e.g., the complexity of tools and users' insufficient BIM knowledge, weak interoperability among various BIM applications, low industrial acceptance of sustainability BIM applications, and limitation of BIM in holistically assessing both the environmental and social sustainability of buildings. The authors suggest that studies and advancements in these areas could provide better guidance for practitioners and lead to more effective project results.

B. BIM Challenges

While organizations see the potential of BIM, its use still leads to challenges and barriers, hindering effective practice by professionals and impeding improvements in project performance. During the interviews, professionals evaluated a set of challenges adapted from Zhao et al. [67], while also being encouraged to identify additional challenges encountered in practice. Fig. 2 summarizes the coding structure for challenges related to BIM implementation, organized by themes and codes. This in-depth coding process, based on qualitative data from multiple interviews, highlights the complexities different stakeholders face in the BIM process. We identified 22 challenges that the interviewees associated with BIM, which we encapsulated in eight categories: organizational and cultural issues, professional and knowledge issues, technological and operational issues,

TABLE II
BIM BENEFITS

Success dimensions	Company A	Company B	Company C	Company D
Product_Service	"It was a project where we were able to apply the process as a whole, the quality gain was very high. As you end up integrating all the information, and here I am talking about a point, even a visual, geometric issue, you do analysis that you would not normally do." (AC1)	Typically, we should get gain on this because yeah, we should first of all have less interference are catch them before. We're working more in collaboration. So, if we are more in collaboration, we're more in communication. We should do a better project. (BRM1)	"We had a BIM model early enough in the project which was able to run accurate for the simulations and we were able to see where the problems were." (CDD)	"BIM has increased the accuracy and reliability of design data, especially when we can get trade partners involved early." (DVDC)
Project management efficiency	"It is a way for us to anticipate gains, capture opportunities, and also mitigate any negative impact on any objective of the project, whether in cost, time or quality." (ARM)	"We definitely save time for collaboration; engineer is getting information easier. With a fully integration environment we save because of collaboration, to look for information where is the data, maybe instead of 100 meeting before the decision making, we can cut down to 50% because information is available and is transparent across disciplines." (BOP)	"I can say that BIM, of course, happened all through the project, it reduced ambiguity and tends to have more understanding of the project environment, project nature in an easier way. So, definitely, it did reduce the risks." (CDD)	"This process just helps us smooth our schedule uncertainty and understand, make sure that we have all the answers before we really get started so that we're not wasting a bunch of time." (DPM) "Enhance visualization, better analysis, better turnaround times for developing these budgets which, like I said, actually allows more frequency, which allows projects stay better in line with the original budget". (DVDC)
Impact on team	"When the civil team used BIM and saw that it worked, it gave them motivation and replicability in the projects." (APM1)	"We will develop some training but it's not only training, it's more like a learn. Sharing information and developing tools and processes. And to develop tools and processes I'm looking to outsource that. So, I am dealing with somebody willing to help us. And so now we are doing it and I'm developing with a BIM manager." (BMEE)	"Yeah, definitely provided training we prompt some external professional people to give a training to all the staff. We sent the staff outside for training, definitely." (CRPM)	"We are basically providing digital prototype of the building before it is ever built. So, people are, project teams are much more informed of visuals as the models. Visual for clarity. The models provide the enhanced data." (DVDC)
Present impact on business	"Recently we made a proposal, and we made a video using the model, and we sent it to the client. So, we added more value to the proposal with this video, with this information from the model, before BIM we would never do this." (ACE1)	We have a committee, and we have a plan to democratize the tools and the process because what I would like to avoid is having specialists that maybe will go out, so you would lose everything. (BMEE)	"One of the things we have done is that, while doing the design we started calculating from the BIM the major packages. So, we were trying to verify that those quantities are correct and add some more accuracy to it to actually get to know our cost to have an agreement with the client, concerning our margin. Without that, it wouldn't have happened." (CDD)	"We also tract our trading partners for past experience as well. So, when we go to new projects, we can have a better negotiation as far as what their expectations are or you know, if they need to have additional supplementing support something to that effect." (DVDC)
Future impact on business	"It was a great opportunity that now we also use it in other projects, because we had no idea of the error, of the precision it would have. When we did it, when we reached millimetre precision, we started to adopt this new type of topographic mapping using drones". (APM1) "The other technological innovation, also for BIM, is concerning the modeling of the existing from the point cloud of an entire industrial plant, we have not found another company that has done this." (ACE2)	"One of the key part of digital twin is connected to just have everything in a digital format. Any business benefit connecting in a smart way to present the fit forecast information is the key. The information can come from many sources like engineer data, propagated visitor data. The idea is right information, right time to go to a right person. So, I have with an advanced type of digital twin. We will be including incoming real-time and historical centre information. This data will use artificial intelligence and machine learning and help us to understand the behaviour of the physical facility." (BOP)	"That's why BIM came on with the priorities, when we start to analyse technology and we had one of the strategic objectives to move towards innovation and more dependence on the technology." (CRPM) "This is what we discovered later, what would we do without the drone to be able to plan for this trust lifting? It's impossible. It could have taken days if not weeks to just go around the site and keep imagining from every angle how to going to be and it's still impossible because you don't get this perspective you have to jump on buildings. You will have to go on top of roofs to take looks and so on while you can just simply do it from a five-minute video." (CDD)	"We have talked about working into 4D and basically working a schedule component into that. But that is not something that we have gotten very far on. So, we will do a little bit of it for a marketing perspective. Like, we will have a model and we will have a schedule and kind of create a nice-looking video of hey! here's how we build your building based on the schedule." (DPM)
Impact on the customer	"We used QR codes on the steel structure drawings. So, the client could, through his cell phone, visualize the project, he could see the whole structure in 3D modeled." (APM1)	"I see the benefits when we have to hand over. We are not hand over a box of documents. We are not hand over just a copy of the database, we hand over smart data, they are able to use that map data, plug-in, and be able to use it for that operation." (BOP)	"Because of our usage of this technology, the client has started working with us on other projects later on and he set this as a standard. So, he told us he became completely reliant on it, that it had to be included in the contract from now on. So, it definitely did affect the business, it was impossible without these kinds of technologies." (CDD)	"In this process you can have the superintendent, project manager for every single company who would be involved to help make the decision along with the designer along with the trade partner along with the general contractor. And you see that information, live opposed to guessing at what the condition might be. So, "the proof is in the pudding" so to speak. It gives you the tools to make the correct analysis." (VDC Director - Virtual Design and Construction)
Social and environment impact	"We didn't even have to do the traditional method, this was a huge gain for the company, because we saved a lot of time, because with the drone scan we did it in one day, and a topographic in that plant would certainly take 2-3 months." (APM1) (reduction of professionals' displacement regarding the topographical mapping service)		"The other thing is that construction down the line and the QAQC and health and safety and how they're utilizing BIM. This is part of the things we're looking honestly. Generally, the directors and the people in the company have realized especially in the health and safety how the BIM and the quality assurance how the BIM model can change how we do these processes. So right now, they are focusing along on trying to find out a framework of the software can help them."(CDD)	"I think one major facet of lead is eliminating waste and using this process does that. Again, goes back to the rework thing I talked about any time you can eliminate cutting, you know, you say you are finished with something and something is the wrong cutting out dry wall, cutting out the pipe, putting the pipe back in, putting the drywall back on. Those are all wasteful things from materials and time standpoints. That BIM can help eliminate." (DPM)

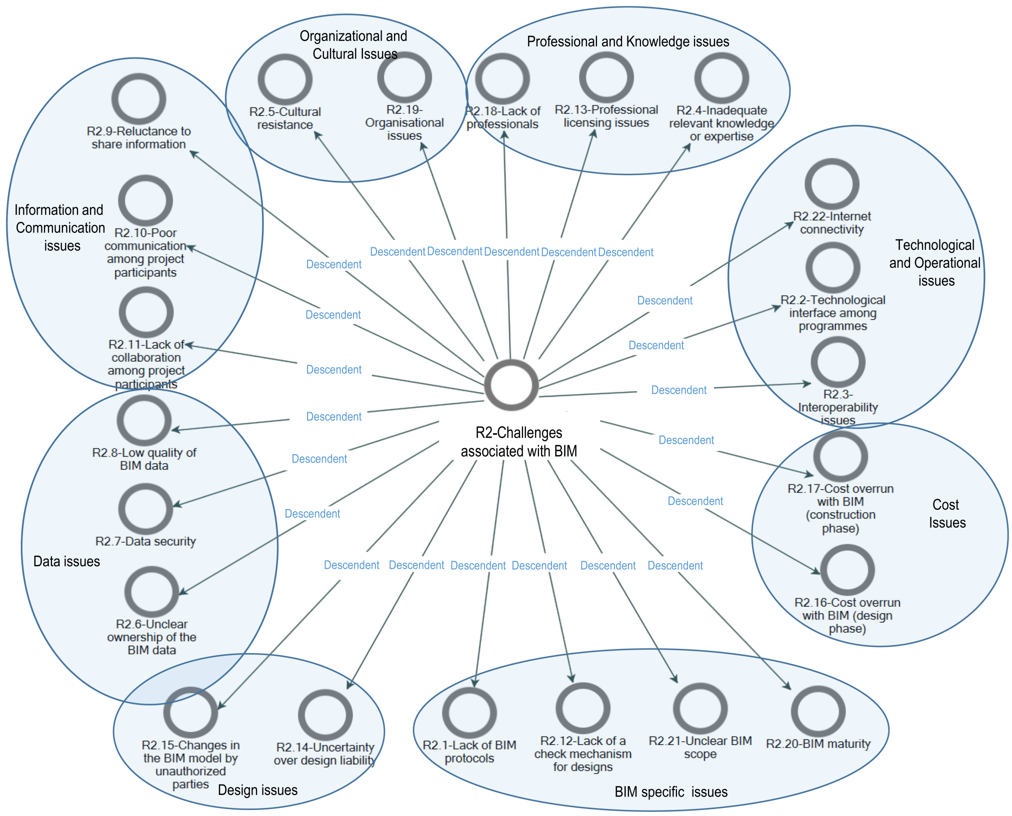

Fig. 2. Challenges associated with BIM. Note: Content analysis codification in the NVIVO software.

cost issues, BIM specific issues, design issues, data issues, and information and communication issues Appendix A presents the code tree, frequencies, and quotations.

The top-ranked challenges were the professional and knowledge issues, followed by cost issues. Several challenges related to professional and knowledge issues were identified, including inadequate relevant knowledge or expertise, professional licensing issues, and a lack of professionals. These issues underscore the need for better training and education in BIM-related skills, as well as clear licensing guidelines to ensure that professionals are adequately qualified to work with BIM technologies. Cost issues related to BIM were another major theme, with references to cost overruns during both the design and construction phases. These quotations reflect concerns that, despite the potential efficiencies offered by BIM, the initial costs could be high and sometimes exceed budget expectations, particularly in the planning stages.

Organizational and cultural issues emerged as a significant theme, with specific challenges such as cultural resistance and organizational issues frequently mentioned, as detailed in Appendix A. Cultural resistance, for instance, is illustrated by quotations indicating that suppliers and companies are often reluctant to adopt new tools and technologies, preferring traditional methods. Organizational issues highlight difficulties within company structures and processes that hinder the effective implementation of BIM.

Technological and operational issues were also prominently featured, with problems related to technological interfaces among programs, interoperability issues, and internet connectivity being frequently cited. These challenges point to the technical difficulties of integrating different software systems and ensuring they work seamlessly together, as well as the practical issue of reliable internet access, which is crucial for the successful use of BIM.

BIM specific issues encompassed a range of concerns, including the lack of standardized BIM protocols, insufficient check mechanisms for designs, issues with BIM maturity, and unclear BIM scope. These problems highlight the need for standardized procedures and clear definitions of scope to ensure that BIM projects are managed effectively and consistently.

Design issues were also a recurring theme, pointing out uncertainty over design liability and unauthorized changes to BIM models. These issues emphasize the importance of clearly defined responsibilities and control mechanisms to prevent unauthorized alterations that could compromise the integrity of the BIM model.

Data issues related to the quality, ownership, and security of BIM data were frequently mentioned. The low quality of BIM data, unclear ownership, and concerns over data security all point to the critical need for robust data management practices to ensure that the information used in BIM is accurate, secure, and properly controlled.

Lastly, information and communication issues were highlighted, with poor communication and collaboration among project participants, as well as a reluctance to share information, being common challenges. These issues underscore the necessity for improved communication and collaboration tools and practices to ensure that all stakeholders are on the same page and can work together effectively.

These findings align with previous literature as identified by Zhao et al. [67], emphasizing these challenges in the implementation and use of BIM. Professionals expressed difficulties related to interface among programs, particularly when a project involves numerous stakeholders with different software and compatibility requirements for exchange information. Zou et al. [68] identified barriers associated with various software vendors for different disciplines, and some of them do not provide linking information. Construction projects still contend with technological concerns alongside collaboration challenges [69], emphasizing the need to integrate process, culture, and management across all stakeholders involved [70]. Furthermore, companies emphasized that stakeholders, especially suppliers, often exhibit limited interest in fully engaging with the BIM model within an integrated work environment. This interest can vary based on their maturity level and knowledge. Furthermore, some stakeholders still work in two-dimensional requesting DWG extension documents or paper copies. The hesitancy of stakeholders to commit can be attributed to the lack of standardized procedures for collaboration with external team members and interoperability issues between software programs [71]. Additionally, some computers faced challenges in running the software due to issues such as insufficient processing power, and storage (RAM).

Moreover, challenges highlighted by certain companies as technology issues may, in fact, stem from a lack of knowledge, misuse of tools, and inappropriate machines. Most design rework and poor design quality can be linked to professionals' inexperience, with inadequate knowledge or expertise emerging as the top-ranked challenge reported by the companies. Professionals often find themselves less acquainted with the tools and processes required by BIM. The demand within the AEC industry for skilled BIM experts is notably high; however, knowledge and experience remain inadequately addressed [72], along with improperly training and education [73].

As noted by Company B (ID interviewee BMEE), "there are limited specialized resources." Professionals have also encountered situations where a "Request for Proposal" demands documents and information from the model that they are not familiar with, or they are uncertain if there is any tool available in the market to address those specific requirements. The companies not only acknowledge these challenges but are also making efforts to provide training to enhance knowledge and achieve the necessary expertise.

Furthermore, professionals noted that subcontractors often lack familiarity with BIM and struggle to adhere to its standards. Additionally, they may also have different levels of knowledge, introducing further challenges to projects. Briefly, the modeling becomes a liability for contractors in ensuring project quality. Inadequate knowledge and expertise further contribute to issues related to information quality, collaboration, technological interface, and data compatibility [67], thereby increasing design cost and duration [74]. Negative project results further lead to resistance to the use of BIM, particularly as engineering and design face fast track projects and market pressure. Professionals perceive BIM implementation as a time-consuming, long-term process. Companies reveal that the learning curve in BIM tools is relatively slow, and they face challenges in mobilizing the entire team for training, given that it must run concurrently with other professional responsibilities.

Despite [75] state that BIM in the design stage enhances the project by reducing costs without compromising quality, the companies have expressed concerns regarding cost overrun, particularly in the design phase, resulting in higher costs and reduced profitability. The decision to adopt BIM is viewed as an investment, and from a business perspective, the costs associated with BIM implementation must be justified by the accrued benefits [76]. The adoption of BIM involves professional training, investments in infrastructure and tools, and the engagement of a skilled team, demanding both time and financial resources [9]. The emphasis on cost overrun in the design phase implies a practical implication; consequently, companies may refrain from adopting BIM in projects where it is not a contractual requirement. As mentioned by Company A

(ID interviewee APM1), "in proposals without a BIM requirement, companies that do not use BIM will be more competitive for presenting lower prices, which does not necessarily guarantee higher project quality; however, at this point, most clients primarily consider the proposal cost."

Professionals emphasize that most BIM benefits manifest during the construction phase, driven by factors such as reliability and design quality, ultimately translating into cost savings. Turn-key or design-build contracts are deemed more advantageous for companies, as they afford better control over the cost-benefit balance. According to Company C (ID interviewee CDD), "a design-build project is streamlined and cost effective. It's constructible and connected from the ground being the most cost-efficient besides making sure that all the participants are involved from the beginning."

It is noteworthy that professionals from the same company, but different disciplines and business units hold differing opinions and experiences. This divergence can be referred to varying levels of BIM knowledge and maturity within the company. BIM implementation has been fragmented across disciplines and business units, reflecting the findings of research by [77], which highlighted a high degree of heterogeneity in BIM expertise among disciplines, marked by fragmented and noncollaborative practices. The authors noted the lack and varying levels of knowledge, underscoring the challenge of assembling project teams with uniformly trained members in the technology.

A critical inquiry arises as to whether the cost overruns in the design phase, as noted by the organizations, are linked to professionals' lack of knowledge leading to rework, project delays and additional costs, or external influences, such as market issues causing design undervaluation. Precisely, the projects are sold at lower prices with reduced profit margins, and companies may not always have precise control to accurately affirm the project's low profitability.

Internet connectivity emerges as an additional challenge, a concern not explicitly highlighted by Zhao et al. [67]. The companies specifically cited this issue, particularly in projects involving a significant number of external team members or the use of BIM in the field, where the likelihood of encountering restricted or limited internet connectivity is high. In such cases, professionals download the model once a day; however, problems in updating the information and working. Company C (ID interviewee CDD) highlighted this challenge, stating, "we receive updates from different stakeholders, and it is very challenging. So, a lot of the BIM capability and working in a common detailed environment is not actually achievable; this is an actual problem that we have."

C. Design Enablers

Organizations emphasize several benefits associated with BIM, including precise and straightforward cost estimation and quantity take-off, risk reduction, improved design verification through clash detection, design duration reduction, earlier and accurate visualization of design, better design quality, enhanced exchange of information, extraction of more accurate key performance indicators (KPIs), accuracy and reliability of data, improved mechanical, electrical, and plumbing (MEP) analysis, and enhanced integration and communication among disciplines and stakeholders.

The implementation of BIM facilitates design visualization and enhances project management [66]. Professionals emphasize the early identification of challenges, a critical factor supporting the decision-making process and ensuring a more reliable and higher-quality project. As highlighted by Company A (ID interviewee ACE2), "it takes a little longer to develop the project, but in the end, it is worth it because you can see all the interferences with all the disciplines and you don't spend as much time analysing them, as you did in CAD. The gain in design quality is very high."

The organizations underscored the advantages of integration and communication among the design team, construction company, suppliers, and trade partners as notable benefit for the project. These findings align with the characteristics of most companies in the sector, where project development is often considered fragmented. The adoption of BIM enhances collaboration. particularly in risk management, as its effective execution relies on collaboration and teamwork. Similarly, Othman and Alamoudy [9] affirm that addressing fragmentation and risks adequately in the design phase can contribute to enhancing project performance. Company C (ID interviewee CDD) emphasizes, "I can say that BIM reduces ambiguity and tends to have more integration and understanding of the project environment more easily. It reduced the number of disruptions we had while implementing the project. Things were a bit more streamlined, all the subcontractors were on board, there were fewer questions, people understood the nature of the project and they participated since the design, which made it much easier, actually. So, definitely, it did reduce the risks, and I would also complement that there were certain issues that we even have not identified as risks because we had BIM; some risks were eliminated." Company B (ID interviewee BOP) added, "we acknowledge the contribution that the BIM gives to the schedule related to risk and mitigation."

The professionals emphasized the improved design verification and validation provided by clash detection. Company B (ID interviewee BMEE) highlighted, "BIM plays an important role concerning clash detection as it looks at interferences to be caught early." Company C (ID interviewee CDD) further stated, "we had regular meetings for design review at milestones like 30%, 50%, 70%, 80% and 100% of physical progress. We were always doing double-checking to verify clash detection between different packages, what were the discrepancies between steel structural design and MEP design and so on." While the companies emphasize significant improvements in quality and project performance by anticipating challenges, analyzing project accesses, escape routes, and interferences, two of them acknowledge that clash detection reports generate too many false alarms. Nonetheless, they recognize that this can happen when criteria are not set properly or when design errors are present, suggesting potential gaps in professionals' knowledge and expertise. The companies also observed that, despite their awareness that clash detection enhanced project visualization, and other BIM issues contribute to risk management, some professionals had not explicitly made this connection. They were unintentionally contributing to a phase of the risk management process. Following the interviews, the companies expressed their intention to create an action plan to better structure this process within the organization.

The companies also emphasized the reliability of material quantities extracted by BIM, leading to precise estimates. Company D (ID interviewee DVDC) asserted that "the model provides the enhanced data allowing the quantities extraction so that we can kind of create a real live cost estimate." Similarly, company C (ID interviewee CRPM) highlighted, "we were extracting the quantity take off from the BIM model; it was very accurate, it was much quicker. Every design stage, once we finish it in a week, we have a deal cue for it. We have quantities and the procurement team starts working right away on the prices, so it doesn't take that much time." Seyis [36] supports the importance of the BIM benefits in promoting accurate cost estimations, confirming budget appropriateness, and contributing to the overall success of the project.

A noteworthy finding of this research concerns the accurate BIM KPI's, presenting potential benefits in both technical and management aspects. Company D (ID interviewee DVDC) affirmed "we utilise clash counts, allocation, and also tract our trading partners for past experience as well. This enables us, when undertaking new projects, to negotiate more effectively based on their expectations or assess the need for additional supplementing support." The professionals also highlighted that the daily extract of interferences contributes to a better project and risk control. BIM further provides data feedback to the commercial department for more assertive proposals. As mentioned by Company A (ID interviewee ARM), "I could provide more assertive insights into the management area, where we offer feedback to the commercial team through productivity indexes. In the engineering area, there are initiatives to

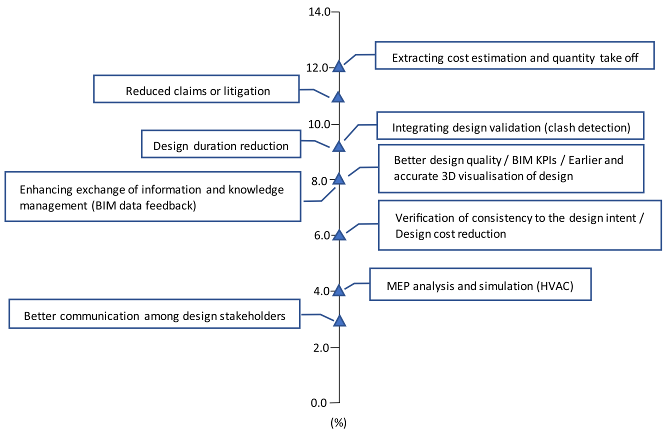

Fig. 3. Main BIM enablers indicated by the companies.

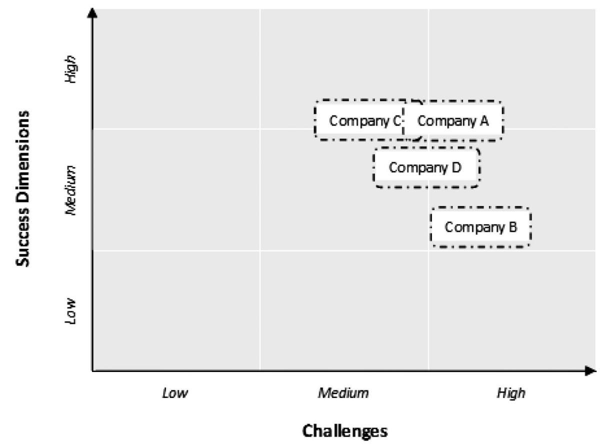

Fig. 4. Success dimensions x BIM challenges.

generate HH indexes by type of document and modelled elements, such as average hours for modelling a line within a model."

Similarly, the enhanced accuracy in project development yields the quantity of modelled elements, facilitating more effective resource allocation and team productivity data. Another significant improvement for project management is linked to the design physical progress. The use of BIM mitigates the subjectivity of progress information reported by designers and engineers, providing precision in measuring the physical progress of the project and in data for project management analysis. Notably, this indicator has not been extensively addressed in the existing literature. Research by Won and Lee [78] identified design errors detected by BIM, change in orders, response times of BIM issues, and schedule conformance as KPIs commonly employed in projects.

Fig. 3 illustrates the primary BIM enablers indicated by the interviewees who were guided by a selection list of the most cited enablers in the literature. The percentage was calculated according to the number of occurrences of each enabler indicated by respective professionals. It is crucial to recognize that these data were collected based on individual perceptions and may not necessarily reflect a formal position of the organizations.

D. BIM Challenges Influence on Project Success Dimensions

In a prior literature review on BIM challenges, a cross-tabulation was conducted [62] between the risks associated with BIM [67], and the dimensions of project success proposed by Carvalho and Rabechini Junior [33]. The findings highlighted that *project management efficiency* was the success dimension most frequently discussed in the literature. The analysis further revealed a close relationship between *project management efficiency* and the following challenges: *technological interface among programs*; *interoperability issues*; and *inadequate relevant knowledge or expertise*, respectively.

Similarly, when analyzing these findings in practice, empirical evidence indicated that the companies share the perception of *project management efficiency* as the most achieved success dimension. Professionals noted a correlation with the same challenges presented in the literature mentioned earlier. Notwithstanding, the companies also identified a strong connection with *lack of BIM protocols*, *cultural resistance*, *cost overrun in the design phase*, and *lack of professionals*; the latter not being listed in the table presented by [67]. Regarding BIM protocols, the lack of standardization of processes may lead to potential misalignment among stakeholders, as they may have differing interpretations of the BIM process [79]. As stated by Company C (ID interviewee CDD), "I would say that generally there is a lack of protocol in a lot of places that are implementing BIM and I think there is also one other problem which is the incompatibility of BIM protocols. So, we have a protocol that we are working with other companies, other stakeholders, and each of them has their own." This inconsistency in protocols can impede effective collaboration and hinder the seamless exchange of information, emphasizing the need for standardized protocols to facilitate smoother project implementation and coordination.

The interviewees also highlighted challenges related to cultural resistance which goes in the opposite direction to BIM implementation, as it necessitates a change in the traditional approach to project development. Additionally, professionals still face lack of skilled personnel, which has hindered BIM implementation.

Therefore, the findings suggested that, in practice, engineering firms have faced more challenges than indicated in the literature. Furthermore, organizations still have difficulties and face numerous barriers to achieving the benefits proposed by BIM. Table III outlines the challenges associated with project management efficiency as highlighted by the literature and by the companies. It also provides statements from professionals.

Fig. 4 provides a qualitative analysis where the "success dimensions" axis indicates the seven dimensions proposed by Carvalho and Rabechini Junior [33], while the *x*-axis represents the challenges related to BIM; both scales range from low to

TABLE III
CROSS-CASES ANALYSIS BETWEEN BIM CHALLENGES AND PROJECT MANAGEMENT EFFICIENCY HIGHLIGHTED BY THEORY AND PRACTICE

Success Dimensions	Challenges	Literature	Practice	Examples of statement
Project management efficiency	Technological interface among programs interoperability issues	✓	✓	"Look, per drawing, per sheet, I believe that we have gained at least one hour per sheet in the elaboration of the steel structure. If you imagine that you can, in a medium-sized project, have, I don't know, 200 sheets, that's 200 hours, more than a professional allocated for a full month. It's nothing to throw away. But the biggest difficulty we found in this implementation was to customize the tool so that the final product came out the way we understood that it was necessary for the project scope. The biggest difficulty is because the software itself, it is not 100% prepared to do the real-life project (ID interviewee AC1 - Company A) We were using first platform A and our risk was that they are not really compatible with every software in the market and they have very limited capabilities that updates take time to come out. So, this is why we shifted a year and a half to platform B. So, we do have bugs even now and things to report and so on. But I would say that the response time and the solutions we get them more quickly. (ID interviewee CDD - Company C)
	Inadequate relevant knowledge or expertise	✓	✓	"It is necessary to know the technology and be able to use it in the right manner that still progressing and getting better, but it's still not there. We are still relying on a designer's model which is not going to have the level of detail to do a thorough job of coordinating. So, there are still errors and omissions that come out of this process that is where you start getting some of that additional risk." (ID interviewee DVDC - Company D)
	Lack of BIM protocols		✓	"I would say that generally there is a lack of protocol in a lot of places that are implementing BIM and I think there is also one other problem which is the incompatibility of BIM protocols. So, we have a protocol that we are working with other companies, other stakeholders and each of them has their own protocol. Here comes the problem at the beginning of every project. How to align those protocols to reduce issues between stakeholders?" (ID interviewee CDD - Company C)
	Cultural resistance		✓	"Certainly. There is still a lot. Also, vendors have no interest in their tools talking to those of competing vendors, creating issues." (ID interviewee ACM - Company A) "We see that a lot on the design side, but we also see that you know within construction" (ID interviewee DVDC - Company D)
	Cost overrun with BIM		✓	"One of the risks that always runs with BIM is the costs associated with its implementation in the project. The software and the specific profile of people as well. Because it is a niche market so you want someone with that background is definitely a bit more costly. Even running all those updated courses, running certificates for the team, and so on. This is why we don't use BIM in all our projects. We still have a specific team and a specific size for projects for which we don't use BIM because it is not worth it. "(ID interviewee CDD - Company C) "It has negatively interfered with the project cost. Yeah, it's still more expensive by far. If I have to do the designs using BIM and working in that environment, it's more costly for us, compared to working on AutoCAD, on the design aspect." (ID interviewee BMEE - Company B)
	Lack of professionals		✓	"One of the main difficulty that we have it's more on the people knowledge. So, I need people being more knowledgeable and as the consequence we do the wrong set up or you know, it's so it's difficult to implement, because your key personal are so busy with their main project and because of that you need to hire some people, but you don't find it. There are limited specialized resources in the market." (ID interviewee BMEE - Company B)

high. The analysis was conducted based on the level of success categories achieved by the company: low (when the company still faces difficulties or has not yet achieved the success dimensions), medium (when the company has made some progress but is still developing strategies), and high (when the company has achieved success dimensions). Additionally, the level of challenges encountered in the implementation and use of BIM was measured as low (when the no significant challenges have been identified), medium (when the challenges have been identified, but the company has mitigating actions to eliminate or reduce it), and high (when the challenges have been identified, and the company is still developing mitigating actions). The interrelation between the success dimensions versus challenges reveals that some companies achieve better success dimensions facing fewer challenges, and others do not.

Company A and C share similar performance achievements; however, company A faces a higher level of challenges. Oppositely, company B does not show significant progress in project performance and indicates a high level of challenges. Company D reports a moderate level of success dimension and challenges.

Company B disclosed additional challenges in implementing BIM related to organizational bureaucratic issues. The adoption of BIM requires profound process changes among involved parties [80], leading to shifts in project, organizational, and professional boundaries [81]. The commitment of the organization and the development of planned processes significantly impact results. BIM adoption relies on a mutually constitutive relationship between user and the organization. In this relationship, the organization plays a central role in supporting, attending to, and enabling user-led change [2].

Furthermore, public policies have initiate efforts to promote the use of BIM through regulations and mandates leading to a trend where contractors increasingly demand its implementation. However, there exists a knowledge and training gap that needs to be addressed, given that the pace of demand surpasses the learning curve. It was not evident that cases already within the public regulatory environment expressed a higher concern regarding effective BIM adoption. It appears to be more a market-driven demand rather than a direct result of public policy initiatives.

V. Conclusion

Through the investigation of BIM enablers, challenges, and success dimensions related to BIM, this research makes significant contributions to both theory and practice, addressing the four proposed research questions (RQs).

First, the findings indicate that BIM adoption positively influences various success dimensions, particularly emphasizing project management efficiency, aligning with existing literature. Although prior research highlights sustainability as an emerging topic [82], the data suggest that its implementation is still in its early stages within the studied companies.

Second, the research investigated the challenges associated with the implementation and use of BIM. The identified challenges included inadequate professional knowledge or expertise and cost overrun, but also technology issues, cultural resistance, particularly in the design phase. The primary challenge identified was inadequate knowledge or expertise, with a notable emphasis on the lack of experience. Insufficient experience emerges as the most significant obstacle to BIM, leading to inefficiencies in the project delivery process, thereby contributing to cost overruns and time delays [36]. Although BIM adoption in organizations has increased, the proficiency of BIM users remains low, requiring extensive knowledge and specialized training over time. Furthermore, persistent challenges such as inadequate internet connectivity, particularly in field settings and projects involving numerous external team members, lead to difficulties with information updates and workflow. These identified challenges, not explicitly addressed in the literature, continue to impede BIM use and contribute to stagnant progress in its implementation. Consequently, the challenges identified in the design phase have practical implications, underscoring the need for companies to invest in professional training to enhance knowledge and develop the necessary expertise across all disciplines involved in the design process. This approach can help address the fragmented implementation of BIM due to varying levels of expertise and foster a more collaborative environment.

Third, the research identified the main BIM enablers in the design phase. Organizations emphasized precise and straightforward cost estimation and quantity take-off, risk reduction, better design verification (clash detection), design duration reduction, earlier and accurate visualization of design, better design quality, enhanced exchange of information, more accurate extraction of KPIs, accuracy and reliability of data, better MEP (mechanical, electrical, and plumbing) analysis, and better integration and communication among disciplines and stakeholders. This research finding advances both scholarly and practical understanding by demonstrating that the accuracy of data provided by BIM, through the integration of multidisciplinary information, enhances project management analysis. It offers greater project visibility and facilitates improved decision-making.

The literature suggests differences in BIM implementation challenges between developed and developing countries, particularly concerning cost and expertise [14], [21]. In developed countries, challenges are more related to high associated costs and the need for structured management methods and tools. In developing countries, challenges are more related to the lack of awareness, skills, expertise, and government support, as well as resistance to change. However, our research indicates that the main differences are more closely related to BIM maturity and company size rather than country differences. This finding suggests that further studies are needed to explore the contextual variables influencing BIM implementation.

In conclusion, professionals acknowledged the BIM challenges highlighted by the literature that influence project management efficiency: technological interface among programs, interoperability issues, inadequate relevant knowledge or expertise, lack of BIM protocols, cultural resistance, cost overrun in the design phase, and lack of capable professionals; the latter item is not presented by [67]. The findings suggest that, in practice, engineering firms face more challenges than those stated in the literature.

One limitation of this study stems from the methodological approach of the case study, which may restrict the generalizability of the findings due to the limited number of companies examined. Additionally, greater access to a larger number of experts, particularly in companies C and D, could have provided more in-depth insights into the difficulties and perceptions related to BIM.

Some companies, such as Company D, primarily support the design phase of engineering projects through design-build contracts, often subcontracting part of the scope or collaborating with design companies. This suggests that engaging suppliers and other related stakeholders could amplify the understanding of collaboration issues. Furthermore, there is a notable gap in the literature regarding the relationship between BIM enablers and risk management, which future research needs to address. The potential of BIM for addressing sustainability issues appears underused in practice, indicating a need for empirical studies in this domain. Future research could benefit from a comparative approach, examining the level of concern and BIM adoption in large versus small companies and companies at different levels of BIM maturity. Such studies would provide a more nuanced understanding of how organizational size and BIM maturity influence the implementation challenges and enablers of BIM, offering valuable insights for both academia and industry.

APPENDIX A
CODING BOOK EXAMPLE

Second-order codes	First-order codes	File	Reference	Example of Quotation
Organizational and Cultural Issues	R2.5-Cultural resistance	5	6	"The first cultural resistance comes from suppliers, as a rule, are not interested in their tools communicating with the tools of competing suppliers "Company A, ID ACE1".
	R2.19-Organizational issues	4	4	"We have organizational problems within large companies...in a large company like ours, you have to go through the IT department, but the IT specialists cannot be experts in every field "Company B, ID BMEE".
Professional and Knowledge issues	R2.4-Inadequate relevant knowledge or expertise	13	51	"You need to help people understand because there are three types of individuals: those born in the last 20 years who are naturally inclined towards innovation, those who have adapted to it as it emerged, and those who are just beginning to grasp it because they never had to use it before. So, to convey the rationale behind innovation effectively, knowledge needs to be robust "Company B, ID BOP".
	R2.13-Professional licensing issues	4	4	"Yeah, that's true, but it's like that for every software. It's not just related to BIM; it's a reality for any software we use "Company B, ID BMEE".
	R2.18-Lack of professionals	3	6	"Yeah, we had resources, but you know, they are still limited, I think it depends maybe on the specialty, I think in structural engineering, for example, it's much easier to find "Company B, ID BMEE".
Technological and Operational issues	R2.2-Technological interface among programs	9	19	"I joke here that, well, only with NASA's computer could you manage to coordinate. You don't have a software supplier that provides software for all disciplines, so you have to work around the fact that one software provider doesn't communicate with another " Company A, ID ACE1".
	R2.3-Interoperability issues	8	10	"Over the years, I believe we've managed to address some of the software's limitations. Early on, we established a process where we use the standard model or any available one, and fortunately, there's some compatibility, mainly with BIM 360 suite. We use Glue to integrate all the models, so we've sorted that out upfront by now" Company D, ID DVDC".
	R2.22-Internet connectivity	2	2	"One of the main risks I always consider is internet connectivity. Since our operations are not limited to one country, we depend on reliable internet speed and connectivity worldwide, which can be very challenging "Company D, ID DVDC"
Cost issues	R2.16-Cost overrun with BIM (design phase)	10	29	"I understand there is a consensus that they are the most advanced tools within the BIM universe, these tools, they are extremely expensive "Company A, ID ACE1"
	R2.17-Cost overrun with BIM (construction phase)	9	23	We now have BIM but it still makes the planning phase a little bit more costly not less costly. But it reduces the cost of the overall projects and our lower ones like any other, you know, spending more money in the planning phase "Company B, ID BMEE"
BIM specific issues	R2.1-Lack of BIM protocols	9	13	"I would say that generally, there's a lack of standard protocol in many places that are adopting BIM. Additionally, there's the issue of incompatible BIM protocols. We have our own protocol, but when working with other companies and stakeholders, each of them has their own "Company C, ID CDD".
	R2.12-Lack of a check mechanism for designs	7	10	"So yesterday I received a non-conformance report from the construction site regarding a steel structure mounted on top of a concrete structure, with columns higher than they should be. I thought, 'How could this happen?' However, upon closer inspection, I realized the there was an error where the column was buried in the model. This could have been visually or automatically detected, but it wasn't, in either way "Company A, ID ACE1".
	R2.20-BIM maturity	4	5	"Back then, working on a common data environment like BIM 360 was challenging for us. Coordinating data among all parties required a dedicated CPE manager to ensure data integrity and prevent conflicts. However, it was a valuable learning experience. Now, on multiple projects, we manage this process easily, but at the time, it was one of our main challenges "Company C, ID CDD".
	R2.21-Unclear BIM scope	3	3	"We face challenges in defining a clear scope. While we have an initial document outlining our BIM objectives, it is crucial to clearly define the scope for each individual involved. This is particularly important because multiple companies are working on the same project" Company C, ID CDD".
Design issues	R2.14-Uncertainty over design liability	6	6	"These trade partners might have ideas that could work, but they're not necessarily the ones responsible for approving or stamping the drawings. Ultimately, it needs to be signed off by the engineer of record. So, sometimes, this can create a bit of an issue "Company D, ID DVDC".
	R2.15-Changes in the BIM model by unauthorized parties	6	6	"In the XXX project, to streamline the overall process of the venture, we should provide the electronic model to a third party, so that they could access our model and perform the pipeline breaks on the spools for fabrication, okay? "Company A, ID ARM".
Data issues	R2.8-Low quality of BIM data	6	6	"Garbage in, garbage out. It's a real struggle. If you don't manage data properly, it can cause significant issues. Even with partners, a single individual setting up the model incorrectly can lead to wasted time and information loss. There's a risk because we're all interconnected. I've heard many stories of people spending days redoing work due to inadequate system setups "Company B, ID BMEE".
	R2.6-Unclear ownership of the BIM data	5	5	"It was well organized. The piping, mechanical, and civil aspects were all clearly defined. We didn't have any issues with BIM data "Company A, ID ACE2".
	R2.7-Data security	4	4	"There is also a risk with data security, of course. Honestly, I would argue that sometimes this risk is overstated, ... we always discuss data security, not only with BIM but also in planning. Nowadays, with data stored in the cloud and other platforms "Company C, ID CDD".
Information and Communication Issues	R2.10-Poor communication among project participants	8	10	"I'm collaborating with different firms for structure, civil work, and the client and architect are also from separate firms. Communication issues arise not only with these external companies but also internally within our team. For instance, when the architect makes decisions, the BIM manager reacts, but the project manager doesn't grasp the decision's impact. This lack of internal alignment is our main challenge "Company B, ID BMEE".
	R2.11-Lack of collaboration among project participants	8	8	"It's about the level of input from trade partners. So, if specialty contractors work in isolation without considering all factors, it can lead to problems because they may overlook important aspects "Company D, ID DVDC".
	R2.9-Reluctance to share information	5	5	"Information sharing has seen notable improvement in recent times "Company D, ID DPM".

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