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BIM and risk management interface in the design phase: a multi-method approach

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ABSTRACT

Silva, T. F. L. (2021). BIM and risk management interface in the design phase: a multi-method approach (Doctoral Thesis). Civil Engineering Department. Polytechnic School, University of Sao Paulo, Sao Paulo.

The effective use of BIM in the design phase generates countless benefits, including contributions to enhance risk management. However, its adoption generates risks, and a better understanding of the critical success factors (CSFs) is essential for improving BIM implementation from the early design stage. The general objective of this thesis is to investigate the relationship between the BIM CSFs in the design phase and risk management. This thesis follows the model for scientific articles, and it consists of four articles. The thesis applies a qualitative and quantitative multi-methods research approach and is carried out through an exploratory and a confirmatory stage. The results indicate that BIM CSFs of the design phase have a positive impact on risk management, suggesting when effectively implemented, BIM can reduce threats and create opportunities during design development. Moreover, this thesis contributes to an important gap in the literature by investigating the relationship between risk management and BIM. In addition, to meet the challenges presented so far in BIM adoption, the research also contributes to identifying the CSFs of the design phase. For practice, results show that risk management is still not effective in engineering projects. Besides, it indicates that lack of knowledge or expertise in risk management, BIM, or both processes was the main barrier identified, revealing the need for better professional training.

Keywords: Risk management. Building information modeling. Design phase. Critical Success factors.

RESUMO

Silva, T. F. L. (2022). Interface entre BIM e gestão de riscos na fase de projeto: uma abordagem multimétodo (Tese de Doutorado). Departamento de Engenharia Civil. Escola Politécnica, Universidade de São Paulo, São Paulo.

O uso efetivo do BIM na fase de projeto gera inúmeros benefícios, incluindo contribuições para melhorar a gestão de riscos. Entretanto, sua adoção gera riscos, e uma melhor compreensão dos fatores críticos de sucesso (FCSs) é essencial para melhorar a implementação do BIM desde a fase inicial de projeto. Esta pesquisa teve como objetivo principal investigar a relação entre os FCSs do BIM na fase de projeto e a gestão de riscos. Esta tese segue o modelo para artigos científicos, e é composta de quatro artigos. A tese aplica uma abordagem de pesquisa qualitativa e quantitativa multimétodo e é realizada por meio de uma fase exploratória e uma fase confirmatória. Os resultados indicam que os FCSs do BIM da fase de projeto têm um impacto positivo na gestão de riscos, sugerindo que, quando efetivamente implementado, o BIM pode reduzir as ameaças e criar oportunidades durante o desenvolvimento do projeto. Além disso, esta tese contribui para uma importante lacuna na literatura, investigando a relação entre a gestão de riscos e o BIM. De forma a atender os desafios ainda presentes na adoção do BIM, a pesquisa também contribui na identificação dos FCSs da fase de projeto. Para a prática, os resultados mostram que a gestão de risco ainda não é eficaz em projetos de engenharia. Além disso, indica que a falta de conhecimento ou experiência em gestão de riscos, BIM ou ambos foi a principal barreira identificada, revelando a necessidade de um melhor treinamento profissional.

Palavras-chave: Gestão de riscos. Modelagem da informação da construção. Fase de projeto. Fatores críticos de sucesso.

LIST OF FIGURES

LIST OF ARTICLES IN THIS PhD THESIS

Article 1

Silva, T.F.L., Arrotéia, A.V., Vieira, D.R., Melhado, S.B., Carvalho, M.M. (2021). Exploring the influence of risks in BIM implementation: a review exploring BIM critical success factors and BIM implementation phases. Journal of Modern Project Management, vol. 8, No 3. 124-135.

Article 2

Silva, T.F.L., Vieira, D.R., Melhado, S.B., Carvalho, M.M. (2019). Risk and uncertainty in engineering projects: a survey with professionals. Journal of Modern Project Management, vol. 7, No 1, 200-213.

Article 3

Silva, T.F.L., Carvalho, M.M. Vieira, D.R. Building Information Modeling and its effects on project success and risk management: exploring a cross-country case studies. Ready to submit.

Article 4

Silva, T.F.L., Carvalho, M.M. Vieira, D.R. BIM critical success factors in the design phase and Risk Management: exploring the mediating effect on knowledge and maturity. Submitted at Journal of Construction Engineering and Management.

LIST OF ABBREVIATIONS

BIM – Building information modeling

AEC – Architecture, engineering, and construction

RM – Risk management

CSFs – Critical success factors

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PART 1 – INTEGRATIVE THESIS OVERVIEW

1 INTRODUCTION

The roles and contributions of risk management (RM) within organisations have evolved and grown, since the mid-90s, when companies recognized the need to integrate risk with schedule, cost and quality (Kezner 2003). Because of challenges that impact supply chains, assets, earnings and operations, more enterprises have recognized the importance and value of enterprise-wide RM (Khameneh et al. 2016), since RM improves performance, encourages innovation and supports the achievement of the company’s objectives (ISO 2018).

Risk assessments are effectively established in the existence of appropriate data and clearly defined boundaries for their use. Statistical and probabilistic tools have been developed and provide decision support for risks responses. However, many risk decisions are defined by numerous uncertainties, which lead to challenges and improvements for an effective risk assessment (Aven 2016).

The distinction between risk and uncertainty is related to the probabilities of occurrence, risks can be known, whereas uncertainties cannot. Rodney et al (2015) state that the current project management tools insist on the description and optimization of a fully known and controlled project situation, ignoring the notion of uncertainty and, therefore, risk. Organisational managers must make decisions in an uncertain environment, and RM as a discipline explicitly takes account of uncertainty and establishes how it can be addressed (Chapman 2016).

As the construction industry faces a lot of challenges, the related techniques are rapidly changing, and risk factors are becoming increasingly diverse. Thus, it is necessary to consider risks that may occur during a project prior to its execution (Park et al. 2016). Therefore, properly identifying and assigning management responsibility and accountability for risk to ensure proper management for the successful delivery of projects is essential (Aghimien et al. 2021).

RM is still rarely applied in practice, presenting limitations for large and complex projects, which need more attention and effective management (Carvalho et al. 2015). The success of a project, if considered time, cost, and quality requirements, depends on large scale on how the project management deals with its risks (Silva 2014). Moreover, failure in identifying risks at an early stage may lead to unawareness and serious consequences (Zou et al. 2019).

The design phase is one of the most critical phases of the construction process, since decisions made during this phase affect the project performance throughout its life cycle. Moreover, the design process is subject to a number of risks that affect project performance (Othman and Alamoudy 2020).

Considering that uncertainty and risk are inevitable in engineering projects, and that their complexity and the new technology involved are likely to give rise to more risks (Vaz-Serra et al. 2021), the risks should be managed, minimized, accepted, shared and transferred, but should not be ignored (Ahmad et al. 2018a). Therefore, through proactive management in the design phase, risks could be eliminated or reduced before they are present on the construction site (Jin et al. 2019).

Few publications have presented a clear understanding of how to conduct a specific risk assessment method in practice (Aven 2016). It appears that even though project managers might be aware that the risk management process exists, they fail to implement these practices (Olechowski et al. 2016). RM comes with a lot of benefits when undertaken effectively; however, companies still do not see the need to implement it, due to insufficient knowledge, lack of integration with the organisation's project methodology and lack of effective risk identification (Amoah and Pretorius 2020). Therefore, the first question emerges regarding the level of knowledge and adoption of risk management in practice.

RQ1: Are project managers and team members proficient in risk management methods, tools, and practices?

Concerning risk identification, many techniques require deep knowledge of previous projects and rely on retrospective analysis by subject matter experts. The development of more predictive risk identification techniques could provide better insight to project managers, particularly if likely risks can be identified in early design phase (Yim et al. 2015). According to ISO 31000(2018), there are several techniques for identifying, analysing, and evaluating projects risks. Although ISO 31010 (2021) describes the advantages and disadvantages of the different techniques at each stage of the risk management process, Zou et al. (2017) affirm that traditional RM techniques can produce decreased efficiency results due to knowledge and experience based on intuition for decision making alongside manual assessment. Moreover, risk analyses are still performed manually, leading to a need for automation improvement towards a better performance of risk management (Ahmad et al. 2018b).

In response to these problems, there is a research trend on the use of Building Information Modeling (BIM) to assist early identification and assessment of risks (Lin et al. 2017; Zou et al. 2016a). BIM is defined by Succar (2009) as “a set of interacting policies, processes and technologies producing a methodology to manage the essential building design and project data in digital format throughout the building's life-cycle.” The rapid advancement of information and communication technologies has promoted the emergence of BIM, which allows the creation of object-based multidimensional parametric models as a tool for construction project management during the whole life cycle (Tomek and Matějka 2014).

BIM has been developing globally, and governments are proposing guidance and policies for its implementation (Lee and Yu 2020). The General Services of Administration (GSA) established a BIM program in the USA in 2003. It was the first government organisation to lead the US Government into BIM (Wong et al. 2011). In 2011 Malaysia received a mandate from the government to lead BIM implementation (Zulkefli et al. 2020). The Australian government pushed BIM adoption in 2012 by an initiative called building SMART Australasia (Hong et al. 2018). The Chinese government published, in 2015, a set of national standards and regulations related to BIM implementation (Chang et al. 2017). Since 2016, as a construction strategy, the UK government has been requiring fully collaborative 3D BIM capabilities in construction projects (Lam et al. 2017a). Brazil follows this trend, with the implementation being mainly driven by the Federal Government’s CG BIM strategy through a decree published in 2019.

Through early and proper involvement in projects, BIM enhances project performance and reduces issues by offering advantages of its features related to risk identification. According to Eastman et al. (2011), BIM can create opportunities of threat reduction for the project and also for the client. The 3D visualisation can facilitate early risk identification; the clash detection can identify conflicts in the model; and interoperability can reduce information loss of data exchange (Zou et al. 2017).

BIM has brought progress and value to the construction industry (Sun et al. 2020). Planning the tasks and responsibilities in a timely manner, promoting collaboration and coordination in the early design phase, and decreasing uncertainties by clarifying risks were the top-ranked BIM benefits in terms of time, cost and sustainability indicated by Seyis (2019).

Nevertheless, BIM presents different issues, difficulties, and risks in its implementation (Xu et al. 2018). Moreover, with BIM advancement, integration with drones, augmented reality, and the internet of things drives the digital information of the built environment (Liu et al. 2021a) and provides a positive impact on business; however, it also brings technological and organisational challenges (Morgan 2019). Indeed, BIM implementation also depends on the maturity level of the organization, which is referred by Succar (2010) to the quality, repeatability and degrees of excellence in delivering a BIM-enabled service or product.

Countering the potential benefits of BIM to projects are the barriers that need to be overcome if effective multi-disciplinary collaborative team working is to be achieved (Bryde et al. 2013). Papadonikolaki et al. (2019) complement that a need for process changes challenges how BIM is applied by engineers, architects, clients, contractors, and suppliers, due to a lack of education and training. Regardless of the significance of new risks introduced by BIM, a proactive approach is needed to further enhance its value proposal (Ahmad et al. 2018a). Thus, the second research question of the thesis is presented below.

RQ2: Which are the main BIM-related risks in practice?

Concerning BIM issues, a better understanding of the critical success factors (CSFs) is necessary to organize strategies for its implementation (Ozorhon and Karahan 2017). According to Rockart (1982), CSFs could be defined as key factors for a project to succeed. Moreover, CSFs are the most significant factors to increase project performance and assure success for construction projects (Babu and Sudhakar 2015). Within the context of risk management, CSFs can also be drivers for successful risk assessment and management practices (Chileshe and Kikwasi 2014). These factors may not be directly measured but can be discussed or analyzed (Badrinath and Hsieh 2019). Liao and Teo (2017) reported several studies that described CSFs that could affect BIM implementation, but few have investigated the interrelationship among these factors. Indeed, the relative importance of CSFs should be investigated considering the different phases of the project life cycle, such as in the design phase. Thus, the third and fourth research questions are presented below.

RQ3: Which are the main BIM CSFs in the design phase in practice?

RQ4: How do BIM CSFs in the design phase influence the RM process?

Therefore, it is fundamental to understand these factors in the design phase, since the decisions made at this time of the project are those that have the highest ability to influence the successive phases (Hossain et al. 2018).

1.1 Justification

In a project management environment, the RM activity seems to be straightforward. Managing risks on engineering projects is a process that includes risk assessment and a mitigation strategy for those risks. Risk assessment includes both the identification and evaluation of risk issues (Kezner 2003). A risk mitigation plan is designed to eliminate or minimize the impact of the risk events occurrences that have a negative impact on the project (Firmenich 2017).

In engineering projects of different countries, regardless of their location, practitioners must deal with risk mitigation. Despite the extensive literature regarding project risk management process and its positive impact on project performance, most professionals do not consider risk as a critical aspect of a project and; therefore, they do not see the need to undertake risk management (Amoah and Pretorius 2020). Furthermore, RM in construction projects has been applied using a reductionist approach that produces poor results, limiting quality and project performance (Serpella et al. 2014).

Through advances in computer technology and the availability of simulation software, various methods of quantitative risk analysis have been developed; however, there are many gaps in the strategies provided by researches to analyse risks (Osama et al. 2021). The challenge regarding the implementation of RM mainly relates to the organisation characteristics, the process of RM and the people involved. The latter is associated with knowledge and experience of the key players as an initial barrier for RM implementation (Rostami et al. 2015).

Moreover, the design process is subject to a number of risks that affect building performance throughout its life cycle (Othman and Alamoudy 2020), and the project's performance could be improved if fragmentation, risks and uncertainties associated with the design phase are addressed properly before moving forward with the construction phase (Alamoudy et al. 2019).

The development and growing use of BIM in construction are bringing new opportunities to improve RM; nevertheless, to date risk management has not been incorporated into major BIM platforms and case studies are still very rare in the literature (Zou et al. 2019). Additionally, BIM projects may involve new challenges and risk factors, leading to a more complex RM (Chien et al. 2014b). Despite the initiatives already developed to integrate BIM and RM in engineering projects, this relation still presents gaps (Ahmad et al. 2018b).

Another point that still needs to be studied is critical success factors, in order to meet the challenges so far present in BIM implementation and take advantage of the benefits that it may provide to RM. Previous studies aimed at identifying CSFs to organisations and project success (Antwi-Afari et al. 2018; Chan et al. 2019; Evans et al. 2021; Liu et al. 2021b; Morlhon et al. 2014; Poirier et al. 2017); nonetheless, there is a lack of studies related to CSFs for BIM adoption at the design phase. It is worth exploring it due to the importance of the design phase in the context of engineering projects. Studies and results in practice show that the design phase plays a significant role delivering successful projects (Othman and Alamoudy 2020).

The lack of effective risk management, still widely practiced in engineering, directly interferes with project performance, and the construction industry tends to look for alternatives that bring advances and better projects results. Therefore, BIM adoption may improve risk analysis in the design phase leading to new perspectives to RM. The gaps identified in the literature indicate the need for complementary empirical research on the relationship between BIM and RM (Ahmad et al. 2018b; Ganbat et al. 2019; Zhao et al. 2018; Zou et al. 2017) in the design phase (Badran et al. 2020; Othman and Alamoudy 2020).

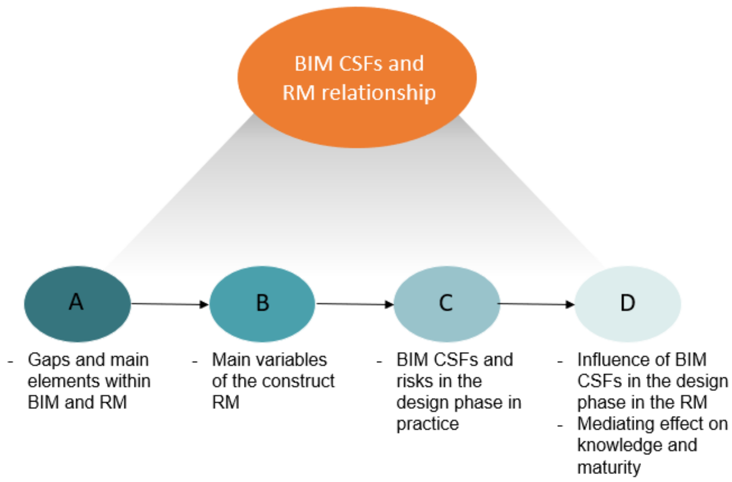
1.2 Research objectives

For the context and the problem presented, the general objective of this thesis is to develop a research model related to BIM CSFs and risk management relationship in the design phase of engineering projects. Linked to the general objective, the thesis' specific objectives were also defined:

A. Identify the gaps and the main elements within the relationship between BIM and RM.
B. Identify the main variables of the construct risk management.
C. Identify the main risks and BIM CSFs in the design phase in practice.
D. Investigate the influence of BIM CSFs in the design phase in the RM, exploring the mediating effect on knowledge and maturity.

Concerning the first specific objective, many constructs have been used over time in studies; for this reason, a literature review is adequate to the proposed objective. Then, the second and third specific objectives involve an exploratory survey and case studies. Finally, the fourth specific objective is related to the definition of the theoretical model, identifying the indicators to evaluate each construct. Then, a test and validation of the model will be conducted through empirical research with a quantitative approach, using the survey method. The general and specific objectives are presented in figure 1.

Figure 1 - General and specific objectives

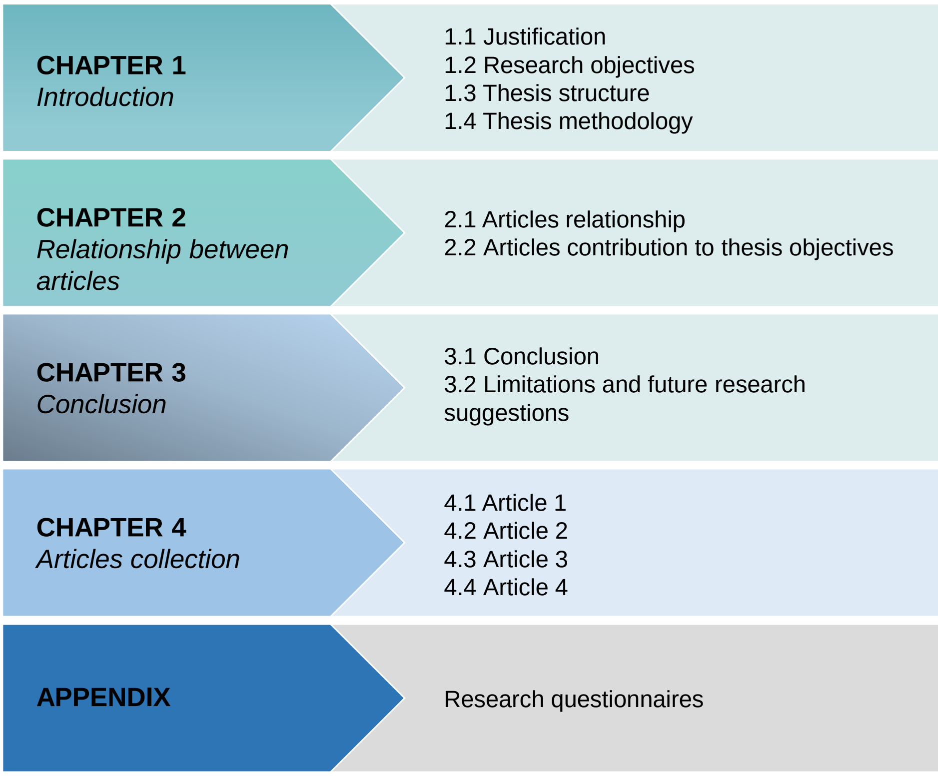


Source: Author

1.3 Thesis structure

This thesis was designed as article-based, and it was separated into two parts. Part 1 is an integrative overview of the four articles, and it is composed of three sections. Section 1 brings the introduction, presenting the context of the research and concepts concerning RM and BIM. Indeed, this section also presents the main objective and specific objectives. Following, section 2 describes the relationship between the four articles and how each article answers the specific objectives of the thesis. The last section, section 3, presents the thesis conclusion. Then, Part 2 is presented the thesis' articles. Figure 2 shows the structure of the thesis.

Figure 2 - Thesis structure



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1.4 Thesis Methodology

This study followed a qualitative and quantitative multi-methods research design and was carried out through an exploratory and a confirmatory stage. The aim of the first, exploratory stage, is to identify study constructs and establish the research model and the exploratory has the purpose to validate it. According to Creswell (2014) qualitative research has the objective to explore and understand social problems through data collect, analysis and data interpretation. On the other hand, quantitative research is an approach for testing objective theories by examining the relationship among variables.

A mixed method designs provide a better understanding of research issues than either qualitative or quantitative approaches alone. Venkatesh et al. (2013) indicates that a mixed research method can propose a complementarity obtaining mutual viewpoints regarding similar experiences, ensure a total completeness, clarify on the knowledge gained from a prior method, evaluate the trustworthiness of inferences gained from one method and obtain opposing viewpoints of the same experiences or associations.

However, Wisdom and Creswell (2013) affirm that it is challenging to implement it and there are some limitations such as: increases the complexity of evaluations, relies on a multidisciplinary team of researchers and requires increased resources. Facing the challenges, the mixed methods can potentially enhance study validity beyond quantitative or qualitative research studies, provide greater insights and defy researchers through divergent findings encouraging them to alter research questions and hypotheses (Caruth 2013).

The choice of multi-methods research allows a more complete and synergistic utilization of data than do separate quantitative and qualitative data collection and analysis. For the present research this is considered the most coherent methodological approach for the development of this study considering the varied forms of data collection (statistic data, bibliographic research, interviews and documents analysis). The diversity of data can provide a more complete results and conclusions to the research problem proposed.

The thesis was developed into three phases; the first was the literature review; the second phase was exploratory research with a survey and case studies with four companies, and finally, in the third confirmatory phase a survey and the thesis theoretical model were developed and tested. Each phase resulted in an article, except phase 2 in which two articles were developed. Concerning publications, two articles were published (articles 1 and 2), one was submitted (article 4), and one is ready to be submitted (article 3). The articles answer both thesis objectives, general and specifics.

The research phases, methods and main aims are summarized in Figure 3.

Figure 3 - Research phases

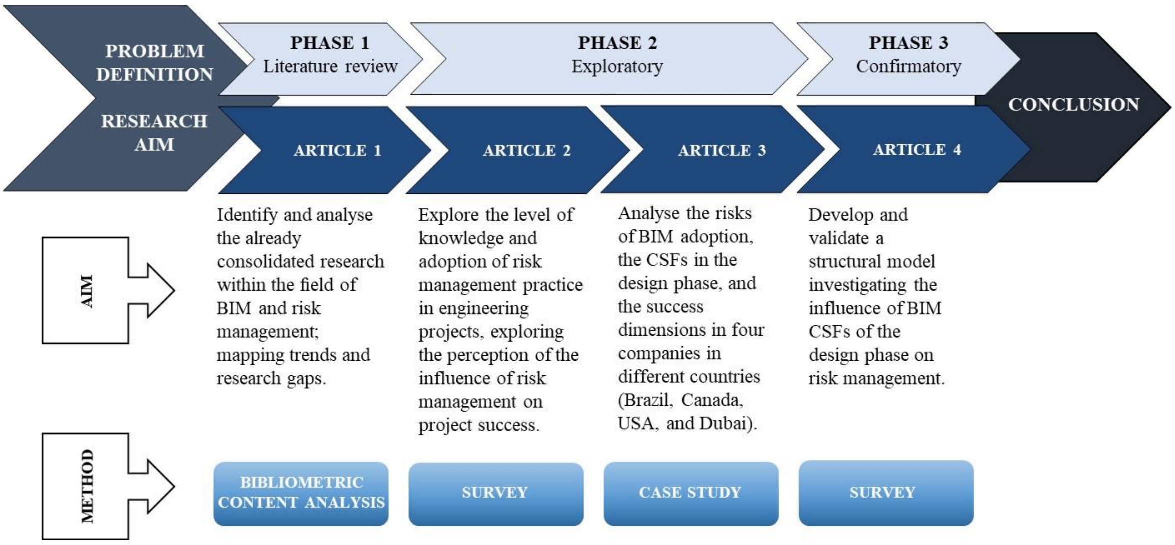

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Figure 4 presents the details of the four articles according to the objectives and research methods adopted.

Figure 4 - Articles by research method, research phase, research question and contribution to the specific's objectives

Article	Article title	Specific objectives	Research method	Research phase	Research question
#1	Exploring the Influence of Risks in BIM Implementation: A Review Exploring BIM Critical Success Factors and BIM Implementation Phases	A	Literature review	1	--
#2	Risk and uncertainty in engineering projects: a survey with professionals	B	Survey	2	RQ1
#3	Building Information Modeling and its effects on Project Success and Risk Management: Exploring a Cross-country Case Studies	C	Case study	2	RQ2 / RQ3
#4	BIM critical success factors in the design phase and Risk Management: exploring the mediating effect on knowledge and maturity	D	Survey	3	RQ3 / RQ4

Source: Author

2 RELATIONSHIP BETWEEN ARTICLES

2.1 Articles relationship

BIM development and its increasing use are bringing new opportunities to improve risk management (Zou et al. 2019) and project success (Olawumi and Chan 2019a) ; however, BIM and RM approaches are considered in progress so far in engineering practice (Amoah and Pretorius 2020; Ganbat et al. 2020). To achieve the benefits of this relationship, it is necessary to understand the difficulties and gaps that remain in practice. Although BIM provides favorable circumstances for RM, its adoption introduces risks that need to be identified to optimise project success through integration between RM and BIM (Othman and Alamoudy 2020).

This proactive approach comes in the form of ‘BIM-based risk management’, which is an emerging process in the construction industry with a several new openings for further development (Ahmad et al. 2018b). The relevance of both topics in the project environment motivated this thesis. To explore and understand the main aspects related to these themes, a systematic literature review, applying bibliometric and content analysis, was adopted originating **Article 1**.

For the bibliometrics, article 1 carries out the publication analysis through the most published journals and keywords network. Its content analysis indicates, through cross-analyses, the risks that influence project success dimensions (represented by (i) in figure 5), particularly with *Project Efficiency* (i’) (Carvalho and Rabechini Junior 2015), and the CSFs of the design phase (ii), which are recognized by the literature effective in identifying and mitigating risks in the early stages of the project (Jin et al. 2019). It was clear that, although researchers relate BIM to RM, the literature lacks empirical studies to clarify the relationship between them, especially in the design phase.

Article 1 also identifies the main risks related to BIM adoption (iii). The study reveals that issues regarding technology, experience, and knowledge produce the most significant risks in the use of BIM. In addition, the finding related to the risk *inadequate knowledge or expertise* (iii’) introduced an interest regarding risk management adoption in practice, motivating the elaboration of **Article 2**. This first article provides elements for the elaboration of articles 2, 3, and 4.

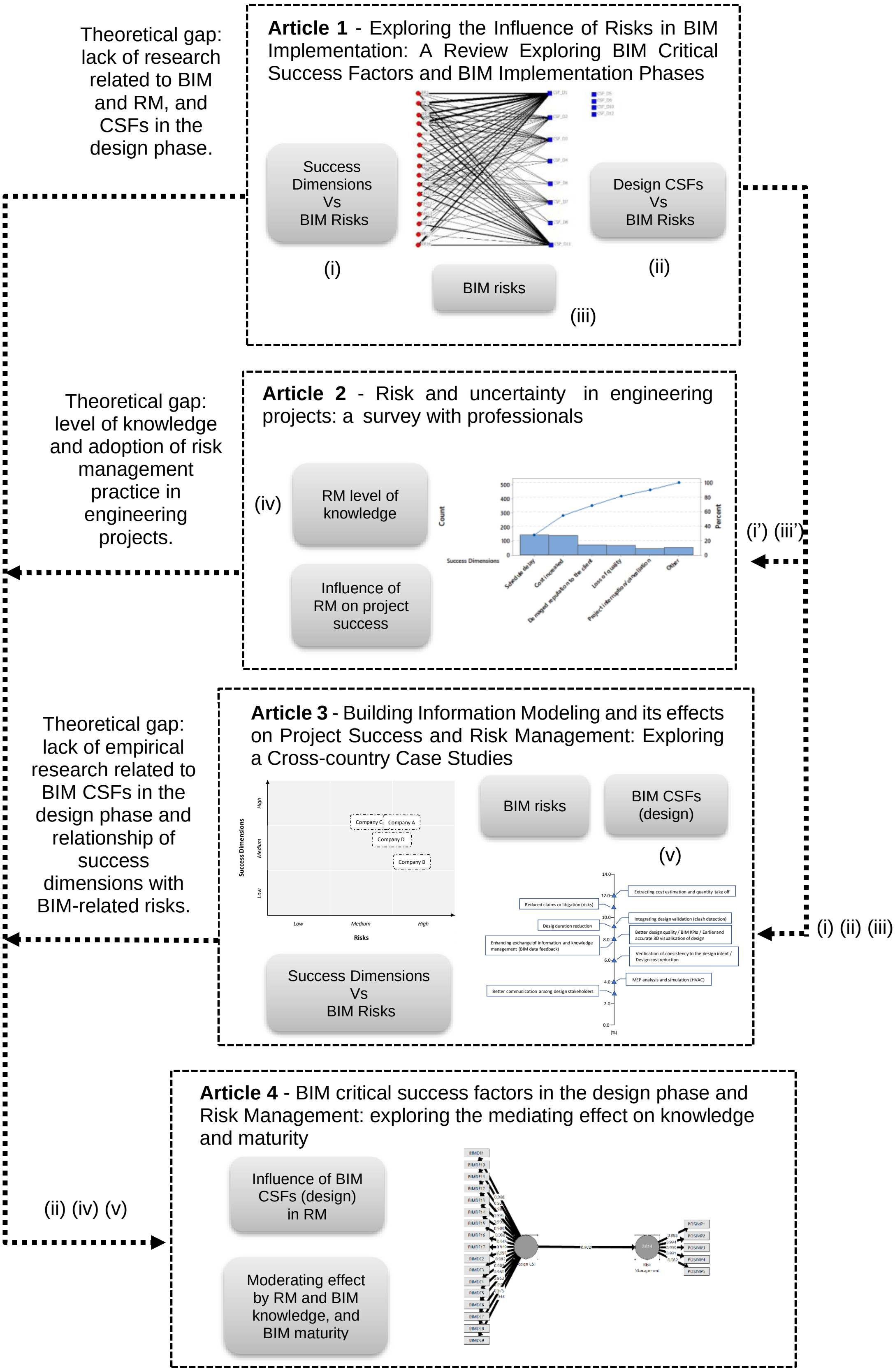
Despite RM importance and extensive theory, article 2 reveals a deficit concerning its adoption in practice in engineering projects. Even though project managers might be aware that RM process exist, they are poorly adopted (Olechowski et al. 2016). To better understand the failures in its application, article 2 explores, through survey research, the level of knowledge and adoption of RM in practice. Besides, it presents professionals' perceptions of RM influence on project success.

Article 3 aims to explore, in practice, the constructs identified in article 1 (success dimensions, CSFs of the design phase and BIM risks) and identify others through the twenty-three (23) semi-structured interviews in four (4) companies from different countries. The objective was to assess practitioners' perceptions and practice in different cultures and professional environments. Moreover, it aims to verify the similarities and differences presented by the theoretical study. Most results corroborate with the literature; however, the research indicates that in practice engineering firms have faced more risks than stated by the literature to achieve project success, indeed. As a further contribution, professionals indicated that accuracy data provided by BIM offers an improvement for project management analysis. In this sense, articles 2 and 3 fulfil the exploratory role of the elements that built the theoretical model of the thesis.

Article 4 presents the confirmatory theoretical model that receives elements from articles 1, 2, and 3. Articles 1 and 3 contribute to the relation between CSFs of the design phase (i) and RM. Article 2 provides the influence of RM knowledge (iv). The other two constructs considered in article 4 (BIM knowledge and BIM maturity level) were based in both the literature review and the case studies research; however, they are not explored in articles 1 and 3. The data is collected via online survey-based research through engineering, construction, and architectural professionals in different countries. In this confirmatory phase, the theoretical model was tested and validated.

In summary, the theoretical model of the thesis aims to analyse the influence of BIM CSFs in the design phase in RM. The literature suggests a potential positive impact; however, there is a lack of quantitative research validating these assumptions. Moreover, article 4 also explores the mediating effect on knowledge and maturity. Figure 5 represents the relation between articles.

Figure 5 - Representation of the relationship between articles



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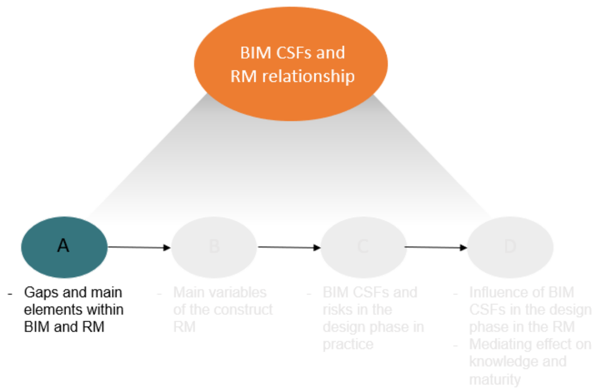
2.2 Articles contribution to the thesis objectives

The specific objective “A” (figure 6) is answered by article 1. It initially begins with a literature review, where it was possible to identify constructs related to BIM and RM. As result, the keywords *risk* and *performance* were grouped in the same cluster; however, they did not belong to any BIM name variation cluster, resulting in a gap between these themes. Moreover, this article identifies the relation between RM and BIM as emerging topic due a lack of research in the literature, while *construction safety* is a research area recognized as a growing topic.

Figure 6 - Specific objective “A” achieved by article 1



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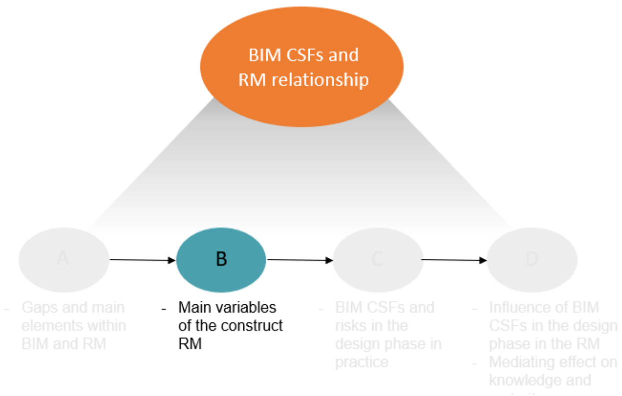
The contribution of article 1 comes from identifying *project management efficiency* as the success dimension most frequently discussed in the literature and the main risks related to BIM adoption, highlighting *technological interface among programs, inadequate relevant knowledge or expertise* and *interoperability issues*. The literature explored convergences in the identification of a positive relation between the CSFs in the design phase and the risks associated with BIM. This cross-analysis indicates that the link between *earlier and accurate 3D visualisation of design* and *reduced claims or litigation* with the same risks (*interface among programs, inadequate relevant knowledge or expertise* and *interoperability issues*) is the most discussed in the literature. Another cross-analysis between BIM risks vs. success dimensions indicates these same risks as the most frequently mentioned.

Article 2 meets the specific objective "B" (figure 7). It presents the level of knowledge and adoption of RM practice in engineering projects. It also aims at exploring the perception of the influence of RM on project success. The results show that most professionals have never worked with RM. Furthermore, there is an interesting finding indicating that professionals have experienced situations in which many risks were not previously identified, suggesting a lack of or ineffective RM in practice.

Moreover, according to article 2, professionals recognize that the risks generated by project management failures are very significant and when underestimated or not considered are the main responsible for negatively affecting the project results. Considering this unsatisfactory results in the projects, the main consequences indicated by practitioners were *schedule delay* and *cost increased*, followed by *damaged reputation to the client*, *loss of quality*, *interruption/cancellation*, *social or environmental impact*, and *scope change*, respectively. This result suggest that the *iron triangle* (schedule, cost, and quality) are still the most representative critical factors of project success.

Figure 7 - Specific objective "B" achieved by article 2



Source: Author

The specific objective "C" is answered by article 3 (figure 8). In this article, the cross-analysis between BIM risks and success dimensions is also further explored. It states that BIM adoption presents a positive impact on the various dimensions of success, highlighting the *project management efficiency*, which corroborates with the literature; nevertheless, the companies indicated that safety and social topics are still limited in practice, which differs from the previous study. Despite the organisations' presented initiatives and strategies, they recognized that there are a lot of challenges to having BIM support in sustainability approaches.

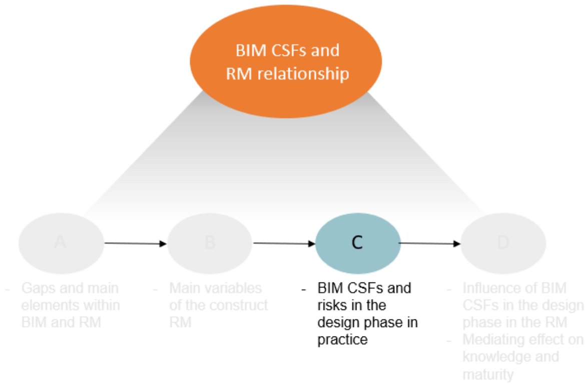
The professionals recognized the risks pointed out by literature that influences this success dimension, such as: technological interface among programs, interoperability issues, inadequate relevant knowledge or expertise, lack of BIM protocols, cultural resistance and cost overrun in the design phase. Lack of professionals is also a risk mentioned by the companies; however, it was not emphasized by the literature.

Moreover, *inadequate knowledge or expertise* is indicated by the professionals as the top-ranked risk involved in the implementation and use of BIM, as likewise by the literature, followed by *cost overrun* (mainly in the design phase), and *technology issues*, respectively. Previous literature results did not highlighted *cost overrun*; spite of BIM adoption requires the cost of staff training, skilled team, and technological infrastructure. Besides, a less qualified hardware or unlicensed software may cause damages in the project's files losing data (Othman and Alamoudy 2020). As a result of that, article 3 points out that some companies do not adopt BIM in all projects, in which it is not a contract request.

Article 3 also identifies the main BIM CSFs in the design phase, highlighting a *precise and straightforward cost estimation and quantity take off*, *reduction of risks*, a *better design verification (clash detection)*, *design duration reduction*, *an earlier and accurate visualisation of design*, *better design quality*, *enhanced exchange of information*, *extract more accurate key performance indicators (KPIs), accuracy and reliability of data, better MEP (mechanical, electrical, and plumbing) analysis*, and *better integration and communication among disciplines and stakeholders*. As a contribution to practice, this research identifies that *accuracy data provided by BIM* offers an improvement for project management analysis. It provides more effective resource allocation and team productivity. Moreover, it decreases the subjectivity of progress information reported by designers and engineers, providing a better accuracy related to the project's physical progress and forecast.

Furthermore, article 3 suggests that an effective BIM adoption may not be related to BIM government decrees or regulations. Results regarding four companies of different countries reveal that the major influence comes more from growing market demand than effectively from public policy.

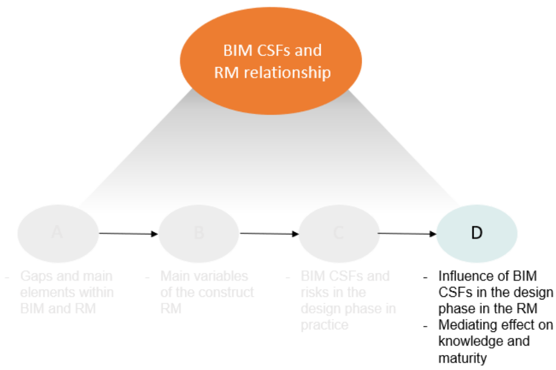
Figure 8 - Specific objective “C” achieved by article 3



Source: Author

Articles 1, 2 and 3 add important contribution to article 4, which meets the specific objective “D” (figure 8). First, it must be said that exploring the literature to elaborate article 1, previous researches have focused on providing an overview of the CSFs; however, these studies failed to provide them separately in the phases of the project life cycle and they do not offer an in-depth understanding of the CSFs in the design phase. Article 4 aims to contribute to fulfilling this gap by investigating the relationship between the BIM CSFs of the design phase (Design CSFs) and RM, exploring the mediating effect played by BIM knowledge, risk management knowledge (RM knowledge), and BIM maturity level.

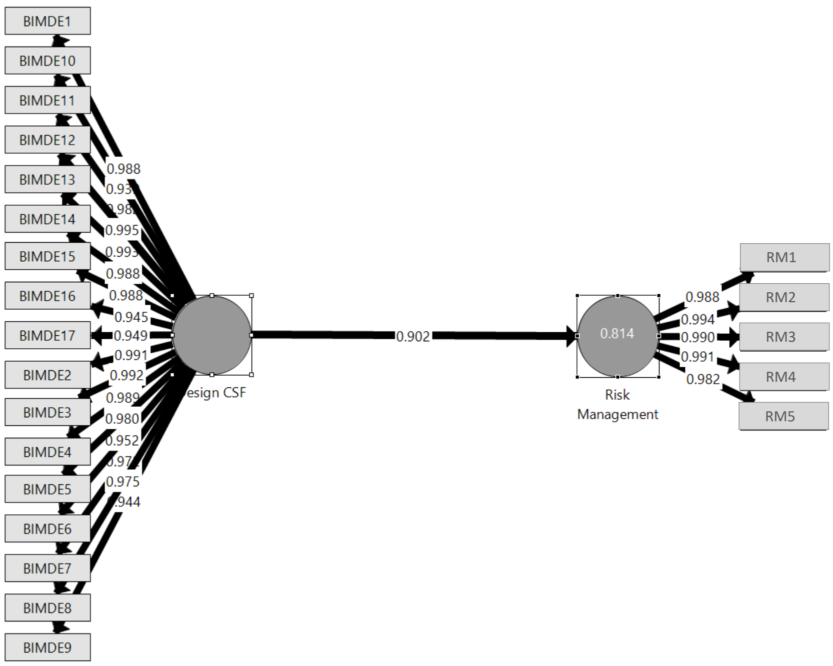
Figure 9 - Specific objective “D” achieved by article 4



Source: Author

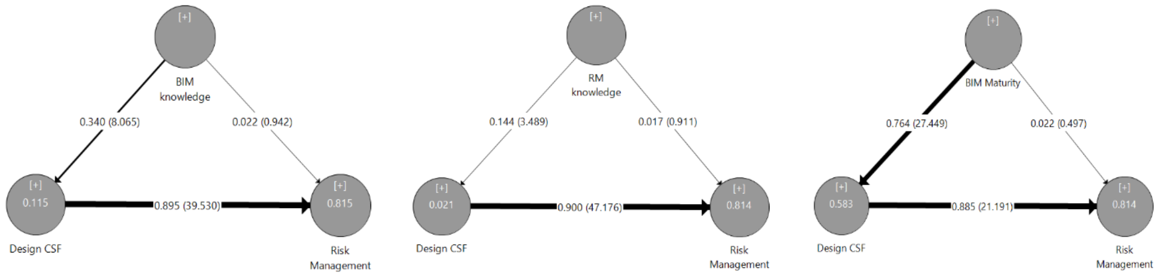
Article 4 presents seven hypotheses: **H1:** The BIM Design CSFs have a positive impact on RM; **H2a:** RM Knowledge positively and significantly direct influences the RM; **H2a':** RM Knowledge has a significant positive indirect effect on RM, which is mediated by a positive effect on Design CSF; **H2b:** BIM knowledge positively and significantly direct influences the RM; **H2b':** BIM Knowledge has a significant positive indirect effect on RM, which is mediated by a positive effect on Design CSF; **H2c:** BIM maturity positively and significantly direct influences the RM and **H2c':** BIM maturity has a significant positive indirect effect on RM, which is mediated by a positive effect on Design CSF. The structural models are elaborated and tested (figures 10 and 11).

Figure 10 - Research model results



Source: Author

Figure 11 - Research model: (a) BIM knowledge, (b) RM knowledge and (c) BIM maturity



(a) (b) (c)

Source: Author

Article 4 is carried out with 195 valid samples of professionals employed in the AEC industry, academia, and other industries in different pays. The reliability and validity of the survey questionnaire were addressed through a pilot study conducted with six professionals, being three architects, and three engineers, all of them has solid knowledge on the subject and experience in construction or engineering projects. The findings in this research indicates that BIM CSFs of the design phase have a positive impact on the risk management process, suggesting when effectively implemented BIM can reduce threats and create opportunities during design development. Furthermore, it was found that the indirect effect of all mediating variables has a positive and significant effect.

Indeed, knowledge and maturity are essential and so far lacking in BIM adoption. In consequence, the role of a BIM manager has emerged to support a successful BIM implementation (Bosch-Sijtsema et al. 2019) as its effectiveness relies more upon people than on the technology itself. Even though BIM roles supplement the lack of BIM expertise played by project managers, it also aligns with their roles as they share similar activities and skills related to management practices (Hosseini et al. 2018).

3 CONCLUSIONS

The general objective of the thesis is to develop a research model related to BIM CSFs and RM relationship in the design phase of engineering projects. This relationship has proved to be not only a current topic of professionals’ and academics’ interest but also a gap in the literature, which indicates the need for empirical research to evaluate and test this influence. More specifically, the literature indicates the importance of this integration to increase efficiency in RM and thereby achieve better projects success; however, there is limited research concerning its practice in engineering projects in the design phase.

This research thesis is article-based developed along its three phases: (a) systematic literature review; (b) exploratory study through a survey and four case studies; and (c) confirmatory study where a survey and the thesis theoretical model were developed and tested. The four articles meet the general and specific objectives.

The first contribution of this research to the literature is given by the first specific objective (A) through the systematic literature review, that allowed the identification of the main constructs and gaps. It was also characterized the main risks, success dimensions, and CSFs in the design phase (article 1), which were further explored (specific objectives B and C) along with the professionals’ level of knowledge and RM adoption (article 2), and the main risks and BIM CSFs in the design phase in practice (article 3). The fourth specific objective (D) was also achieved with the testing and validation of the structural model (article 4).

This research presents an important contribution to theory, since it introduces in a structured way reflections concerning the research theme relevance, answering to an important gap in the literature by investigating the relationship between RM and BIM. Moreover, in order to meet the challenges presented so far in BIM adoption, the research also contributes to identifying the CSFs of the design phase to take advantage of the benefits that it may provide to RM.

Furthermore, the literature indicates safety and social impacts as emergent topics; however, in practice, these topics are still limited, showing that companies must deal with several BIM-related challenges to reach them. Another contribution is concerning BIM public policies, which have created initiatives in some countries for BIM use with regulations and mandates; nonetheless, the cases which already have decrees approved by the government did not present an advanced and effective BIM adoption. It implies that BIM development is more of growing demand from the market than effectively from public policy.

The research findings also suggest contributions for the practice oriented to companies and professionals. Results show that RM is still not an effective practice in engineering projects and the risks not previously identified are responsible for negative project results. Moreover, a lack of knowledge or expertise in RM, BIM or both, were the main barrier identified, revealing the need for better professional training.

In addition, it was verified that RM supported by BIM in the design phase is premature, presenting limitations that hinder its dissemination. One challenge that was highlighted by the companies was cost overrun, mainly in the design phase. With a competitive market and undervaluation of the design, companies experience further difficulties in achieving cost-related benefits in the design phase. The organisations also revealed a lack of professionals and indicated that it remains a strong cultural resistance, emphasizing in-depth professional qualification.

As a contribution for practitioners, the research identified that accuracy data provided by BIM offers an improvement for project management analysis. Finally, the professionals revealed that the interviews revolved very important topics stimulating thinking processes for both aspects, professional and organisational. Moreover, companies identified issues that they have never even thought about, which demanded actions, indicating that the research somehow benefited them.

Despite the contributions indicated, the qualitative approach applied in treatment of data and analysis of the results, conducted in this multiple case study can be considered a limitation. Likewise, the survey research presents certain inherent limitations as the sample is composed predominantly of Brazilian professionals with unbalance sample relating to other countries presenting geographical limitations on the findings.

The results suggest possibilities for future research concerning empirical studies regarding the potential of BIM for sustainability issues in practice; comparison between the level of BIM adoption in countries that already have decrees from the government and countries that do not have them; and an in-depth study of the barriers linked to the project manager and BIM manager roles approach.

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PART 2 – THESIS ARTICLES

4 ARTICLE #1 - Exploring the Influence of Risks in BIM Implementation: A Review Exploring BIM Critical Success Factors and BIM Implementation Phases

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Abstract

The adoption of building information modeling (BIM) has a strong potential to influence project performance positively. However, the implementation and use of BIM also involve challenges and risks that must be considered for its practice's success. This study aims to identify gaps and future research direction within the field of BIM and risk management. Besides, it explores the relationship between risks related to BIM implementation and project success dimensions. For this, a literature review is applied, merging bibliometric and content analysis. The results show that the three most frequently mentioned risks are technological interface among programs, followed by interoperability issues, and inadequate knowledge or expertise. Besides, insights pinpoint the positive relation between the BIM critical success factors and the risks associated with BIM, particularly in the design phase.

Keywords: Building information modeling, BIM, risk, uncertainty, project performance

Status: Published at Journal of Modern Project Management

4.1 Introduction

As the construction industry has been facing different challenges, the related techniques are rapidly changing and risk factors in construction projects are becoming increasingly diverse (Park et al. 2016). The success of a project, if considering time, cost and other aspects integrated to project management requirements, depends on a large scale on how projects deal with the risks embedded in it (Silva and Melhado

2014). According to Eastman (2008), building information modelling (BIM) can create opportunities reducing threats for the project and for the client. BIM has a considerable potential for enhancing construction projects performance by providing collaboration between designers, engineers, constructors and all the stakeholders involved over the whole project life cycle (Kivits and Furneaux 2013). Therefore, BIM can contain all the information on a project within a single comprehensive model (Arshad et al. 2019). The published literature presented other innumerable benefits in the use of BIM, such as design consistency and visualization, cost estimations, automatic quantities extraction (Hartmann et al. 2012), clash detection, stakeholder collaboration, risk mitigation and improved data management (Volk et al. 2014). Another benefit of BIM is that once the information created is inserted in the system, it can be reused resulting in fewer errors, better consistency, clarity and accuracy (Kivits and Furneaux 2013).

Taking into account all these positives aspects, Aranda-Mena et al. (2009) stated that BIM can reduce risks in the project. Yet BIM is still considered experimental in the architectural, engineering, construction and operations (AECO) industries (Arshad et al. 2019). The use of BIM presents potential risks involving challenges concerning teamwork, collaboration, and information sharing (Chien et al. 2014). Considering the increased use of BIM in the AECO field due to its benefits and strengths, Zou et al (2016) describe initiatives already developed by researches in relation to the integration of BIM and risk management. However, the literature shows that such integration still has some gaps. According to Ahmad et al (2018), the analysis of eliminating existing risks or having newer ones with the use of BIM is yet to be investigated. The authors evaluated the risks evolution before and after applying BIM through case studies; this analysis brought important contributions to the theme. Nonetheless, studies related with risks associated with the BIM implementation and their relationship with the criteria success factors (CSFs) have not been addressed in the academy yet. Antwi-Afari et al (2018) report that a number of CSFs for successful BIM implementation have been suggested in the literature, and they also summarize a common set of CSFs that provide guidance to professional and academic areas. This study aims to review the domain knowledge and to identify gaps and future research direction within the field of BIM and risk management in engineering projects. For this, a mixed method is employed. In general, this method consists in combining elements of qualitative and quantitative research approaches, in order to have an extend and an in-depth understanding of the research analysis for a better comprehension (Johnson et al. 2007). Also, with an extensive research provided by the mixed method, it is possible to eliminate subjective analysis interpretation or conclusions (Harden and Thomas 2010). Therefore, a systematic literature review, applying bibliometric and content analysis, are applied. This process seeks to contribute to the body of knowledge by exploring the following research questions: (RQ1) What are the main topics, trends and gaps in the literature concerning risk management and BIM? (RQ2) Which risks related to the implementation and use of BIM have a greater influence on the success dimensions of the project? A conceptual model is presented linking the main constructs, variables, and their relations to better understand the role of BIM in risk management.

4.2 Literature Review

BIM and Risk Management

Risk and uncertainty are extensively explored in the literature on project management in reference guides and in the academic context (Carvalho and Rabechini 2015). Risk assessments are effectively established in the existence of appropriate data and clearly defined boundaries for their use. Statistical and probabilistic tools have been developed and provide decision support for risks responses. However, many risk decisions are defined by numerous uncertainties which lead to challenges and improvements for an effective risk assessment (Aven 2016).

Risk management is not accomplished in the same way for all projects, as risks do not impact all projects to the same extent (Thamhain 2013). Despite risk analysis using traditional process may be satisfactory for small projects, it presents limitations for large and complex projects, which need more attention and effective management (Carvalho et al. 2015). A survey developed by Silva et al (2019) demonstrated that professionals perceive that inadequate risk management can lead to different negative impacts including an unfavourable project performance.

According to ISO (2009), there are a number of techniques for identifying, analysing and evaluating projects risks. The standard recommends that risk identification includes all risks, even if their sources and causes may not be evident or under the control of the organization. However, risk techniques produce limited statistical data, which are ineffective in practice (Zhang et al. 2014), and decisions are mostly based on existing knowledge and previous experience through a brainstorming method (Zou et al. 2016). Moreover, risk analyses are still manual undertaking, leading to a need for automation improvement in order to have a better performance of risk management (Ahmad et al. 2018).

Concerning this demand, BIM is as a process to improve the creation and management of information throughout the design process (Matthews et al. 2015) and has been globally applied to assist early identification and assessment of risks (Zou et al. 2016; Lin et al. 2017). Furthermore, Hwang et al (2020) found out that BIM has a notable impact on reducing rework by decreasing risk of errors in construction projects. New regulations from the UK government incentivise the integration between BIM and risk management due to its importance to manage risks successfully (Zou et al. 2017). Nevertheless, BIM presents different challenges, difficulties and risks in its implementation (Xu et al. 2018) concerning teamwork, collaboration, information sharing and technology issues (Chien 2014). Also, BIM and risk management integration is a new field of study and, while some features of BIM can help address project risks, it is not possible to conduct comprehensive risk management (Ganbat et al. 2018). A suitable system to help designers identify and mitigate risks is still lacking (Hossain et al. 2018).

BIM, Risk Management and Project Success

Project success is defined by different authors through the triangle of scope, time and cost (Tahir et al. 2018). However, apart from researches related to deadlines, budget and deliverables compliance, there are few studies associated to risks and success (Carvalho and Rabechini Junior 2015) and success factors with BIM (Antwi-Afari et al. 2018). BIM evolution is expected to be effective in improving project quality and performance (Tahir et al, 2018); nevertheless, BIM implementation implies varied and complex risks (Ghaffarianhoseini et al. 2017). Ozorhon and Krahan (2017) affirm that BIM lead to many challenges and a better understanding of the critical success factors (CSFs) is necessary to organize strategies for its implementation.

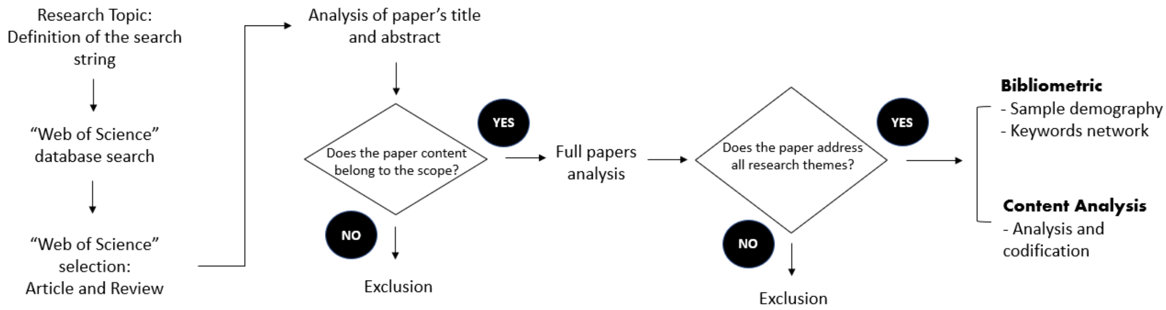
Liao and Teo (2017) reported many studies that described success factors that could affect BIM implementation, but few have investigated the interrelationship among these factors. Moreover, there is a lack of understanding of the influence of risks on the potential benefits provided by BIM (Zhao et al. 2017).

4.3 Research Method

The literature review is important to address the diversity of knowledge in a specific academic area (Tranfield et al. 2003). Levy and Ellis (2006) affirm that effective research presents what is already known and what needs to be known.

The research workflow of this study is shown in Fig. 1.

Figure 1 – Research workflow



Sampling Process

The dataset was generated through a topic search in the Web of Science Core Collection. This selected database was chosen because it provides access to the main journals and publishers across different sources (Franco et al. 2017). The strings "Build* Information model*" AND (uncertain* OR risk) were used for all topics. Following the keyword input, the publication source was limited to articles and reviews, since they are published in journals only after being evaluated through processes and criteria (Carnevalli and Miguel 2008). The review started in 2019, and during the whole period of analysis, we maintain a monthly updating process until October 2020. The initial sample in 2029 using 219 and the last update in October 2020 with the same string, logical operators, and filters results in 291 publications, i.e., an increase of 72 (32%) publications in a year shoes the increasing interest in the topic.

In the second phase, all publications in the initial sample follow the screening selection protocol, based on exclusion criteria is detailed in Table 1.

Table 1 – Criteria for paper exclusion

Criteria for paper exclusion	
Criterion	Criteria for elimination
BIM concepts	Not addressed or just mentioned without in-depth content
Risk or uncertainty concepts	Not addressed or just mentioned risk management or uncertainty theme without in-depth content
Research theme	Not related to the research topic

Firstly, each research individually analyzed paper adherence to paper exclusion criteria (see Table 1), based on the paper's title and abstract. The papers that all researchers agree (consensus) in excluding were automatically out of the sample; otherwise (lack of consensus), the analysis should go further. Secondly, all researchers read the full papers that lack consensus in the exclusion to analyze and decide about the exclusion. Although many papers introduce both topics in the title and in the abstract, many of them do not address a relationship between them or present BIM and risk management (or uncertainty) superficially.

After all the stages of selection, 107 papers were selected for bibliometric and content analysis due to their potential relevance.

4.4 Data analysis

According to Carvalho et al. (2013), the literature review can combine different methodological approaches, such as bibliometric analysis, network analysis, meta-analysis, semantic analysis, and content analysis. In this study, we combine bibliometric, network, and content analysis. The bibliometric analysis is based on the description and quantification of publications and consists of analyzing the publications' elements with statistical and mathematic methods. In the case of scientific publications, it is possible to identify all the periodicals that publish a specific theme. These authors work or are considered a reference in the theme, citations, and the number of published papers.

Content analysis is a method that selects, filters, and summarizes large volumes of data, besides determining viewpoints and tendencies (Sanchez-Cazorla et al. 2016). The key activities include encoding based on the literature and identified categories, frequency counts on categories, cross-tabulations, and results' interpretation (Do Vale et al. 2018).

Bibliometric Study

In this study, the bibliometric analysis of the literature was conduted using VOSViewer®, the science mapping tool developed by Van Eck and Waltman (2010). VOSViewer® is a software that supports the analysis of clustering solutions with visualisations (Van Eck and Waltman 2017). For the bibliometrics, analysis concerning the publication evolution over time, most productive journals and keywords network were developed.

Content Analysis

In order to identify the contents covered by each study, the papers selected were analysed and coded. Coding is a fundamental skill for qualitative analysis and provides managing, identifying, sorting and ordering data. Thoughtful coding ensures familiarity with the detail of data (Bazeley 2013). The content analysis was applied to address the research question regarding the influence of risks (or uncertainties) related to BIM on the success dimensions of the project (RQ2). Thus, the coding schema developed had iterative phases. First, three different categories (BIM, critical success factors, and risk codes) derived from the literature review discussed in the previous section (axial) drive the ignition in-depth content analysis of all articles. New emergent codes were then added as the content analysis progressed (Saldaña, 2013) and organized into the aforementioned theoretical categories if appropriate or new categories emerged.

The coding schema starts with BIM codes, classified into macro, meso, and micro levels. The BIM codes explored technology, people, and process issues, as suggested by Liu et al. (2017). Then, emerging codes were identified, and the final BIM codes group has 33 codes and sub-codes.

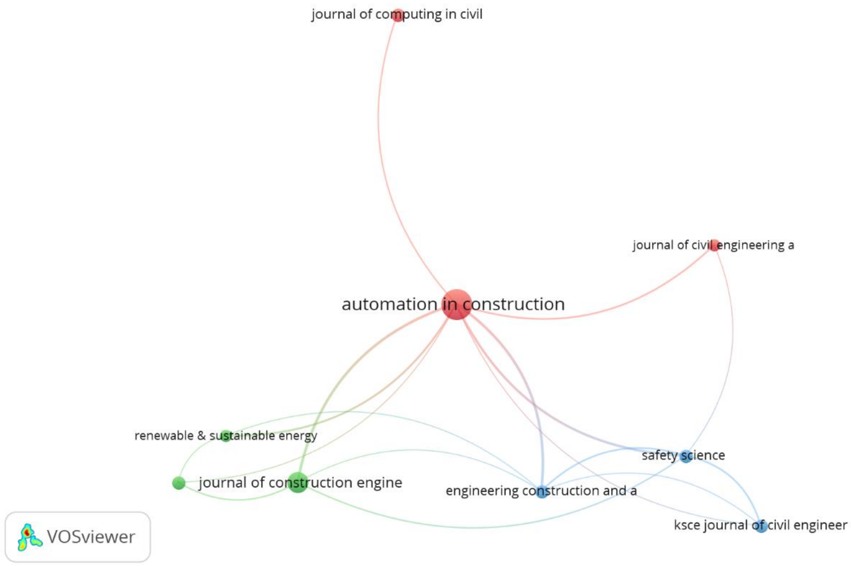
The theoretical codes (axial) related to BIM critical success factors (CSFs) were grounded in Antwi-Afari et al. (2018) were summarized a set of thirty-four CSFs. CSFs codes were classified according to each phase of the project life cycle: design (11 codes), pre-construction (12 codes), construction (9 codes), and operation (2 codes).

The starting point for risks associated with BIM codes was the 16 risks suggested by Zhao et al. (2017), and then new codes emerged during the content analysis reaching 80 codes. Finally, project success codes influenced by BIM risk was based on the emerging codes added during the content analysis process. The coding cycles result in the whole coding schema presented in Section 4.

Bibliometric Analysis

The papers selected were published in different journals and the top 7 journals that published the most papers are *Automation in Construction, Journal of Construction Engineering and Management, Engineering Construction and Architectural Management, Journal of Computing in Civil Engineering, Journal of Management in Engineering, KSCE Journal of Civil Engineering and Safety Science*, respectively. For the journals network presented in Figure 2, a setting on the minimum number of documents and minimum citation number of a journal to be 3 and 10, respectively, were considered and a total of 9 journals met the threshold. Although the journals *Renewable & Sustainable Energy Reviews and Journal of Civil Engineering and Management* are not among the top 7 journals concerning the publication number, they were considered in the network of main outlets due to their number of citations.

Figure 2 – Main journals concerning publication and citation



Note: Journal names may not be fully presented in VOSViewer.

Figure 3 shows the keyword network containing at least 4 occurrences. The keywords distance reveals the proximity between the terms, and the lines represent the links and concomitant occurrences. The relationships among the keywords can be summarised as follows:

- BIM and management are widely discussed in the literature with the highest number of occurrences (37 and 34, respectively) and they are linked among all the 5 different clusters identified by the software VosViewer®. According to He et al (2017), an effective BIM implementation requires an improvement in the management practices as well as extensive changes in all the project process (Volk et al. 2014).
- construction safety is another important research area giving the increasing number of topics related to safety monitoring, hazard identification and systems for safety information (Park et al. 2017; Wetzel and Thabet 2015).
- the keywords *risk* and *performance* emerge as the tenth (10th) and eleventh (11th) largest hotspot in the occurrences ranking, respectively, and these keywords presented 13 occurrences each (Table 2). They were grouped into the same cluster, but they do not belong to BIM or building information modelling or any other BIM name variation cluster, resulting in a gap between these

themes. As projects often involve multiple risk factors, their identification can guide BIM users resulting in a better project performance (Chien et al. 2014).

- a cluster involving risk management and building information modelling is identified; however, these themes can be considered as an emerging topic as they only present 6 occurrences. Despite the (upward, downward?) research trend between risk management and BIM, there is a lack of studies integrating both topics (Zou et al. 2017).

Figure 3 – Keywords co-occurrence network

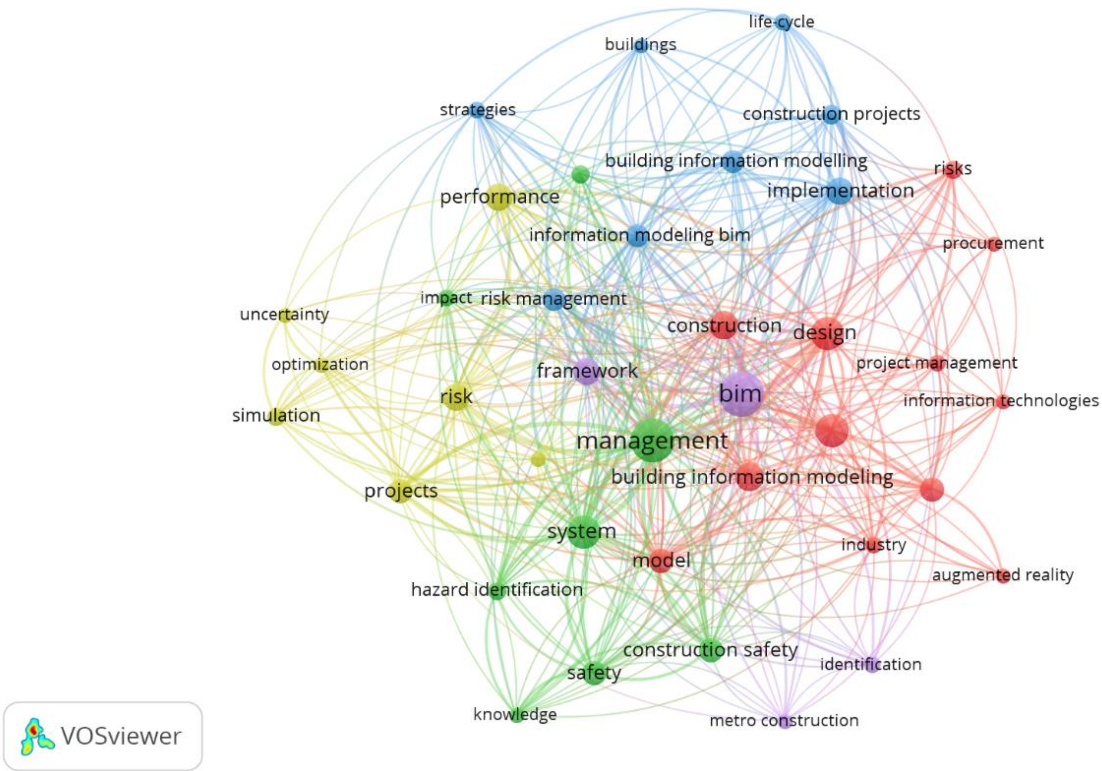


Table 2: Keywords and occurrences

Keyword	Ocurrences	Keyword	Ocurrences	Keyword	Ocurrences
bim	37	safety	11	life-cycle	5
mamangement	34	adoption	11	identification	5
system	21	information	11	project management	5
design	21	building information modelling	10	checking	4
building information modeling	21	information modeling bim	9	knowledge	4
construction	15	risk management	9	buildings	4
building information modeling (bim)	15	construction projects	7	optimization	4
implementation	14	hazard identification	6	metro construction	4
framework	14	risks	6	construction management	4
risk	13	building information modelling (bim)	6	information technologies	4
performance	13	simulation	6	ontology	4
projects	11	industry	5	uncertainty	4
model	11	strategies	5	augmented reality	4
construction safety	11	impact	5	procurement	4

Content Analysis

BIM influence on project success dimensions

The results show that the three most frequently mentioned risks are technological interface among programs (BR2), inadequate knowledge or expertise (BR4), and followed by interoperability issues (BR3) (see Table 3).

Table 3 – Coding schema: Risks in BIM implementation

Category	Sub-category	Code	n	%*
	Lack of BIM protocols	BR1	26	24%
	Technological interface among programmes	BR2	45	42%
	Interoperability issues	BR3	36	34%
	Inadequate relevant knowledge or expertise	BR4	37	35%
	Cultural resistance	BR5	14	13%
Risks in BIM implementation	Unclear ownership of the BIM data	BR6	17	16%
	Data security	BR7	18	17%
	Low quality of BIM data	BR8	18	17%
	Reluctance to share information	BR9	10	9%
	Poor communication among project participants	BR10	20	19%
	Lack of collaboration among project participants	BR11	19	18%
	Lack of a check mechanism for designs	BR12	6	6%
	Professional licensing issues	BR13	5	5%
	Uncertainty over design liability	BR14	23	21%
	Changes in the BIM model by unauthorized parties	BR15	5	5%
	Cost overrun with BIM	BR16	26	24%

* % in 107 articles

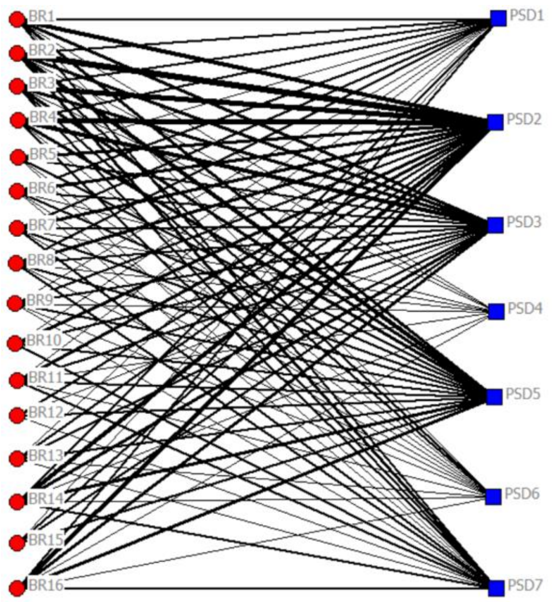
Figure 4 exhibits the cross-tabulation between the 16 risks associated with BIM, identified in an extensive research by Zhao et al (2017), and the dimension of project success presented by Carvalho and Rabechini Junior (2015), both presented in Table 4. The relative amount (column "%") was calculated based on the number of papers selected and the code frequency is demonstrated in column "n".

The data analysis allows affirming that *project management efficiency* (PSD2) is the success dimension most frequently discussed in the literature, followed by the *future impact on business* (PSD5). The analysis shows a closer relationship between

PSD2 and: (a) *technological interface among programmes* (BR2); (b) *interoperability issues* (BR3); and (c) *inadequate relevant knowledge or expertise* (BR4), respectively. Manderson et al (2015) state that BIM implementation presents many challenges including technological barriers and an analysis conducted by Bryde et al (2013) of 35 construction projects; interoperability issues were highlighted as a major negative effect in the use of BIM. Becerik-Gerber et al (2012) also stated that there are countless technological challenges to be addressed as a key to BIM effective implementation. A study conducted across countries by Hong et al (2020) demonstrated that technical issues were tightly present in BIM adoption by construction companies. According to Cao et al. (2017), construction projects still have concerns related to interoperability problems, which are considered not only technical issue, but also a support for collaboration. This collaboration consists in involving process, culture and management of all the stakeholders involved (He et al, 2017). Some efforts have been made in order to solve this issue, such as the industry foundation classes (IFCs). However, there are some barriers to its implementation and adoption due to incomplete and incompatible data exchanges for specific tasks (Eastman et al, 2010). Concerning the risk related to inadequate relevant knowledge or expertise, for Chien et al (2014), inadequate experience and lack of available skilled professionals are considerable risks and they are mostly present in an early stage of BIM development.

With reference to the success dimension related to PSD5, the same risks were shown as the greatest influencers for the *future impact on business* (BR2, BR3 and BR4, respectively). Ghaffarianhoseini et al (2017) state that many companies that use BIM, mostly the smaller ones, present a low return on business. Difficulties involving interoperability issues combined with the lack of professionals' skills and experience are the main concerns that tend to affect a business outcome. Considerable attention and investments in these factors are required to overturn this scenario and have positive trends in the company business.

Figure 4 - Project Success Dimensions X Risks associated with BIM



	PSD1	PSD2	PSD3	PSD4	PSD5	PSD6	PSD7
BR1	9	26	14	2	17	2	6
	8	40	16	1	21	4	15
	5	33	13	2	19	4	11
	7	31	20	0	19	1	10
	1	13	11	0	9	1	3
	4	17	11	2	9	3	3
	6	16	10	2	11	2	5
	4	17	9	2	8	1	4
	2	9	7	1	7	1	2
0	3	17	9	0	9	0	7
1	2	17	10	1	10	1	4
2	0	6	3	0	4	0	1
3	1	5	4	0	5	1	1
4	5	22	14	1	14	3	4
BR15	1	5	4	0	4	0	0
BR16	4	25	14	2	15	2	4

Table 4 – Coding schema: Project success dimensions

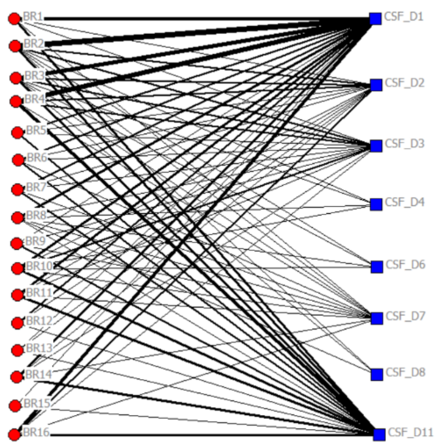
Category	Sub-category	Code	n	%*
	Product/Service	PSD1	16	15%
	Project Management Efficiency	PSD2	85	79%
	Impact on Team	PSD3	24	22%
Project Success Dimensions	Present impact on business	PSD4	7	7%
	Future impact on business	PSD5	35	33%
	Impact on the customer	PSD6	6	6%
	Social and Environmental Impact	PSD7	48	45%

* % in 107 articles

BIM risk influence on design critical success factors

The literature explored convergences in the identification of a positive relation between the critical success factors and the risks associated with BIM. The cross-analysis indicate that the link between *earlier and accurate 3D visualisation of design* (CSF_D1) and *reduced claims or litigation* (CSF_D11) with BR2, BR3 and BR4 is the most discussed in the literature (Figure 5). The technology embedded in BIM contributes to the precision and quality of the design visualisation (Zou et al, 2016); however, software-interoperability is still a challenge for successful BIM adoption (Gourlis, 2017) and the lack of integrity of three-dimensional (3D) models issued by designers create uncertainties to BIM users (Aibinu and Venkatesh, 2014). A survey developed by Jin et al (2017) to identify risks in implementing BIM shows that limited functions within existing BIM software tools was the major risk identified by the participants from different professions, including architects, engineers, owners, BIM consultants, and other AEC practitioners. Conversely, BIM has played an important role in developing new opportunities to improve risk management (Zou et al, 2019) as researches established strong link concerning the support to risk identification and risk assessment (Zou et al. 2019; Ganbat et al. 2018; Ahmad et al. 2018; Zou et al. 2017). Lin et al (2017) confirm that BIM has been effective in identifying and mitigating risks in the early stages of the project.

Figure 5 - Critical success factors X Risks associated with BIM



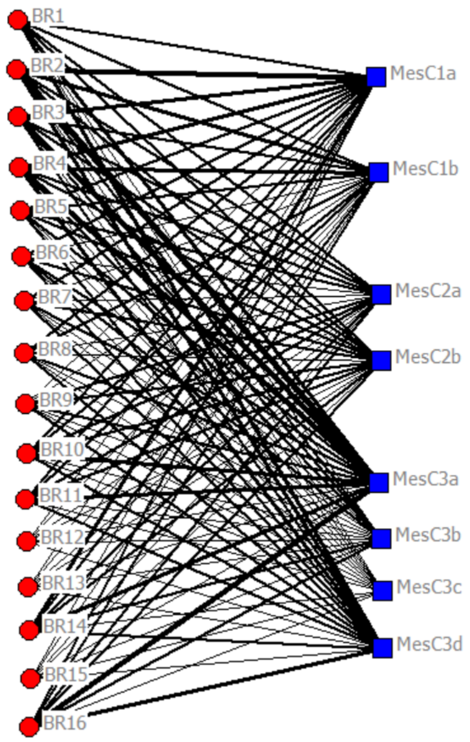
	CSF_D1	CSF_D2	CSF_D3	CSF_D4	CSF_D5	CSF_D6	CSF_D7	CSF_D8	CSF_D9	CSF_D10	CSF_D11
BR1	16	3	3	0	0	0	1	0	0	0	9
BR2	27	7	6	2	0	1	2	1	0	0	11
BR3	19	7	5	1	0	1	1	1	0	0	11
BR4	21	6	5	0	0	0	2	0	0	0	12
BR5	7	2	2	0	0	0	0	0	0	0	5
BR6	7	2	1	0	0	0	1	0	0	0	6
BR7	7	3	2	0	0	0	1	0	0	0	7
BR8	9	0	1	2	0	1	1	1	0	0	3
BR9	3	0	1	0	0	0	1	0	0	0	5
BR10	8	2	4	1	0	1	2	0	0	0	9
BR11	9	1	2	0	0	0	1	0	0	0	8
BR12	4	1	0	0	0	0	0	0	0	0	3
BR13	2	1	0	0	0	0	0	0	0	0	3
BR14	11	3	1	0	0	0	1	0	0	0	9
BR15	1	0	0	0	0	0	0	0	0	0	2
BR16	15	4	2	0	0	0	1	0	0	0	9

BIM risks influence on factors that affect the project performance

The connections between *communication* (MesC3a) and the risks *technology* (BR2), *knowledge and expertise* (BR4) and *interoperability* (BR3) are the most frequent co-occurrence, respectively (see Figure 6). Baptistucci et al (2018) conducted face-to-face interviews with experts from engineering projects to investigate which risks have occurred more frequently and the result showed that risks related to the lack of communication between stakeholders were the most common. BIM effectiveness is related to communication, cooperation and collaboration between the designers and all the agents involved (Aibinu and Venkatesh, 2014). Technology and interoperability are key factors for a successful information exchange. According to Jamil et al (2020), interoperability issues have a direct relation with communication and information exchange among all stakeholders, outstandingly with subcontractors. For a communication improvement using BIM, strong computer design skills and specialized software knowledge are required (Hong et al, 2019). Furthermore, *IT capacity* (MesC1a), the most frequent factor is also tightly linked with BR2.

Learning experience (MesC3d) has the most representative link with *knowledge and expertise* (BR4). In a list of 32 risks identified in the literature and experts' opinion, the highest ranked risk "lack of BIM knowledge" was the greatest barrier to BIM implementation presented by Ahmad et al (2018). Professionals with limited knowledge and expertise related to BIM led to cultural resistance and technical and interoperability issues, which can hinder BIM implementation and experience achievement (Zhao et al, 2018).

Figure 6 - Factors that affect the project performance X Risks associated with BIM



	MesC1a	MesC1b	MesC2a	MesC2b	MesC3a	MesC3b	MesC3c	MesC3d
BR1	12	8	8	9	21	5	4	15
BR2	22	17	10	10	32	7	4	16
BR3	20	13	9	9	24	7	3	13
BR4	19	15	11	10	27	7	4	20
BR5	7	7	9	8	10	6	2	8
BR6	11	5	6	7	13	7	3	8
BR7	9	6	6	7	13	6	5	8
BR8	13	9	5	6	10	5	3	9
BR9	6	5	7	7	8	5	2	7
BR10	11	9	8	8	17	5	2	12
BR11	9	8	7	7	16	6	2	10
BR12	3	4	2	2	6	3	0	3
BR13	4	3	2	2	5	2	0	3
BR14	14	8	9	11	17	7	5	13
BR15	3	3	2	2	5	2	1	4
BR16	13	9	10	10	22	7	4	14

4.5 Conclusion

This article contributed to the literature with an in-depth analysis of 107 articles dealing with BIM implementation risk that answer the two research questions (RQs) proposed. The first research question explores the core topics in the literature of BIM related to risk, pointing out the three most frequently mentioned risks: technological interface among programs, interoperability issues, and inadequate knowledge or expertise. Second, the relation between BIM risks and project success dimensions are explored in the literature, particularly with Project Efficiency. Finally, insights pinpoint the positive association between the BIM critical success factors and the risks associated with BIM, particularly in the design phase.

This paper presents certain inherent limitations to the literature review method. First, the sample demonstrates limitations related to the search strategy, including selecting WoS databases, search strings, and logical operators adopted. Therefore, we may lose some relevant studies. The screening phases can show some bias related to the researcher's interpretation of the exclusion criteria.

For future research, an in-depth study of the relationship between BIM-related risks and project performance through quantitative research approaches. Besides, there is a new room for future research on the relationship between BIM-related risk and critical success factors, particularly in the design phase.

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5 ARTICLE #2 - Risk and uncertainty in engineering projects: a survey of professionals

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Abstract

Engineering projects tend to present numerous uncertainties due toa lack of information or unreliable information, new technologies, project complexity or even unpredictable factors. These uncertainties can affect the project´s success. This paper aims to investigate the level of knowledge and adoption of risk management practices in engineering projects. Moreover, thepaper aims to explore the perception of the influence of risk management onproject success. The methodological approach was a survey-based study with a sample of 596 respondents. The results indicated that most professionals (61.6%) know of the PMBoK® and try to partially or totally apply it, followed byISO 31000 (24.7%) and ICB/IPMA (13.6%). Considering the success dimensions, the most frequent consequences associated with risk were delayed schedule, increased cost, damaged client reputation, and decreased quality.

Keywords: Project Management. Uncertainty. Risk. Engineering projects. Project Success

Status: Published at Journal of Modern Project Management

5.1 Introduction

The roles and contributions of risk management within organizations have evolved and grown over the years. Because of challenges that impact supply chains, assets, earnings and operations, more enterprises have recognized the importance and value of firm-wide risk management, and risk managers have both fueled and responded to rising expectations. Increased expectations generally bring new challenges. Since organizations are increasing their overall expectations of the risk management function, it is important to explicitly define a framework for measuring the performance of risk management [1].

According to [2], most projects deal with uncertainties, and many projects depend, to a certain extent, on unforeseen circumstances that are beyond the control of the owners, stakeholders, project managers, contractors and suppliers. Risk should be routinely considered from the very beginning in all aspects of the project, including its development (to update risks, incorporate new risks or eliminate those already identified), and the project should be oriented towards managed risks, but studies have shown that risk management practices are poorly adopted by project managers [3]. Although project management has expanded into engineering projects, many companies still do not value it and consider it only as a cost. Given this scenario, risk management deserves more space and attention in the context of project management, and this is due, among other factors, to its impact on the overall results. The success of a project, when considering time, cost and quality, largely depends on how management addresses the risks involved [4].

According to [5], many projects have been delayed or have exceeded their budgets because project managers cannot effectively manage risk. Currently, projects are considerably more exposed to risks and uncertainties due to factors such as complexity in planning and design as well as the number of stakeholders.

Engineering project organizations face a very dynamic business environment; therefore, establishing an appropriate risk management system is of crucial importance. However, due to the lack of practices in this field, it is still necessary to explore this important knowledge area to achieve better results in projects [1]. Due to the importance of risk management in engineering projects, this research aims at investigating the level of knowledge and adoption of risk management practices by exploring the following research questions: (RQ1) Which are the main frameworks and guidelines applied in engineering projects? (RQ2) Are project managers and team members proficient in risk management methods, tools and practices? (RQ3) What are the perceptions of the influence risk management on project success? The survey focused on practices and results related to risk management in engineering projects and their impact on various project success dimensions. The main findings aim to identify the risk management approach in the professional environment in different countries and industries. The data analysis will be evaluated to identify possible gaps and contribute to project management practices as well as to academic knowledge. Therefore, a questionnaire was developed to examine the major environmental features of engineering projects companies.

The paper is structured as follows: Section 2 provides a literature review of the main theme concepts. Section 3 describes the exploratory study composed of the survey method. Section 4 presents the results and discussion. Section 5 concludes the paper.

5.2 Literature Review

Risks in Engineering Projects

In project management, uncertainties can affect the necessary information during decision making. From the beginning of a project, it is necessary to obtain relevant and necessary information for its development. However, not all the information required is provided, and often, much of the information received contains missing documentation, creating uncertainty. Considering that uncertainty and risk are inevitable in such projects, they should be managed, minimized, accepted, shared and transferred but should not be ignored [6]. The most common interpretation of uncertainty in the extant literature on projects is the risk and/or uncertainty caused by unreliable information or a lack thereof [3, 7, 8]; novel, immature or unproven technology [9]; project complexity [10–13] and other unpredictable factors. In projects, these risks are overcome by proactively employing project managers' and team members' combined knowledge and judgment based on experience and creativity, e.g., [14–16].

Despite the extensive research conducted in this field, there is a gap concerning the analysis and identification of risks in practice from the earliest phases of projects [17, 18].

Regarding risk identification, many techniques require deep knowledge of previous projects and rely on retrospective analysis by subject matter experts. The development of more predictive risk identification techniques could provide tremendous insight to project managers, particularly if likely risks can be identified in early design phases [19].

A case study developed by [20] in three Brazilian construction companies identified that national companies do not have formal procedures for risk management. The authors attributed the inexistence of these practices to the size, limited resources and less formal culture of the companies. Reducing uncertainty means greater project maturity and a higher level of information available for its implementation as well as the enhancement of the project manager's ability to make decisions and anticipate a series of typical problems in project development. Industrial projects are included in this scenario since most Brazilian companies that develop projects in this segment do not have adequate risk management in their processes.

Risk Management Methods

Risk management frameworks and processes need to reflect the characteristics of the project environment and organization. In dynamic and complex project deliveries, this requirement implies the well-organized use of collective knowledge and coordinated responses, which are often spread among several participant organizations [21].

Complexity and project diversity have led to varied communities of practice and bodies of knowledge and have been a challenge to reaching a common and workable understanding of project management best practices. The same problem has occurred in the project risk management field, where some popular guidelines exist for implementing risk management in engineering project domains [22].

Managing risks on construction projects is a process that includes a risk assessment and a mitigation strategy for those risks. A risk assessment includes both the identification of a potential risk and the evaluation of the potential impact of the risk. A risk mitigation plan is designed to eliminate or minimize the impact of the risk events—which are occurrences that have a negative impact on the project.

The guide to the project management body of knowledge (PMBoK®), the most widely distributed of the available knowledge guides [23], proposes project risk management that is in accordance with the following processes: a) plan risk management; b) identify the risks; c) conduct the qualitative risk analysis; d) carry out the quantitative risk analysis; e) plan the responses to the risks; f) monitor and control risks [24]. This guide is one of the most used technical developments for controlling risks [25], and it is widely used for training and underpins the development of competency standards [26]. The International Project Management Association (IPMA) is a more accepted and recognized association in European countries, and it also developed a guide for best practices in project management that is similar to the PMBoK® and is called the IPMA Competence Baseline (ICB®). The latter has some peculiarities and allows each country to make necessary process adaptations and changes and provides flexibility to meet local standards. Introduced in 2009, the ISO 31000 standard is intended to help organizations manage diverse types of risk in a systematic and comprehensive manner by offering a universal framework 'to assist the organization to integrate risk management into its overall management system' [27]. The standard quite clearly defines the main responsibilities of organizations, including establishing a policy on risk management, communicating its beneficial effects to the various stakeholders, and ensuring that sufficient resources are in place [28].

Most project risk management research is presented from a very restrictive perspective considering a single-organizational project delivery team and covering limited risk perceptions and risk management approaches. Therefore, some traditional approaches based on risk management best practices deal with only two aspects of risk, probability and impact, considering the occurrence possibility of certain events and how the risks impact project objectives [21].

According to Carvalho and Rabechini Junior [18], there is a convergence in the literature with regard to these best practice processes, but there is growing interest in others that involve not only risk management but also uncertainties such as "context and the strategic approach to risks/uncertainties", "relationship with stakeholders" and "crisis management".

Moreover, [27] affirm that these guidelines generally consist of a list of so-called "best practices" in risk management, which is assumed to be captured from experience and lessons learned over time; however, the guidelines fail to include evidence to support the effectiveness of their prescriptions. It appears that, even though project managers might be aware that risk management practices exist, project managers fail to implement these practices.

[3] argue that, despite a great number of risk management guidelines, little work exists to reveal what risk management is actually accomplished (or not accomplished) by project managers and why. The adoption of a risk management guideline is not as important as the actions risk managers take [28].

Risk Management and Project Success

Project success includes the classical success criteria, which are also called the iron triangle: budget, schedule, and quality adherence, as well as customer satisfaction with regard to all the projects in the portfolio [29]. Constantino et al. [30] argues that these factors are not always enough to consider a project successful. Well-defined objectives, the communication of a project's aims to team members and the approval of deliveries by a multiplicity of stakeholders are crucial. Another important and critical issue that must be considered is scope management as well as project managers' competence. A study developed by Rabechini Junior and Carvalho [31] shows that uncertainties and individual business knowledge have a significant impact on project success. In considering this scenario, the conceptual understanding of uncertainty and risk is important.

The critical success factors (CSFs) are the main factors that increase the ability of organizations to carry a project through to its full implementation. A continuous assessment of all the decisions made during the project life cycle that impact project risks and CSFs allows managers to set priorities and determine the actions that can drive the project towards success [30].

According to [32], the importance of managing risk in projects attests to the recognition and importance of requisite variables that affect business effectiveness at the operational and strategic levels. As a consequence, risk management is one of the most important tools a project manager has to increase the likelihood of success.

5.3 Research Method

Due to the nature of the research questions that drive this research, a survey-based approach was selected. According to [33], one of the main survey challenges is the difficulty of attracting individuals to complete the questionnaire and obtaining significant samples for the research. The author suggests that attention should be paid to certain issues when developing questionnaires, such as considering only questions related to the research proposal, writing clearly and accurately, allowing only one interpretation, and writing questions that do not lead the respondents to a particular response. Therefore, writing the questions requires attention to how survey constructs are conceptualized and how questions must be phrased to obtain information that respondents are willing and able to provide [34].

Sampling Process

The survey sampling process was carried out through a list of approximately 5,500 professionals from the LinkedIn® platform for engineering, construction and architecture and professional contacts from different countries. A pilot test was performed with a short list of Brazilian and international professionals as a facial test of the questionnaire in English and Portuguese.

The intention was to ensure the understandability and interpretability of the questions and to make adjustments if necessary.

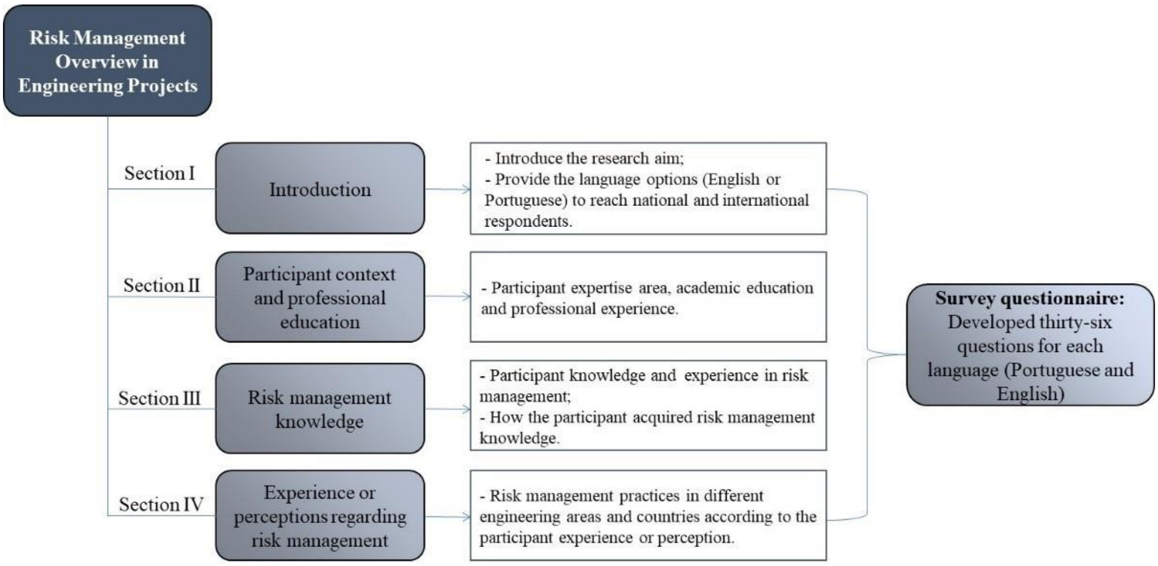
Data Collection and Analysis

In line with the conceptual basis derived from the literature review discussed in Section 2, the questions and the questionnaire were structured and established in a way that would draw out the necessary data from the respondents in a direct, clear and synthetic way.

Based on the proposed aim, the questionnaire was developed in four main sections: introduction, participant context, professional education, and risk management knowledge and experience or perceptions regarding risk management (Figure 1). The survey was disseminated online through the SurveyMonkey® platform.

The descriptive statistics and the cross-tabulation analysis of the variables were performed using IBM SPSS software and Minitab.

Figure 1: Questionnaire structure



5.4 Results and Discussion

Sample Demographics

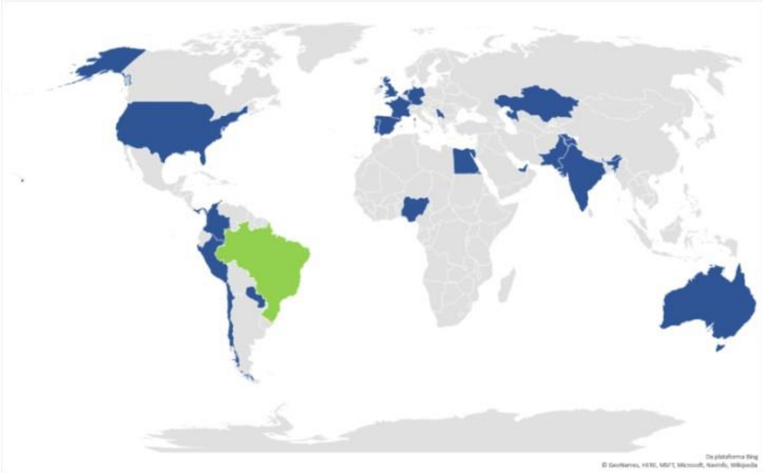
The survey has 668 answers in total, and 72 responses were discarded due to incomplete answers. Hence, 596 valid answers were considered (table 1).

Table 1: Valid answers

Parameters	Value
Total Questionnaires	668
Discarded Questionnaires	72
Validated Questionnaires	596

Figure 2 shows the countries of origin of the professionals who responded to the questionnaire.

Figure 2: Countries of origin of the survey data



Participant Context and Professional Education

The relevant information regarding the participants' contexts and education levels is presented through an analysis of the data on their sex, education level and age.

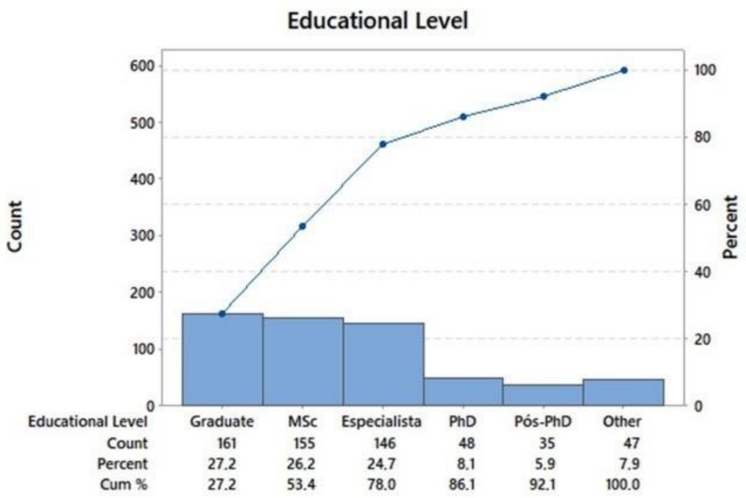
Most of the professionals who responded to the questionnaire were female, representing 51.8% of the total (Table 2).

Table 2: Respondents' sex

Sex	Female	Male
Count	305	284
Percentage	51.8	48.2
Cum (%)	51.8	100.0

Regarding the education level, Graph 1 demonstrates that most of the respondents have a graduate level education, representing 27.2% of the total, followed by MSc professionals (26.2%) and specialists (24.7%). The number of PhD professionals represents 8.1% of the respondents.

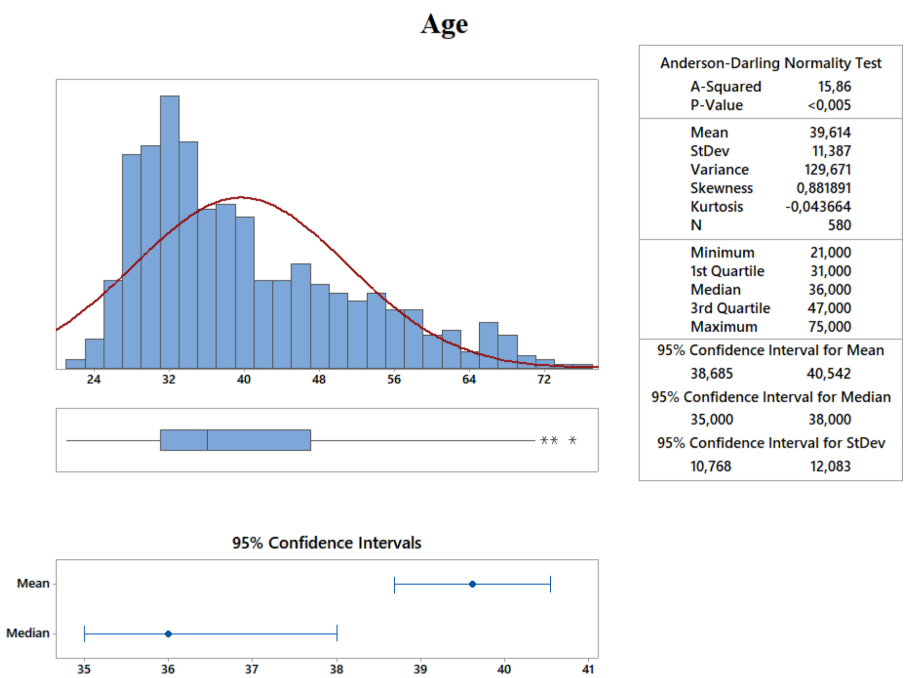
Graph 1: Respondents' education level



Thus, we can assume that the professionals who participated in the survey are well qualified and have a good conceptual background since 64.9% of them have a post-graduate education.

Most of the respondents are between 30 and 34 years old, and the majority are 32 years old (Graph 2).

Graph 2: Respondents age



Knowledge, Experience or Perceptions Regarding Risk Management

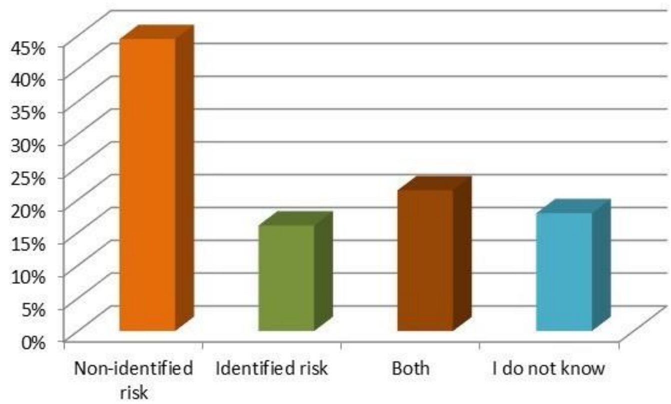
In asking the respondents about their experience in risk management, 56.2% of the professionals answered that they had never worked with risk management, and 43.8% had experience being responsible for risk management or working with it in an indirect way (Table 3).

Table 3: Distribution of answers to the question: have you ever worked with risk management?

	Have never worked	Have experience
Count	329	256
Percentage	56.2	43.8
Cum (%)	56.2	100.0

Regarding identified and nonidentified risks, the research showed that professionals have more difficulty facing nonidentified risk than identified risk, with 44.5% and 16.1%, respectively. Additionally, 21.4% of the respondents indicated that both are difficult to face, and 18% did not know which one they had more difficulty facing (Graph 3).

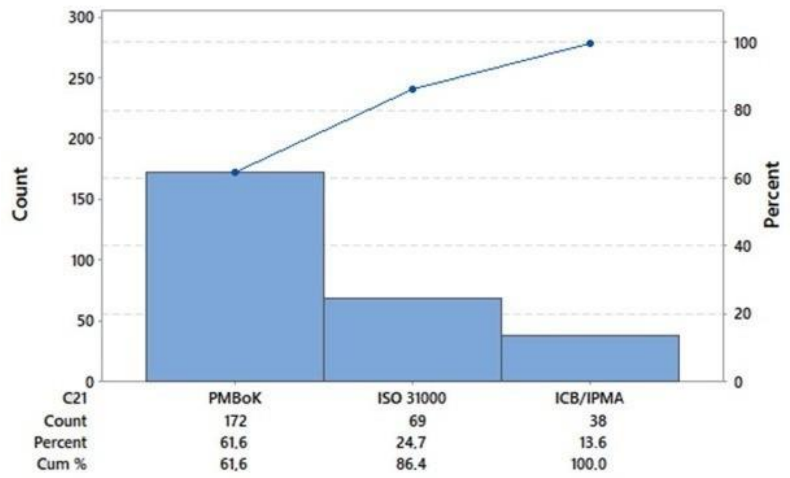
Graph 3: Distribution of answers to the following question: Over your career, have you had more difficulty facing identified risks or nonidentified risks?



Furthermore, there is an interesting finding regarding professionals' uncertainties in projects. The data indicated that professionals have experienced situations in which many risks were not previously identified, and they had more difficulty in dealing with nonidentified risks than identified risks. The data indicate the lack of information or knowledge regarding the result of an action or decision making in projects. These data confirm the importance of studies concerning how the professional environment addresses risk and uncertainty. Against this backdrop, dealing with uncertainty has an embracing and determinant significance for the project as a whole [35].

The professionals were about a good reference to a risk management method, and Graph 4 illustrated that most professionals (61.6%) recognized the PMBoK® as the best practice, followed by ISO 31000 (24.7%) and ICB/IPMA (13.6%).

Graph 4: Distribution of answers to the following question: What is a good reference for a risk management method?



Most of the participants indicated that the PMBoK® guide is a good reference for a risk management method because, among other factors, it is widely known and available for study and consultation [36]. Even although it is a general guide, the research indicates that most engineering professionals recognize the PMBoK® as the best practice for risk management. Despite the professionals' knowledge concerning guidelines for implementing risk management, most of them have never experienced risk management practices in engineering projects, even in an indirect way (contact with stakeholders or colleagues from their area that worked with risk management); that is, they are familiar with certain concepts and the literature, but in practice, the professionals do not apply risk management in their processes. Despite the knowledge of its importance, the effective implementation of risk management in organizations and projects is not common [37].

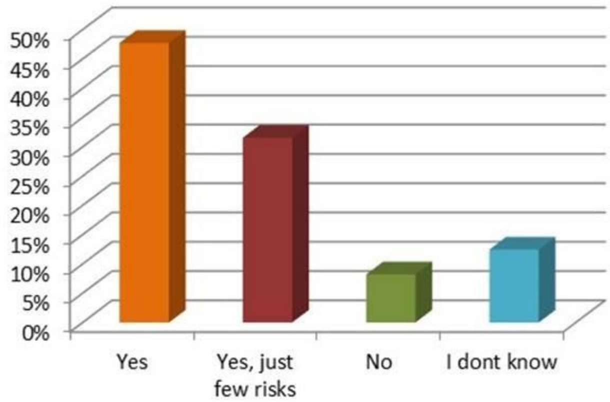
When asking the respondents about any situation in which disregarded or underestimated risks were responsible for unsatisfactory results in the project, the answers indicate that 48.4% of the professionals had experienced this problem, followed by 32.8% of the respondents who did not know if they had experienced this problem, and 18.8% of the professionals who never had this experience. It is observed that most of the professionals recognize that the risks generated by project management failures are very significant and, when underestimated or not considered, are the main factors negatively affecting the project results (Table 4).

Table 4: Distribution of answers to the following question: based on your experience, was there any situation in which disregarded or underestimated risks were responsible for unsatisfactory results in the project?

	Yes	No	I do not know
Count	180	70	122
Percentage	48.4	18.8	32.8
Cum (%)	48.4	67.2	100.0

Concerning situations in which risks were not previously identified, 47.7% of the answers demonstrated that the professionals had experienced such a situation, 31.6% indicated that they had experienced situations in which just a few risks had not been previously identified, 8.2% of the professionals stated that they had never been in this situation, and 12.5% did not know if they had previously experienced this (Graph 5).

Graph 5: Distribution of answers to the following question: Over your career, have you ever been in a situation in which many risks were not previously identified?



Considering situations in which disregarded or underestimated risks were responsible for unsatisfactory results in the project, the professionals indicated the main consequences of this phenomenon (Table 5).

Graph 6 illustrates that schedule delay and cost increase are the main consequences, with 28% and 27%, respectively. Damaged client reputation represents 14%, followed by reduced quality (13%), project interruption/cancellation (9%), social or environmental impact (6%) and scope change (4%).

The main consequences of situations in which disregarded or underestimated risks were responsible for unsatisfactory results in the project, as indicated by the professionals, suggest that the iron triangle (schedule, cost and quality) is still the most representative critical factor of project success.

Frequently, projects are viewed as isolated processes, without taking into consideration their environment. Therefore, important influencing factors producing uncertainty can be dismissed [35].

Graph 6: Distribution of answers to the following question: What were the main consequences of a situation in which disregarded or underestimated risks were responsible for unsatisfactory results in the project?

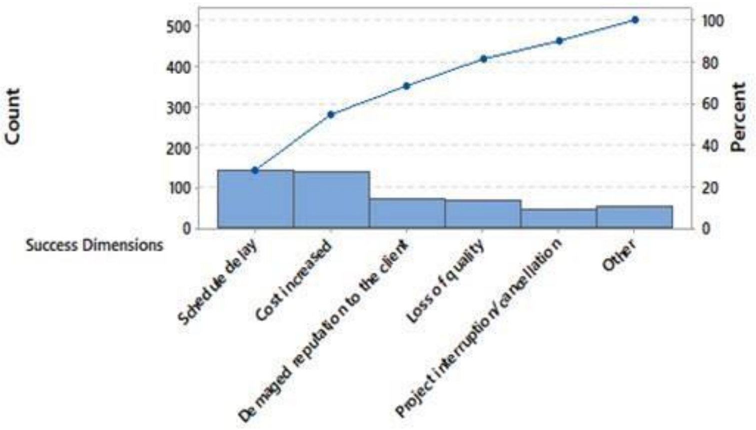


Table 5: Main consequences of situations in which disregarded or underestimated risks were responsible for unsatisfactory results in the project

Project Success Dimension	%
Schedule delay	28%
Cost increased	27%
Damaged reputation to the client	14%
Loss of quality	13%
Project interruption/cancellation	9%
Social or environmental impact	6%
Scope change or reduction	3%

5.5 Conclusion

This paper contributes to the literature in 3 ways by answering the three research questions posed. First, the study sought to identify the main risk management approach noted by the professionals involved in engineering projects, revealing the predominance of the PMBoK approach. Second, the study aimed to explore the level of professional knowledge and the application of risk management, showing a lack of risk management experience by professionals who still do not use it in practice in engineering. Third, the study demonstrates that most professionals perceive that poor risk management can lead to delayed schedules, increased costs, damaged client reputation, decreased quality and other negative impacts, leading to an unfavorable project performance. Additionally, professionals demonstrate that they have more difficulty facing nonidentified risks and uncertainties in projects, suggesting the need for further studies related to this theme to contribute to the effective practice of risk uncertainty management by engineering companies.

This research has limitations because the nonprobabilistic sampling process can generate some bias. In addition, the sample is composed predominantly of Brazilian professionals; therefore, the sample is unbalanced in relation to other countries.

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6 ARTICLE #3 - Building Information Modeling and its effects on project success and risk management: exploring a cross-country case studies

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Abstract

Given the benefits of risk identification and mitigation through the integration between building information modeling (BIM) and risk management, this research seeks to identify the risks, the critical success factors (CSFs) in the design phase, and the success dimensions in BIM projects. To address these objectives, cross-country case studies were conducted in four companies from different countries. Data were collected based on semi-structured interviews. The results show that inadequate knowledge or expertise was indicated as the top-ranked risk in BIM projects; however, BIM adoption presents a positive impact on the various dimensions of success, highlighting the project management efficiency. As a contribution for both scholars and practitioners, the professionals also indicated the main BIM CSFs in the design phase, including accuracy data provided by BIM, which enhances project management analysis.

Keywords: BIM critical success factors, design phase, risk management, success dimensions.

Status: Ready to be submitted

6.1 Introduction

Engineering projects comprehend a set of technical teams from various disciplines, including civil, MEP (Mechanical, Electrical, Plumbing), chemical and mineral process, firefighting, subcontractors, consultants, material, and equipment suppliers. This project environment introduces challenges and risks due to its process. The extensive quantity of information that needs to be exchanged among all these professionals, and the use of information technology provides collaboration across this process (Liu et al. 2017) to ensure better project success and results.

Digital technologies, such as building information modeling (BIM), have been identified as valuable for increasing efficiency in projects. Moreover, advanced applications of BIM, automation, the internet of things, drone technology are examples of the digital technologies that drive the transformation of the built environment to deliver efficiency and quality improvements (Morgan 2019). BIM can also create opportunities to reduce threats for the project and manage its risks (Zou et al. 2017).

Initiatives have been developed by researchers in order to integrate BIM and risk management (Ahmad et al. 2018b; Arshad et al. 2019; Hossain et al. 2018; Othman and Alamoudy 2020; Tabatabaee et al. 2021; Zhang et al. 2015; Zou et al. 2016b); however, the literature shows that such integration still has some gaps. In addition, most studies are related to safety context in construction presenting limited research concerning practice in the design phase of engineering projects. Furthermore, while BIM enhances risk management, its adoption triggers considerable risks regarding the required changes in process, technology, and people, whose interactions are complementary and highly challenging. (Liu et al. 2017). Likewise, Ghaffarianhoseini et al. (2017) report a weak implementation linked to risks and challenges hindering its effectiveness.

There is a need to align BIM with risk management in the design phase to take advantage of the benefits from this relationship. However, it is essential to mobilize initiatives concerning success factors guiding professional and academic areas. In this regard, several authors have identified factors that influence the BIM adoption process. According to Rockart (1982), critical success factors (CSFs) could be defined as key factors for a project to succeed. Moreover, CSFs are the most significant factors to increase project performance and assure success for construction projects (Babu and Sudhakar 2015). Liu et al. (2021b) distinguished a comprehensive set of critical factors to support professionals to execute proper strategies to successfully implement BIM in Singapore. Evans et al. (2021) identified 30 critical success factors (CSF) that enhances and support construction organisations to apply BIM technologies along with lean construction approaches. Chan et al. (2019) established 12 potential critical factors for BIM execution built environment in Hong Kong. Giel and Issa (2016) identified 66 CSFs that influences BIM implementation, establishing a guideline to organisations for its improvement.

Poirier et al. (2017) discussed a series of factors that influence BIM collaboration process at the comprehensive design-build project in Canada. However, there is a lack of studies that are related to CSFs for BIM adoption at the design phase in the context of engineering projects and the relashionship of success dimensions with BIM-related risks. To address this research gap, this study aims to identify the risks and CSFs in the design phase, and the success dimensions with the use of BIM achieved by the companies. Furthermore, the mostly discussed success dimension in the literature, namely project management efficiency, was also identified in practice as shown in the corpus analysed in this paper. Then, a cross-case analysis between this success dimension and BIM risks was performed. In consequence, the study will answer the four research questions presented below.

RQ1: What are the success dimensions achieved by the companies with the use of BIM?

RQ2: Which are the main BIM-related risks in practice?

RQ3: Which are the main BIM CSFs in the design phase in practice?

RQ4: Which BIM-related risks influence project management efficiency in practice?

To answer these research questions, four engineering companies from different countried were studied. Data were collected based on twenty-three (23) semi-structure interviews with managers, engineers and directors. This paper is structured as follows. Firstly, section 2 presents the main theme concepts in the literature review. Secondly, section 3 describes the case study method. Thirdly, section 4 presents the main findings from the research and their discussion. Finally, section 5 concludes the paper.

6.2 Literature Review

BIM Success Dimensions and CSFs

Project success is related to benefits, delivering results with the desired functionality and performance, including schedule and budget compliance (Turner and Xue 2018). Carvalho and Rabechini Junior (2015) 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 (2019) suggest some measures for an optimal project management success, such as the use of BIM. The authors state that BIM approach can become a catalyst, improve synergy and project performance.

BIM integrates multidisciplinary and structural data to reproduce a virtual model throughout the project life cycle. BIM leads to organizational and technical innovation in order to develop capabilities and opportunities (Morgan 2019).

When properly implemented, BIM enhances project performance in several of aspects, including project quality and value, team performance and project management efficiency. BIM provides an integrated design and construction process, resulting in better quality at lower cost and duration (Eastman et al. 2011). It enables professionals to create an accurate 3D digital model (Seyis 2019), to track potential conflicts and clashes at the design stage, reducing errors, thereby eliminating the need for the many requests for information (RFIs) (Liu et al. 2021b). BIM also creates an opportunity to integrate sustainability analysis into the design process and offers potential assistance to minimize construction waste during the design phase (Lu et al. 2017).

Moreover, BIM benefits can be seen in an organisational context such as the impact on the client and business. The ability to apply BIM in different management processes and analyses make attainment of high project performance (Al-Ashmori et al. 2020). A case study conducted by Almuntaser et al. (2018) highlighted that BIM provides an expansion of the services to the clients, gain in competitive advantage in the market, and the adoption of modern technology for a more effective business process. The authors also identified effective reuse of information through a knowledge database and client satisfaction. Likewise, Olawumi and Chan (2019b) revealed the following advantages: resource planning and management, compliance with the project's delivery schedule, and facilitating collaboration among stakeholders.

Although the literature suggests countless benefits in the use of BIM, which can lead the project to success, a better understanding of the critical success factors (CSFs) is necessary to meet the challenges still present in its implementation. Despite growing academic consideration, a comprehensive analysis of CSFs is not well established (Antwi-Afari et al. 2018).

BIM adoption in design firms remains poorly understood, which often fail in the face of implementing the technology (Morgan 2019). According to Fakhimi (2017), BIM successful results have not yet been reported by engineers in certain industrial sectors, due to a lack of adequate studies. Moreover, Evans et al. (2021) affirm that there is an essential need to conduct critical analysis of CSFs for improving BIM application from early design stage, since the decisions made at this time of the project are those that have the highest ability to influence the successive phases (Hossain et al. 2018). Furthermore, the design phase is subject to several risks, which can cause errors, project failure, unsatisfied clients, cost overruns, etc (Othman and Alamoudy 2020).

BIM and Risk Management interface

BIM has been considered a technology innovation in which risk management has been strengthened (Ahmad et al. 2018b). Despite countless advantages, BIM adoption remains numerous risks to its use and implementation (Zhao et al. 2018). These risks associated with BIM have been explored in many studies in different countries.

The research investigated by Almarri et al. (2020) indicated the most likely risks emerged from BIM, among them: lack of experienced and skilled personnel, lack of collaborative work processes, and lack of BIM processes understanding. Liao and Ai Lin Teo (2018a) also revealed lack of stakeholders involvement to work collaboratively from early design and unwillingness to change. Moreover, professionals expressed concerns related to technology issues, more specifically, software functionally, technology immature, and compatibility (Liu et al. 2017). 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 (2021).

There are few initiatives in the literature to integrate BIM and risk management to enhance the benefits provided by this relationship. Othman and Alamoudy (2020) proposed a framework to optimize project performance during the design phase; however, the authors pointed out that its application is a time-consuming process, which requires full dedication from all project participants for its success, including the organisation's assistance and investment in training, skilled professionals, and technological infrastructure. Although Ahmad et al. (2018b) suggested automated risk management using BIM in construction projects, for its use is still necessary manual risk selection and opinion-based probability input. In addition, it is in the initial version and its development is beyond the expertise of the authors, who recommended BIM software developers to take the lead by coding the proposed framework.

6.3 Research method

This section presents the methodology used to answer the research questions. A preliminary literature review is undertaken to identify gaps and relevant topics related to this study. Afterward, exploratory case-based research is proposed with four case studies conducted by interviews and analyses of documents shared by the companies. Case study research can be comprised of the study's questions, along with its propositions and the criteria for interpreting the findings (Yazan 2015). The case study method was chosen in this study because it enables to analyse of the investigated topic in practice, identify new variables and hypotheses, and evaluate the inferences by combining within-case and cross-case analyses (Bennett and George 2005).

Sample characterization and data collection

The data were collected in companies of different countries. The companies were selected based on the following criteria: (a) have a well-defined management structure; (b) have risk management practices in its management process; (c) develop projects using BIM; (d) the organizations should operate in engineering projects; (e) access to certain internal documents and stakeholders for data collection and interviews.

Semi-structured interviews were carried out with key stakeholders as directors, project managers, field managers, and engineers. Each interview was recorded and transcribed, and field notes were taken during the interviews, as suggested by Voss et al. (2002). Although the authors also recommend interviews with multiple respondents per case study, the number of participants depends on the nature of the research and the quality of data. It is possible to have a smaller sample if results are strengthened by other data collection methods alongside interviews (Baker and Edwards 2012). In this study, a review of archival data was performed. The key documents analysed were the following: policies, procedures, work instructions, internal standards, and technical documents related to risk management and BIM. The interviews were made face-to-face, via skype call, or in virtual meeting rooms, and each one lasts for around one hour. 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 collected data.

To collect information and data, a research protocol was developed, which was oriented by the literature review and the researcher's previous experience. This protocol includes the following questionary's themes: (1) BIM and risk management in the company`s organizational context: applied to the company`s stakeholders who had participated actively in the BIM implementation and risk management process; (2) BIM in the design phase: adopted to the stakeholder's involved in the projects design phase; and (3) relationship between BIM and risk management: applied with project`s stakeholders to analyse the impacts and risks identified with BIM implementation and to verify projects performance with the use of BIM.

A pilot case was developed aiming at improving the quality of the research related to data collection and procedures to be followed (Yin 2002). After going over the feedback from practitioners and researchers, slight improvements were made to eliminate possible misinterpretation. Table 1 describes the characteristics of the four exploratory case studies.

Table 1 – Companies and areas interviewed

Company	Sector	Country	Number of professionals interviewed	Number of interviews	ID Code	Areas interviewed
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
B	Consulting, engineering, construction, operation, maitenance, intelligent networks	Canada	4	6	BRM1 / BRM2 BMEE BOP	Corporate Risk management Mechanical and Electrical Engineering Operational Intelligence
C	Engineering and construction	Dubai	2	6	CRPM CDD	Risk and Project management Digitalization & Development
D	Engineering and construction	EUA	2	3	DPM DVDC	Project management Virtual Design and Construction

Data analysis

The interviews were analysed qualitatively through the coding process, the analysis of content, and interpretation of results, as suggested by Duriau et al. (2007). A computer-aided approach was applied, using NVIVO ® software to manage data, and increase its effectiveness and efficiency (Bazeley and Jackson 2013). The software was useful to separate the interview data into categories arranged in a tree words structure connecting text segments grouped into separate categories of codes or "nodes" to further carry out a thoroughness data analysis.

In multiple cases, the analysis should explore similarities and differences across cases towards theoretical generalizations (Morioka and Carvalho 2016). For this study, a cross-case analysis was performed in two aspects aligned with research objectives: BIM-related risks and the success dimension mostly reached associated with BIM. The research design is summarized in Figure 1.

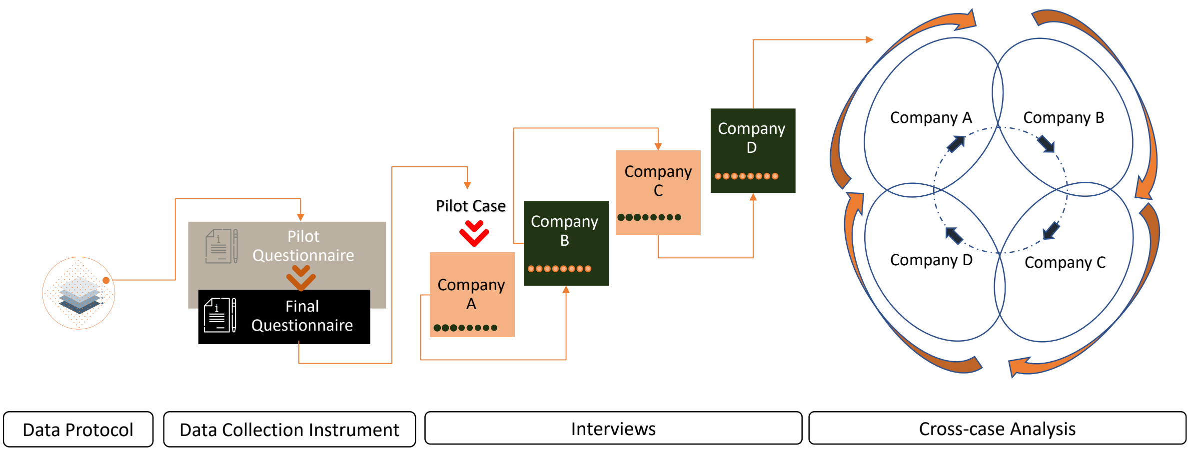

Figure 1 – Research design

6.4 Results and discussion

This section presents and analyses the main evidence collected in the case studies toward answering the research questions described in section 1.

Success Dimension

The success dimensions proposed by Carvalho and Rabechini Junior (2015) were identified in the data analysis, which indicates that the professionals interviewed recognize positive project performance in the use of BIM. Statements to illustrate these aspects are shown in Table 2.

The case studies show that although the use of the technology still brings threats, opportunities and positive results are emergent. Aligned with the literature, BIM adoption has brought companies a better budget and schedule compliance, and project quality (Bryde et al. 2013; Eastman et al. 2011; Georgiadou 2019; Kivits and Furneaux 2013; Morgan 2019). A previous study developed by Silva et al. (2021) listed *project management efficiency* as the success dimension most frequently discussed in the literature. The study also revealed emergent topics, as safety and social impact. In practice, the companies indicated that these topics are still limited. They presented some actions and strategies to enable BIM adoption to support sustainable approaches (table 2); nevertheless, the companies pointed out that so far, they have a lot of challenges to reach this level. Company B (ID interviewee BMEE) mentioned "I see a lot of people interested in this topic, but honestly, only a few are doing it."

Some initiatives can be seen to achieve better project performance regarding the social and environmental concerns; however, companies still face difficulties in working in a collaborative and integrative environment, which in part is due to the design culture established in the sector. BIM development is still at the primitive stage (Cao et al. 2017b) , which may not have the information and conditions necessary to reach sustainability benefits (Asgari and Noorzai 2021). Studies show that restrictions and issues related to technology and a lack of knowledge among professionals also hinder this goal.

Although research related to BIM and sustainability are growing in the academia, there are few or none studies on how to apply these concepts in the industry (Saieg et al. 2018). The combination of BIM and sustainability leads to the improvement economic, social and environmental performance of engineering projects; nevertheless, preliminary measures to achieve sustainability require complete knowledge and classification of BIM uses and environmental indicators since the early stages of design (Asgari and Noorzai 2021). Olawumi and Chan (2019a) highlighted that for the achievement of any sustainable smart initiative, there must be a proper integration of the knowledge and skills of the stakeholders and an increase in their involvement, considering that few are experienced with BIM.

Research conducted by Lu et al. (2017) recognized the potential of this integration resulting in various benefits; however, the authors identified challenges concerning e.g. the complexity of tools and users' lack of appropriate 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. According to the authors, studies and improvements related to these topics could better guide practitioners and achieve more effective project results.

Table 2 - Success dimensions

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 wich 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, specially 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 a more easy 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)

Success dimensions	Company A	Company B	Company C	Company D
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 millimeter 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 center information. This data will use artificial intelligence and machine learning and help us to understand the behavior 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 had 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 displacementregarding 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 this 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)

Risks associated with BIM

Despite the organisations considered that BIM has an impact positive on risk management, its use still leads to risks and barriers for effective practice by professionals and project performance improvement. Among 16 risks associated with BIM, identified in an extensive research by Zhao et al. (2017), professional inadequate knowledge or expertise was the top-ranked risk mentioned by the companies, followed by cost overrun (mainly in the design phase), risks related to technology issues, and cultural resistance.

The professionals revealed difficulties concerning interface among programs, mainly when the project has a big number of stakeholders with different software and compatibilities to exchange information. Zou et al. (2019) stated that there are barriers related to different software vendors for different disciplines, and some of them do not provide linking information. Construction projects still have concerns related to technology along with collaboration (Cao et al. 2017a), which consists in connecting process, culture, and management of all the stakeholders involved (He et al. 2017). Moreover, the companies highlighted that stakeholders, mainly suppliers, most of the time do not demonstrate an interest in fully engaging the BIM model in an integrated work environment, which can vary depending on their maturity level and knowledge. In addition, there are those who still work in 2D demanding DWG extension documents or paper copies. The reluctance of stakeholders to commit can be related to the lack of standardized procedures for collaboration with external team members and interoperability issues between software programs (Ku and Taiebat 2011). In some cases, computers were unable to run the software, due to eg. lack of process power, and storage (RAM).

Furthermore, difficulties indicated by certain companies as technology issues, actually, can be attributed to a lack of knowledge and misuse of tools, and inappropriate machines. Most design rework and poor design quality can be traced back to professionals' inexperience. Inadequate knowledge or expertise was the top-ranked risk revealed by the companies. Professionals are not familiar enough with the tools and processes requested by BIM. The demand of the AEC industry for skilled BIM experts is extremely high; however, knowledge and experience is still too inadequate (Chien et al. 2014a). According to Company B (ID interviewee BMEE), "there are limited specialized resources". Professionals have also experienced situations in which a "Request for Proposal" (RFP) requests documents and information from the model that they did not know how to do that or even if there is any tool in the market that could be used. Not only the companies recognize facing this difficulty, but also they have been made efforts providing training to develop knowledge and achieve the necessary expertise.

Additionally, the professionals mentioned that subcontractors are also unfamiliar with BIM and they are not able to adhere to its standards. Moreover, they may have different levels of knowledge, which makes the project even more challenging. In brief, the modelling becomes more of a liability to the contractor to guarantee project quality. Inadequate knowledge and expertise also contribute to issues related to information quality, collaboration, technological interface, and data compatibility (Zhao et al. 2017), increasing design cost and duration (Tan et al. 2019). Negative project results tend to contribute to a resistance in the use of BIM, since engineering and design face fast track projects and market pressure, and its implementation is seen by the professionals as a time consuming and a long-term process. Companies reveal that the learning curve in BIM tools is somewhat slower, and they are not able to mobilize the whole team for training, which is always in parallel with the other attributions of the professionals.

Although Olanrewaju et al. (2021) affirm that BIM in the design stage enhances the project by reducing the cost without affecting the quality, the companies reported a concern related to cost overrun, mainly in the design phase, ending up more costly and less profitable. BIM adoption is an investment decision, so from a business perspective, the cost of BIM implementation must be justified by the benefits accrued from it (Chang et al. 2017). The use of BIM requires professional training, investments in infrastructure and tools, and the engagement of a skilled team, demanding time and cost (Othman and Alamoudy 2020). This emphasis concerning cost overrun in the design phase can be considered an implication to practice, and as a result, companies do not adopt BIM in all projects, in which it is not a contract request. According to Company A (ID interviewee APM1), "in a proposal where there is no BIM requirement, companies that do not use BIM will be more competitive for presenting lower prices, which does not mean that the project will have higher quality; however, at this point most clients only consider the proposal cost".

According to the professionals, the most BIM benefits are reflected in the construction phase due to, among other factors, reliability, and design quality transferred to construction, leading to savings. Turn-key or design-build contracts can be more advantageous for companies, considering that they may have better control of the cost-benefit balance. As stated by 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.”

Interestingly, professionals from the same company, but different disciplines and business unit differ in opinions and experiences. One of the reasons can be attributed to the different levels of BIM knowledge and maturity in the company. BIM implementation has been fragmented among disciplines and business units. Research developed by Loyola and López (2018) indicated high heterogeneity of BIM expertise among disciplines, characterized by fragmented and non-collaborative practices. The authors refer to the lack and heterogeneity level of knowledge, complementing the difficulty of having project teams where all members share a similar level of training in the technology. It should be inquired if the cost overrun in the design phase pointed out by the organisations is related to the lack of knowledge of the professionals leading to rework, project delay and additional cost, or even external influence such as market issues causing design undervaluation. In the latter, the projects are sold cheaper with lower profit margins and the companies do not always have an assertive control to affirm with accuracy the low-profit of the project.

Internet connectivity is another risk in which the organisations are concerned and it was not listed by Zhao et al. (2017). The companies mentioned this issue, especially in projects involving a large number of external team members or the use of BIM in the field, where there is a high probability of having a restricted or limited connection. In this case, the professionals download the model once a day; however, there is a high risk of not being able to update the information and working with an outdated project. As mentioned by Company C (ID interviewee CDD), “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.”

Design CSFs

Organisations highlighted a precise and straightforward cost estimation and quantity take off, reduction of risks, a better design verification (clash detection), design duration reduction, an earlier and accurate visualisation of design, better design quality, enhanced exchange of information, extract more accurate key performance indicators (KPIs), accuracy and reliability of data, better MEP (mechanical, electrical, and plumbing) analysis, and better integration and communication among disciplines and stakeholders.

The deployed BIM eases the design visualisation and provides a boost to managing the project (Olawumi and Chan 2019a). Professionals emphasize the early identification of issues and risks that significantly supports the decision-making process and ensures a more reliable and better-quality project. Company A (ID interviewee ACE2) mentioned that “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 organisations also referred to integration and communication between the design team, construction company, suppliers, and trade partners as another effective advantage for the project. These findings correlate with the characteristics of most companies in the sector whereby the project development is considered fragmented, and the use of BIM enhanced its collaboration, even concerning risk management as it cannot be executed effectively if there is a lack of collaboration and teamwork. Likewise, Othman and Alamoudy (2020) affirm that the project performance could be improved if fragmentation and risks are addressed properly in the design phase. As stated by Company C (ID interviewee CDD), “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) complemented, “we acknowledge the contribution that the BIM gives to the schedule related to risk and mitigation”.

The professionals highlighted the enhancement of design verification and validation provided by clash detection. According to company B (ID interviewee BMEE), “BIM plays an important role concerning clash detection as it looks at interferences to be caught early”. Company C (ID interviewee CDD) complemented that “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”. Although the companies emphasize that they have gained a huge improvement in quality and project performance anticipating issues and risks, analysing project accesses, escape routes, and interferences, two of them mentioned that clash detection reports produce too many false alarms. At the same time, they recognize that this occurs when the criteria are not set properly or when there are design errors, suggesting professionals lack of knowledge and expertise. The companies also realised that, even though they know that clash detection, better project visualisation, and other BIM issues contribute to risk management, some professionals had not made this link. They were contributing to a phase of the risk management process unintentionally. After the interviews, they mentioned that they would create an action plan to better structure this process in the company.

The companies also highlighted the reliability of material quantities extracted by BIM, leading to accurate estimates. Company D (ID interviewee DVDC) stated that “the model provides the enhanced data allowing the quantities extraction so that we can kind of create a real live cost estimate”. Likewise, company C (ID interviewee CRPM) mentioned, “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”. Research conducted by Seyis (2019) indicated the importance of the BIM benefit related to promoting cost estimations and confirming appropriateness of the budget, which support the overall increase of project success.

An important finding of this research is related to accurate BIM Key Performance Indicators (KPI's). The companies revealed potential benefit regarding technical and management aspects. Company D (ID interviewee DVDC) declared "we use clash counts, allocation and 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 their expectations are or you know, if they need to have additional supplementing support". The professionals also mentioned that the daily extract of interferences contributes to a better project and risk control. BIM also provides data feedback to the commercial department for more assertive proposals. According to Company A (ID interviewee ARM), "I could tell you about more assertive feedbacks that exist in the management area, where we feedback to the commercial team through productivity indexes. In the engineering area, there are initiatives to generate HH indexes by type of document and modeled elements, such as average hours for modeling a line within a model".

Likewise, better accuracy of the project development provides the quantity of modelled elements, hence a more effective resource allocation and team productivity data. One other major improvement for project management is related to the design physical progress. The use of BIM decreases the subjectivity of progress information reported by designers and engineers, providing accuracy in measuring the physical progress of the project and in data for project management analysis. This indicator has not yet been addressed in the literature. Research conducted by Won and Lee (2016) indicated design errors detected by BIM, change orders, response times of BIM issues, and schedule conformance as KPIs commonly utilized in the projects.

Figure 2 shows the main critical success factors indicated by the interviewees. It should be kept in mind that these data were collected based on individual perceptions and do not necessarily represent a formal position of the organisations.

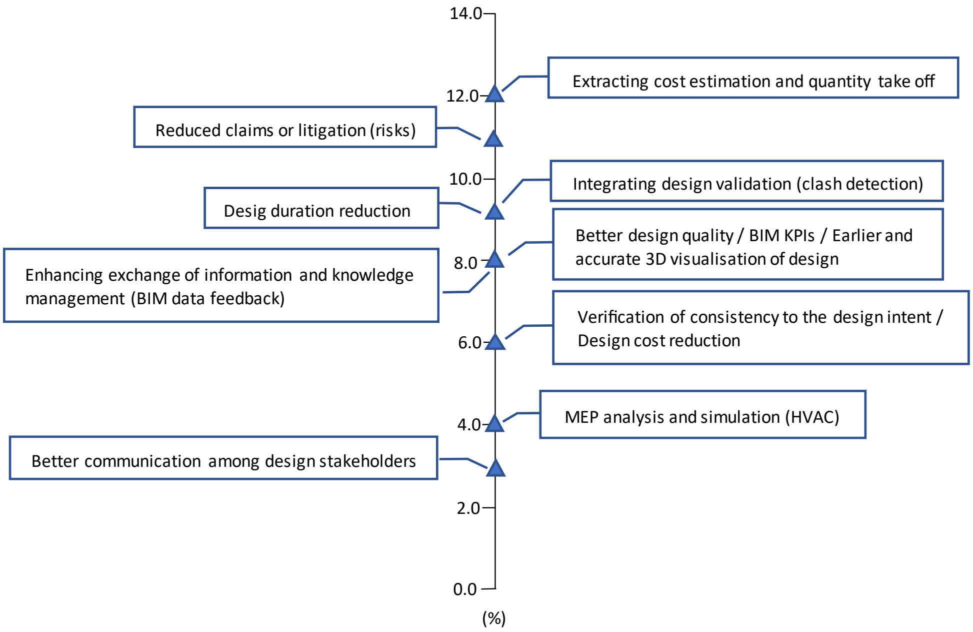

Figure 2 – Main CSFs indicated by the companies

BIM risks influence on project success dimensions

Previous literature research regarding BIM and risk management presented a cross-tabulation (Silva et al. 2021) between the risks associated with BIM (Zhao et al. 2017), and the dimensions of project success proposed by Carvalho and Rabechini Junior (2015). The results showed that *project management efficiency* was the success dimension most frequently discussed in the literature, and the analysis also revealed a closer relationship between *project management efficiency* and the following risks: *technological interface among programmes*; *interoperability issues*; and *inadequate relevant knowledge or expertise*, respectively.

Likewise, empirical evidence showed that the companies have the same perception, indicating *project management efficiency* as the success dimension mostly reached. The professionals pointed out a link with the same risks presented in the aforementioned in the literature; however, the companies also revealed a strong link with *lack of BIM protocols*, *cultural resistance, cost overrun in the design phase*, and *lack of professionals*, the latter is not listed in the table presented by Zhao et al. (2017).

The results indicate that in practice, engineering firms have faced more risks than stated by the literature. Moreover, organisations still have difficulties and face numerous barriers to achieving the benefits proposed by BIM. Table 3 indicates the risks related to the project management efficiency highlighted by the literature and the companies. It is also shown examples of the statement from the professionals.

Table 3 – Cross-cases analysis between BIM risks and project management efficiency highlighted by theory and practice

Succes Dimesions	Risks	Literature	Practice	Examples of statement
Project management efficiency	Technological interface among programmes 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 plataform 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 plataform 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 stkeholders?" (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)

Figure 3 presents a qualitative analysis in which the 'success dimensions' axis indicates the seven dimensions proposed by Carvalho and Rabechini Junior (2015), while the ‘risk’ axis represents the risks related to BIM, both scales stem from low to high. The interrelation between the success dimensions vs. risks reveals that some companies achieve a better success dimensions facing less risks and others that do not. Company A and C share the same performance achievement; however, company A faces a higher level of risks. In contrast, company B does not reveal considerable progress in project performance, and furthermore, it indicates a high level of risks. Company D reports a medium level of success dimension and risks.

Company B revealed additional difficulties to implement BIM related to organisational bureaucratic issues. The use of BIM requires deep process changes of the involved parties (Volk et al. 2014a). It shifts project, organisational, and professional boundaries (Papadonikolaki et al. 2019). The organisation commitment and the development of planned processes reflect on the results as BIM adoption is facilitated by a mutually constitutive relationship between user and organisation, wherein the latter plays a central role in supporting, attending to, and enabling user-led change (Morgan 2019).

Moreover, the public policy has created initiatives for the use of BIM with regulations and mandates leading to a tendency of contractors to demand its use; however, there is a knowledge and training gap that needs to be filled as the speed of demand is higher than the learning curve. It was not possible to identify that the cases already in the public regulatory environment presented a higher concern in relation to an effective BIM adoption. It seems that it is much more a growing demand from the market than effectively from public policy.

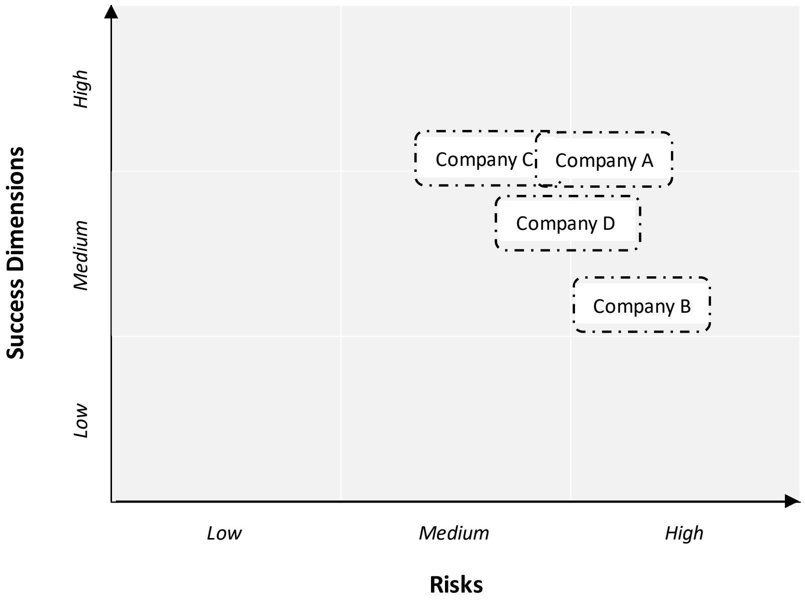

Figure 3 – Success dimensions x Risks associated with BIM

6.5 Conclusion

By investigating the CSFs, risks, and success dimensions related to BIM, the research provides several contributions to both theory and practice answering the four research questions (RQs) proposed. The first research question is related to project performance with the use of BIM. The research found that BIM adoption presents a positive impact on the various dimensions of success, highlighting the project management efficiency, which corroborates with the findings of the literature. Previous research also indicates sustainability as an emerging topic. Although BIM has the ability to support several sustainability analyses (Zulkefli et al. 2020), the data show that this approach is still in an early stage in the companies studied.

Second, we explored the risks involved in the implementation and use of BIM; as a result, professional inadequate knowledge or expertise, technology issues, cultural resistance, and cost overrun, mainly in the design phase, were the main risks mentioned by the companies.

Inadequate knowledge or expertise was indicated as the top-ranked risk. Lack of experience is the most challenge of BIM resulting in time and cost waste in the project delivery process, that in return cause cost overruns and time delays (Seyis 2019). The rate of BIM introduction in organisations has increased, while BIM user proficiency is still low. BIM requires knowledge and specialized training over an extended period. Moreover, the factors that hinder BIM use are still left unresolved, remaining its progress unchanged (Lee and Yu 2020). Internet connectivity is another risk in which the organisations were concerned, and it was not presented by the literature.

Third, the research identified the main BIM CSFs in the design phase. The organisations highlighted a precise and straightforward cost estimation and quantity take off, reduction of risks, a better design verification (clash detection), design duration reduction, an earlier and accurate visualisation of design, better design quality, enhanced exchange of information, extract more accurate key performance indicators (KPIs), accuracy and reliability of data, better MEP (mechanical, electrical, and plumbing) analysis, and better integration and communication among disciplines and stakeholders. As a contribution for both scholars and practitioners, the research identified that accuracy data provided by BIM offers an improvement for project management analysis.

Finally, the professionals recognized the risks pointed out by literature that influences 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 professionals, the latter is not presented by Zhao et al. (2017). The results indicate that in practice, engineering firms have faced more risks than stated by the literature.

Limitations and future research

One limitation of this study stems from the number of professionals interviewed. If we had access to more experts, we could have further explored the difficulties and perceptions between BIM, risk management and success dimensions. Moreover, Company D assists the design phase of engineering projects only by design-build contracts. Furthermore, due to the limit team the organisation often subcontracts part of the scope or makes partnership with design companies. Another limitation concerns the methodological approach of the case study, which may limit the generalization of the findings, considering the number of companies studied.

The potential of BIM for sustainability issues is still underused in practice, which suggests empirical studies concerning this topic. In addition, new research comparing the level of concern and BIM adoption from countries that already have regulations and mandates from the government and countries that do not have may be interesting, seeking to understand the influence of public policies in the effective use of BIM.

Acknowledgments

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7 ARTICLE #4 - Building information modeling and its effects on project success and risk management: exploring a cross-country case studies

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Abstract

The effective use of building information modeling (BIM) in the design phase generates countless benefits, which contributes to risk management (RM). However, a better understanding of the relationship between the critical success factors (CSFs) in the design phase has not yet been addressed. This study aims to investigate the influence of BIM CSFs in the design phase in the RM process, exploring the mediating effect played by BIM knowledge, RM knowledge, and BIM maturity. The research design applies the Partial Least Squares Structural Equation Modeling technique, and the variables were collected by a survey with a sample of 195 respondents from different countries. The results pointed out that earlier and accurate 3D visualization of the design was the top-ranked recognized design factor in the use of BIM. The findings also indicated that BIM design CSFs have a positive impact on the RM process. Furthermore, there is a positive and significant indirect effect of BIM knowledge, RM knowledge, and BIM maturity through the path of BIM Design CSF on RM.

Keywords: BIM critical success factors, design phase, risk management.

Status: Submitted at Journal of Construction Engineering and Management.

7.1 Introduction

The design phase defines the necessary information for project implementation, in which decisions can be made to avoid negative impact and rework in the project. At the same time, with the development of new technologies the design phase needs more sophisticated methods, techniques, and a skilled team to face its challenges (Abbasianjahromi et al. 2019). In this scenario, Building Information Modeling (BIM) is sparking more interest in the construction industry, and it is becoming increasingly necessary as technology development drives the continuous transformation of the sector (Won and Lee 2016). According to Lee and Yu (2020), BIM has been developing globally, and governments are proposing guidance and policies for BIM implementation. The Chinese government published in 2015 a set of national standards and regulations related to BIM implementation (Chang et al. 2017). Since 2016, as a construction strategy, the UK government has been requiring fully collaborative 3D BIM capabilities in construction projects (Lam et al. 2017). In Brazil, a decree was published in 2020 requiring the mandatory use of BIM in the construction sector for engineering works and services executed by the federal public administration.

Moreover, BIM has also been worldwide applied to assist early identification and assessment of risks (Lin et al. 2017; Zou et al. 2016). Hwang et al. (2019) found out that BIM has a notable impact on reducing rework by decreasing risk of errors in construction projects. New regulations from the UK government incentivise the integration between BIM and risk management (RM) due to its importance to manage risks successfully (Zou et al. 2017). BIM has brought progress and value to the construction industry (Sun et al. 2020). Nevertheless, it presents different challenges, difficulties, and risks in its implementation (Xu et al. 2018). Zou et al. (2016) describe initiatives already developed through researchers concerning the integration of BIM and RM . However, the literature shows that such integration still has some gaps. According to the research developed by Silva et al. (2021), BIM and RM are widely discussed in the literature; however, specific studies concerning BIM and RM, particularly in the design phase, can be considered as an emerging topic. Likewise, Zou et al. (2017) affirm that despite the rising research trend between RM and BIM, there is a lack of studies integrating both themes. Moreover, RM incorporation into BIM platforms is still a challenge and case studies are very rare in the literature (Zou et al. 2019). The authors pointed out that BIM technology is inefficient in providing and supporting information needed for RM during the project development process, and still lacks the knowledge to analyse risk data within BIM.

Nonetheless, studies related to risks associated with the BIM implementation and their relationship with the critical success factors (CSFs) have presented some gaps. A better understanding of CSFs is necessary to devise appropriate strategies and to conduct essential measures to implement BIM successfully (Antwi-Afari et al. 2018; Ozorhon and Karahan 2017). In addition, the relative importance of CSFs should be investigated considering the different phases of the project life cycle. Previous studies (Chen et al. 2019; Olawumi and Chan 2019; Ozorhon and Karahan 2017; Sinoh et al. 2020; Sun et al. 2020) have focused on providing an overview of the CSFs. However, these studies failed to provide them separately and they do not offer an in-depth understanding of the CSFs in the design phase.

Given this background, this study aims to contribute to fulfilling the discussed research gap by investigating the relationship between the BIM CSFs of the design phase in the RM, exploring the mediating effect on knowledge and maturity.. The literature suggests a potential positive impact; however, there is a lack of quantitative research that confirms these hypotheses. To achieve this objective, first, a comprehensive literature review was conducted to compile CSFs of BIM implementation. These factors were then refined and categorized into the design phase of the project's life cycle, as the importance of the CSFs should be not considered equivalent across the whole project development (Pinto and Slevin 1989). For this study, only design CSFs were considered. Secondly, a questionnaire survey was designed and administered to engineering, construction, and architectural professionals in different countries. Finally, the data were examined for observing the practices and points of view of professionals from different industries in terms of BIM implementation and RM.

Due to the importance of BIM and RM in engineering projects, this research aims at investigating the relation of BIM CSFs and RM practice, exploring the following research questions: (RQ1) Which are the main BIM CSFs in the design phase? (RQ2) Which risks associated with the use and implementation of BIM frequently occur in practice? (RQ3) How do BIM CSFs in the design phase influence the RM process? (RQ4) Do the BIM knowledge, RM knowledge, and BIM maturity have a mediating effect on this relationship?

The article is structured as follows: Section 2 brings in the literature review the main theme concepts. Section 3 describes the exploratory study composed by the survey method. Section 4 and 5 give the results and discussion, respectively. Section 6 brings conclusions.

7.2 Literature Review

BIM CSFs in the design phase

As BIM leads to many challenges, a better understanding of the CSFs is necessary to organize strategies for its implementation (Ozorhon and Karahan 2017). Liao and Teo (2017) reported many studies that described CSFs that could affect BIM implementation, but few have investigated the interrelationship among these factors.

Moreover, the use of BIM is a considerable challenge to the original workflow, process, cooperation, and boundaries of all parties involved in the project. The adoption of BIM technology confronts both technical and non-technical issues (Chan et al. 2019), both vital for adopting BIM (Won et al. 2013).

An essential feature of BIM technology is that it runs through the whole building life cycle, comprising design, construction, and operation (Succar 2009). Each stage requires a high degree of collaboration involving process, culture, and management among all project participants (He et al. 2017; Sun et al. 2020). This study focuses on the design phase, one of the most significant phase in BIM projects accordingly (Lam et al. 2017).

The design phase is one of the most important and critical phases of the project process, Liao et al. (2017) identified 32 CSFs linked to BIM, and Antwi-Afari et al. (2018) proposes 34 CSFs. Although there is no categorisation of the different phases of the project life cycle in both studies, they present valuable CSFs related to the design phase. When evaluating the success of BIM projects, Won and Lee (2016) stated that design changes and insufficient BIM training programs were barriers hindering the successful application of BIM. Lack of knowledge leads to design errors and rework, thus in early phase, the non-technical readiness is more critical than technological readiness (Won et al. 2013).

Indeed, the decisions made at this time of the project are those that have the greatest capacity to influence the other phases (Hossain et al. 2018; Melhado 1994). Moreover, the design phase is exposed to several risks, which can affect the project performance, and BIM is an effective approach to support the design phase to be addressed properly before moving forward with the successive phases (Malekitabar et al. 2016; Othman and Alamoudy 2020). The theoretical framework was oriented by the literature review, which guided the selection and categorisation of the most cited CSFs in BIM design phase (BIMDE) in the literature. Table 1 summarizes the key CSFs in design phase.

Table 1. Critical Success Factors (CSFs): BIM design phase (BIMDE)

Description	**Code**	**Reference**
Earlier and accurate 3D visualization of design	BIMDE1	(Antwi-Afari et al. 2018; Jin et al. 2017; Liao and Teo 2017; Zhang et al. 2017)
Better design/multi-dimensional design alternatives/applications	BIMDE2	(Antwi-Afari et al. 2018; Volk et al. 2014; Zou et al. 2017)
Design coordination on various elements/components	BIMDE3	(Antwi-Afari et al. 2018; Eastman et al. 2011; Jin et al. 2017)
Verification of consistency to the design intent	BIMDE4	(Antwi-Afari et al. 2018; Eastman et al. 2011; Liao and Teo 2017; Zhang et al. 2013)
Predictive analysis of performance	BIMDE5	(Antwi-Afari et al. 2018; Sacks et al. 2010; Wong and Zhou 2015)
Thermal energy analysis and visualization	BIMDE6	(Antwi-Afari et al. 2018; Kim et al. 2015; Lu et al. 2017)
MEP analysis and visualization (HVAC)	BIMDE7	(Antwi-Afari et al. 2018; Sha et al. 2019; Wong and Zhou 2015)
Structural analysis and design	BIMDE8	(Ahmad et al. 2018; Antwi-Afari et al. 2018; Zhang et al. 2013)
Predicting environmental analysis and visualization	BIMDE9	(Antwi-Afari et al. 2018; Gourlis and Kovacic 2017; Lu et al. 2017; Wong and Zhou 2015)
Acoustical analysis and visualization	BIMDE10	(Antwi-Afari et al. 2018; El-Diraby et al. 2017; Lu et al. 2017)
Photorealistic rendering for marketing purposes	BIMDE11	(Antwi-Afari et al. 2018; Hartmann et al. 2012)
Accuracy and reliability of data	BIMDE12	(Ahmad et al. 2018; Antwi-Afari et al. 2018; Ham et al. 2018; Zhang et al. 2013)
Better design quality	BIMDE13	(Cao et al. 2015; Liao and Teo 2017)
Better integration among design disciplines	BIMDE14	(Ghaffarianhoseini et al. 2017; Liao and Teo 2017)
Better communication among design stakeholders	BIMDE15	(Antwi-Afari et al. 2018; Liao and Teo 2017; Succar 2009; Zhang et al. 2017)
Design cost reduction	BIMDE16	(Eadie et al. 2013; Elghaish et al. 2019; Kavuma et al. 2019; Popov et al. 2010)
Design duration reduction	BIMDE17	(Bortolini et al. 2019; Tahir et al. 2018; Wang et al. 2014; Zhou et al. 2015)

BIM and Risk Management

According to ISO (2018), there are several techniques for identifying, analysing, and evaluating projects risks. Backwards risk techniques produced limited statistical data, which were ineffective in practice (Zhang et al. 2014), and decisions are mostly based on existing knowledge, normally inadequate, and previous experience through a brainstorming method (Zou et al. 2016). The standard brings an update on analysis;

however, risk analyses are still performed manually, leading to a need for automation improvement towards a better performance of RM (Ahmad et al. 2018).

Most construction organisations are highly experienced in managing traditional construction projects; however, BIM generates a new process that may involve risk factors that must be managed differently from those of traditional projects (Chien et al. 2014).

BIM is expected to be effective in improving project quality and performance (Tahir et al. 2018), enhancing the creation and management of information throughout the design process (Matthews et al. 2015) supporting architects, engineers, and constructors to identify and anticipate any potential design, construction, or operational issues (Seyis 2019).

With the growing use of BIM in construction, there is a trend to integrate RM into the BIM process for managing, analysing, and visualizing risk information (Zou et al. 2019). Early involvement in BIM projects can reduce issues and threats and offer advantages of its features related to risks identification. Hwang et al. (2019) found out that BIM has a notable impact on reducing rework by decreasing risk of errors in construction projects. Likewise, Volk et al (2014) recognize reasonable advantages in risk mitigation. Regardless of new risks introduced by BIM, (Ahmad et al. 2018) affirm that it eliminates significant risks and enhances RM. In addition, (Hossain et al. 2018) state that BIM is useful in identifying risks and mitigating them early in the design phase. A previous literature review addressed the related issues of how BIM has impacted RM, as summarized in Table 2.

Table 2. BIM and RM

Description	Code	Reference
BIM has a positive impact on risk management	RM1	(Ahmad et al. 2018; Hossain et al. 2018; Lam et al. 2017)
BIM has improved risk identification	RM2	(Ahmad et al. 2018; Ganbat et al. 2018; Li et al. 2018)
BIM has improved the risk response plan	RM3	(Hossain et al. 2018; Zou et al. 2019)
BIM has improved the risk monitoring and control	RM4	(Hossain et al. 2018; Zou et al. 2019)
BIM has been used for data feedback and risk mitigation	RM5	(Ganbat et al. 2020; Othman and Alamoudy 2020; Zou et al. 2017, 2019)

Hypotheses development

There is a lack of understanding of the influence of risks on the potential benefits provided by BIM (Zhao et al. 2017). Silva et al. (2021) pointed out it is an emerging topic that deserves the researchers attention, particularly related to design CSFs and risks associates with BIM. The literature suggests the potential positive impact (Ahmad et al. 2018; Ganbat et al. 2018, 2020; Hossain et al. 2018; Lam et al. 2017; Li et al. 2018; Othman and Alamoudy 2020; Zou et al. 2017, 2019), but there is a lack of quantitative research validating these assumptions. Therefore, the research hypothesis that emerges on this topic relates BIM CSFs in the design phase and positive influence in RM:

H1: The BIM design CSFs (BIMDE) have a positive impact on risk management (RM).

Moreover, BIM implementation itself introduces diverse and complex risks (Ghaffarianhoseini et al. 2017) in the project. The increase in technology and risks in engineering projects leads to new risks that the construction industry must face and look for alternatives that bring advances and better project results. Hence, effective RM is necessary to achieve project objectives. However, the lack of RM knowledge contributes to inadequate RM, still widely practiced, and interferes directly in the project performance. In addition, insufficient RM knowledge is the primary barrier to effective RM (Chien et al. 2014). Hypothesis H2a, we will explore if the risk management knowledge (RM knowledge) has a direct and indirect effect on RM, as stated in H2a and H2a'.

H2a: RM Knowledge positively and significantly direct influences the RM.

H2a': RM Knowledge has a significant positive indirect effect on RM, which is mediated by a positive effect on BIM Design CSF (BIMDE).

Besides, the use of BIM in the design phase comprises diverse challenges, including insufficient knowledge and competence (Arayici et al. 2011; Liu et al. 2015) . Ozorhon and Karahan (2017) reinforce that BIM knowledge was one of the most significant among 16 CSFs for BIM implementation.

Individuals are an integrated component of BIM, which should be capable of handling all aspect of the process including the technical, managerial, and technological (Ozorhon and Karahan 2017). Therefore, insufficient BIM training programs were the barriers hindering the successful application of BIM (Amuda-Yusuf 2018; Won and Lee 2016).

The inconsistency of assignments results in overlapping responsibilities between the Project Manager and the BIM Manager (Rahman et al. 2016). Hosseini et al. (2018) believe that the role of the BIM Manager is temporary and will be absorbed by the Project Manager in the future; however, Bosch-Sijtsema and Gluch (2019) reinforce the thesis that the role of the BIM Manager remains critical.

Although the BIM knowledge subject and its impact have already been discussed in the literature, its influence on Design CSFs and RM is still lacking. Therefore, we suggest the following hypothesis:

H2b: BIM knowledge positively and significantly direct influences the RM.

H2b': BIM Knowledge has a significant positive indirect effect on RM, which is mediated by a positive effect on BIM Design CSF (BIMDE).

Finally, we explore the influence of BIM maturity in the research model. Succar and Kassem (2015) divide BIM implementation into three phases: BIM readiness, BIM capability, and BIM maturity. The first phase is related to the organization's level of preparation, the potential to participate and capacity to innovate, which describe the pre-implementation status. The second phase involves the organization's capability concerning technology, process, and policy topics; and the third phase BIM maturity is recognized as the gradual improvement in quality, repeatability, and predictability within available capabilities. Each level provides a significant enhancement to the capability in the performance of a process (Joblot et al. 2019) and can support the organization in identifying priorities for improving the BIM implementation process (Siebelink et al. 2018).

Because of its relevance, the BIM maturity phase is an object of this study, which is classified into levels (Barlish and Sullivan 2012; BIM Task Group 2011; Succar 2009) and includes *BIM Level 0*: low collaboration (projects developed in 2D); *BIM Level 1*: partial collaboration (file-based collaboration); *BIM Level 2*: full collaboration (file-based collaboration & library management); and *BIM Level 3*: full integrated (interoperable data). The scale represents the extent to which the company managed to change and adapt its processes reaching the performance required to achieve BIM implementation effectively.

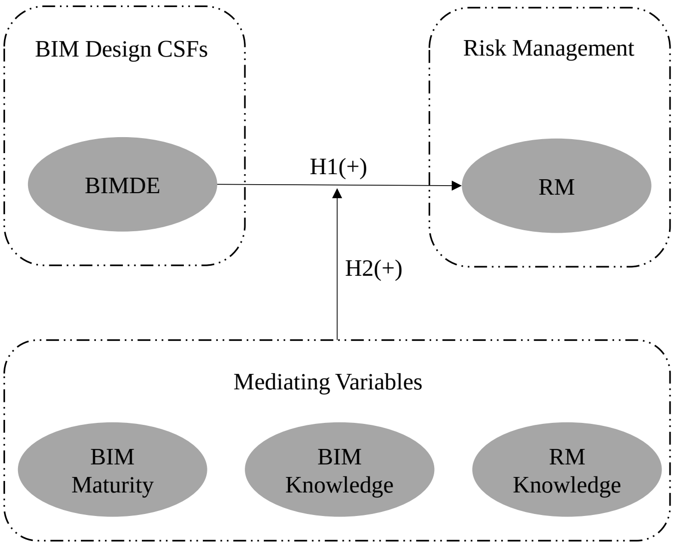
Considering existing challenges in BIM implementation, the organizational maturity level can influence its quality and performance. However, it is unknown whether BIM maturity affects BIM design CSFs and RM. It leads to the research hypotheses emerges H2c.

H2c: BIM maturity positively and significantly direct influences the RM.

H2c': BIM maturity has a significant positive indirect effect on RM, which is mediated by a positive effect on BIM Design CSF (BIMDE).

Then, it is possible to propose the following structural model, according to Fig. 1.

Fig.1. Research model



7.3 Research Method

The research applies a survey approach, developed in two phases: first, an in-depth literature review ground the research model, hypothesis, and questionnaire. The second phase was data collection via online survey-based research. Then, the structural equation modelling was applied to validate the research model and hypotheses.

Data collection

In line with the conceptual basis derived from the literature review discussed in Section 2, a survey was designed to evaluate the impact of the BIM CSFs in the design phase on RM. The questionnaire was structured and established to draw out the necessary data from the respondents in a direct, clear, and synthetic way. The reliability and validity of the survey questionnaire were addressed through a pilot study conducted with six professionals, being three architects, and three engineers, all of them has solid knowledge on the subject and experience in construction or engineering projects. Upon completion of the pilot test, respondent recommendations improved the clarity of language and questions comprehension. Based on the proposed aim, the questionnaire was developed in five main sections: (1) general information, (2) the use of RM in the company's project, (3) the use of BIM in the company's project, (4) BIM design CSFs (BIMDE) and (5) BIM impact on RM.

As presented in Section 2, literature review, we developed a measurement model for BIM Design CSFs (BIMDE) with 17 manifest variables (indicators) adapted from Antwi-Afari et al. (2018) and other references, as discussed in Table 1. For RM, we identified five variables in the literature (Ahmad et al. 2018; Ganbat et al. 2018, 2020; Hossain et al. 2018; Lam et al. 2017; Li et al. 2018; Othman and Alamoudy 2020; Zou et al. 2017, 2019), as shown in Table 2. The respondents evaluated a statement formulated to be answered on a seven-point Likert perception scale ranging from strongly disagree to agree strongly.

For BIM Knowledge, RM Knowledge, and BIM maturity, the questions were categorical, and the respondent must choose one alternative among the four available. For this study, the alternatives were simplified into three categories. Table 3 shows the structure of the research instrument composed of 25 questions.

Table 3. Research questionnaire

Latent Variables	Codes	Manifest Variables	Scale	Response Options
BIM design CSFs	BIMDE	17 statements	Likert	7 points
Risk Management	RM	5 statements	Likert	7 points
RM Knowledge	RM knowledge	1 statements	Categorical	3 alternatives
BIM Knowledge	BIM knowledge	1 statements	Categorical	3 alternatives
BIM maturity	BIM maturity	1 statements	Categorical	3 alternatives

The survey sampling process was carried out through professionals from engineering, construction, and architecture from AEC industry, academia, and other industries from different countries. The survey was disseminated online through the SurveyMonkey® platform, and data were collected between May 2020 and August 2020.

Variables Operationalization

The measurement model follows the conceptual reasoning previously discussed (Hair et al. 2012) and empirical test were performed to decide between the formative and reflective measurement models (Coltman et al. 2008). The latent variables were designed as first-order deployed in reflective indicators. Both research measurement model of the independent latent variable BIMDE and the dependent latent variable, RM are reflective.

BIM knowledge, RM knowledge, and BIM maturity were categorical variables. These nominal variables were operationalized as dummy variables, consistent with Falk and Miller (1992). Therefore, a value equal to 1 was attributed to the professionals that belonged to the same category, and 0 to all the other categories, as detailed in Table 4.

Data Analysis

Common Method Bias (CMB)

Common method biases can have potential effects on research findings owing to independent and dependent variables are measured at the same time using the same sources (Liang et al. 2007), social, personal, and behavioral characteristics of the respondents, survey design structure, context of the topic and any artifactual covariation produced from the context in which the measures are obtained (Podsakoff et al. 2003).

Addressing CMB must start at the research design phase (Guide and Ketokivi 2015). According to Chang et al. (2010), to avoid or minimize CMB it is important to collect measures for different constructs from different respondents, have a strategy to develop and manage the questionnaire, adding complexity such as mediating, moderating and/or non-linear effects in the model, and evaluate CMB by statistical analyses.

Research Model validation

The data collected were processed and analysed statistically using the multivariate statistical approach of Structural Equation Modeling (SEM) with Partial Least Squares estimation (PLS), and performed using Smart PLS3 software. This study was based on the research of Ringle, Silva e Bido (2014).

SEM is a multivariate statistical technique that allows hypotheses and theories to be tested among constructs and variables (Kline 2015) including confirmatory factor and path analysis simultaneously (Liao and Teo 2017). SEM offers advantages in terms of (1) allowing the simultaneous use of several indicator variables per construct for valid conclusions on the construct level, (2) offering a confirmatory approach, (3) allowing for the modeling and testing of complex patterns of relationships, including simultaneously testing a large group of hypotheses, and (4) providing conclusions about relationships between constructs unbiased by measurement error (Werner and Schermelleh-Eagel 2009). SEM can either be partial least squares based (PLS-SEM) or covariance based (CB-SEM). The basic difference between both is in the way they treat data (Ringle et al. 2014). Xiong et al. (2015) define PLS-SEM as a “soft” and component-based modelling technique involving less strict inherent model assumptions, where the sample size is relatively small, and/or the available data is non-normal (Hair et al. 2012). The advantages of PLS-SEM include flexibility, robustness, and fewer demands concerning distributional assumptions (Kline 2015). Liao and Teo (2017) indicate that Partial Least Squares (PLS) has been used by a large number of researchers from project management, and the use of PLS-SEM in this study was chosen due to the sample size, the complexity of the model (many indicators) and the absence of multivariate normality of the data (Bido and Da Silva 2019).

The measurement model for both the independent and dependent latent variables, BIM *design* CSFs (BIMDE) and *risk management* (RM), are designed in a reflective way. In contrast, the mediating variables (*BIM knowledge*, *RM knowledge*; and *BIM maturity level*) are characterized in a formative model. According to Hair et al (2020), construct indicators of a reflective model are assumed to be influenced by and seen as a function of the latent variable. In contrast, the indicators of a formative model are viewed as causing rather than being caused by the underlying latent construct Coltman et al. (2008) present an interesting study concerning theoretical and empirical considerations for choosing between formative and reflective measurement models. The theoretical aspects discussed in the study are the nature of the construct, the direction of causality, and the characteristics of the indicators, while the empirical ones are the indicators' intercorrelation, the indicators' relationships with the constructs, measurement error, and collinearity.

Xiong et al. (2015) state that it is important to validate the characteristics of data. The validation process includes internal consistency, indicator reliability, convergent validity, discriminant validity, and nomological validity (Padovani and Carvalho 2016). Ringle et al.(2014) suggest first observing the convergent validities of the measuring model, obtained by the average variance extracted (AVE), which is the average of the factorial loads squared. The value of AVE should be greater than 0.50 to affirm that the model converges with a satisfactory result (Fornell and Larcker 1981; Hair et al. 2017). The internal consistency values Cronbach's Alpha (CA) and Composite Reliability (CR), which are used to evaluate if the sample is free of biases and if it is reliable, should both exceed 0.70 (Hair et al. 2017). According to Hair et al. (2020), there is a difference concerning reliability between both indicators. Thus, composite reliability, which is weighted, should be also evaluated as it is more accurate than Cronbach alpha (unweighted). Furthermore, discriminant validity is supported when there is a low correlation between variables of different constructs (Lee and Yu 2020), and it is established when the shared variance within a constructs' (AVE) goes beyond the shared variance between the constructs (Hair et al. 2020). Lastly, nomological validity refers to the correlation of the constructs score with different but related constructs in the nomological network (Hair et al. 2020).

We explore mediating effects in the research model, assessing the direct and indirect effects on SmartPLS software, following the procedures suggested by Zhao et al. (2010) and Nitzl et al. (2016), which includes the mediator into the model to investigate both full mediation (only indirect effect is significant) and partial mediation (direct effect is significant).

7.4 Research results

This section presents the results of the survey demographics, reliability test, and findings of the SEM.

Demographics

The survey resulted in 195 valid samples of professionals employed in the AEC industry (65%), academia (27%), and other industries (8%) in different countries. Although 27% of the respondents indicated that they are employed in academia, most of them pointed out that they hold positions with a link to the engineering sector. Therefore, we believed that the experience of these respondents would bring contributions to the research. Most of these professionals declared have an MBA or specialist diploma (29%), followed by MSc (26%), Ph.D. (25%), and bachelor (18%). In addition, 37% have over 20 years of work experience.

Regarding BIM and RM level of knowledge, the respondents affirmed having none or basic level (45% and 55% respectively). Considering BIM maturity, most respondents pointed out partial collaboration (42%). These data indicate that few professionals have come across these concepts and that there is a lack of knowledge in the engineering field. It also confirms the importance of studies relating to improvement and investments in BIM and RM knowledge and skills. BIM Knowledge, RM Knowledge, and BIM Maturity are dummy variables. According to Falk and Miller (1992), any category might be used as a reference; thus, in our study, we selected the most often point category as a reference (see Table 4).

Table 4. BIM knowledge, RM knowledge and BIM maturity operationalization through dummy formative indicators

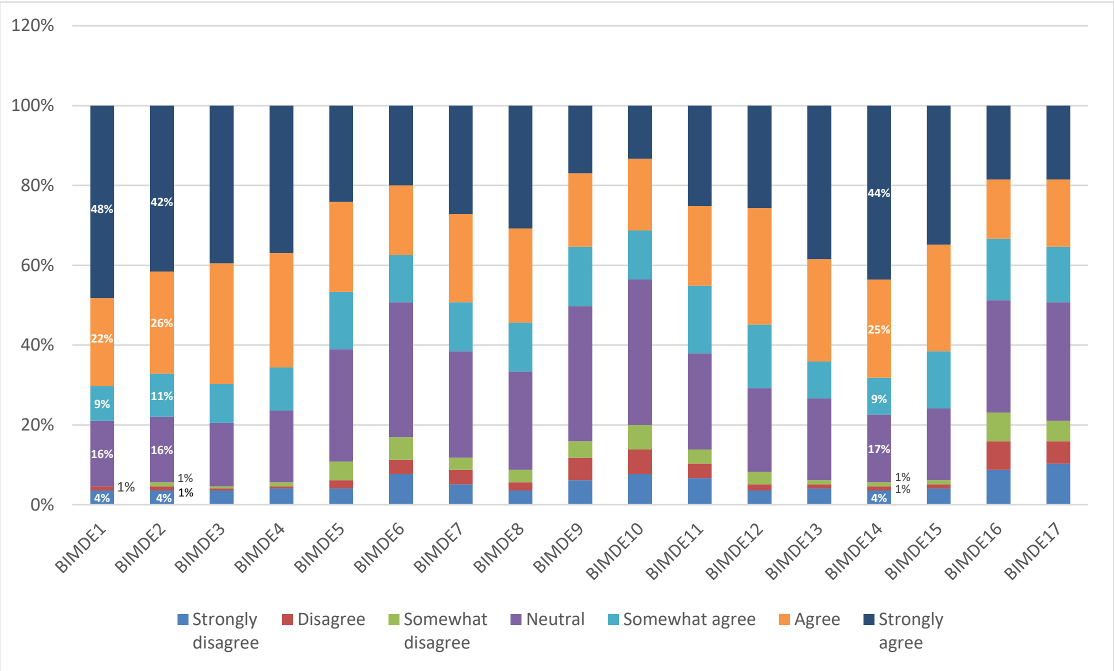
BIM knowledge	D_IN	D_AE	n	%
none/basic*	0	0	88	45%
intermediate	1	0	57	29%
advanced/expert	0	1	50	26%
RM knowledge	D_IN	D_AE	n	%
none/basic*	0	0	108	55%
intermediate	1	0	46	24%
advanced/expert	0	1	41	21%
BIM maturity	NON_COLL	FULL_COLL	n	%
non collaboration	1	0	54	28%
partial collaboration*	0	0	81	42%
full collaboration	0	1	60	31%

Note: * Reference categories are the most often point category

Regarding BIM design CSFs, graphic 1 illustrates that *earlier and accurate 3D visualization of design* (BIMDE1) was the top-ranked recognized factor in the use of BIM (48%), followed by *better integration among design disciplines* (BIMDE14) and *better design alternatives and applications* (BIMDE2), with 44% and 42%, respectively. Survey participants strongly agreed that the use of BIM enhances the accuracy of design information. This could be attributed to the fact that BIM contributes to a better design representation and better project quality. BIM allows for an effective evaluation of the project's performance, which supports decision making and improves the effectiveness of collaboration. In the design phase of a multidisciplinary project, each discipline can include or update the information contents of their models at different stages. Therefore, an integrated environment allows issue identification in advance, reducing project errors and, consequently, reducing risks. It also provides reliable and real-time information that makes the project's process more practical and efficient. BIM provides coordinated design and opens communication channels to all project design disciplines (Hwang et al. 2019).

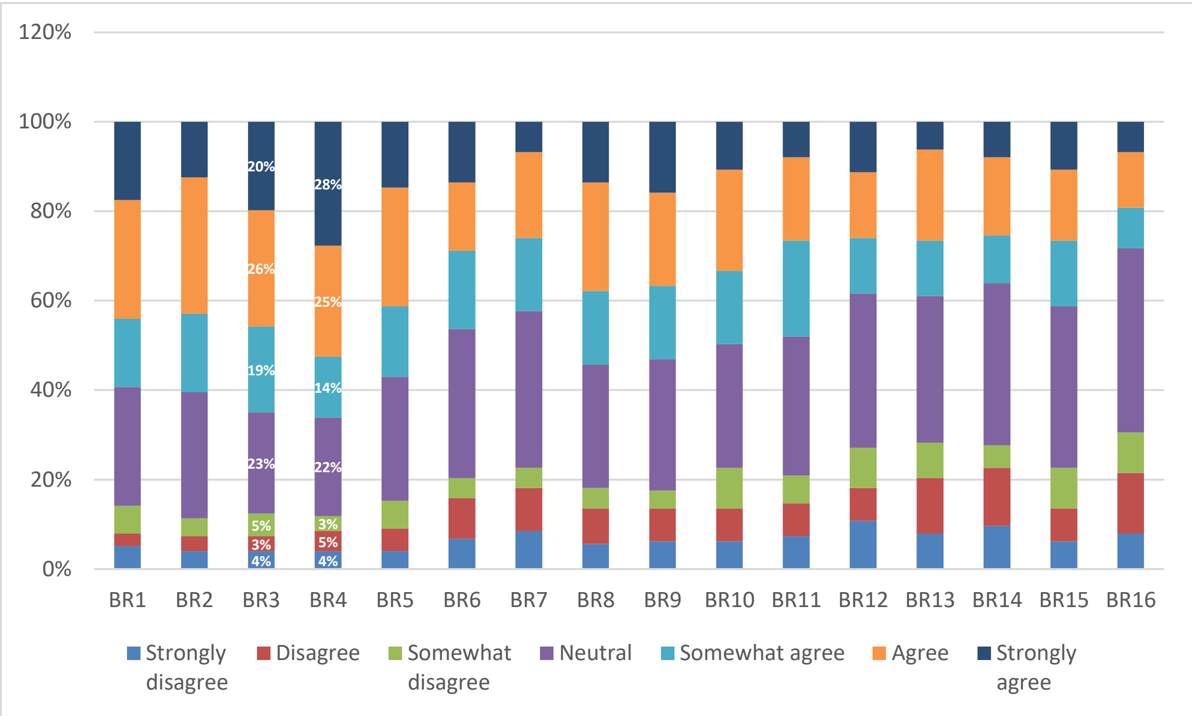
In turn, the factors that the respondents most strongly disagree with were that the use of BIM has enhanced *design cost reduction* (BIMDE16) and *design duration reduction* (BIMDE17). Engineering companies still tend to not implement BIM effectively, especially small to medium-sized enterprises (SMEs), since they have difficulties adapting to a new process inquired by BIM. Additionally, most SMEs have a tight budget to support the investment demanded from BIM implementation, and present a low return on business (Ghaffarianhoseini et al. 2017). Difficulties involving the lack of professionals' skills and experience are the main concerns that tend to affect project performance. Research conducted by Kavuma et al. (2019) indicated that BIM-related factors were the most critical factors on the project in terms of causing time overruns. Lack of knowledge and training is also critical, concerning increased design cost and duration in BIM projects (Tan et al. 2019). As the organization progresses in its BIM effective implementation process, the expectation would be that BIM would not cause cost and time overrun for the design phase, due to experience and the similar nature of project settings (Poirier et al. 2015). However, according to the respondents, there are companies that have not yet reached the benefit of cost and duration reduction provided by the use of BIM. Considerable attention and investments in these factors are required to overturn this scenario and promote positive trends concerning cost and duration reduction, and consequently leading to a positive impact on project performance. (Silva et al, 2021).

Fig. 2. Distribution of answers to the question: In the design phase, do you agree that BIM adoption has enhanced each CSF listed below?



Considering the risks associated with the use and implementation of BIM, *cultural resistance* (BR4) was the most recognized, followed by *inadequate relevant knowledge* *or expertise* (BR3). The use of BIM demands a new project process, and some engineering companies still have resistance to adapting to new ways of working. To implement an organizational change, it is necessary to ensure that the professionals are qualified and can adapt to the change. Moreover, a lack of relevant expertise may even undermine BIM practices (Liao and Teo 2018). Inadequate knowledge and expertise also contribute to issues related to information quality, collaboration, technological interface, and data compatibility (Zhao et al. 2017). As a potential mitigation strategy, it is reasonable to develop comprehensive standards and introduce training and education programs to provide relevant knowledge and expertise to the professionals. Furthermore, Liao and Teo (2018) state that for an effective BIM implementation a supportive culture in the project organization is essential and, without sufficient knowledge and expertise among the professionals, BIM implementation might not be successful.

Fig. 3. Distribution of answers to the question: Concerning the following risks associated with the use of BIM, do you agree that they frequently occur in the projects developed by the company?



Measuring Model Evaluation

The validation of the model involved the same steps as those described in section 3.3. Only one round was needed to validate the measurement model and there was no need to exclude any indicator for model validation. Table 5 summarizes all parameters used in the validation process for the latent variable BIM design CSFs and RM.

According to the reliability analysis results, the suggested Cronbach's alpha coefficient of the measurement model indicates a relatively high overall reliability, which should be higher than 0.70 (Hair et al. 2017) Furthermore, the values presented for AVE and composite reliability likewise attend the evaluation criteria, which expected values higher than 0.5. These results suggest that all the validation criteria for internal consistency and convergent validity for the model were satisfied.

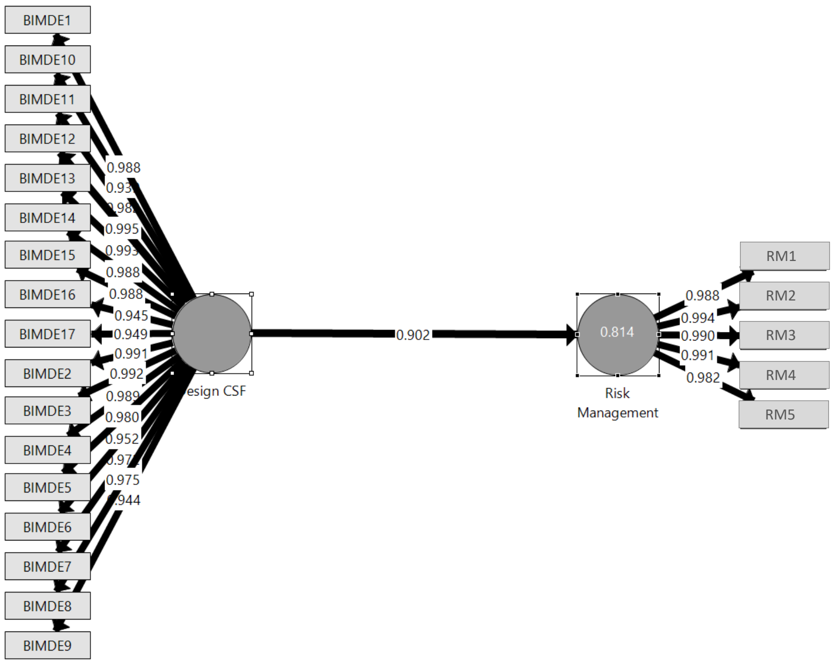
Table 5. Measurement model evaluation

	Design CSF	Risk Management	
Design CSF	0.974		
Risk Management	0.902	0.989	
Composite Reliability (CR)	0.997	0.996	>0.7
Average Variance Extracted (AVE)	0.949	0.978	>0.5
Cronbach's Alpha	0.997	0.996	>0.7

Note 1: The numbers in the diagonal contains the AVE square root. and all values higher than |0.08| are significant at the 1% level.

The discriminant validity was performed analysing the square root of the AVE of the latent variables, which should be higher than its highest correlation with them (Henseler et al. 2009; Xiong et al. 2015). The results in Table 5 show that the square root of the AVE is higher than the correlation among variables; hence, the discriminant validity was achieved, and the model quality is acceptable. The results of the final model applied to the PLS are shown in Fig. 4.

Fig. 4. Research model results



Structural Model Evaluation

For the structural model evaluation, the coefficient of determination (R^2 value) was used to assess the predictive accuracy of the model. R^2 values range from zero to one, and are described as substantial, moderate, or weak (0.75, 0.50, or 0.25, respectively) (Hair et al. 2011). The higher the R^2 value, the higher the predictive accuracy, therefore an R^2 value of 0.814 is considered substantial. Another predictive validity is evaluated through the effect size (f^2), which indicates the impact of each exogenous variable on endogenous variables in the structural model (Hair et al. 2017). This coefficient is also considered high ($f^2 = 4.378$) according to the criteria presented by Cohen (1988): $0.02<f2\leq0.15$ (small effect); $0.15\leq f2<0.35$ (medium effect); and $f2\geq0.35$ (large effect). The constructs' path coefficients were analysed through bootstrapping, a resampled technique used to evaluate the significance (p-value) of the correlations (measuring models) and the regressions (structural model) (Ringle et al. 2014), and which was conducted for 5,000 iterations. Thus, evaluating the statistical significance of the model path, the t-value, and p-value, Table 6 shows that RM is statistically and positively impacted by the design CSFs, which suggests that hypothesis H1 is valid.

Table 6. T-values and p-values for the path model

	Hypothesis	fSquare	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (|O/STDEV|)	P Values	R Square
Design CSF -> Risk Management	H01	4.378	0.902	0.902	0.019	47.693	0.000	0.814

Additionally, the blindfolding was used to calculate the predictivity validity (Q^2), in which were obtained the values of redundancy and commonality, used in the analysis proposed by Ringle et al. (2014). For evaluation criteria, values are considered adequate when greater than zero and it can variate from 0 < Q2 < 1, being the lowest a model with no relevance and the highest, a model that reflects the reality, without errors. The values are presented in table 7.

Table 7. Redundancy and Commonality between constructs

	Redundancy	Communality
Design CSF		0.941
RM	0.789	0.956

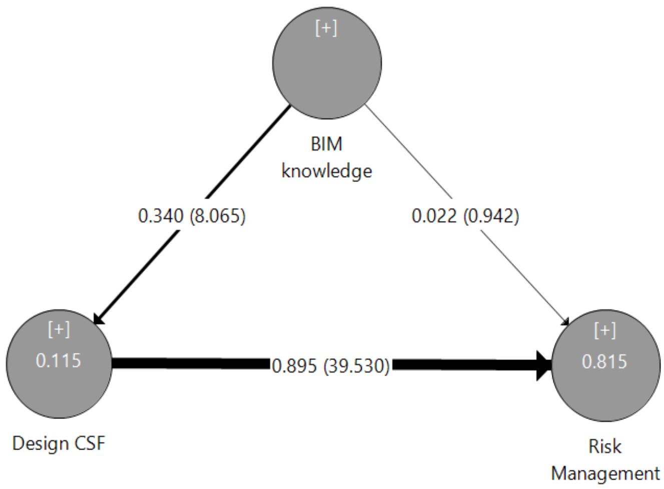
Evaluation for the dummy variables

For the dummy variables (BIM maturity level, BIM knowledge, RM knowledge), each category was coded as variable formative measurement model, which was later modelled as a formative indicator (Falk and Miller 1992). Each dummy variable was linked to the dependent latent variable to evaluate a possible exhibition of endogeneity (Hult et al. 2018). Moreover, the dummy variables were linked to the independent variable to explore direct and indirect effects, towards identifying mediating effects through the path of Design CSF on RM (Table 8). It is worth noticing that the indirect effect of all mediating variables has a positive and significant effect (Table 8). The bootstrapping results for the moderating variables are shown in Fig. 5, 6, and 7.

Table 8. Models Effect Analysis

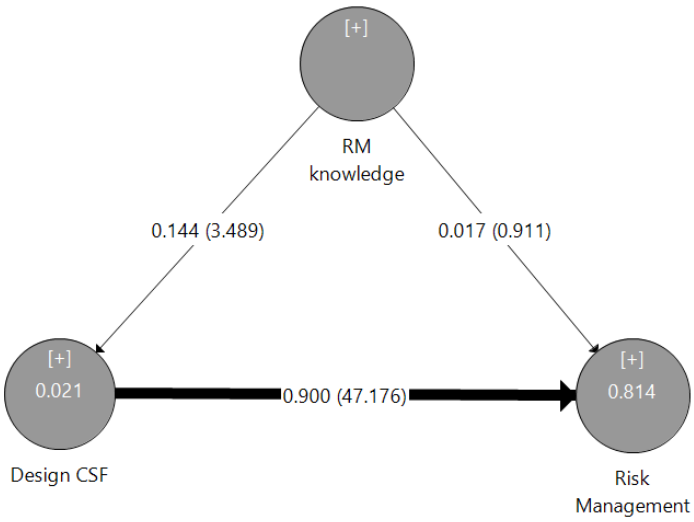
Effects	Path	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (|O/STDEV|)	P Values
Model 2						
Direct	BIM knowledge -> Risk Management	0.022	0.022	0.023	0.942	0.346
	Design CSF -> Risk Management	0.895	0.895	0.023	39.530	0.000
Indirect	BIM knowledge -> Design CSF -> Risk Management	0.304	0.307	0.038	7.987	0.000
Total	BIM knowledge -> Risk Management	0.325	0.329	0.044	7.334	0.000
	Design CSF -> Risk Management	0.895	0.895	0.023	39.530	0.000
Model 3						
Direct	Design CSF -> Risk Management	0.896	0.896	0.019	46.158	0.000
	RM knowledge -> Risk Management	0.018	0.019	0.020	0.906	0.365
Indirect	RM knowledge -> Design CSF -> Risk Management	0.130	0.136	0.037	3.466	0.001
Total	Design CSF -> Risk Management	0.900	0.900	0.019	47.176	0.000
	RM knowledge -> Risk Management	0.147	0.154	0.042	3.542	0.000
Model 4						
Direct	BIM Maturity -> Risk Management	0.022	0.023	0.044	0.497	0.619
	Design CSF -> Risk Management	0.885	0.885	0.042	21.191	0.000
Indirect	BIM Maturity -> Design CSF -> Risk Management	0.676	0.676	0.043	15.873	0.000
Total	BIM Maturity -> Risk Management	0.698	0.700	0.031	22.234	0.000
	Design CSF -> Risk Management	0.885	0.885	0.042	21.191	0.000

Fig. 5. Research Model 2: BIM knowledge



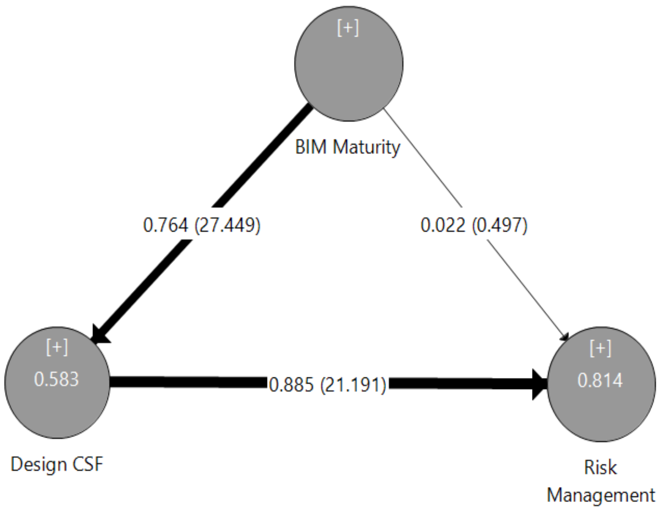
Note: Arrow path (t-student)

Fig. 6. Research Model 3: RM knowledge



Note: Arrow path (t-student)

Fig. 7. Research Model 4: BIM maturity



Note: Arrow path (t-student)

Discussion

The analysis of the model confirms the positive influence of BIM CSFs in the design phase in RM (H1). When implemented effectively, BIM can create opportunities to reduce threats and improve accuracy and communication, such as early risk identification with 3D visualization, identification of conflicts in the model through clash detection, better communication, and integration among designers. Furthermore, BIM contribution in RM is also related to cost estimation, coordination, planning, and quality. BIM provides a reduced misuse of resources and project delay through monitoring and controlling processes (Othman and Alamoudy 2020). Additionally, BIM can be used as an RM tool and an enabler to allow other BIM-based tools to carry out additional risk analysis (Zou et al. 2017).

The model also presents a positive and significant indirect mediating effect of BIM maturity, BIM knowledge, and RM knowledge through the path of Design CSF on RM. In a study conducted by Hosseini et al. (2016) regarding the CSFs of RM, the results showed that education and training subjects were the second most important factors and were strongly linked with the awareness and knowledge of the RM process.

Indeed, knowledge and expertise were recognized as a highly ranked CSF, concerning effective RM process in construction companies (Shayan et al. 2019; Zhao et al. 2013).

Moreover, collaboration, integration, and effectiveness of information sharing are other examples considered CSFs in BIM implementation. However, a lack of BIM knowledge can directly influence information sharing, collaboration, and technological issues creating risks (Zhao et al. 2017), and suggesting as influence in the design phase.

Consequently, the organization must be aware of CSFs and be prepared to implement the process effectively (Abbasianjahromi et al. 2019). Morlhon et al. (2014) complement that when the relevant challenges are known in advance, they can be treated separately, which contributes to better preparation for BIM execution. However, better implementation and use of BIM also depends on the maturity level of each organization. Companies also face, during BIM implementation, barriers across different organizational levels, which are related to different degrees of BIM maturity (Siebelink et al. 2021). Research conducted by Van Roy and Firdaus (2020) showed that BIM knowledge problems were the high ranked barriers to BIM implementation, and most respondents indicated that they apprehend BIM as a collaboration concept but are not familiar with the BIM maturity level. It is worth noticing that a low level of knowledge and ability to implement BIM may also compromise competitiveness and lead to a decrease of efficiency in projects results. Indeed, practice shows that inconsistency of BIM maturity level influences the effectiveness of its implementation. Furthermore, a better understanding of this topic can prioritize actions and needs to be developed towards a wider BIM implementation.

In consequence, the role of a BIM manager has emerged to oversee project information models, clarify constructability issues combining efforts of different stakeholders, and bring together data, drawings, and schedules associated with the design and construction project phases. According to Merschbrock and Munkvold (2015), a BIM manager is engaged to disseminate BIM knowledge and facilitate BIM use, which can contribute to better management and implementation of its processes. Additionally, BIM managers can supplement the lack of BIM expertise within the role of project manager handling information, people, and the model itself (Hosseini et al. 2018).

7.5 Conclusion

This research's contributions to an emerging theme in the literature in three folds. First, it sought to identify the main BIM CSFs in the design phase approach pointed out by the professionals involved in construction and engineering projects. The result reveals that earlier 3D visualization of design enhances the accuracy of the information and enables issues identification in advance. Furthermore, most professionals agree that cultural resistance and lack of BIM knowledge or expertise are the main risks in practice associated with BIM implementation and use and BIM.

Second, the development of maturity and growing use of BIM in the project design phase leads to new opportunities to improve RM and the study suggests the acceptance of H1. The validated model indicated a significative and positive impact of BIM CSFs in the design phase on RM.

Third, the results demonstrated the influence of RM knowledge (H2a'), BIM knowledge (H2b'), and BIM maturity (H3c'), presenting a mediating effect in the relationship between the latent variables. The effective use of BIM in the design phase positively influences RM; however, BIM comprehends technology, process, and people, involving a significant influence of factors and variables related to knowledge and maturity.

Limitations and future research

This study presents certain inherent limitations as the sample is composed predominantly of Brazilian professionals with unbalance sample relating to other countries presenting geographical limitations on the findings. Furthermore, the categorization of the CSFs of the design phase was oriented by the literature review conducted by this article's authors and can have some bias based on the authors 'knowledge and perception regarding the topic'.

With the increased use of BIM across the construction sector there is a need for BIM managers role. BIM requires profound changes in work teams and the corporate organization chart. However, the BIM knowledge gap brings issues related to technical and management features. For future research, an in-depth study of the barriers linked to the project manager and BIM manager roles approach is recommended, as an effective BIM implementation relies more upon people than on the technology itself. Moreover, both roles share several similar skills and are involved in management practices.

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APENDIX

QUESTIONNAIRE 1 (ARTICLE 2)

O Panorama da Gestão de Riscos em Projetos de Engenharia I The Risk Management Overview in Engineering Projects

Bem-Vindo(a) à pesquisa! / Welcome to the Survey!

Este questionário faz parte de uma pesquisa de doutorado em andamento, realizado pela Escola Politécnica da Universidade de São Paulo. Possui objetivo de avaliar a atuação da gestão de riscos no ambiente profissional.
A sua participação é voluntária e anônima.
Desde já agradecemos muito pela sua colaboração!

This questionnaire is part of a PhD research developed at Polytechnic School of University of São Paulo. It aims to evaluate the performance of risk management in the professional environment.
Your participation is voluntary and anonymous.
Thanks in advance for your contribution!

* 1. Eu prefiro responder a survey em/ I prefer to answer this survey in:

- ◯ Inglês/English
- ◯ Português/Portuguese

O Panorama da Gestão de Riscos em Projetos de Engenharia I The Risk Management Overview in Engineering Projects

About the Respondent

The first part of this Survey is composed of some personal questions and will give us the understanding about who are you, within the context of risk management.
Later, we will analyze whether it is possible to establish some correlation between your knowledge and the practice of Risk Management.

2. Where are you from? (Country)

3. How old are you?

4. Gender

- Male
- Female

5. Educational Level

- Technician
- Graduate
- Specialist
- MSc
- PhD
- Post-Doctor
- Other (please specify) :

6. What is your professional education?

- ◯ Architect and Urbanist
- ◯ Civil Engineer
- ◯ Mechanical Engineer
- ◯ Industrial Engineer
- ◯ Engineer (other)
- ◯ Technical Level
- ◯ Administrator
- ◯ Economist
- ◯ Other (please specify) :

7. How long have you been graduated in the profession above?

- ◯ Less than 1 year
- ◯ 1 to 5 years
- ◯ 6 to 10 years
- ◯ 11 to 15 years
- ◯ 16 to 20 years
- ◯ 21 years or more

8. What is your current activity area?

Design development (technical team)

Planning

Management and Coordination

Administration

Production

Production Management

Academic Area

R&D

Other (please specify) :

9. What is your current position?

Director

Manager

Coordinator

Consultant

Engineer

Architect

Analyst

Technician

Designer

Draftsman

Researcher

Other (please specify) :

10. Experience period in the position informed above:

Less than 1 year

1 to 5 years

6 to 10 years

11 to 15 years

16 to 20 years

21 years or more

11. Which professional area segment?

- ◯ Agriculture, forestry and fishing
- ◯ Mining and quarrying
- ◯ Manufacturing
- ◯ Electricity, gas, steam and air conditioning supply
- ◯ Water supply; sewerage, waste management and remediation activities
- ◯ Construction - Construction of buildings
- ◯ Construction - Civil engineering/heavy construction
- ◯ Construction - Specialized construction activities
- ◯ Wholesale and retail trade; repair of motor vehicles and motorcycles
- ◯ Transportation and storage
- ◯ Accommodation and food service activities
- ◯ Information and communication
- ◯ Financial and insurance activities
- ◯ Real estate activities
- ◯ Professional, scientific and technical activities
- ◯ Administrative and support service activities
- ◯ Public administration and defense; compulsory social security
- ◯ Education
- ◯ Human health and social work activities
- ◯ Arts, entertainment and recreation
- ◯ Other service activities
- ◯ Activities of households as employers;undifferentiated goods- and services-producing activities of households for own use
- ◯ Activities of extraterritorial organizations and bodies
- ◯ Other (please specify) :

12. Do you have any certification in project management or risk management?

- ◯ Yes, PMI-PMP Certification
- ◯ Yes, PMI-RMP Certification
- ◯ Yes, ISO 31000 Certification
- ◯ I do not have one
- ◯ Other (please specify) :

O Panorama da Gestão de Riscos em Projetos de Engenharia I The Risk Management Overview in Engineering Projects

About your Risk Management Knowledge

The second part of this Survey is composed of some questions to analyse your knowledge regarding risk management, and how you use it .

24. In relation to risk management, how do you classify yourself?

- Professional Expert
- Professional with knowledge above the average
- Professional with basic knowledge
- Professional with little knowledge
- It is not my expertise area

25. How did you learn Risk Management?

- Certification Preparatory Course
- Postgraduate or MBA
- MSc
- PhD
- By myself
- At Work
- University
- I have never learnt such knowledge
- Other (please specify) :

26. Have you ever worked with risk management?

- Yes, I have worked as the responsible for risk management or for managing a specific risk
- Yes, I have worked as collaborator in risk management or in managing a specific risk
- Yes, I have worked with risk management, but indirectly. Some stakeholders or colleagues from my area worked with risk management.
- No, I have not.

O Panorama da Gestão de Riscos em Projetos de Engenharia I The Risk Management Overview in Engineering Projects

Experiences and/or perceptions about Risk Management

The third part of this Survey is composed of some questions about your experiences and/or perceptions about Risk Management, and will give us an overview about risk management within the professional areas and how it is used in engineering projects.

30. If you have already worked with risk management, when was the first time? (Report the year)

31. If you have already worked with risk management, for how long (in total) have you worked? (Report in years)

32. If you have already worked with risk management, what is the origin of the company's capital in which you have worked with it? If there are more than one, please mark multiple origins

South America

Brazil

Europe

France

England

Germany

North America

Central America

Asia

Africa

Oceania

33. What could be a good reference in risk management method?

ISO 31000

IPMA (International Project Management Association)

PMBoK

I do not know

Other (please specify) :

34. In your opinion, could the reference method mentioned above, fail to consider any relevant risk through the process of risk identification?

- Yes
- No
- I do not know

35. According to your experience, was there any situation in which disregarded or underestimated risks were responsible for unsatisfactory results in the project?

- Yes
- No
- I do not know

36. In case of "Yes" in the previous question, which was (were) the risk(s)?

Technical risks

Project Management risks

Organizational risks

External risks

Compliance

Other

37. Which were the main consequences? Select multiple if required

Schedule delay

Cost increased

Scope Change - reduction

Loss of quality

Project interruption/cancellation

Demaged reputation to the client

Social or Environmental Impact

Other (please specify) :

38. According to your experience, was there any situation in which disregarded or underestimated risks were responsible for satisfactory results in the project?

Yes

No

I do not know

39. In case of "Yes" in the previous question, which was (were) the risk(s)?

Technical risks

Project Management risks

Organizational risks

External risks

Compliance

Others

40. What were the main consequences? Select multiple if required

- Schedule anticipation
- Cost reduction
- Better technical performance of the team, in comparison to the original scope
- Improved reputation to the client
- Reduction of Social or Environmental Impact
- Other (please specify) :

41. In your opinion, sharing experience in risk management can help to improve the performance of project management?

- Yes
- No
- I do not know

42. Based on your own experience, how significant are the risks generated by project management failures?

- Not Significant
- Reasonably Significant
- Very Significan
- I do not know

43. In your opinion, how accessible is risk management information for study or learning?

- Very accessible
- Reasonably accessible
- Not very accessible
- I do not know

44. What are the main strategies used in your company to respond to risks?

Avoid risk - Not initiate or stop an activity

Remove risk's cause

Change risk's probability

Change risk's consequences

Share risk with stakeholders

Retention of risk by a conscious and well-informed decision

Acceptance or Increase of risk to benefit from opportunity

I do not know

My company does not use it

Other (please specify) :

45. Classify the tools for risk analysis, according to your degree of knowledge (I do know well, I know a little, I do not know) and the use for professional activities (I do use or I do not use)

	Tools that you know	Tools used in your company
Risk probability and impact		
Impact scale (PMBok)		
Sensitivity analysis		
Expected Monetary Value (EMV)		
Decision tree		
Modeling and Simulation		

Other (please specify) :

46. Over your career, have you ever been in a situation of many risks that were not previously identified?

- Yes
- Yes, just a little
- No
- I do not know

47. Over your career, did you have more difficult to face identified or non-identified risks

- Identified risk
- Non-identified risk
- Both
- I do not know

48. If you have never worked with risk management, what were the reasons for it?

- Lack of opportunity
- I am not interested
- Lack of specific training
- Little knowledge on the subject
- It is not my priority area
- Other (please specify) :

49. Since you have never worked with risk management, would you like to work with it?

- Yes
- No
- I do know
- I have already worked

50. Do you believe that the implementation of Risk Management methods would be important for an area that you have contact with, but which is not your responsibility within your company?

- Yes
- No
- I do not know

O Panorama da Gestão de Riscos em Projetos de Engenharia I The Risk Management Overview in Engineering Projects

Obrigado por participar!
Thank you for participating!

QUESTIONNAIRE 2 (ARTICLE 4)

This questionnaire is part of two PhD studies entitled “BIM as a management methodology of the design and construction interface” and “Risk management and BIM in engineering projects”, both conducted at Escola Politécnica of the University of São Paulo, Brazil.

You have been invited to contribute to this research. Your participation is voluntary and anonymous.

..

Este questionário é parte de dois estudos de doutorado entitulados "BIM como metodologia de gestão da interface projeto-obra" e "Gestão de Riscos e BIM em projetos de engenharia", ambos desenvolvidas pela Escola Politénica da Universidade de São Paulo.

Você foi convidado a contribuir com esta pesquisa. Sua participação é voluntária e anônima.

1. What is your preferred language?
   Qual é a sua língua de preferência?

- ◯ English
- ◯ Portuguese

1 | Participant information

* 2. Age group:

- 18-25
- 26-33
- 34-41
- 42-49
- 50 and over

3. Gender:

- Female
- Male
- I prefer not to answer

* 4. What is your educational level? (complete or ongoing)

- Technician
- Bachelor of Science
- Specialist or MBA
- Master of Science
- Doctor of Science
- Other

* 5. What was the field of your bachelor science?

- Architecture
- Civil engineering
- Chemical engineering
- Electrical engineering
- Mechanical engineering
- Industrial engineering
- Business
- Other

* 6. How long ago did you concluded your bachelor science?

- Up to 1 year ago
- Between 1-5 years ago
- Between 5-10 years ago
- Between 10-15 years ago
- Between 15-20 years ago
- Over 20 years ago

7. What is your current job status?

- Self-employed
- Employed in academia
- Employed in AEC industry
- Researcher/Graduate student
- I am not from this field

2 | Company information

* 8. What is your position in the company that you have been working or worked?

- Technical engineer
- Proposal engineer
- Planning engineer
- Design manager
- BIM manager
- Planning manager
- Project manager
- Construction manager
- Designer
- Draftsman
- Analyst
- Consultant
- Client/Sponsor
- Owner
- Other

* 9. How long have been working in the company or worked in the last one?

- Up to 1 year
- Between 1-5 years
- Between 5-10 years
- Between 10-15 years
- Between 15-20 years
- Over 20 years

* 10. What is the main kind of project do you usually work with?

- Infrastructure projects (water, sewer, energy, bridges, transportation and urban maintenance)
- Arenas, gymnasium and sport complexes
- Industrial facilities
- Commercial facilities (shopping malls, shopping centers)
- Institutional facilities (ex: hospitals, daycare, schools, heath center)
- Cultural facilities (ex: museums, theaters)
- Multiple families housing developing
- Single family houses
- Social housing
- Retrofits
- Other

* 11. In which country is or was located the co

3 | Your BIM and Risk Management knowledge

* 12. How long have you been developing projects in BIM?

- I do not use BIM
- Up to 1 year
- Between 1-3 years
- Between 3-6 years
- Between 6-10 years
- Over 10 years

* 13. How do you classify your level of BIM knowledge?

- None
- Basic
- Intermediate
- Advanced
- Expert

* 14. How do you classify your level of risk management knowledge?

- It is not my area of expertise
- Basic
- Intermediate
- Advanced
- Expert

4| Risk Management tools, process and categories

* 15. Considering only the projects **developed in BIM** by the company, please rate the frequency in which the following risk management qualitative techniques are used:

	Never 1	Very rarely 2	Rarely 3	Neutral 4	Occasionally 5	Frequently 6	Very frequently 7
Probability and impact description / tables							
Assumptions analysis							
Checklists							
Data precision ranking							
Flowcharts							
Influence diagrams							
Cause and effect diagrams							
Event and fault trees							
Risk Impact Assessment							
Risk classification							
Analysis of trends, deviations and exceptions							
Ranking of risks							
Periodic document reviews							
Periodic trend reporting							
Subcontractor management							
Quality management							
Training programs							
FMEA (Failure Mode and Effect Analysis)*							

* 16. Considering only the projects **developed in BIM** by the company, please rate the frequency in which the following risk management quantitative techniques are used:

	Never 1	Very rarely 2	Rarely 3	Neutral 4	Occasionally 5	Frequently 6	Very frequently 7
Sensitive analysis	○	○	○	○	○	○	○
Probabilistic sums	○	○	○	○	○	○	○
Monte Carlo	○	○	○	○	○	○	○
LHC simulation	○	○	○	○	○	○	○
Expected value tables	○	○	○	○	○	○	○
Decision trees	○	○	○	○	○	○	○
Multicriteria decision make (DMSM) and Analytic Hierarchy Process (AHP)	○	○	○	○	○	○	○
Fuzzy logic	○	○	○	○	○	○	○
Processes simulation	○	○	○	○	○	○	○
Systems dynamics	○	○	○	○	○	○	○
Customer satisfaction surveys	○	○	○	○	○	○	○

* 17. Considering only the projects **developed in BIM**, please rate which risk management process are frequently used by the company:

	Strongly disagree 1	Disagree 2	More or less disagree 3	Neutral 4	More or less agree 5	Agree 6	Strongly agree 7
Strategic approach to risks and uncertainties							
Attitude, assignment and relationship with stakeholders							
Risk communication and information							
Crises management							
Risk planning							
Risk identification							
Qualitative Risk analysis							
Quantitative Risk analysis							
Risk monitoring and control							
Risk responses							

* 18. Please rate which risk categories frequently occur in the projects **developed in BIM** by the company:

	Strongly disagree 1	Disagree 2	More or less disagree 3	Neutral 4	More or less agree 5	Agree 6	Strongly agree 7
Management Risks							
Technical Risks							
Organisational Risks							
Compliance Risks							
Legal Risks							
Political Risks							
Economic Risks							
Social Risks							
Natural risks							

5 | BIM adoption in the company

* 19. How do you classify the BIM maturity level of the projects developed by your company? *

- Level 0 | Low collaboration / Projects developed in 2D (AutoCAD)
- Level 1 | Partial collaboration (file-based collaboration) / Models and objects
- Level 2 | Full collaboration (file-based collaboration & library management) / Models and objects developed in collaboration
- Level 3 | Full integrated (interoperable data) / Integrated web-services BIM Hub
- I do not know

* 20. In respect to the following categories, please rank which ones have been mainly impacted by BIM in your company?

***Consider the first one for the most impacted and the last one the least impacted.**

O

Management

O

Technology

O

Policy

O

Process

O

People

* 21. In the **design phase**, do you agree that BIM has positively impacted the options listed below?

*Consider only the projects developed in BIM by the company.

	Strongly disagree 1	Moderately disagree 2	Slightly disagree 3	Neutral 4	Slightly agree 5	Moderately agree 6	Strongly agree 7
Earlier and accurate 3D visualization of design							
Better design/multi-dimensional design alternatives/applications							
Design coordination on various elements/components							
Verification of consistency to the design intent							
Predictive analysis of performance							
Thermal energy analysis and simulation							
MEP analysis and simulation (HVAC)							
Structural analysis and design							
Predicting environmental analysis and simulation							
Acoustical analysis and simulation							
Photorealistic rendering for marketing purposes							
Accuracy and reliability of data							
Better design quality							
Better integration among design disciplines							
Better communication among design stakeholders							
Design cost reduction							
Design duration reduction							

* 22. In the **preconstruction phase**, do you agree that BIM has positively impacted the options listed below?

*Consider only the projects developed in BIM by the company.

	Strongly disagree 1	Moderately disagree 2	Slightly disagree 3	Neutral 4	Slightly agree 5	Moderately agree 6	Strongly agree 7
Better integration and design validation (clash detection)	○	○	○	○	○	○	○
Better collaboration among design and construction's stakeholders	○	○	○	○	○	○	○
More effective communication among design and construction's stakeholders	○	○	○	○	○	○	○
Better exchange of information	○	○	○	○	○	○	○
Model checking and validation (reviewing code)	○	○	○	○	○	○	○
Reduction of claims and risks	○	○	○	○	○	○	○
Improved site layout, planning and site safety	○	○	○	○	○	○	○
Better coordination and planning of construction works	○	○	○	○	○	○	○
Integrating project documentation/bid preparation	○	○	○	○	○	○	○
Synchronization of procurement with design and construction	○	○	○	○	○	○	○
Providing BIM models for offsite prefabrication	○	○	○	○	○	○	○
Better implementation of lean construction	○	○	○	○	○	○	○

* 23. In the **construction phase**, do you agree that BIM has positively impacted the options listed below?

*Consider only the projects developed in BIM by the company.

	Strongly disagree 1	Moderately disagree 2	Slightly disagree 3	Neutral 4	Slightly agree 5	Moderately agree 6	Strongly agree 7
Collaboration of simultaneous access of construction work	○	○	○	○	○	○	○
Construction duration reduction	○	○	○	○	○	○	○
Construction cost reduction	○	○	○	○	○	○	○
Improved construction project performance and quality	○	○	○	○	○	○	○
Providing BIM models for shop drawings	○	○	○	○	○	○	○
4D construction scheduling and sequencing	○	○	○	○	○	○	○
5D cost estimation and scheduling	○	○	○	○	○	○	○
Extracting cost estimation and quantity	○	○	○	○	○	○	○
Improvement of the project's constructability	○	○	○	○	○	○	○

7 | BIM impact on Risk Management practices

* 24. Concerning the following **risks** associated with the use of **BIM**, please rate if you agree that they frequently occur in the projects developed by the company:

	Strongly disagree 1	Disagree 2	More or less disagree 3	Neutral 4	More or less agree 5	Agree 6	Strongly agree 7
Lack of BIM protocols	○	○	○	○	○	○	○
Technological interface among programmers and interoperabillity issues	○	○	○	○	○	○	○
Inadequate relevant knowledge or expertise	○	○	○	○	○	○	○
Cultural resistance	○	○	○	○	○	○	○
Unclear ownership of BIM data	○	○	○	○	○	○	○
Low quality of BIM data	○	○	○	○	○	○	○
Data security	○	○	○	○	○	○	○
Reluctance to share information	○	○	○	○	○	○	○
Poor communication among project participants	○	○	○	○	○	○	○
Lack of collaboration among project participants	○	○	○	○	○	○	○
Lack of a check mechanism for designers	○	○	○	○	○	○	○
Professional licensing issues	○	○	○	○	○	○	○
Uncertainty over design liability	○	○	○	○	○	○	○
Changes in the BIM model by unauthorized parties	○	○	○	○	○	○	○
Cost overrun in the design phase	○	○	○	○	○	○	○
Cost overrun in the construction phase	○	○	○	○	○	○	○

* 25. Concerning the relation of **BIM** and **Risk Management**, please rate the statements below:

	Strongly disagree 1	Disagree 2	More or less disagree 3	Neutral 4	More or less agree 5	Agree 6	Strongly agree 7
BIM has a positive impact on Risk Management							
The use of BIM has improved risk planning							
The use of BIM has improved risk identification							
The use of BIM has improved the risk response plan							
The use of BIM has improved the risk monitoring and control							
The company uses BIM for data feedback and risk mitigation (eg more							

* 26. Concerning the **uncertainties** that are not in the list of identified risks of projecs developed in **BIM** , please rate the statements below:

	Strongly disagree 1	Disagree 2	More or less disagree 3	Neutral 4	More or less agree 5	Agree 6	Strongly agree 7
The uncertainties changed the time, cost, scope or other aspects integrated into project management (eg contract change, resources, etc.)	◯	◯	◯	◯	◯	◯	◯
The uncertainties are included in the model to be tracked so, in future projects, can be identified as risks (and no more as uncertainties).	◯	◯	◯	◯	◯	◯	◯

* 27. Concerning governance and risk management in the organization, please rate the statements below:

	Strongly disagree 1	Disagree 2	More or less disagree 3	Neutral 4	More or less agree 5	Agree 6	Strongly agree 7	N/A
The company has a department dedicated to the corporate Risk Management process.	◯	◯	◯	◯	◯	◯	◯	◯
The company uses standards (eg ISO 31000 or others related to compliance)	◯	◯	◯	◯	◯	◯	◯	◯
The company has a different risk management process for separate business unit or distinct clients.	◯	◯	◯	◯	◯	◯	◯	◯

8 | (KPI's) Key performance factors in BIM projects

* 28. Has your company developed or is developing new KPI's for projects after BIM adoption?

- Yes
- No
- I do not know

* 29. If yes, which KPI's were developed or are being developed?

* 30. Considering the use of BIM as a facilitator to identify risks, please rate the options below:

	Strongly disagree 1	Disagree 2	More or less disagree 3	Neutral 4	More or less agree 5	Agree 6	Strongly agree 7
The company uses KPIs provided by BIM to identify project risks.							
The company has KPIs to identify how many mitigating actions have been included after the risk analysis.							