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Critical success factors for BIM in the design and construction interface

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Fatores críticos de sucesso do BIM na interface projeto-obra

Versão corrigida

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ABSTRACT

Arrotéia, A.V. (2022). Critical success factors for BIM in the design and construction interface (Doctoral Thesis). Civil Construction Engineering Department. Polytechnic School, University of Sao Paulo, Sao Paulo.

BIM has become a common process and one of the latest technologies that have significantly changed the AEC industry worldwide in the management of construction projects. However, the increasement of the design disciplines and the number of professionals involved in the project has contributed to the fragmentation of the design and construction phases. In this context, the AEC industry has been searching for more collaborative practices through tools, methods, and processes in BIM. Therefore, for the success of a project, the adoption of critical success factors (CSFs) is considered a key facilitator in the organization of strategies for BIM. Thus, the general research objective was to identify critical success factors for BIM in the design and construction interface. The research method applied mixed methods considering qualitative and quantitative approaches developed through two exploratory surveys, bibliometrics, content analysis, and multi-case studies. Findings showed the application of the CSFs in theoretical and practical approaches. We developed the categorization of 14 different BIM codes which can be used in future works. Likewise, we applied the analysis of CSFs for BIM with three principal categories: technology, people, and process. The CSFs were founded in literature, classified, and framed into three main phases: design, pre-construction, and construction phases. As contributions to practitioners, this research identified CSFs for BIM in the design and construction interface.

Keywords: Building Information Modeling, Critical success factors, Pre-construction, Design and construction interface, AEC industry

RESUMO

Arrotéia, A.V. (2022). Fatores críticos de sucesso do BIM na interface projeto-obra (Tese de Doutorado). Departamento de Engenharia de Construção Civil. Escola Politécnica, Universidade de São Paulo, São Paulo.

O BIM tornou-se um processo comum e uma das tecnologias mais recentes que mudou significativamente a indústria da construção em todo o mundo na gestão de projetos de construção. No entanto, o aumento das disciplinas de projeto e do número de profissionais envolvidos no projeto tem contribuído para a fragmentação das fases de projeto e construção. Nesse contexto, a indústria da construção tem buscado práticas mais colaborativas por meio de ferramentas, métodos e processos em BIM. Portanto, para o sucesso de um projeto considera-se a adoção dos fatores críticos de sucesso (CSFs) um facilitador chave na organização de estratégias para o BIM. Dessa forma, o objetivo geral da pesquisa foi identificar fatores críticos de sucesso para o BIM na interface projeto-obra. O método de pesquisa adotado foi a aplicação de métodos mistos considerando abordagens qualitativas e quantitativas desenvolvidas por meio de duas survey exploratórias, bibliometria, análise de conteúdo e estudos de casos múltiplos. Os resultados mostraram a aplicação dos CSFs de forma teórica e prática. Desenvolvemos uma categorização de 14 tipos de códigos BIM, os quais podem ser utilizados em trabalhos futuros. Da mesma forma, analisamos o uso dos CSFs para BIM com três categorias principais: tecnologia, pessoas e processo. Os CSFs foram embasados a partir da literatura, classificados e enquadrados em três fases principais: fases de projeto, pré-construção e construção para avaliação do desempenho do BIM em projetos. Como contribuições para os profissionais, esta pesquisa identificou CSFs para BIM na interface de projeto e construção.

Palavras-chave: Modelagem da informação da construção, Fatores críticos de sucesso, Pré-construção, Interface projeto-obra, Indústria da construção

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LIST OF ABBREVIATIONS

BIM	| Building Information Modeling
AEC	| Architecture, Engineering, and Construction
CSFs	| Critical Success Factors
PEO	| Preparação da Execução de Obras (*in Portuguese*)
MEP	| Mechanical, Electrical and Plumbing
IT	| Information Technology
BLC	| Building Life Cycle
VDC	| Virtual, Design and Construction
3D	| Three Dimension
4D	| Four Dimension
5D	| Five Dimension

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1 INTRODUCTION

With the rapid development of economic globalization, science, and technology, construction projects are increasingly complex with schedules and quality requirements more stringent (Zhang et al., 2017). As a result, construction industry professionals need to be able to handle complex projects that require multidisciplinary and collaborative solutions (Becerik-Gerber, Gerber & Ku, 2011).

The Architectural, Engineering and Construction (AEC) industry is stronger linked to economic development and job creation, which makes this industry expressive on the national scene. However, the AEC industry is underdeveloped compared to the other industries. The low level of productivity and the lack of construction industrialization generates waste, reworks, additional project cost and time, which impact building performance and quality (Oliveira and Melhado, 2006; Grilo et al., 2007; Melhado et al., 2005).

In Brazil, the AEC industry is characterized by low-performance levels. The slow evolution of constructive technology, the lack of collaboration among stakeholders, the fragmentation of the project stages, and the usage of obsolete management methods corroborate the low performance levels (Melhado, 2001).

Additionally, in Brazil, the hiring process is linear (Addor and Santos, 2013). The traditional design process follows a sequential way of designing, triggering sequenced activities, where each stage starts after the previous one ends. This process promotes a lack of interaction among project stakeholders and an absence of efficient planning and coordination between the design and construction phases (Melhado et al., 2005).

A large amount of information is lost due to the absence of effective coordination in the design and construction phases. The absence of project coordination causes improvised changes and redone services, where there is a lack of project details to provide the information for the planning, and project decisions are made by untrained people at inappropriate times (Souza et al., 2001).

Previously the industrial revolution, the design and construction phases were strongly connected. However, the increasement of the design disciplines and the number of the professionals involved in the project has contributed to the fragmentation of the design and construction phases into two separate and distinct stages (Co; Chung, 2014).

Given this scenario, the AEC industry suffers from fragmentation throughout the project life cycle phases since projects are developed by a large number of stakeholders involved who do not work together in the search for better integration in the design and construction interface (Xue; Shen; Ren, 2010).

Hence, the lack of integration in the design and construction phases corroborates the construction industry fragmentation, where construction projects are focused on individual benefits instead of integrated project solutions (Migilinskas, 2013; Yang and Wei, 2010; Kovacic, Oberwinter, and Müler, 2013).

Although, construction projects require a collaborative and dynamic environment due to the increasement in design complexity, a higher number of project disciplines and stakeholders with different roles, interests and scopes during the project development (Pereira and Salgado, 2013).

Despite the advances in construction management methods, project managers face problems related to the management of data and the manipulation of information (Francis, 2019). Therefore, the main challenges faced by the AEC industry are how to provide a more collaborative environment among project stakeholders, and how to manage and exchange project information during the building life cycle phases (Arrotéia, Amaral, and Melhado, 2014).

For Koskela et al. (2015), the large number of stakeholders involved in the project and controlment of the project information flow are significant challenges. Thus, the insertion of tools such as Building Information Modeling (BIM) and other technologies can bring gains to project management, from the design conception throughout construction to the building maintenance.

In the last decades, there has been considerable evolution in the construction field, understanding the importance of how design plays throughout the building life cycle (Silva, Arrotéia, and Melhado (2017). However, there is a reluctance to change traditional practices and current procedures by professionals to learn BIM, and there is an increased demand for trained professionals with BIM skills (Suwal and Singh, 2018; Zhang et al., 2018; Ahan and Kim, 2016).

In this context, the AEC industry has been searching for more collaborative practices through tools, methods, and processes in BIM. However, the shortage of skilled professionals is a challenge for the construction industry, as collaborative work requires much more than understanding new technologies. That is, professionals need to learn a new work culture based on project collaboration and information, by involving different stakeholders with BIM (Macdonald, 2012; Macdonald and Mills, 2011). Based on that, the first research question is:

RQ1: Which is the level of BIM knowledge among professionals in the AEC industry in Brazil?

Since its inception, BIM has delivered valuable benefits through a more collaborative approach by managing the project's digital information throughout the building life cycle phases (Donato, Lo Turco, and Bocconcino 2018; Mohamed, Abdallah, & Marzouk, 2020). For Eastman et al., 2011, the benefits of BIM are coordination and communication improvement, data management, analysis, simulation, construction productivity, and facilities management.

For Succar (2009), BIM can be an important tool to reduce project fragmentation. From the limitation of the existing CAD technology, BIM features a broader and more aggressive approach, which produces and manages various pieces of information for construction activities throughout the building life cycle phases (Ahn and Kim, 2016).

Thus, BIM eliminates design discipline incompatibilities, minimizing common errors such as quantitative extraction compared to other computational tools. In other words, the possibility of mistakes is much lower with BIM by obtaining more precise budgets and services, and increasing quality and productivity during the construction phase (Andrade, Silva and Lima, 2013).

BIM has become a common process and one of the latest technologies that has significantly changed the AEC industry worldwide on the management of construction projects (Puolitaival and Forsythe, 2016; Alizadehsalehi, Hadavi, and Huang 2020; Sinoh et al., 2020).

However, BIM has changed not only the AEC industry but also the academic environment by requiring new strands of expertise for all disciplines compared to more traditional projects (Succar et al.,2013; Lu et al., 2017; Donato et al., 2018). Consequently, BIM has been considered a significant research topic in Academia in the last decades and its approach can be conceptualized in diverse ways by different authors (Bynum et al., 2013).

As in other countries, in Brazil, there is a broad need for reformulation in the aspects related to people, processes, technology, and data involved in the design and construction phases to meet the growing needs and improve quality in civil construction (Manzione, 2013).

For Liu, Nederveen, and Hertogh, (2017), the success of BIM relies on three main categories: technology, people, and process. These categories are complementary, and synergistic, and can be implemented independently. However, the lack of any of these dimensions will result in a more negligible effect on successful project collaboration during BIM implementation. Thus, the second research question is:

RQ2: How BIM has been approached in theory by Academia in terms of technology, process, and people categories?

Some authors considered BIM as a process, others as a technology or even only as a tool. For Succar (2009), BIM is not just a technology, but also a project management tool and process consisting of all aspects, disciplines, and systems of a facility within a model, with which all stakeholders (owners, architects, engineers, contractors, subcontractors, and suppliers) can collaborate more accurately and efficiently than traditional processes (Azhar et al, 2012).

Volk, Stengel, & Schultmann (2014) considered BIM as a process and a corresponding technology that improves the efficiency and the effectiveness of project delivery, from the early design stages, during the construction phase through to the facility maintenance.

Whereas, Olawumi et al. (2018), BIM can be viewed from two different perspectives: (1) a 3D technology for building modeling and analysis using software; (2) a process that enables other knowledge domains such as cost, schedule, and project management, safety, sustainability parameters that provide a source of information for project stakeholders.

As a valuable tool that allows the use of three-dimensional, real-time, smart, and dynamic modeling, BIM facilitates successful coordination and collaboration to optimize building design solutions (Holness, 2008). It also provides views from multiple angles, and each object element has its corresponding information attached (Wang, Cho, & Kim, 2015).

BIM promises an integration of information by combining geometric and non-geometric information in a comprehensive model that accommodates all aspects of the construction (Koutamanis, 2017), enhancing not only the design phase but also the pre-construction phase and construction phases (Arrotéia, 2013).

BIM has brought significant advancements in the AEC industry by increasing project quality, providing accurate scheduling timetables, yielding quantity takeoffs, and reducing total project costs (Akintola, Venkatachalam, & Root, 2017; Sacks et al., 2018). However, BIM is new to many companies, and its adoption is consequently challenging itself. Challenges include unstructured and fragmented processes that often lead to time and cost overruns (Grytting et al., 2017).

Currently, design and construction companies in Brazil have increasingly implemented BIM in the design of projects. On the other hand, BIM adoption in Brazilian construction sites is still a gap, since the use of this technology is very little adopted in the construction environment (Garro, Ishihata, Santos, 2013).

The main difficulties to BIM adoption in the construction industry are related to the need for integration and transparency of the stages, the constant updates of the digital model, the communication among stakeholders, the organizational structure, and the work processes (Kiviniemi and Codinhoto, 2014). Based on that, the third research question is:

RQ3: How BIM has been adopted in practice by the AEC industry from companies based in different countries?

Therefore, with the increasement of design complexity and processes involved in the project, the AEC industry seeks alternatives towards construction industrialization, since the artisanal construction method practiced in Brazil directly interferes with the building performance.

As stated by Chen et al. (2020), “as BIM has an inherent capability to well connect professionals by collecting and sharing constant accurate data and information among all stakeholders, the adoption is therefore recommended for the project team to effectively tackle the challenge on professional competences”. Likewise Troncoso-Pastoriza et al. (2018) define: “BIM is a collaborative work method for the creation and management of a construction project.”

In this way, the adoption of BIM-based tools, processes, or even people trained with BIM skills can bring improvements to the design and construction interface, and consequently can be alternatives to construction industrialization. Therefore, BIM as a management method in the design, pre-construction, and, construction phases bring a new perspective to this scenario. Lastly, the fourth research question is:

RQ4: How BIM has been performing in the design, pre-construction and construction phases?

1.1 Justification

BIM is an efficient technology and a disruptive process, which manages design data throughout the building design development and operation (Gerrish et al., 2017). Many initiatives have been developed toward BIM adoption in the construction sector. However, BIM adoption requires a significant change in how construction businesses operate at almost every level within a building process (Arayici et al., 2011).

BIM requires a long continuous process that needs to be improved step by step encompassing all BIM stages and new strands of expertise for all disciplines compared to more traditional projects (Succar et. al., 2013). It is well-known that BIM facilitates information flow in the design process and improves communication among stakeholders throughout the project building life cycle phases. Therefore, there is a need for the development of tools, methodologies and processes allied to BIM that promotes the integration of the design and construction phases by considering the pre-construction phase.

Studies have shown the importance of design coordination at the pre-construction stage of construction projects (Ndekugri, Ankrah & Adaku, 2021). The employment of tools and methods dedicated to the pre-construction phase can promote better collaboration among project stakeholders and provide a favorable environment for data information management and exchange (Arrotéia, 2013).

BIM is a potential tool to promote a better integration in the design and construction phases, improving the management of the project information flow and stakeholders' communication (Garrido et al.;2013).

Furthermore, BIM anticipates problems through a three-dimensional model bringing a more coherent planning in the design phase, and it is considered a fundamental tool to help the construction team in an understanding of the design disciplines' interfaces (Arrotéia, 2013).

However, collaboration among stakeholders is considered one of the basic premises for the design development with BIM. The constant need for the three-dimensional model update requires a collaborative environment among stakeholders, capable of providing interaction and fundamental communication during the design and construction phases, starting from meetings that discuss the project insertions, extractions and modifications (National Institute of Building Sciences, 2007).

In other words, the stakeholders need to discuss the design throughout "face-to-face" meetings to keep the three-dimensional model updated according to the existing building under construction. Thus, the constant design adjustments require interaction among design and construction teams not only in the design phase, yet in the construction phase (Arrotéia, Amaral and Melhado, 2014).

Therefore, to minimize the problems related to construction fragmentation, it is important to have a dedicated stage such as the pre-construction to minimize the lack of integration between the design and construction phases through methodologies toward project collaboration and stakeholders' communication (Arrotéia, 2013).

The Preparation for Building Construction, *Preparação da Execução de Obras (PEO) in Portuguese*, is a method based on a set of activities at the pre-construction stage created to minimize the lack of integration between design and construction phases, bringing expressive gains in terms of waste, time and cost reduction, and improvements in project quality and performance (Souza and Melhado, 2003).

BIM enhances the application of the PEO method in construction projects by anticipating problems in the design phase and working as an important tool to help the construction team to better understand the design inconsistencies among disciplines (Arrotéia, 2013).

Concerning BIM adoption, a better understanding of the critical success factors (CSFs) is necessary to organize strategies for its adoption (Ozorhon and Karahan 2017). According to Rockart (1982), CSFs could be defined as key factors for a project to succeed. Moreover, CSFs are significant factors to increase project performance and assure the success of construction projects (Babu and Sudhakar 2015).

Liao and Teo (2017) reported several studies that described CSFs that could affect BIM adoption, but few have investigated the interrelationship among these factors. Indeed, the relative importance of CSFs should be investigated considering different phases of the project life cycle, from the design to the construction phase.

Therefore, this research proposes to study the application of CSFs for BIM in the design and construction interface focused on the pre-construction phase from the perspective of theory and practice. We understand the importance of the theme to the construction field by developing alternatives in Academia that can help professionals and construction companies to enhance their processes with methodologies focused on project performance and quality.

1.2 Research objectives

Based on the presented problem, the general research objective is to identify critical success factors for BIM in the design and construction interface. To achieve the general research objective, we strategized the following specific objectives:

1. Evaluate BIM knowledge among professionals in the AEC industry in Brazil;
2. Draw an overview of BIM in theory and investigate the relationship of the BIM CSFs with technology, process, and people categories in the building life cycle phases.

3. Analyze BIM adoption from different companies throughout the pre-construction phase.
4. Analyze the usage of BIM through BIM CSFs in the design, pre-construction, and construction phases

1.3 Thesis structure

The thesis is structured into seven main chapters described below and as illustrated in **Figure 1.**

Chapter 1 begins with the introduction of the thesis by contextualizing the research problem context and presenting the research justification, the research objectives, and the research scope and contributions.

Chapter 2 delineates the research methodological approach by showing the research framework and the selected methods for the development of the doctorate research and its relationship among them.

Chapter 3 shows the initial exploratory survey developed to answer the first specific research goal of the thesis. In this chapter, we presented the research steps, the survey questionnaire, the sample and the data obtained to develop the method. After, we structured the results into two main topics: BIM knowledge among professionals and BIM education among professionals.

Chapter 4 presents the results obtained from bibliometrics based on the second specific research goal of the thesis. In this chapter, we showed how the sampling process was developed to collect data and how we analyzed the data in bibliometrics and content analysis. After, we presented the results baseonin the following topic structure: sample demographics, bibliometrics and content analysis. To conclude, we addressed the discussion by proposing future works.

Chapter 5 shows the case studies approach based on the third specific research goal of the thesis. In this chapter, we present how the case studies research phases worked during the data collection process, and explain sample characterization and data analysis.

After, we structured the findings in five main topics: (1) BIM in the companies ‘organizational context; (2) Comparison among technology, people and BIM categories; (3) BIM in the design, pre-construction and construction phases through CSFs; (4) Companies ‘initiatives for the pre-construction phase; and (5) BIM-related changes in the design and construction interface.

Chapter 6 shows the final exploratory survey developed to respond to the last specific research goal of the thesis. In this chapter, we present the results concerning BIM adoption in the design, pre-construction, and construction phases.

Chapter 7 presents the conclusions concerning each research method applied in this research and the conclusions concerning the research questions and objectives. Lastly, we end by presenting research limitations and further works.

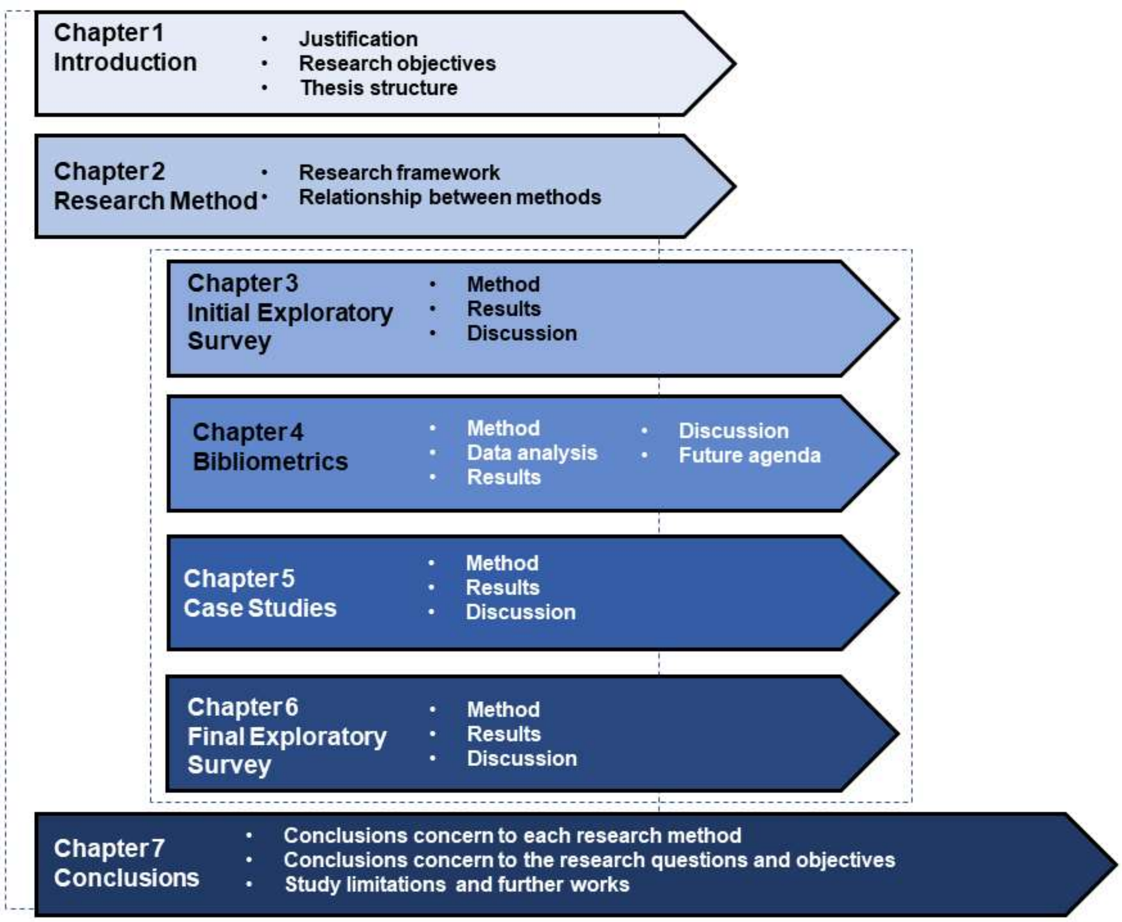


Figure 1: Thesis’ structure | Source: Author

2 RESEARCH METHOD

The thesis's research method applied mixed methods considering qualitative and quantitative approaches, allowing synergistic research approaches. The qualitative approach aims to understand social problems through data collection of individuals or groups and generates more common information about human experiences. The quantitative approach tests objective theories by analyzing the relationship between measurable variables (Creswell, 2009).

Mixed methods offer methodological eclecticism and paradigmatic pluralism. As long as the researchers know how to identify the method's potentials and limitations, mixed methods provide great relevance to education and several benefits such as (Dal-Farra and Lopes, 2013; Wisdom and Creswell, 2013):

- Comparison through quantitative and qualitative data
- Reflection of the participants' perception and experience
- Encouragement of academic interaction
- Application of methodological flexibility
- Collection of rich and comprehensive data.

For Venkatesh et al. (2013), mixed methods propose complementarity viewpoints regarding similar experiences, ensure total completeness, clarify the knowledge from a prior method, evaluate the trustworthiness of inferences from one method and obtain opposing viewpoints of the same experiences or associations.

On the other hand, mixed methods have some methodological limitations such as increased information complexity, the need for a multidisciplinary team of researchers, the request for resources, and time to conduct the chosen methods (Dal-Farra and Lopes, 2013; Wisdom and Creswell, 2013).

In the construction field, there is greatly important to combine different methods in research at the doctoral level. According to Taschakkori and Teddlie (2010), mixed methods bring considerable gains to the investigative process development. Therefore, we considered mixed methods the most coherent methodological approach for this work due to the plurality of possible results after its application. The varied forms of qualitative and quantitative data collection were statistical data, bibliographical research, interviews, questionnaires, company documents analysis, and observations, delivering more comprehensive answers to the research problem.

After defining the methodological approach, we studied which method would be more suitable to respond to the research objectives. Then, we draw a research framework by phases of research development described in the following topic.

2.1 Research framework

The research framework started by defining the research problem and the general research objective. To address the general research problem, we established four other specific objectives to finally develop the thesis proposal as illustrated in **Figure 2**. Each specific objective was answered by the application of different mixed methods in three main phases of research namely:

- **Phase 1 – Exploratory:** this phase corresponds to the very beginning of the research which developed an initial exploratory survey to understand an overview regarding BIM knowledge among AEC professionals in Brazil.
- **Phase 2 – Theory X Practice:** this phase focused on crossing data from theory and practice in the BIM field. After concluding the exploratory survey in the first phase, we started the second research phase by applying bibliometrics with content analysis to draw a panorama of the BIM research in Academia. In the same phase, we carried out four case studies in different companies, two in Brazil and two abroad. The case studies aimed to investigate the usage of BIM by different companies throughout the pre-construction phase.
- **Phase 3 – Exploratory:** at this phase, we developed a survey and ran a final exploratory analysis of BIM adoption in the design, pre-construction and construction phases based on CSFs for BIM.

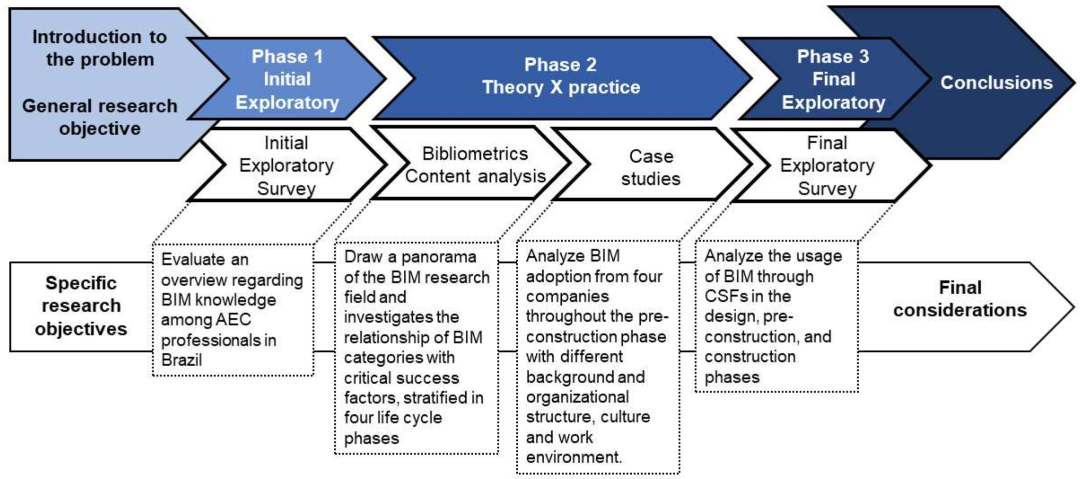


Figure 2: Research framework | Source: Author

2.2 Relationship between methods

Based on the main research objective, we strategized the research framework based on four different research methods to be developed throughout three main phases for data collection during the doctorate research. Each research method was planned and thought to respond one specific research objective as illustrated in **Figure 2** above.

We begin the research, first with the application of the initial exploratory survey to investigate the BIM knowledge among professionals in the AEC industry in Brazil. We chose an exploratory survey as a method to be able to collect a great number of responses to have a reasonable sample to analyze. The results were important to understand the relationship of BIM knowledge and the professionals 'educational level.

In the second research method, bibliometrics, we aimed to draw a panorama of the BIM research field from a theoretical perspective and evaluate how Academia has explored BIM studies in terms of technology, process and people. We analyzed the data using two different approaches: bibliometrics and content analysis. We also analyzed BIM adoption in the design, pre-construction and construction phases based on 32 CSFs extracted from the literature. Thus, we classified and evaluate a sample of 119 studies in the field. The purpose was to understand the main CSFs for BIM studied in the theory.

To respond to the third specific research goal, we developed a case studies approach with four different construction companies, two in Brazil and two abroad. The case studies focused on the investigation of BIM adoption in practice. Thus, we evaluated construction companies with different organizational contexts and backgrounds to compare the benefits brought by BIM in the project and the main barriers faced by the companies during its adoption.

To achieve the fourth specific research objective, we applied the final exploratory survey to analyze BIM adoption through CSFs with the different approaches used in bibliometrics. Thus, we evaluated CSFs for BIM in the design, pre-construction and construction phases. As we did in content analysis in bibliometrics, we did not consider the operation phase once facility management using BIM is not commonly practiced by the AEC industry in Brazil.

Lastly, each research method corroborated the development of a mixed methods approach, bringing a rich and diverse sample of data for the doctorate research. This research focused on the understanding of BIM adoption not only in theory, but also in practice, in the last years. The choice of the application of different methods was fundamental to understanding the research problem from the theoretical viewpoint as observed in the studied literature and from practice as pointed out by the professionals from the AEC industry.

3 INITIAL EXPLORATORY SURVEY

Despite the efforts from the AEC industry to implement BIM, the lack of trained professionals still presents a significant constraint (Barison and Santos, 2010; Becerik-Gerber, Gerber & Ku, 2011; Kocaturk and Kiviniemi, 2013).

Although in the past decade, there have been significant advances in construction-related collaborative technologies, BIM implementation is a long path and depends on many aspects, such as adequate method, trained personnel, the availability of technology, and, industry policies (Akintola et al., 2017). According to Abaurre et al (2011), there are several project and work process issues inherent to the Brazilian civil engineering production chain, therefore these mentioned aspects can impact BIM adoption in this country's companies.

The AEC industry in developing countries such as Brazil still facing challenges in BIM implementation. The main obstacles are related to the need to change work culture and practices, the lack of understanding of the stakeholders 'roles and responsibilities, the lack of knowledge about processes and workflows and the high investment in training and skills required for BIM (Olawumi, 2018; Mahalingam et al. 2015; Khosrowshahi and Arayici 2012; Singh et al. 2011; Hartmann and Fischer, 2008).

The exploratory survey goal was to evaluate BIM knowledge among professionals to delineate an overview concerning BIM adoption in the AEC industry in Brazil with the purpose to answer the following research question: "What is the BIM level of maturity among professionals by the AEC industry in Brazil? "In this study, we surveyed approximately six hundred individuals from the construction industry aiming to identify their level of BIM proficiency.

3.1 Method

The research method consisted of the application of a quantitative and qualitative online survey questionnaire. According to Fink (2003), a survey is a system of data collection to describe, compare and explain the knowledge, attitude, and behavior of a specific group of individuals. In other words, a survey is a research method that aims to collect data from a significant sample through a quantitative and statistical analysis of information from dozens or thousands of people (GIL, 2010). There are different types of surveys: exploratory, confirmatory, or descriptive (Forza, 2002). In this study, we developed an exploratory survey and statistically analyzed it to obtain an overview of BIM knowledge among professionals in the AEC industry in Brazil.

3.1.1 Research Steps

Based on *The Survey Handbook* by Fink (2003), we developed our survey in six main steps illustrated in **Figure 3**. First, we defined the survey`s goal. Second, we planned the study by conducting a literature review concerning BIM adoption in the AEC industry, BIM professional education, and BIM maturity levels. After, we focused on the questionnaire development, critical analysis, and validation. In the fourth step, we concentrated on data collection by selecting an adequate platform for data collection, the definition of possible respondents, and, lastly, sending the questionnaire to the respondents' list. In the fifth step, we developed data analysis and result discussion. Finally, on the last step, we presented the research`s conclusions, research gaps, limitations, and future works.

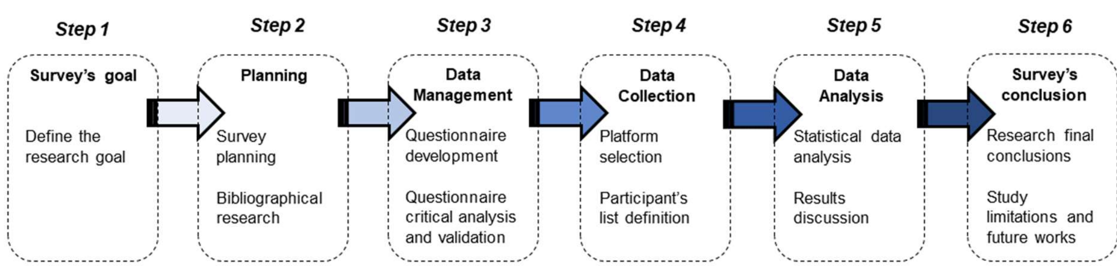


Figure 3: Survey research steps

3.1.2 Survey questionnaire

The survey questionnaire consisted of 21 multiple-choice questions developed through a web-based platform to evaluate BIM proficiency levels among professionals. We considered four main categories to develop the questionnaire: 1) BIM knowledge, (2) organization/general company information, (3) BIM adoption by the organization/company, and (4) participants' educational attainment.

We first validated the questionnaire with professionals with expertise in the BIM field. Second, we updated the questionnaire based on their recommendations and, finally, we defined the final version of the survey. Mainly, we collected information from educational attainment, professional major, years of experience, previous BIM knowledge, the self-evaluation of BIM level of proficiency, and opinions about the role of academia in BIM teaching in professional education.

3.1.3 Sample and data

Based on our research goal, we surveyed individuals from several professions related to the AEC industry in the market in Brazil. We collected the data under the condition of anonymity. For data analysis, the sample was calculated by the software R 3.3.0 (R Core Team, 2017) by considering the level of statistical significance (α) at 5%.

We collected 591 (≈15% response rate) answers in a sample of approximately four thousand individuals from LinkedIn. It is a non-probabilistic sample composed of professionals who have responded to the questionnaire on behalf of their companies from online professional web-based platforms. Data analysis showed a variance regarding the number of responses in each different question. Consequently, the results` response rate varied according to each question. The sum of relative frequencies of the answers might not add up to 100 percent %, once more than one response was possible. Thus, it was not possible to determine if each completed survey represented a different organization.

3.2 Results

Participants' profiles indicated that 49,5% of the respondents were architects, 45,6% were engineers, 10,1 % were professors, 5,2% were consultants, and 4,3% were in other positions. Regarding years of professional experience in the field, one-third of the respondents (31,3%) declared having between 10 and 25 years of experience; 29,5% between 5 and 10 years, 18,3% more than 25 years, 17,7% between 1 and 5 years, and only 3,2 % with less than one year of experience. Mostly, the participants are involved in the design phases, such as design development, management, and coordination, instead of the construction and facility management phases.

Regarding BIM implementation, 38% of the companies adopted BIM and, 62% responded not. The main difficulties to BIM implementation rely on (45,1%) high cost of training, infrastructure, and the company`s organizational structure; (38,2%) lack of trained professionals; (31,9%) low reward from the client; (27,1%) software incompatibility and undefined cost of implementation; and (27,1%) long path for BIM implementation.

Regarding BIM skills for professional recruitment, 43,3% of the participants answered that BIM is not a required skill, 34,8% confirmed that BIM is a demanding qualification, and 21,9% may be a previous prerequisite. Fifty-five point three (55,3%) of the respondents said that their companies were planning to implement BIM shortly, while 26,6% were in doubt and 18,1% answered negatively.

3.2.1 BIM knowledge among professionals

Figure 4 shows the concept of BIM by the participants (professionals from the AEC industry in Brazil). Only 586 of 591 answers were valid since five participants did not answer the question. Participants were able to choose more than one answer. Therefore, all answers are added to the total of each option. Sixty-eight-point four percent (68,4%) indicated BIM as a construction data management process; (52 %) as project data management software, (45,6%) as project representation technology, (45,4%) as project data management software, (34,3%) all previous answers (3,1%) others, and (2%) none for the given options.

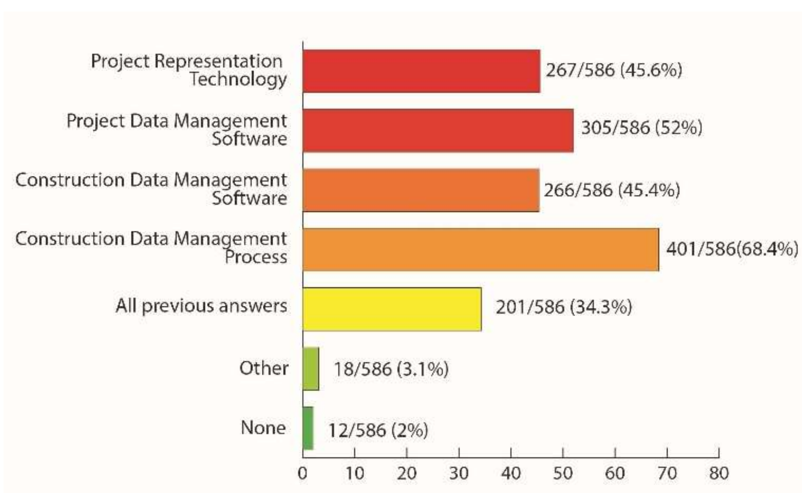


Figure 4: The concept of BIM understood by the participants

Regarding the advantages and disadvantages of BIM implementation, the participants answered 585 of 591 (total sample). The advantages were: BIM improves project data management (89,9%) and clash detection (89,2%), followed by precision on material take-off (80,5%), enhancement of collaboration between stakeholders (80%), improvement of 3D visualization (76,4%), facility management (69,2%), reduction in construction cost and time (67%), environmental performance simulation (59,5%), all answers (48,4%) and none (0,9%) as illustrated in **Figure 5.**

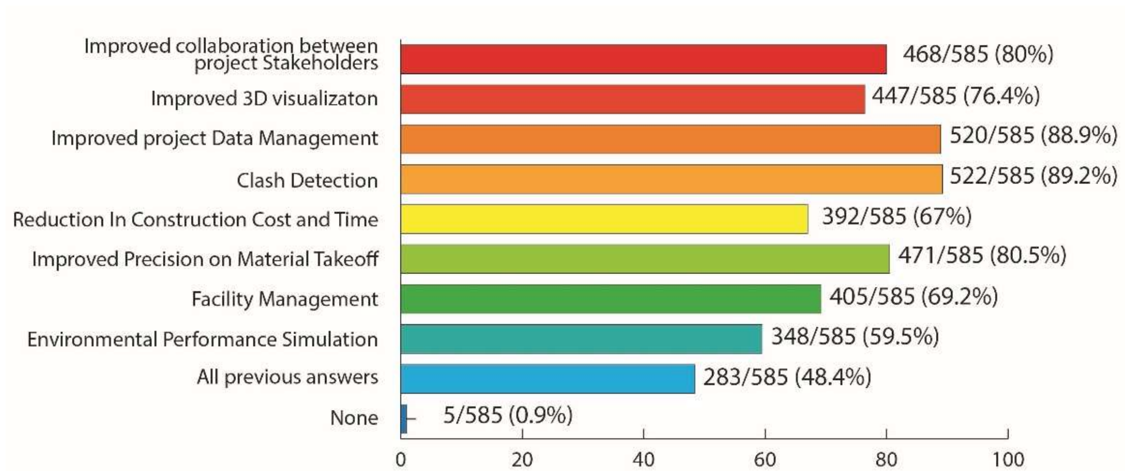


Figure 5: Participants `opinion about the advantages of BIM

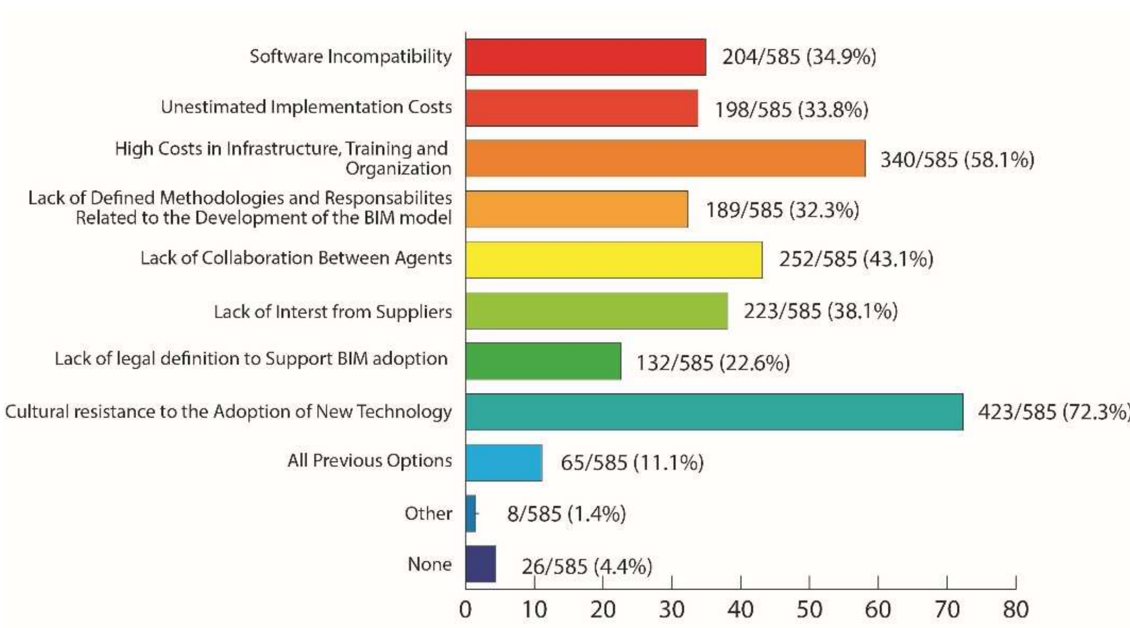


Figure 6: Participants ‘opinions regarding the disadvantages of BIM

The disadvantages were: cultural resistance to the adoption of new technology (72,3%), high costs in infrastructure, training, and organization (58,1%), lack of collaboration among stakeholders (43,1%), lack of interest from suppliers (38,1%), software incompatibility (34,9%), unestimated implementation costs (33,8%), lack of defined methodologies and responsibilities related to the development of BIM model (32,3%), lack of legal definition to support BIM adoption (22,6%), and all given options (11,1%) as illustrated in **Figure 6.**

3.2.2 BIM education among professionals

Regarding participants' professional education, 71,9% considered their level of BIM knowledge at the end of their undergraduate program insufficient, 14,7% intermediate, 8,9% good, and 4,4% advanced, as illustrated in **Figure 7.**

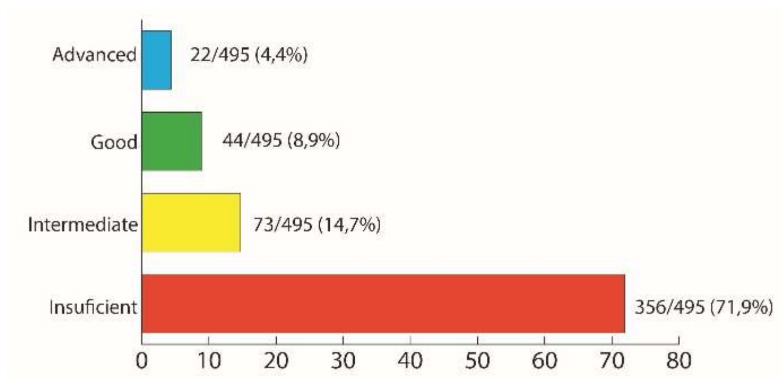


Figure 7: Participants 'opinions about their level of BIM knowledge at the end of the undergraduate program

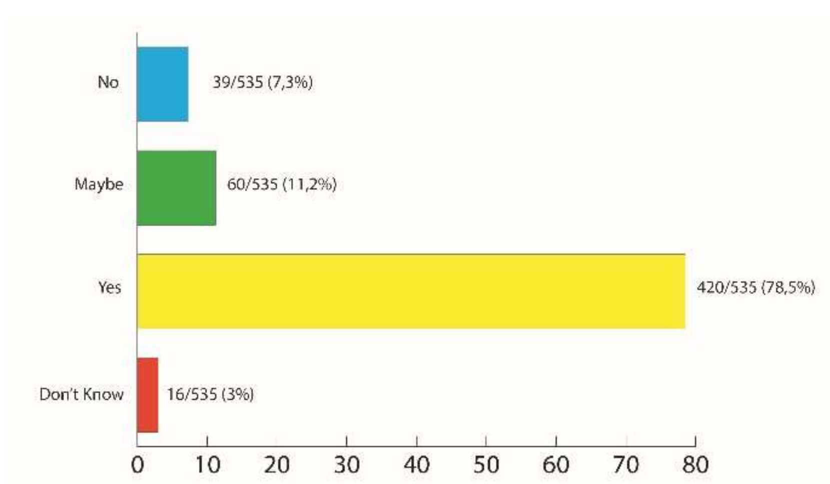


Figure 8: Participants `opinions about the role of academia in the professional education

Concerning the role of Academia in professional education, 78,5% responded that Academia has a relevant role in BIM professional education, 11,2% of them were in doubt, 7,3% do not believe that Academia is responsible for introducing BIM into their professional education and, 3% said that they do not know about it, as illustrated in **Figure 8.**

Figure 9 shows where the participants have acquired BIM knowledge from. Thirty-six-point eight percent (36,8%) learned BIM in a graduate program, 29,2% in an undergraduate program, 19% from practice, 3,5% from training courses, 3% from self-learning, 5% had contact with BIM from academic events and 3,5% from specialized media. The number of valid answers was 462 out of 591.

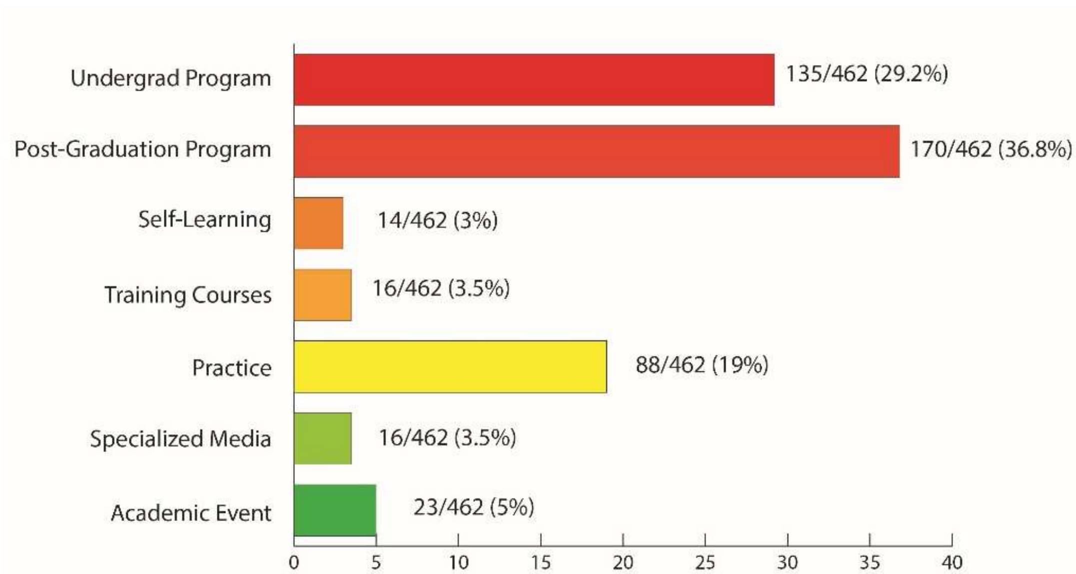


Figure 9: from where the participants have acquired BIM knowledge

3.3 Discussion

Findings have shown an overview of BIM knowledge among approximately six hundred professionals in the AEC industry in Brazil. The level of BIM proficiency was classified as insufficient after undergraduate education. Consequently, 36,8% of the participants obtained BIM knowledge from a graduate program instead of 29,2% learned during an undergraduate program. Academia performs as relevant support towards BIM education.

Participants pointed to professional education as the most relevant reason for the lack of BIM knowledge among practitioners. The lack of BIM skills and experience still being a concern (Ghaffarianhoseini et al., 2017). Thus, AEC schools have been searching for new alternatives that can improve BIM implementation in practice due to the considerable impact of the BIM approach in the construction industry (Morton, 2012; Sacks and Pikas, 2013).

The adoption of BIM from the early stages of undergraduate education can provide future professionals with more experience with the technology by using BIM applications as powerful teaching tools that help instructors to engage students with the class content, improving their learning experiences (Irizarry et al., 2013).

Many BIM users attribute the low return on investment to the users' level of experience and BIM engagement. Accordingly, the most significant reason for the lack of BIM adoption was cultural resistance to new technologies (73%). The other notable ones were: high costs in training and software, lack of demand and stakeholders' collaboration, lack of defined methodologies and responsibilities related to the development of the BIM model and, interoperability issues.

On another side, the survey suggests that the notion of BIM as a data management technology prevails among the respondents. Participants have recognized that the main improvement brought by BIM is the improvement in project data management capacity and clash detection. Furthermore, when asked to pick a more accurate definition of BIM, most respondents indicated that BIM is a construction management process.

Additionally, there are still some difficulties with BIM implementation in the AEC industry in Brazil, such as the lack of BIM in curricula in the AEC schools and cost implementation and regulation of norms and laws from the government. Several authors have proposed that BIM should be advertised through education or mandated by governments (Turk, 2016). To provide students with BIM skills as required by the current construction industry, many construction education institutions are introducing the concept in their coursework and hiring new faculty based on their expertise in BIM (Joannides, Olbina & Issa, 2012).

Concerning the usage o BIM among professionals, architects have been more frequently using BIM compared to engineers. It may be because BIM is also a (3D) three-dimensional modeling tool for architects. According to the participants, three-dimensional modeling has been well known (approximately 90%) when compared to other types of BIM modeling such as 4D (cost), 5D (time), 6D (facility management, and 7D (sustainability).

Finally, BIM has been adopted by firms related to design development and design management. There was no evidence that firms with more experience in the AEC industry were prone to implement BIM. Although many researchers suggest a pressing need for new alternatives based on collaborative practices, the adoption of BIM in a collaborative work environment has been little developed by institutions (Macdonald, 2012).

Based on that, there is a continuous demand for professionals with BIM skills in virtue of the traditional and fragmented teaching practice. As a result, AEC schools have been looking for the development of integrated solutions for BIM in academia (Macdonald and Mills, 2011).

In conclusion, the success of BIM depends on a collaborative learning environment (Lindkvist, 2015) when BIM is experienced in a dynamic and collaborative learning environment, BIM brings better conditions to prepare the students to solve problems commonly experienced in the labor market. This teaching proposal conducts significant gains to the students` education, since it increases the level of cognition, learning and understanding of the design process (Mathews (2013).

4 BIBLIOMETRICS

BIM efficiently manages data exchanges throughout the built asset life cycle, including the operational phase using BIM-based tools, workflows, and standards (Patacas, Dawood, & Kassem, 2020). The building life cycle (BLC) comprises three phases: Design, Construction, and Operation (Succar, 2009). In each phase, different critical success factors (CSFs) emerge, with distinctive effects through the four BLC phases (Antwi-Afari, Li, Pärn, & Edwards, 2018).

The success of the BIM approach relies on three main categories: technology, people, and process (Liu, Nederveen, and Hertogh, 2017). These categories are complementary, synergistic, and can be implemented independently. However, the lack of any of these dimensions will result in a more negligible effect on successful project collaboration during BIM implementation.

In this context, BIM has transformed the AEC industry and attracted increasing attention from practitioners and researchers (Zhao 2017). The publication curve has steepened, showing that the BIM approach has consistently grown in recent years in Academia, with more than 90% of the papers being published in the last five years, resulting in a productive period in terms of BIM research publications (Santos, Costa, and Grilo 2017).

On the one hand, there is an impressive and up-to-date body of literature available (Santos, Costa, and Grilo 2017). On the other hand, the extant literature is replete with a widespread endorsement for BIM (Pärn, Edwards, and Sing 2017). Thus, it is essential to depict the available literature looking for patterns, understanding the influence of the CSF in different BLC (Antwi-Afari, Li, Pärn, & Edwards, 2018), through the technology, people, and process lenses (Liu, Nederveen, and Hertogh, 2017).

This study, therefore, aims to narrow these gaps by answering the following research questions: RQ1) How has BIM literature evolved in the last decades? and RQ2) What is the BIM CSFs, considering BLC phases and BIM categories?

The bibliometrics goal was to draw a scene of the BIM research field, investigating the relationship of the BIM CFSs, BIM categories (technology, process, and people), and BLC phases. The research design is a literature review

(SLR) performed through bibliometrics and content analysis to meet this objective. A two-step sample process was developed, first in the Web of Science database, then a backward snowballing towards the key references.

4.1 Method

The research method used to address the research questions was a systematic literature review (SLR). The SLR consists in identifying and synthesizing all the research evidence available concerning a specific subject in organized, transparent, and replicable procedures (Victor, 2008; Littell et al., 2008) in three main phases: planning the review, conducting the review and reporting the review (Kitchenham, 2004). For meeting the research goal, we performed the SLR by applying the following methods: bibliometrics, content analysis and cross-tabulation of the content analysis.

The research method was developed in five main steps as shown in **Figure 10.** In step 1 we concentrated on the definition of the research goal and the strings for data collection. In step 2, we focused on data collection from the Web of Science database, which is detailed in the “Sampling process” topic below. In step 3, we analyzed the data obtained from bibliometrics, content analysis and cross-tabulation of the content analysis. In step 4, after crossing quantitative and qualitative data, we worked on discussing the results. Finally, in step 5 we presented research achievements, limitations, and suggestions for future works.

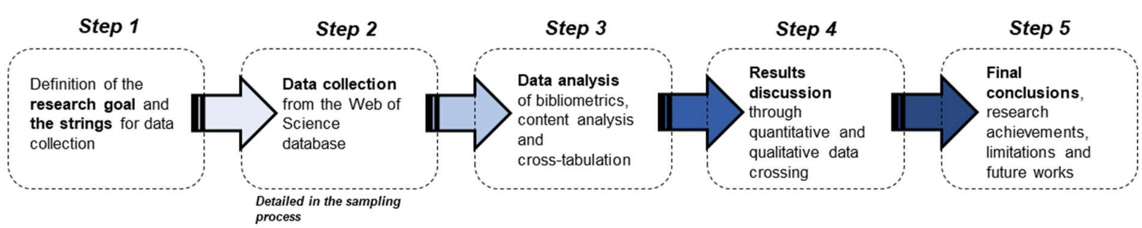


Figure 10: Research method steps

4.1.1 Sampling process

A two-step sample process was developed, first in articles and reviews from the Web of Science database, then a backward snowballing towards the key references. The sampling process started with an initial search in the Web of Science core collection database. We selected Web of Science database due to be a reliable database for academic research. We conducted the first search in February 2021 using the strings ***''Building Information Modeling'', ''BIM'', ''Building Information Modelling''*** and the logical operator ***"OR"*** between terms, which yielded 13.238 results.

To select only papers from the field of research, we applied the following filters: 1) Web of Science category: ***"construction building technology"*** and ***"architecture***; 2) Document types: ***"articles" and "reviews"*** (as in *peer-reviewed*); 3) Research area: ***"construction building technology"*** and ***"architecture".*** As a result of this filtering process, we obtained 1,378 publications published from 2000 to 2020 for the final sample.

The sampling process was designed to develop a qualitative approach via content analysis and quantitative approach through bibliometrics and cross-tabulation of the content analysis. **Figure 11** shows how we developed the sampling process for data collection.

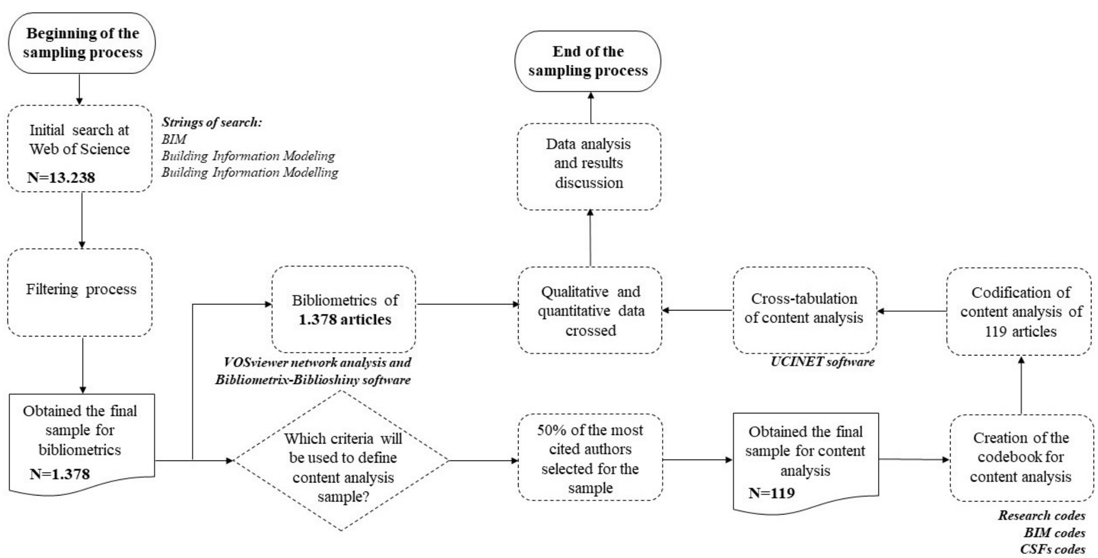


Figure 11: Sampling process

The quantitative approach concentrated on running the data extracted from the Web of Science database through network analysis software. We applied another filter to find a reasonable sample. Due to the large sample of articles, we considered selecting 50% of the most cited publications by annual average. The 1,378 papers corresponded to 2,993 citations/per year. Thus, choosing 50% of 2,993 citations/per year resulted in 119 papers.

After this final filtering process, we created a codebook for content analysis, which is presented in the Appendix. Subsequently, we qualitatively analyzed the 119 articles and crossed quantitative and qualitative data to obtain the results. Finally, we concentrated on data analysis and results discussion.

4.2 Data analysis

Data analysis was developed by crossing quantitative and qualitative data. This combination of quantitative and qualitative data contributed to a better understanding of the research theme from the data collected. In the following topics, we explain how we developed bibliometrics, content analysis and cross-tabulation content analysis.

4.2.1 Bibliometrics

For drawing a scenario of the BIM research field through bibliometrics, we examined the scientific database to analyze the main patterns and important academic studies based on citation analysis as a proxy of impact (Takey and Carvalho 2016). Bibliometric is helpful to visualize the relevance and the impact of themes, articles, authors, and sources in the literature aligned with RQ1.

Besides, network analysis facilitates mapping the relationship between keywords, authors, and references, which helps obtain the relationship among the variables (Carvalho, Fleury, and Lopes, 2013).

To visualize and analyze the BIM scientific knowledge in the literature, we explored a sample of 1,378 papers, performing bibliometric analysis through VOSviewer software (version 1.6.13 for Windows) and Bibliometrix-Biblioshiny software (Aria & Cuccurullo, 2017).

We characterized the sample demographics in the initial step by identifying the most relevant authors, documents, sources, countries, and institutions (Paul and Criado, 2020), with the aim of descriptive statistic and Bibliometrix-Biblioshiny software, drawing sources dynamics, and top authors production over time.

Before performing this analysis, we sorted the metadata, particularly regarding keywords; for example, we identified nine different keywords for BIM (BIM; Building Information Model; Building Information Model (BIM); Building Information Models; Building Information Model (BIM); Building Information Modeling; Building Information Modeling (BIM); Building Information Modelling; Building Information Modelling (BIM)).

In the second step, we mapped the relationship among authors, references and sources with the VOSviewer software, performing three types of networks: co-citation network, co-occurrence of keywords, and sources. Then, in Bibliometrix-Biblioshiny software, we performed the conceptual structure and intellectual structure analysis (Ramos-Rodríguez & Ruíz-Navarro, 2004), running thematic mapping, thematic evolution in selected time slices, and a historiographic analysis.

4.2.2 Content analysis

According to Duriau, Reger, & Pfarrer, (2007) ‘’content analysis allows for rendering the rich meaning associated with organizational documents combined with powerful quantitative analysis’’. In other words, content analysis is a structured and systematic technique for compressing several words of text into a volume of textual data in an organized manner to identify the focus of the subject matter, and to observe emerging patterns in the literature (Krippendorff, 2004; Weber,1990). For content analysis, we structured a codebook based on three main clusters of codes, namely: (A) Research codes, (B) BIM codes, and (C) CSFs related to the building life cycle phases (BLC) codes.

The research codes aimed to identify the main research patterns considering general research aspects to classify the selected publications. To develop the BIM codes, we extracted the top 10 papers of the sample from the Web of Science database. Then, we intensely studied each paper to create the BIM codes and then improved them during the content analysis process.

The code analysis allows investigation of the relationship between codes through cross-tabulation, network analysis, and core-periphery analysis, performed with the IBM SPSS software, UCINET6, and Netdraw software (Borgatti et al., 2002). We created fourteen (14) BIM codes based on the 10 most cited papers, as illustrated in **Table 1.**

To create the third cluster "CSFs related to BLC phases", we first defined four main phases, Design, Pre-construction, Construction and Operation, as aforementioned in the introduction. Then, based on a summary of 34 CSFs for BIM implementation found in the literature and gathered by Antwi-Afari, Li, Pärn, & Edwards (2018), we took the 34 CSFs and distributed them into, the four main phases based on our knowledge categorizing each CSF into each BLC phase.

Table 1: Top 10 most cited publications of the sample (1 is the most cited and 10 is the least cited)

Paper order	Title	Authors	Journal
1	Building information modeling (BIM) for existing buildings – Literature review and future needs	Volk, Stengel, & Schultmann (2014)	Automation in Construction
2	Building information modeling framework: A research and delivery foundation for industry stakeholders	Succar (2009)	Automation in Construction
3	The project benefits of building information modeling (BIM)	Bryde, Broquetas, & Volm (2013)	International Journal of Project Management
4	Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules	Zhang, Teizer, Lee, Eastman, & Venugopal (2013)	Automation in Construction
5	Application areas and data requirements for BIM-enabled facility management	Becerik-Gerber, Jazizadeh, Li, & Calis (2012)	Journal of Construction Engineering and Management
6	Enhancing environmental sustainability over building life cycles through green BIM: A review	Wong & Zhou (2015)	Automation in Construction
7	A scientometric review of global BIM research: Analysis and visualization	Zhao (2017)	Automation in Construction
8	Mapping the managerial areas of building information modeling (BIM) using scientometric analysis	He et al. (2017)	International Journal of Project Management
9	Understanding the effects of BIM on collaborative design and construction: An empirical study in China	Liu, van Nederveen, & Hertogh (2017)	International Journal of Project Management
10	Identifying and contextualizing the motivations for BIM implementation in construction projects: An empirical study in China	Cao et al. (2017)	International Journal of Project Management

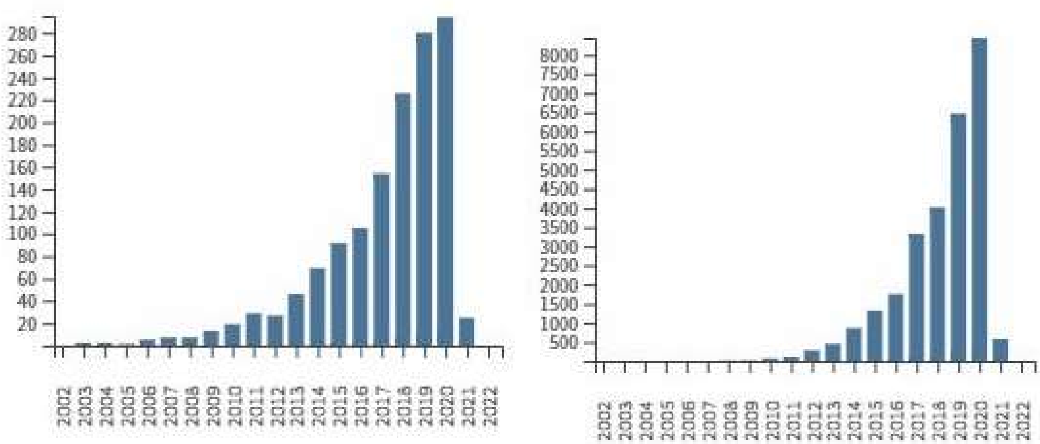
4.3 Results

This study analyzed all the articles from the WOS core collection database, which consists of the most important and influential journals in the academic environment and includes most publications on BIM. Only articles and reviews were selected for analysis, while book reviews, editorials, and conference papers were excluded. This is because articles usually provide more comprehensive and higher-quality information than other types of publications, and most reviews in the area of construction management have only covered articles.

4.3.1 Sample demographics

The annual number of publications has significantly increased publication patterns since 2009, which could be explained by the globally rising trend of BIM adoption. The publications surveyed were published from 2002 to 2021 (see **Figure 3**).

Based on Web of Science data, we observed the number of publications has massively risen from under 40 to more than 280 publications in 10 years (2010-2020), as illustrated in **Figure 12a.** Furthermore, there was a relevant expansion in the number of citations in the last 10 years, starting from nearly 100 citations/year in 2010 and growing sharply up to 8,000 citations/year in 2020 as observed in **Figure 12b.**



a: Publications per year **b:** Citations per year

Figure 12: Publications evolution per year

In our sample, five countries stood out with the highest number of publications and citations. The most productive country is the USA (549 articles), followed by China (470), the United Kingdom (315), Australia (224), and South Korea (190). However, in the top 5 most productive affiliations in the sample, the first one is Curtin University in Australia, three are Chinese universities (The Hong Kong Polytechnic University,

University of Hong Kong, and Tsinghua University) and one from South Korea (Kyung Hee University).

The most relevant source in our sample is *Automation in Construction* (576 articles); the following top ones were the *Journal of Construction Engineering and Management* (106), *Buildings* (50), *Advances in Engineering* (50), *Journal of Building Engineering* (45), *Energy and Buildings* (39), and *Building and Environment* (30), reinforcing the current tendency of treating this theme in the leading international journals, as shown in **Figure 13**, which illustrates sources dynamics.

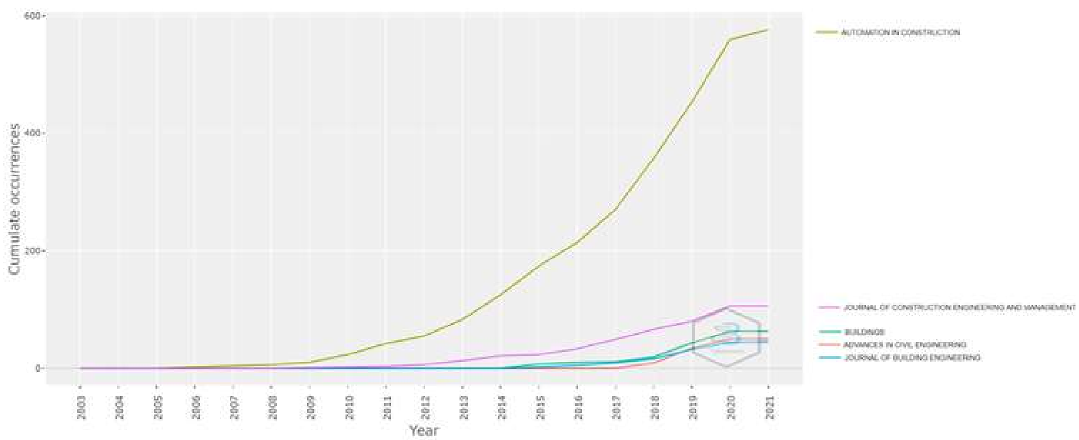


Figure 13: Number of publications per year (Note: Applying Biblioshiny software)

4.3.2 Bibliometrics

4.3.2.1 4.1 Key authors, documents, and references

For depicting the intellectual structure, we draw the historiographic, which explores the paths through the top 30 documents, applying the local citation score (Schöggl et al., 2020). **Figure 14** shows the historiographic development from 2006 to 2017, starting with Lee, Sacks, & Eastman (2006) and finishing with Santos, Costa, & Grilo (2017).

After identifying the top documents, we surveyed the core authors, considering both productivity and citations over time (see **Figure 15)**. Note that while some authors stood out in recent years, such as Hosseini and Edwards, others have consistently influenced the field for more than a decade such as Eastman, Sacks, and Lee.

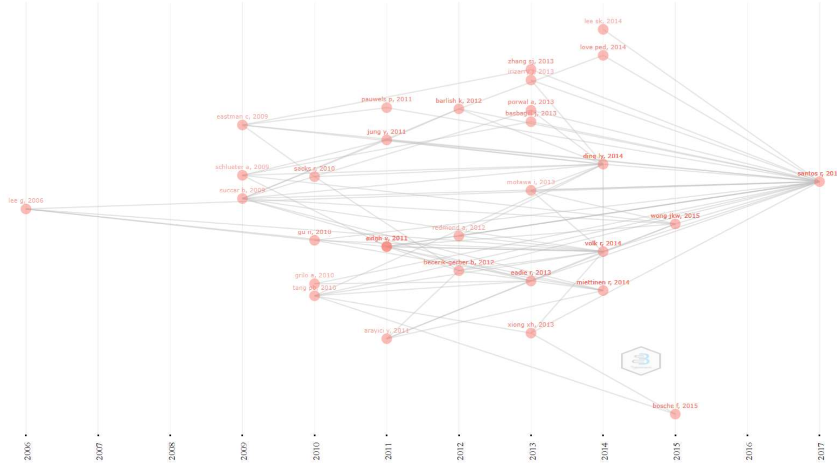


Figure 14: Number of nodes = 30. (Note: Extracted using Biblioshiny).

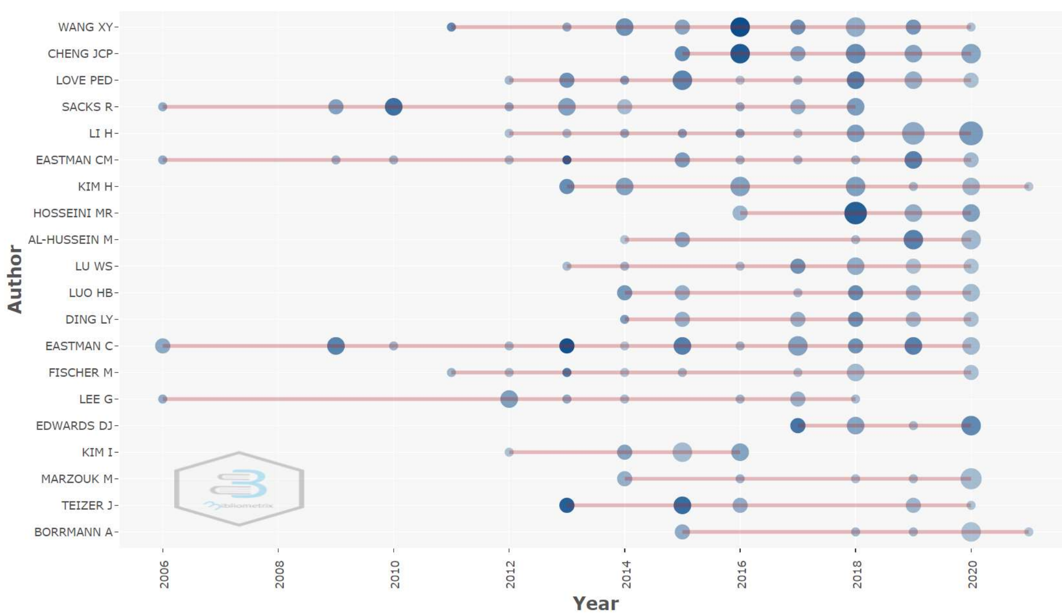


Figure 15: Top authors' production over time. (Note: Extracted using Biblioshiny).

Legend:
Lines represent the authors' timeline.
Bubble size is proportional to the number of documents.
Color intensity is proportional to the total citations per year.

According to Carvalho et al. (2013), co-citation networks allow observing the relatedness of items based on the number of times they are cited together in the sample. The network permits understanding the affinities of researchers, the intellectual structures of the knowledge body and how research groups are related to each other. A co-citation network is shown in **Figure 16,** where each node represents a reference and the links between references denote the collaboration established through the co-citation in the articles.

During the analysis process, the minimum number of citations of the cited references was 20 out of 43,451, of which 152 meet the thresholds. For each of the 152 references, the total strength of the co-citation links with other cited references was calculated. From the VOSviewer analysis, the co-citation network contains five clusters, 152 citations, 8,277 links and 27,646 total link strength. The node size reflects the number of co-citations of each reference, and the links between references represent indirect cooperative relationships established based on the co-citation frequency.

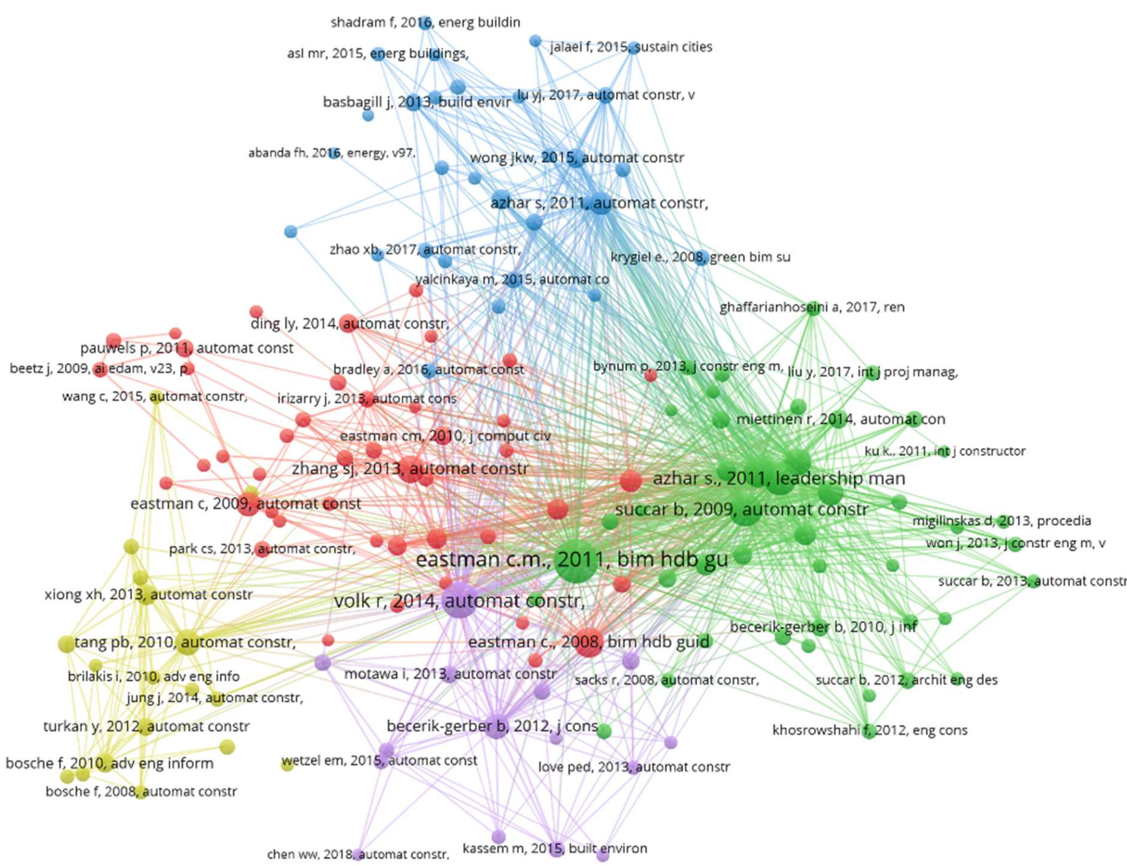


Figure 16: Co-citation network. (Note: Applying VoS Viewer software)

The co-citation network analysis is presented by five different colored clusters showing important connections between authors. Cluster 1 (red color) contains 45 references, cluster 2 (green color), has 44 references, cluster 3 (blue color) has 30 references, cluster 4 (yellow color) has 18 references, and cluster 5 (purple color) has 15 references.

The most cited reference in the co-citation network analysis was Eastman et al. (2011) (green cluster) with 228 citations, who developed *The BIM Handbook: A guide to Building Information Modeling*. The top-five following authors were: Volk et al. (2014), with 152 references (purple cluster), Succar (2009), with 132 citations (green cluster), Azhar (2011), with 127 citations (green cluster), Eastman (2008), with 104 citations (red cluster) and Zhang et al. (2013), with 89 citations (red cluster). Other significant cited references were Becerik-Gerber et al. (2012) with 79 citations (purple cluster), Eastman et al. (2009) with 71 citations and Azhar et al. (2011) with 64 citations.

Thus, the pattern of the relationship among top authors, references, and keywords are depicted in **Figure 17.** It could be noted that most authors explore BIM general themes and Industry Foundation Classes (IFC). However, facility management (Edwards and Marzouk), sustainability (Chan), life-cycle assessment (LCA) (Fischer), and virtual reality (Sacks) are explored only by a few authors. Based on the locally cited reference score, the most influential reference is Eastman et al. (2011), as mentioned before.

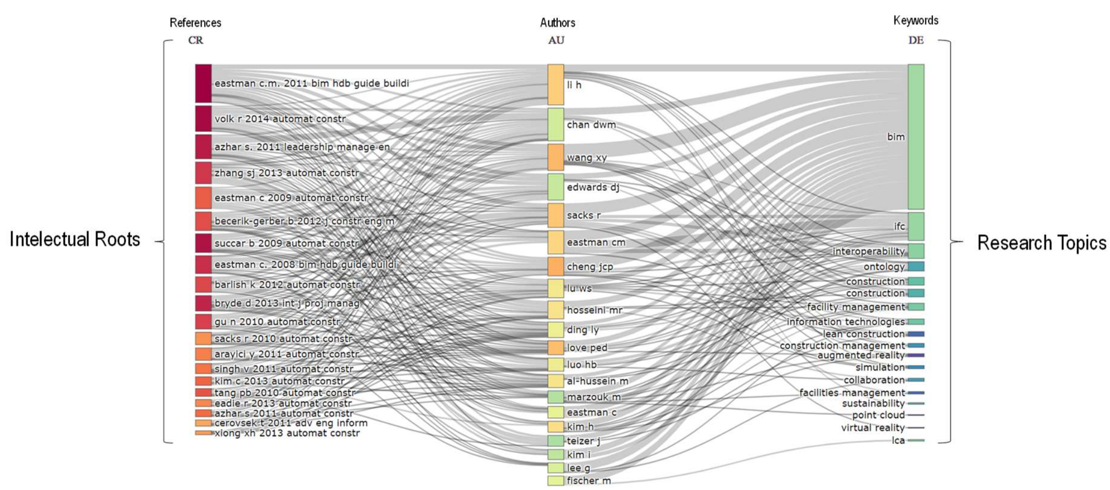


Figure 17: Relationship among top authors, cited references and keywords

4.3.2.2 Trend topics and thematic evolution

According to Zhao (2017) ‘’keywords present the core content of articles and show the development of research topics over time’’. During the VOSviewer configuration process, we chose full counting and ‘’Author keywords’’ with a minimum of five occurrences by keyword representing 4,865 keywords; 347 met the thresholds. **Figure 18** shows the co-occurrence keywords network with 347 keywords, 8 clusters, 9,533 links and 20,612 total link strength. The node size represents the keyword frequency in the sample.

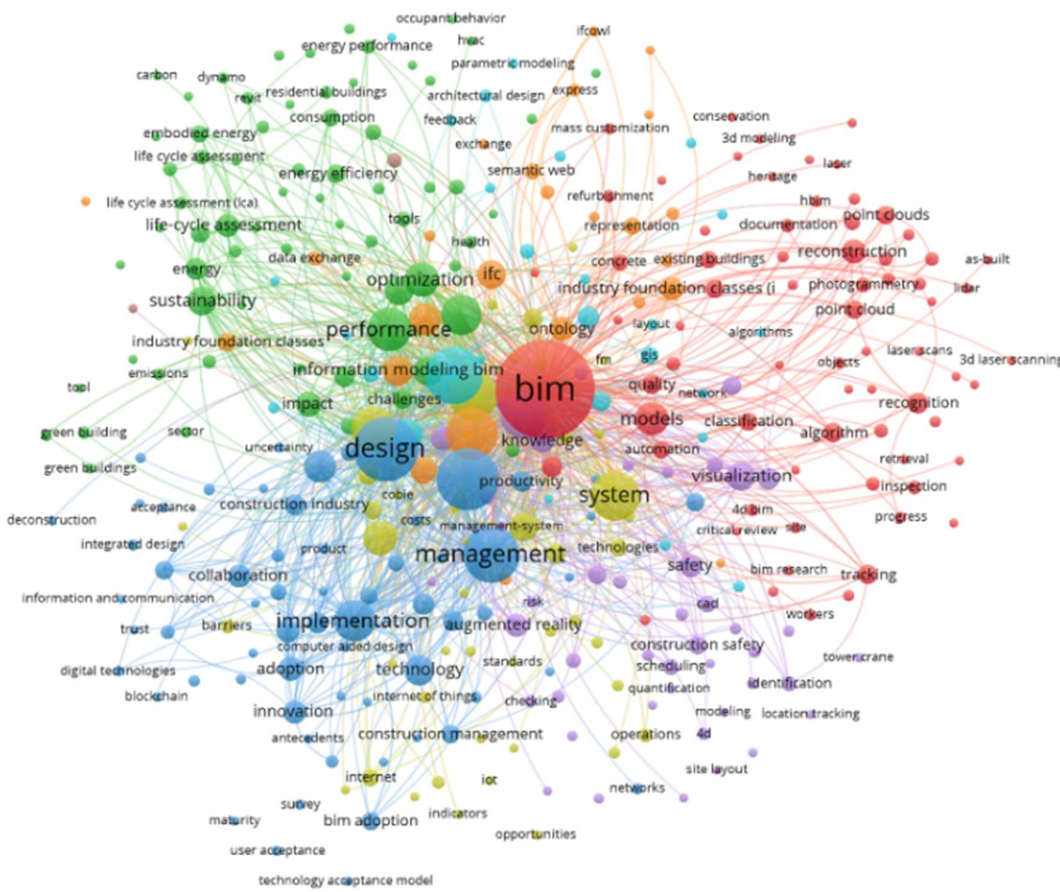


Figure 18: Co-occurrence network. (Note: Applying VOSviewer software)

The most high-frequency keywords were BIM, design, management, construction, system, implementation, performance. BIM (red node) appeared as the main node of the network followed by design, construction, and management (blue nodes). Building information modeling (orange and light blue nodes) represented a noticeable number of total link strengths and occurrences. According to Yalcinkaya & Singh (2015), Building Information Modeling (BIM) has emerged as one of the key streams in the construction industry and received a considerable amount of attention from researchers within the last decade, an accelerated increase in the number of publications.

To identify the core concepts and topics over time, we performed a Thematic Evolution analysis using Biblioshiny, exploring asymmetric time slices because the literature evolution has had a craggy curve in recent years, as shown in **Figure 19.** New topics have emerged as niche themes lately, particularly data exchange, lean construction, and smart contracts, while two motor themes stood out, artificial intelligence and construction supply chain.

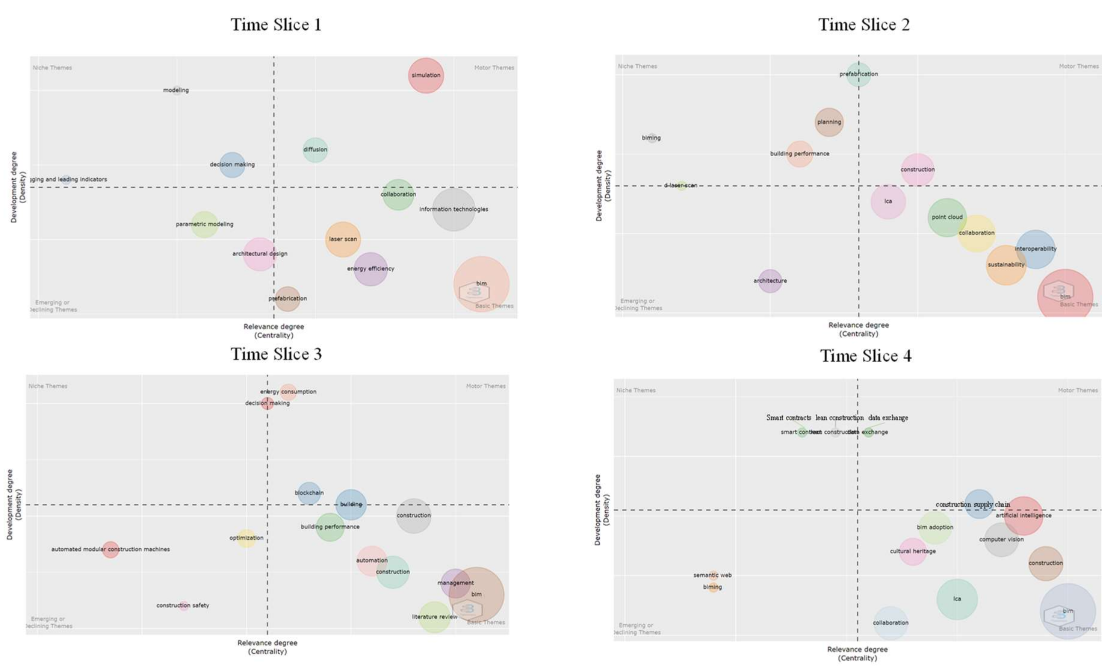


Figure 19: Thematic evolution over time (Note: Extracted using Biblioshiny).

4.3.3 Content analysis

The content analysis developed an investigation of 119 selected articles which correspond to 50% of the most cited publications by annual average. We analyzed each paper thoroughly, categorizing them into twenty-six created codes to understand the main patterns of BIM research in the field and, the correlation of BIM categories with CSFs in the BLC phases. All the articles studied are listed in Appendix A.

The following topics present the findings of content analysis. First, we introduced an overview of research code analysis. Second, we presented the understanding of the BIM approach through a descriptive statistical and cross-tabulation code analysis. Third, we correlated BIM categories (technology, process, and people) with CSFs in the BLC phases.

4.3.3.1 Overview of research codes analysis

Regarding research approach codes, the content analysis showed the kind of studies in the analyzed articles were mostly case studies (42%), followed by a literature review (18%); theoretical-conceptual and simulation, both with 11%. Some authors developed their studies using two types of methods, such as literature review and case study or literature review and action research. Mostly, the period of analysis of the studies was retrospective (81%) followed by longitudinal (15%) and contemporary (3%). The qualitative approach appeared as the most significant one with 98%, followed by the quantitative approach with 72%.

As observed in the kind of study, the studies combined qualitative and quantitative approach in the majority of the articles. The analytic units were mainly design (62%) and process (32%); and the top-five sources of evidence used were biography (83%); parametric data (45%); algorithm (36%); documents (14%) and interviews (13%). Lastly, regarding the geographic scope, approximately forty-nine percent (49.5%) of the studies were developed in the international sphere; forty-eight (48.7%) in the national sphere, and only 1.7% were considered regional.

4.3.3.2 Understanding the BIM approach in Academia

BIM codes analysis first started with the understanding of BIM research areas of study in the field. We established eleven major areas of study to classify the field of BIM research in each article. **Table 2** summarizes a descriptive statistical analysis of BIM research (code B1) which is presented by number and subcode name (research area);

number and percentage of the paper's occurrence classified into each research area; and the authors corresponded to each BIM research area.

Table 2: BIM research descriptive statistical analysis

Code (B1)	BIM research subcodes	N. of papers	%	Authors
R1	BIM ontology (linked data; semantic web technology)	14	12%	Succar (2009); Zhang, Boukamp, & Teizer (2015); Park, Lee, Kwon, & Wang (2013); Lee, Kim, & Yu (2014); Pauwels et al. (2017); Deng, Cheng, & Anumba (2016); Succar & Sher (2013); Pauwels et al. (2011); Succar & Kassem (2015); Vanlande, Nicolle, & Cruz (2008); Karan & Irizarry (2015); Yalcinkaya & Singh (2015);Santos, Costa, & Grilo (2017); Li et al. (2017)
R2	BIM in the AEC education	4	3%	Zhao (2017); Yalcinkaya & Singh (2015); Santos, Costa, & Grilo (2017); Li et al. (2017)
R3	BIM in the AEC industry	25	21%	Succar (2009); Barlish & Sullivan (2012); Gu & London (2010);(Eadie et al. (2013); Singh, Gu, & Wang (2011); Porwal & Hewage (2013); Miettinen & Paavola (2014); Arayici et al. (2011); Jung & Joo (2011); (Hosseini et al. (2018); Cao et al. (2015); Chen & Luo (2014); (Sacks et al. (2010); Hartmann et al. (2012); Bradley et al. (2016); Succar & Sher (2013); Lee, Sacks, & Eastman (2006); Franz et al. (2017); Succar & Kassem (2015); Yalcinkaya & Singh (2015); Santos, Costa, & Grilo (2017); Li et al. (2017); Monteiro & Poças Martins (2013); Love et al. (2015); Cao et al. (2014)
R4	Safety (construction safety rule and code checking)	18	15%	Zhang et al. (2013); Eastman et al. (2009); Zhang et al. (2015); (Ding et al., 2014); Dossick & Neff (2010); J. Park, Kim, & Cho (2017); Guo et al. (2019); Park & Kim (2013); Hu & Zhang (2011); Zhou, Whyte, & Sacks (2012); Solihin & Eastman (2015); Fang et al. (2018); Yalcinkaya & Singh (2015); Santos, Costa, & Grilo (2017); Li et al. (2017); Zhang et al. (2015); Kim, Cho, & Zhang (2016); Fang et al. (2016)
R5	Sustainability (energy, acoustic, energy simulation)	18	15%	Basbagill et al. (2013); Wong & Zhou (2015); Schlueter & Thesseling (2009); Azhar et al. (2011); Doan et al. (2017); Soust-Verdaguer, Llatas, & García-Martínez (2017); Lu et al. (2017); Shadram et al. (2016); Bynum, Issa, & Olbina (2013); Jalaei & Jrade (2015); Liu, Meng, & Tam (2015); Ilhan & Yaman (2016); El-Diraby, Krijnen, & Papagelis (2017); Yalcinkaya & Singh (2015); Santos, Costa, & Grilo (2017); Li et al. (2017); Akbarnezhad, Ong, & Chandra (2014); Iddon & Firth (2013)
R6	Facility management (existing buildings, reconstruction, performance control)	13	11%	Volk et al. (2014); Becerik-Gerber et al. (2012); Pärn, Edwards, & Sing (2017); Love et a. (2014); Motawa & Almarshad (2013); (Lyu et al. (2019); Kang & Hong (2015); Motamedi, Hammad, & Asen (2014); Wetzel & Thabet (2015); Pishdad-Bozorgi et al. (2018); Yalcinkaya & Singh (2015); Santos, Costa, & Grilo (2017); Li et al. (2017)
R7	BIM technology applications (Laser scanning, Virtual reality/UAV)	14	12%	Tang et al. (2010); Xiong, Adan, Akinci, & Huber (2013); (Bosché et al. (2015); Wang, Cho, & Kim (2015); Park et al. (2013); Jung et al. (2014); Kim et al. (2015); Wang et al. (2013); Yalcinkaya & Singh (2015); Santos, Costa, & Grilo (2017); Li et al. (2017); Klein, Li, & Becerik-Gerber (2012); Kim et al. (2016); Du et al. (2018)

R8	H-BIM (Historic Building Information Modeling)	4	3%	Yalcinkaya & Singh (2015); Santos, Costa, & Grilo (2017); Li et al. (2017); Bruno, De Fino, & Fatiguso (2018)
R9	Innovation (3D-printing, critical success factor, Lean construction, LPS)	10	8%	Wu, Wang, & Wang (2016); Sacks, Radosavljevic, & Barak (2010); Dave et al. 2016); Chien, Wu, & Huang (2014); Son, Lee, & Kim (2015); Li et al. (2018); Yalcinkaya & Singh (2015); Santos, Costa, & Grilo (2017); Li et al. (2017); Love et al. (2013)
R10	Intelligence (interoperability, building performance, construction simulation)	31	26%	Irizarry, Karan, & Jalaei (2013); Grilo & Jardim-Goncalves (2010); Wang et al. (2015); Kim, Kim, & Son (2013); Lee, Kim, & Yu (2014); Pauwels et al. (2017); (Redmond et al. (2012); Deng, Cheng, & Anumba (2016); Gerrish et al. (2017); Zhong et al. (2017); (Kim et al. (2015); Li et al. (2014); Negendahl (2015); Ham & Golparvar-Fard (2015); Wang & Zhai (2016); Kumar & Cheng (2015); Göçer, Hua, & Göçer (2015); Vanlande, Nicolle, & Cruz (2008); Pinheiro et al. (2018); Karan & Irizarry (2015); Borrmann et al. (2015); Rahmani Asl (2015); Sacks et al. (2017); Yalcinkaya & Singh (2015); Santos, Costa, & Grilo (2017); Li et al. (2017); Goedert & Meadati (2008); Dong, O'Neill, & Li (2014); H. Liu, Al-Hussein, & Lu (2015); Park & Cai (2017); Habibi (2017); Kim et al. (2013)
R11	Mobile computing (BIM cloud, multi-scale)	8	7%	Wang et al. (2014); Han & Golparvar-Fard (2017); Han & Golparvar-Fard (2015); Anil et al. (2019); Davies & Harty (2013); Yalcinkaya & Singh (2015); Santos, Costa, & Grilo (2017); Li et al. (2017)

% in 119 articles

The analysis showed *Intelligence* (R10) characterized by *interoperability, building performance, and construction simulation* as the most representative area of study in the BIM field with 26% of the sample (31 of 119 articles). Followed by *BIM adoption in the AEC industry* (R3) with 21% (25 of 119 articles), *Safety* (R4) defined by *construction safety and code checking* and *Sustainability* (R5) defined by *energy, acoustic and energy simulation* both with 15% each (18 of 119 articles).

From cross-tabulation we observed a strong relationship between *BIM ontology* (R1) and *BIM in the AEC industry* (R3), and *BIM ontology* (R1) and *Intelligence* (R10). Additionally, there was a significant relationship between *BIM ontology* (R1) and *Safety* (R4), and *BIM ontology* (R1) and *BIM technologies applications* (R4) as illustrated in **Figure 20.**

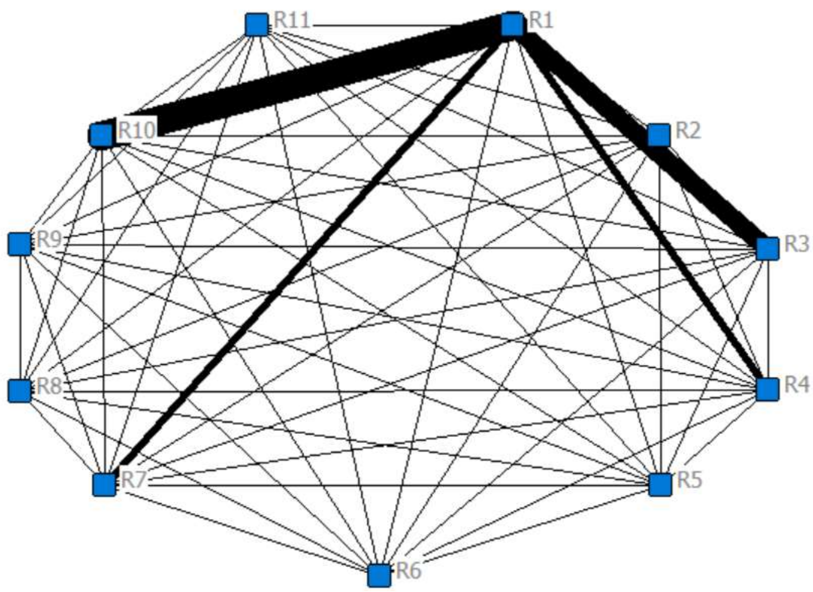


Figure 20: BIM research network (Note: Applying the Ucinet software)

After analyzing BIM research fields, we focused on understanding BIM adoption classified into macro, meso and micro-categories. Based on Y. Liu et al. (2017), we first classified BIM macro categories named by *Technology, People and Process focused issues.* Second, we subdivided each macro-category into meso categories. **Table 3** illustrates BIM macro categories descriptive statistical analysis. **Table** 4 shows BIM meso categories descriptive statistical analysis and **Table 5** illustrates BIM micro-categories descriptive statistical analysis.

Table 3: BIM macro categories descriptive statistical analysis

Code (B2)	BIM macro-category subcodes	N. of papers	%
MacC1	Technology-focused issues	94	79%
MacC2	People-focused issues	13	11%
MacC3	Process-focused issues	50	42%

Table 4: BIM meso-categories descriptive statistical analysis

Code(B3)	BIM meso-category subcodes	N. of papers	%
MesC1a	IT capacity	79	66%
MesC1b	Technology management	58	49%
MesC2a	Attitude and behavior	7	6%
MesC2b	Role taking	11	9%
MesC3a	Communication	35	29%
MesC3b	Leadership	3	3%
MesC3c	Trust	16	13%
MesC3d	Learning and experience	13	11%

Table 5: BIM micro-categories descriptive statistical analysis

Code (B4)	BIM micro-category subcodes	N. of papers	%
MicC1a1	software functionality	61	51%
MicC1a2	software immaturity	8	7%
MicC1a3	compatibility	34	29%
MicC1b1	model creation management	14	12%
MicC1b2	model sharing management	48	40%
MicC2a1	designer attitude	6	5%
MicC2a2	reluctance to initiate new works flows	5	4%
MicC2b1	emergence of new roles	5	4%
MicC2b2	confliction obligations	7	6%
MicC3a1	information exchange	22	18%
MicC3a2	direct access to collaboration	9	8%
MicC3a3	organizational structure	18	15%
MicC3a4	business purposes	11	9%
MicC3a5	different requirements	3	3%
MicC3b1	third party as a leader	1	1%
MicC3b2	direct participants as leaders	3	3%
MicC3c1	trust effects	12	10%
MicC3c2	affecting trust	2	2%
MicC3c3	past experience	5	4%
MicC3c1	inadequate BIM skills	6	5%
MicC3d2	learning approach	7	6%
MicC3d3	organizational learning	7	6%

% in 119 articles

The descriptive statistical analysis showed that *Technology-focused issues* (MacC1) was the most BIM macro-category studied followed by *Process-focused issues* (MacC3) with 42%, and *People-focused issues* (MacC2) with 11% of our sample. In the BIM meso-categories, we noticed the most representative ones were: *IT capacity* (66%),*technology management* (49%) and *Communication* (29%). Concerning the BIM micro-categories, we observed *Software functionality* (51%), *Model sharing management* (40%) and, *Compatibility* (29%) as the most studied of the sample.

From the cross-tabulation, we recognized a stronger network between *Technology* (MacC1) and *Process* (MacC3) in comparison to the *Technology* and *People* (MacC2) network, and the *Process* and *People* network as illustrated in **Figure 21**. In the BIM meso-categories network, we primarily observed a robust relationship between *IT capacity* (MesC1a) and *Technology Management* (MesC1b) and a considerable relationship between these two meso-categories with *Communication* (MesC3a).

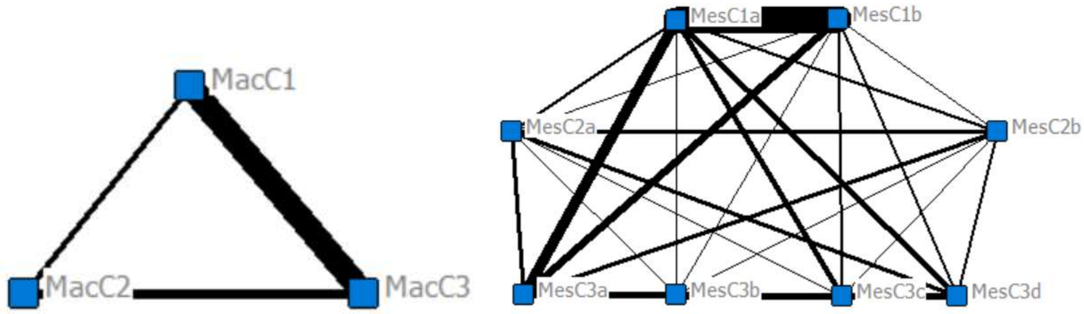


Figure 21: BIM macro categories and meso-categories network (Note: Applying Ucinet software)

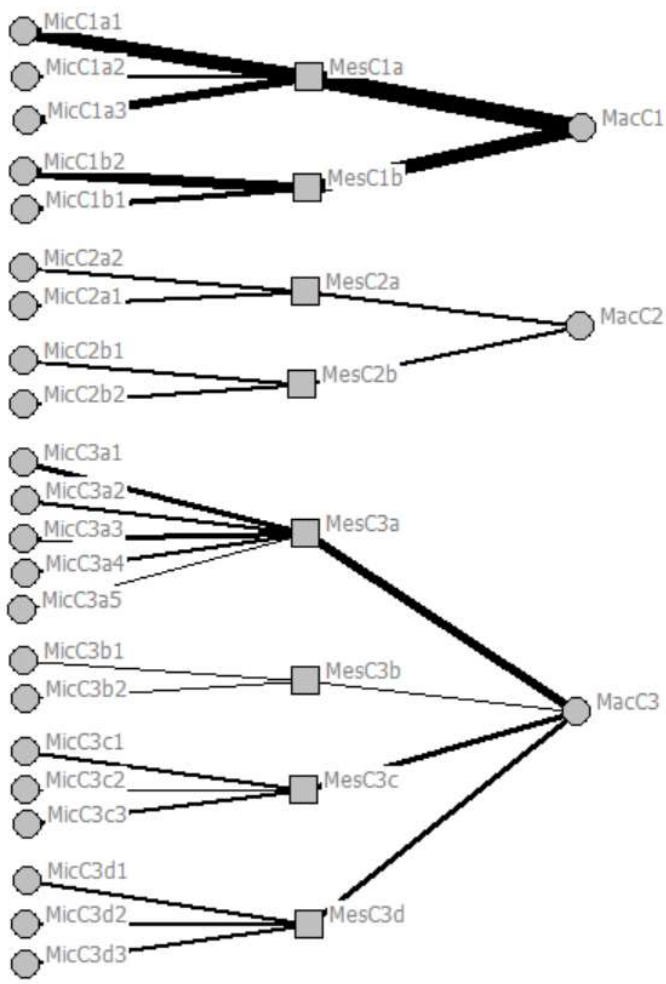


Figure 22: BIM macro, meso and micro-categories code tree (Note: Applying Ucinet software)

Figure 22 shows a code tree analysis between *BIM macro, meso and micro-categories*. As previously observed in the descriptive statistical code analysis, *Technology-focused issues* (MacC1) composed the most notorious BIM macro-category compared to *People and Process-focused issues*.

From the code tree analysis, we identified *IT capacity* (MicC1a) and *Tecnology management* (MicC1b) as the most relevant meso-categories and *Software functionality* (MicC1a1) and *Model sharing management* (MicC1b2) as the most representative micro-categories related to *Technology-focused issues* (MacC1). *Communication* (MesC3a) represented the most mentioned meso-category and *Information exchange* (MicC3a1) and *Organizational structure* (MicC3a3), the most studied micro-categories related to *Process-focused issues* (MacC3).

Besides the analysis of BIM research (B1), BIM macro, meso and micro-categories (respectively B2, B3 and B4), we proposed other BIM codes to investigate the BIM approach in the literature. **Table 6** shows a descriptive statistical analysis from BIM code B5 to B14 presented by code number, BIM code name, BIM subcode names and the number of papers and their percentage by the occurrence of each category in a total of 119 articles.

BIM implementation motivations (B5) was categorized into four different motivations, named image, reactive, project-based economic and cross-project economic motives. *Project-based economic motives* were the most noticeable in motivation yielding 55% of the sample.

This result shows that the articles analyzed used BIM as project-based economic motivation in three main aspects: first as a tool to solve related design and construction problems in the project, second as a tool to improve cost and schedule performances in the project and third direct economic benefits of BIM use will outweigh its costs in the project (Cao et al., 2017).

Table 6: Descriptive statistical analysis from BIM code B5 to B14

Code	BIM Code name	BIM subcodes names	N. of papers	%
B5	BIM implementation motivations	Image motives	23	19%
		Reactive motives	12	10%
		Project-based economic motives	66	55%
		Cross-project economic motives	23	19%
B6	BIM relation in the building life cycle	Functional issues	46	39%
		Informational issues	21	18%
		Technical issues	28	24%
		Organizational and legal issues	32	27%
B7	Building life cycle phase	Design	62	52%
		Construction	66	55%
		Operation	38	32%

B8	Building life cycle subphase	Conceptualization, programming, and cost planning	36	30%
		Architectural, structural and systems design	21	18%
		Analysis, detailing, coordination and specification	42	35%
		Construction planning and construction detailing	55	46%
		Construction, manufacturing, and procurement	36	30%
		Commissioning, as built and handover	24	20%
		Occupancy and operations	22	18%
		Asset management and facility maintenance	33	28%
		Decommissioning and major re-programming	17	14%
B9	BIM dimensions	2D	13	11%
		3D	73	61%
		4D	36	30%
		5D	19	16%
		6D	34	29%
		7D	32	27%
		8D	21	18%
B10	BIM fields	Policy	14	12%
		Process	53	45%
		Technology	92	77%
B11	BIM stages	Pre-BIM status	7	6%
		BIM stage 1	13	11%
		BIM stage 2	76	64%
		BIM stage 3	41	34%
		Post-BIM	8	7%
B12	BIM lenses	Disciplinary lenses	29	24%
		Scoping lenses	83	70%
		Conceptual lenses	8	7%
B13	BIM maturity	Initial	7	6%
		Defined	15	13%
		Managed	68	57%
		Integrated	45	38%
		Optimized	10	8%
B14	BIM organizational scale	Macro: markets and industry	30	25%
		Meso: projects and their teams	87	73%
		Micro: organizations, units, their teams, and members	11	9%

% in 119 articles

Functional issues were the most researched category (39%) in comparison to *informational* (18%); *technical* (24%); *organizational and legal issues* (27%) as regards the building life cycle (B6). According to Volk et al. (2014), functional issues are BIM functionalities and applications, accuracy and capability.

Concerning the Building life cycle phase (B7), BIM has been more studied in the *construction* phase (55%) when compared to *design* (52%) and *operation* (32%) phases. Regarding the building life cycle subphase (B8), *Analysis, detailing, coordination and specification* (35% of the design phase), *Construction planning and construction detailing* (46% of construction phase), *and Asset management and facility maintenance* (28% of operation phase) were the most relevant subphases.

Three-dimensional was considered the most BIM dimension (B9) studied with (61%). *Technology* (77%) represented the largest BIM field (B10) compared to *Policy* (12%) and *Process* (45%). *BIM stage 2* (64%) was the most researched BIM stage (B11) and *Scoping lenses* (70%) were the most studied BIM lenses (B12). Regarding BIM maturity (B13), *Managed* (57%) was the most studied in the sample. Finally, *Meso: projects and their teams* (73%) were the most frequent BIM organizational scale (B14).

In addition to the BIM code's descriptive statistical analysis, we performed a matrix analysis of the BIM codes. The analysis resulted in a correlation of 0.8575 fits between the core and periphery matrix. The core matrix indicated eighteen main BIM codes, which are described in **Figure 23.**

Findings showed BIM macro-category (B2) twice in the core matrix analysis evidencing *Technology* followed by *Process*. *IT capacity* and *Technology management* appeared as BIM meso-categories (B3) and *Model sharing management* and *Software functionality* as BIM micro-category (B4) in the core matrix. *Technology* also arose as the most BIM field (B10) studied followed by *Process* in the analyzed sample. As observed in the BIM codes descriptive statistical analysis, we found in the core matrix: *BIM Stage 2* as BIM stage (B11); *Managed* as BIM maturity level (B13); *3D (Three-dimensional modeling)* as BIM dimension (B12); and *Meso: projects and their teams* as BIM organizational scale (B14).

Design and *Construction* appeared as the most relevant phases of the building life cycle (B7), and *Construction planning and construction detailing* as the most noticeable sub-phase (B8). *Project-based economic motives* as BIM implementation motivations (B5); and *Functional issues* as the BIM relation in the building life cycle (B6) were also found in the core matrix.

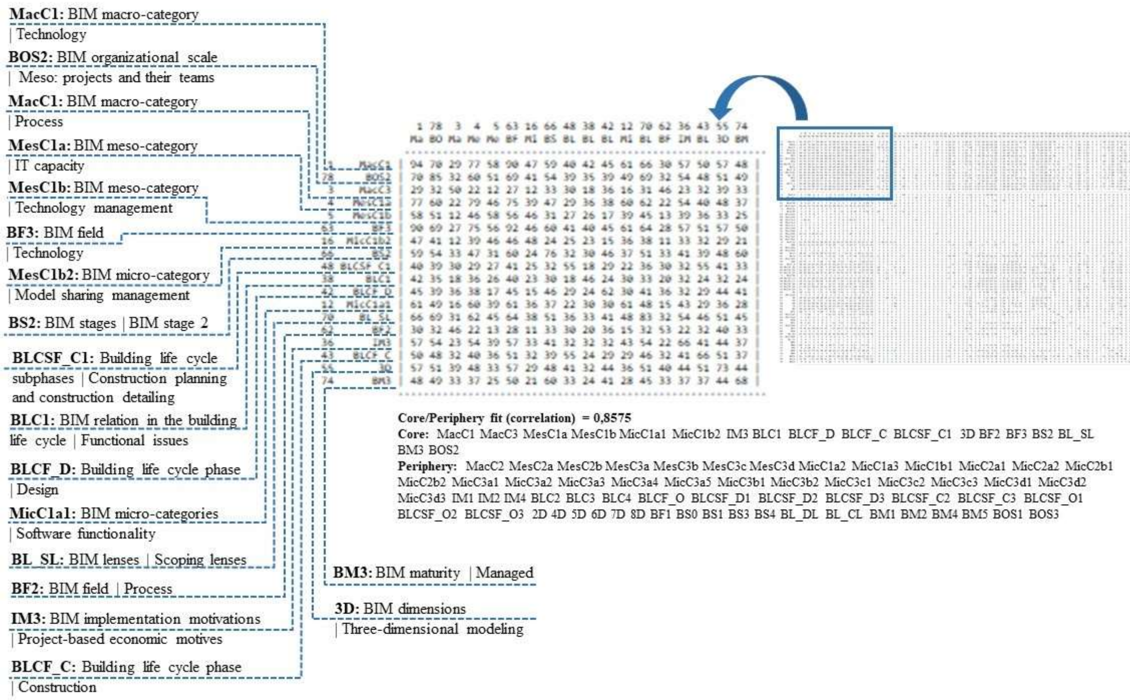


Figure 23: Core and periphery of BIM codes matrix (Note: Applying Ucinet software)

4.3.3.3 BIM macro categories relationship with CSFs in the BLC phases

Since our secondary research goal was to investigate the correlation of BIM macro categories with CSFs in the building life cycle phases, we crossed technology, process, and people as BIM macro categories codes with the four CSFs codes using UCINET software. The CSF codes were categorized into the design, pre-construction, construction, and operation phases as previously defined in the methonresearch.

The analysis showed *Process* (MacC3) BIM macro-category has more significant correlations with CSFs codes than with *Technology* and *People.* **Figure 24** illustrates the relationship between *Technology* with CFS codes in each building life cycle phase. The network analysis showed stronger correlations between *CSFs* ***D12*** with the *design phase*; *CSFs* ***PC4*** and ***PC6*** with the *pre-construction phase*; *CSFs* ***C4*** with *construction phase* and *CSFs* ***O1*** with the *operation phase* compared to the other correlations between technology and CSFs in each BLC phase.

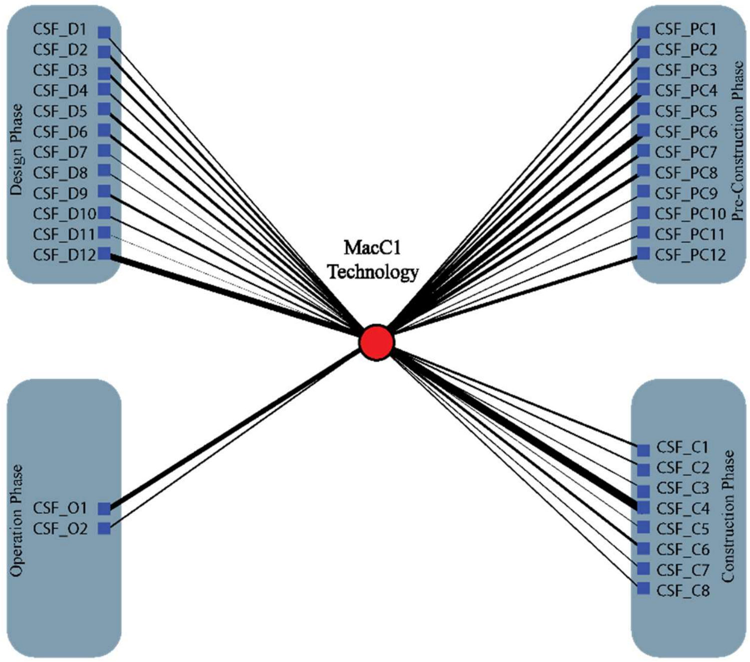


Figure 24: Correlation of technology BIM macro-category with CSFs codes (Note: Applying Ucinet software)

By cross-tabulation, we observed a narrow correlation between *People (MacC3)* and CSFs codes in the building life cycle phases represented in **Figure 25.** In turn, we noticed an expressive network between *Process (MacC3) and CSFs codes* represented by the links in **Figure 26.**

The network analysis showed stronger correlations between *CSFs **D1, D2, D3, D4** and **D12*** with the *design phase*; *CSFs **PC2, PC4, PC6*** with the *pre-construction phase*; *CSFs **C4*** with *construction phase* compared to other correlations.

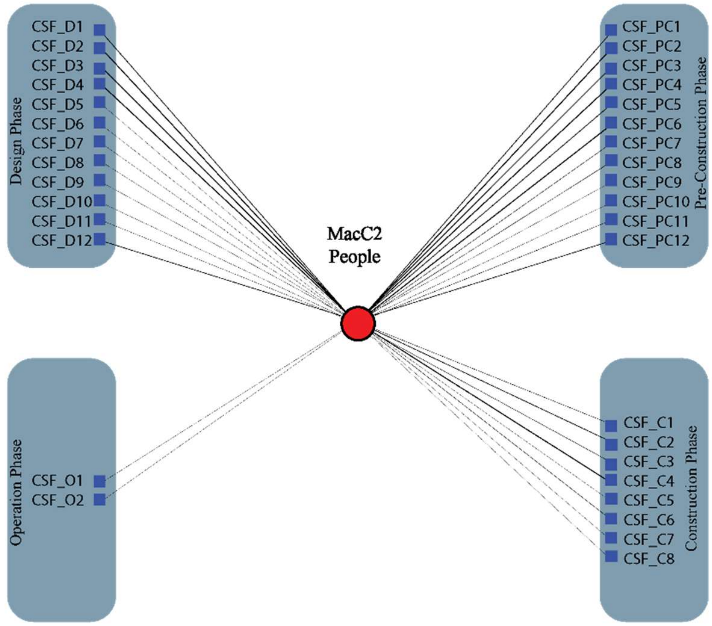


Figure 25: Correlation of people BIM macro-category with CSFs codes (Note: Applying Ucinet software)

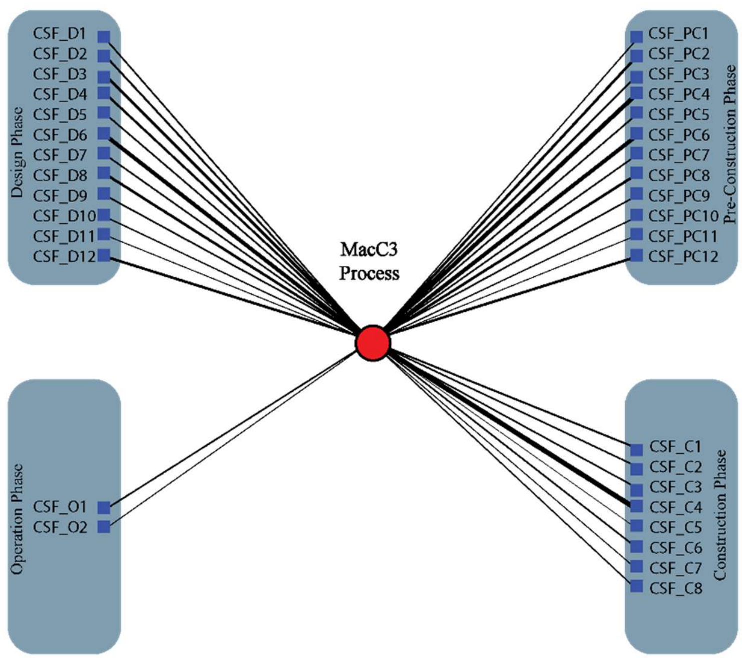


Figure 26: Correlation of process BIM macro-category with CSFs codes (Note: Applying Ucinet software)

We performed a matrix codes analysis of the CFS codes in the BLC phases. The analysis resulted in a correlation of 0.8028 fits between the core and periphery matrix. **Figure 27** shows the core matrix of CSFs codes in the BLC phases.

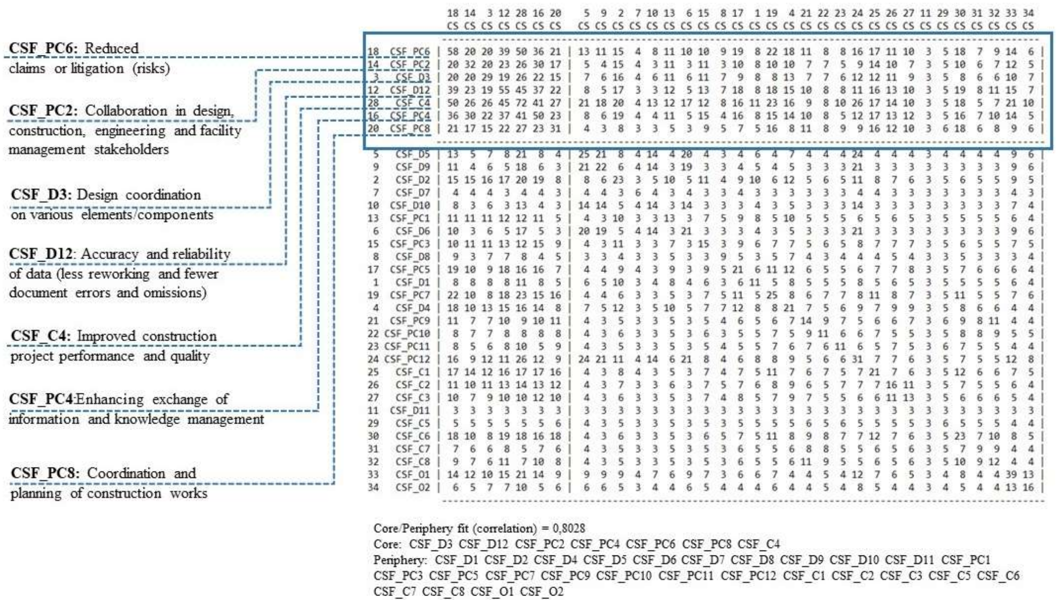


Figure 27: Core and periphery of CSFs codes matrix (Note: Applying Ucinet software)

The core matrix indicated seven main CSFs codes, two of which are related to the design phase, four to the pre-construction phase and one code related to the construction. these are listed in **Table 7** by a number of occurrences:

Table 7: CSFs codes list of the core matrix analysis

Building life cycle phase	Critical success factors for BIM	Code	Number of occurrences
Design CSFs	Design coordination of various elements/components	CSF_D3	20
	Accuracy and reliability of data (less rework and fewer document errors and omissions)	CSF_D12	39
Pre-construction CSFs	Collaboration in design, construction, engineering, and facility management stakeholders	CSF_PC2	20
	Enhancing exchange of information and knowledge management	CSF_PC4	36
	Reduced claims or litigation (risks)	CSF_PC6	58
	Coordination and planning of construction works	CSF_PC8	21
Construction CSFs	Improved construction project performance and quality	CSF_C4	50

Table 8 summarizes the descriptive statistical analysis of CSFs codes for BIM classified into four main building life cycle phases: design, pre-construction, construction, and operation.

Table 8: Descriptive statistical analysis of CSFs for BIM by building life cycle phase

Building life cycle phase	Critical success factors for BIM	Code	N. of papers	%
Design CSFs	Earlier and accurate 3D visualization of design	CSF_D1	11	9%
	Better design/multi-dimensional design alternatives/applications	CSF_D2	23	19%
	Design coordination of various elements/components	CSF_D3	29	24%
	Verification of consistency to the design intent	CSF_D4	21	18%
	Predictive analysis of performance (energy analysis, e.g. CO2)	CSF_D5	25	21%
	Thermal energy analysis and simulation	CSF_D6	21	18%
	MEP analysis and simulation (HVAC)	CSF_D7	6	5%
	Structural analysis and design	CSF_D8	9	8%
	Predicting environmental analysis and simulation (airflow, weather)	CSF_D9	22	18%
	Acoustic analysis and simulation (sound)	CSF_D10	14	12%
	Photorealistic rendering for marketing purposes	CSF_D11	3	13%
	Accuracy and reliability of data (less rework and fewer document errors and omissions)	CSF_D12	55	46%
Pre-construction CSFs	Integrating design validation (clash detection)	CSF_PC1	13	11%
	Collaboration in design, construction, engineering, and facility management stakeholders	CSF_PC2	32	27%
	Ensuring effective communication among project participants	CSF_PC3	15	13%
	Enhancing exchange of information and knowledge management	CSF_PC4	50	42%
	Model checking and validation (reviewing code)	CSF_PC5	21	18%
	Reduced claims or litigation (risks)	CSF_PC6	58	49%
	Improved site layout, planning and site safety	CSF_PC7	25	21%
	Coordination and planning of construction works	CSF_PC8	31	26%
	Integrating project documentation/bid preparation	CSF_PC9	14	12%
	Synchronization of procurement with design and construction	CSF_PC10	11	9%
	Providing BIM models for offsite prefabrication	CSF_PC11	11	9%
	Providing better implementation of lean construction, green sustainability and IPD	CSF_PC12	31	26%
Construction CSFs	Collaboration of simultaneous access of construction work	CSF_C1	21	18%
	Reducing construction project duration	CSF_C2	16	13%
	Reducing construction project cost	CSF_C3	13	11%
	Improved construction project performance and quality	CSF_C4	72	61%
	Providing BIM models for shop drawings	CSF_C5	6	5%
	4D construction scheduling and sequencing (3D+time)	CSF_C6	23	19%
	5D cost estimation and scheduling (3D+time+cost)	CSF_C7	9	8%
	Extracting cost estimation and quantity take off	CSF_C8	12	10%
Operation CSFs	Improved operations and maintenance (facility management)	CSF_O1	39	33%
	Remodeling and renovation	CSF_O2	16	13%

The descriptive statistical analysis of the 119 articles showed *Accuracy and reliability of data* as the most representative CSF in the design phase with 46% of the sample; *Reduced claims or litigation (risks)* as the top one in the pre-construction phase representing 49%; *Improved construction project performance and quality* as the most notorious (61%) in the construction phase and *Improved operations and maintenance (facility management)* as the most studied CSF in the operation phase.

4.4 Discussion and future research agenda

By addressing *Research question 1 (How has BIM been approached by Academia in the last decade?)* we observed that BIM research has been more focused on topics related to technology than compared processes and people in the last decade. From our findings, we encountered research topics related to *Intelligence, BIM adoption in the AEC industry, Safety* and *Sustainability* in the research field.

Regarding *Research question 2 (How can critical success factors (CSFs) be correlated with BIM in macro categories?)* we identified a stronger correlation between CSFs and Process BIM macro category than compared with the Technology and People BIM macro categories.

We understood there is still a gap in the field to develop research exploring BIM not only as a technology itself but as an integrated process in the building life cycle phases. We understand that the BIM technology itself cannot solve construction problems commonly faced by the AEC industry.

There is a need for rethinking design and construction process integrated with BIM solutions that rely on BIM-trained professionals. BIM adoption would require a change in the existing work practice (Porwal and Hewage, 2013). Thus, we consider Process and People as important macro categories and as strong research streams to be developed in the BIM field.

Operational and management themes have been neglected compared to product themes in the field Hosseini et al. (2018). For Barlish and Sullivan (2012), Organizational and project management functions can be affected by the implementation of BIM. By understanding there is a need to better integrate design and construction interface, we recognize the importance of developing new studies in the BIM research field allied to solutions of construction management methods, which can be able to diminish the lack of integration between design and construction phases in a more collaborative work environment.

We recognize there is a gap in knowledge between the design and construction interface in the AEC industry. We hence considered the Pre-construction an important phase to be investigated and understood for reducing the fragmentation between design and construction phases. Thus, to better discuss this gap, we suggest a future research agenda presenting key findings and unsolved questions related to the Pre-construction phase by BIM macro-categories, as illustrated in **Table 9.**

To discuss future research agenda, we selected papers from the content analysis database classified as *BIM in the AEC industry* (BIM research code) and *Pre-construction CSFs* code. We here present the main key findings and unsolved questions related to the Pre-construction phase codes categorized by BIM macro categories.

Table 9: Future research agenda proposition

BIM macro categories	Key findings	Unsolved questions	References
Technology MacC1	BIM servers should provide technical features to support information sharing, communication media, process management, exploration space, privacy, and flexible system configuration. BIM-server technologies should not be limited to functional and operational requirements only because AEC projects are mostly multi-organizational and multi-disciplinary.	• The success of the BIM server depends on its collective adoption by the stakeholders, who are expected to participate in the collaboration activities.	(Singh et al., 2011)
	The choice of modeling tool should not be constrained by the type of object It is essential to use a structured system of IDs and layers to ensure the consistency of workflows. The success of the quantity takeoff process is highly dependent on parameters.	• The BIM model is still not able to fully meet all the users' needs • The approach to design has to change to adjust to these new tools, frameworks, and standards for structuring the use need to be developed and optimizing performance	(Monteiro and Poças Martins, 2013)
	The benefits of the BIM framework involved: (1) Return metrics: change orders, RFIs, and schedule; and (2) Investment metrics: design costs and contractor costs.	• Large need for managerial effectiveness for BIM success • Organizational and project management functions affect the BIM implementation	(Barlish and Sullivan, 2012)

Process MacC2	Identified technical tool functional requirements and needs, and non-technical strategic issues for BIM adoption. There are varying levels of BIM adoption from country to country	• The need for guidance on where to start, how to work through the legal, procurement, and cultural challenges • BIM adoption would require a change in the existing work practice • Need for greater collaboration and communication across disciplines, data organization, and management	(Gu and London, 2010)
	Insights into how different types of institutional forces can be better manipulated to facilitate the diffusion of BIM in the construction industry	• The need to consider BIM adoption as a complex activity	(Cao et al., 2014)
	Performance measurement is a prerequisite for ensuring that PPPs are delivered by the project goals.	• There has been limited use of BIM within PPPs	(Love et al., 2015)
	Developed a framework to evaluate promising areas and to identify driving factors for practical BIM effectiveness	• Knowledge (of property level variable), reasoning (in ontology variable) and cost-effective approaches using structured BIM properties are the promising areas for advanced BIM	(Jung and Joo, 2011)
	BIM technology adoption should be undertaken with a bottom-up approach rather than a top-down approach for a successful change in management and in dealing with the resistance to change.	• Successful BIM adoption needs an implementation strategy and professional guidelines are required for that.	(Arayici et al., 2011)
People MacC3	BIM is most often used in the early stages (design and pre-construction) with progressively less use in the later stages (construction and operation). 3D models are less significant compared to the increased collaboration, management aspects of the process, reduction of waste, and accuracy in the impacts of BIM. Lack of industry expertise and training providing an opportunity for education providers.	• Lack of expertise within the project team and external organizations • Need for educational and professional development for BIM training	(Eadie et al., 2013)
	Understanding how delivery decisions influence the integration and development of project teams and make building	• Determine the effect of team integration and group cohesion on both	(Franz et al., 2017b)

	owners aware of how decisions affect the project performance	sustainability and safety performance.	
	Focuses on a building object behavior (BOB) description notation and method, developed as a shorthand protocol for designing, validating, and sharing the design intent of parametric objects.	• Clear communication and collaboration between domain experts, consultants and software developers are essential for the success of any advanced parametric modeling system for project development.	(Lee et al., 2006)

5 CASE STUDIES

Construction companies focused on infrastructure projects have adopted BIM as a valuable alternative for highly complex projects to minimize problems commonly found in the design and construction phases. There is still limited bibliography reporting BIM adoption in infrastructure projects.

Mainly, the difficulties of BIM adoption rely on the construction industry fragmentation. The necessity of the work culture and practices changes, lack of the stakeholders' roles and responsibilities understanding, lack of knowledge about processes, and high investment in training are some of the constraints faced by the construction companies to BIM adoption.

In Brazil, construction companies are looking for the best strategies for BIM adoption in their processes. The main obstacles are related to the need of changing the work culture and practices, the scarcity of understanding of the stakeholders' roles and responsibilities, the lack of knowledge about processes and workflows, and the high investment in training required for learning BIM skills (Olawumi, 2018; Mahalingam et al. 2015; Khosrowshahi and Arayici 2012; Singh et al. 2011; Hartmann and Fischer, 2008).

The case studies aim to understand BIM adoption in four different companies by answering the research questions were: (Q1) How BIM has been implemented into the company's organizational context? (Q2) Which macro-category (Technology, Process or People) has BIM impacted the most? (Q3) Which has been the main difficulties to BIM adoption throughout the pre-construction phase? Therefore, **the case study's goal was to investigate the usage of BIM by different companies throughout the pre-construction phase.**

This research studied four different companies, two in Brazil and two others abroad with the purpose to apply a comparative study among companies with different backgrounds and organizational structures, cultures, and work environments.

5.1 Method

The research method was exploratory and qualitative, through multiple case studies (Silva and Menezes, 2005), conducted through interviews and document analysis. Based on a literature review, multiple case studies aim to understand a deep the experience of different companies through a global approach (Yin, 2017). In addition, case studies enable analyzing a topic in practice, identifying new variables and hypotheses, and evaluating the inferences by combining within-case and cross-case analyses (Bennett and George 2005).

5.1.1 Research phases

The research was developed in five main phases as illustrated in **Figure 28.** The research began with phase 1 by defining the research goal, reviewing the literature regarding the research topic, and selecting the companies for the study. In phase 2, we concentrated on developing the research protocol. In phase 3, we applied a pilot case in Company A.

A pilot case was developed aiming at improving the quality of the research related to data collection and procedures to be followed (Yin, 2017). After going over the feedback from practitioners and researchers, slight improvements were made to eliminate possible misinterpretation.

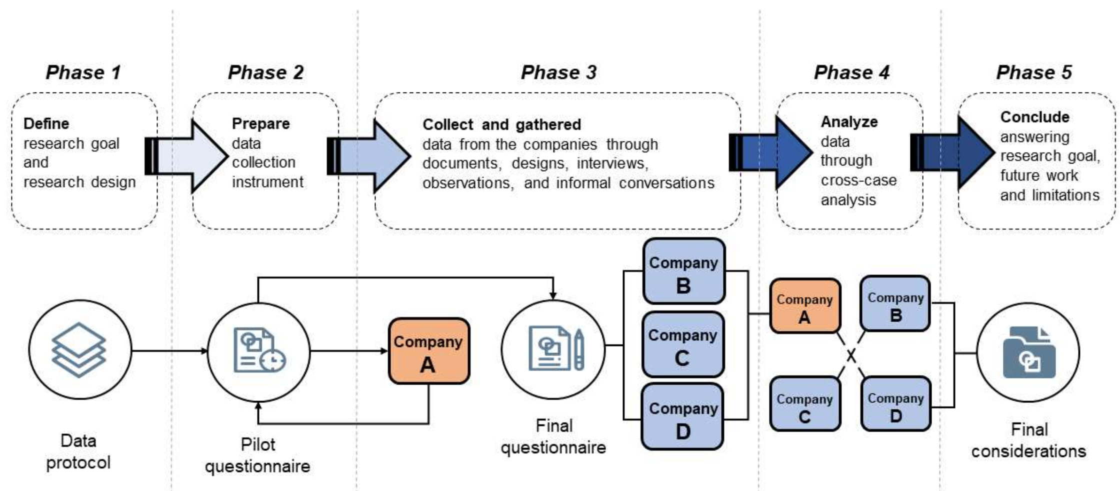


Figure 28: Case studies research phases

After concluding the pilot case, we reviewed the research protocol and applied it to the other three companies. Additionally, we presented the research goal for the company and defined the project to be studied and the key stakeholders to be interviewed.

During the data collection process (phase 3), we first analyzed information about the company and documents related to the project, such as the contract, project scope and schedule and design deliverables. Second, we interviewed the company's stakeholders. In phase 4 we focused on data cross-case analysis and results discussion. Lastly, in phase 5, we concluded the study by presenting achievements and recommendations for the research topic.

5.1.2 Data collection and sample characterization

As mentioned before, the data was collected from four different companies. Two companies were based in Brazil, one in the United States and one in the United Arab Emirates. The criteria for the companies' selection were: (a) being a construction company focused on infrastructure projects; (b) having a well-defined management structure; (c) have access to internal documents and stakeholders for data collection and interviews; (d) have implemented BIM or its implementation in progress; and (e) developing projects using BIM.

Data collection was gathered using a semi-structured research protocol. The research protocol contained two different semi-structured questionnaires as can be seen in Appendix B. The questionnaires were applied to key stakeholders according to their position in the company and their participation in the project selected for the study.

The first questionnaire aimed at collecting data related to BIM implementation in the company's organizational context. This questionnaire was applied to the stakeholders who had participated actively in the implementation process.

The second questionnaire focused on understanding the main barriers to BIM adoption in the pre-construction phase of the project studied. For these interviews, we spoke to stakeholders involved in the design and construction phases of the project, but who may not have participated in the BIM implementation process in the company.

The study sources of evidence were documents, designs, interviews, informal conversations, and observations. Most of the data were obtained from the interviews. According to Blumberg et al. (2011), interviews provide rich data collection by allowing an expansion and clarification of questions and answers during the interview process.

In this case, the interview process was oriented by the research protocol using the semi-structured questionnaires, with clarifications being made by using complementary questions throughout the interviews when necessary. Annotations were made and the interviews were recorded and transcribed for content data analysis.

The interviews were made face-to-face, via skype call, or in virtual meeting rooms, and each one lasts for around one hour. Interviewees were informed that the responses were completely anonymous and confidential, and each one signed a consent form.

The data collection phase consisted of two years of research, initiated with a pilot case at Company A. After the pilot case, we remodel the research protocol and applied the final questionnaire with Company B, C and D. During phase 3 (see **Figure 28**), we spoke to 12 different stakeholders, four from Company A and four from Company B, both Brazilian construction companies, and two from Company C e other two Company D, respectively from United Arab Emirates and United States as can be seen in **Table 10.**

Table 10: Description of the interviewed companies

Company	Sector	Field	Market experience	Country	Number of interviewees
A	Industrial projects, infrastructure works, urban mobility, energy, oil and gas	Infrastructure	73 years	Brazil	4
B	Industrial (Energy, Infrastructure and Logistics, Mining and Metallurgy, Chemical and Petrochemical, Manufacturing, Oil & Gas)	Engineering, Consulting, Construction Management	62 years	Brazil	4
C	Residential, Commercial, Infrastructure, Industrial, Healthcare, Transport, Oil & Gas	Engineering, Consulting, Construction Management	33 years	United Arab Emirates	2
D	Contracting, construction management, and design-build services	Engineering, Consulting, Construction Management	98 years	United States	2

5.1.3 Data analysis

The data from the interviews were qualitatively analyzed through a coding process that supported content analysis and results interpretation 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 data from the interviews into categories arranged in a tree words structure connecting text segments grouped into separate categories of codes or “nodes” to further carry out a thorough data analysis (Silva et al., 2021). We contemplated the BIM codes and CSFs codes created for bibliometric research to codify the interviews into clusters of interest.

In addition, during the analysis, we create other codes that we considered important to be analyzed, such as (1) design management process, (2) important aspects of the project, (3) initiatives for the pre-construction phase and (4) problems related to the pre-construction phase. Thus, we classified the interviews throughout 17 main codes divided into nine BIM codes, four CSFs codes e four other codes. Each code has a different quantity of subcodes as can be seen in Appendix A.

5.2 Results and discussion

The case study results are a data-sum obtained from stakeholders’ perspectives based on their own opinion about the usage of BIM and its application in their daily professional experience. Additionally, we also studied one engineering project per construction company to understand the main barriers to BIM adoption in the pre-construction phase, except for Company D, which has not selected any project.

5.2.1 BIM in the companies’ organizational context

The case studies showed that BIM implementation relies on the BIM maturity level of the company and the construction industry culture. Results pointed the level of BIM maturity in the companies studied in Brazil is lower compared to the companies studied abroad. We observed there is a higher awareness among AEC professionals of the benefits of BIM adoption in the two international companies compared to the Brazilian cases. Additionally, results suggest that professionals who work in developed countries are prone to be more valued and well-paid compared to those who work in developing countries.

Based on the data, BIM has been incorporated as a fundamental part of the company process in Companies C and D since earl's 2000. According to the interviewed professional from Company C, BIM started in the United States with the advancement of mechanical trading partners since 1980 by doing 3D modeling. After that, general contractors beginning a relationship with designers and trade partners in nearly 2000, exploring tools and uses for BIM. In the Brazilian context, BIM has been partially implemented into their process during data collection, which implementation started around 2017-2018.

During BIM implementation, Companies A and B noted barriers to change management. At Company C, BIM implementation was phased in 2 steps: the first one, management support for the BIM implementation plan, and the second one, an arrangement of a decent budget to proceed with it. The main barriers found during implementation were related to the resistance to change, people's awareness, and improving their awareness by giving them training and acquiring the schedule to proceed with it.

During BIM implementation, Company C established some changes regarding policy and processes. First, communication with the client and contractors started early in the design phase. Even if the client did not demand BIM, Company C started to implement it in every project to compare the difference to develop the design using conventional and BIM processes to gain experience and lessons learned from each. Second, contractual obligations among stakeholders concerning the usage of BIM. According to the participant's opinion, these internal processes completely changed the technical department structure.

At Company D, changes concerning policy and process started with new contracts, developing a new contractual language with MEP (Mechanical, Electrical, and Plumbing Engineering), fire protection, and structural trade partners. Additionally, an application of the BIM execution plan and the front-end documentation went into contracts along with specific language. Thus, the BIM department is developing and growing in some project types depending on project complexity based on lessons learned through the coordination process.

Lastly, the professionals from the Brazilian companies classified the company's BIM maturity level between BIM Stage 1 (Object-based modeling) and BIM Stage 2 (Model-based collaboration). On the other side, the international companies categorized their level of BIM maturity between BIM Stage 2 (model-based collaboration) and BIM Stage 3 (network-based integration), considering there is room for improvement until it is fully adopted across the AEC industry.

5.2.2 Comparison among technology, people and process BIM categories

In bibliometrics (Chapter 4), we identify a stronger network between technology and process compared to technology and people from the cross-tabulation analysis. From content analysis, findings showed more studies in Academia in the BIM field related to technology (79%) compared to process (42%) and people (11%) in a sample of 157 papers.

Case studies results showed process as the most impacted category impacted by BIM implementation, followed by people and technology. According to Company C, technology has enabled collaboration from the design team to the contractor once the design was more paper-based. During data collection, professionals pointed out the main barriers to BIM adoption in technology were:

- Problems with software interoperability and compatibility;
- Technology and IT capacity;
- Tool limitation on modeling design details such as concrete armor;
- Difficulties in parameterizing design details and tool customization;
- Difficulties with BIM model partnership;
- Software limitation to develop the design and how is built in reality;
- Lack of materials and family for infrastructure design;
- Clash detection is useless when reports are more than 15 thousand clashes.

Concerning process and people categories, the main difficulties addressed were:

- Badly usage of the tools expecting technology automates everything itself
- The learning curve takes time for all stakeholders and construction companies
- Not even all designers have BIM skills
- Lack of collaboration among stakeholders

- Work process redesign
- Lack of model updating through pre-construction and construction phases

In bibliometrics, we analyzed BIM macro categories relationship with CSFs in the BLC phases, considering the design, pre-construction, construction and operation phases. The network analyses showed a stronger occurrence of studies related to technology than process and people as can be seen in Chapter 4. For the case studies, we did not study the operation phase, once the companies did not work with facility management. In the next topic, we draw a comparative analysis between design, pre-construction and construction CSFs for BIM based on the data collected from the interviews.

5.2.3 BIM in the design, pre-construction and construction phases through CSFs

In the last part of the interviews, we guideline the questions to the professionals based on the 32 CSFs for BIM in the design (12), pre-construction (12) and construction (8 phases) as can be seen in (Appendix B). BIM was considered a driver of improvement in the studied projects and the main CSFs for BIM pointed out by the professional are illustrated in Table 11.

Table 11: CSFs for BIM pointed by the professionals in the case studies

CSFs for BIM in the design phase
(CSF_D1) Earlier and accurate 3D visualization of design (CSF_D2) Better design/multi-dimensional design alternatives/applications (CSF_D3) Design coordination of various elements/components (CSF_D4) Verification of consistency to the design intent (CSF_D12) Accuracy and reliability of data (less rework and fewer document errors and omissions)
CSFs for BIM in the pre-construction phase
(CSF_PC1) Integrating design validation (clash detection) (CSF_PC4) Enhancing exchange of information and knowledge management (CSF_PC5) Model checking and validation (reviewing code) (CSF_PC6) Reduced claims or litigation (risks) (CSF_PC7) Improved site layout, planning and site safety (CSF_PC8) Coordination and planning of construction works (CSF_PC9) Integrating project documentation/bid preparation (CSF_PC11) Providing BIM models for offsite prefabrication
CSFs for BIM in the construction phase
(CSF_C2) Reducing construction project duration (CSF_C3) Reducing construction project cost (CSF_C8) Extracting cost estimation and quantity take off (CSF_C10) Synchronization of procurement with design and construction

Concerning the design phase, findings showed more accuracy and reliability of design data when trade partners were involved early in the project. According to Company C, there is not any additional work if you use the tool correctly. The model creates all necessary views to provide better information, fewer errors, and omissions.

In addition, it depends on how the designers create the model. It's how much trade partners input information during the design phase. However, design performance relies first on a collaborative process among professionals before starting the construction phase, and, second, on experienced trade partners and subcontractors. Thus, one of the main challenges of the project building life cycle is to manage a lot of data with professionals with different backgrounds and experiences.

Another important aspect of collaboration is making the design process more transparent to the entire team by integrating through project websites and checking the information is not siloed and is available to everyone. Communication among stakeholders improves if all players use the same tools to manage project information easier and quicker.

Furthermore, there is a need for weekly or biweekly meetings for the model management during the design and construction interface to discuss the project needs. Collaboration depends on stakeholders 'participation, which makes difference when all players work on BIM early making sure that all of them are understanding the same.

Regarding the pre-construction phase, BIM enhanced project documentation, and bid preparation enabling the process to start much earlier, transforming how designers work compared to the conventional way using 2D CAD drawings. BIM improved not only design validation through clash detection but also the coordination and planning of construction works, the provision of pre-assembly documents for pre-fabrication and the reduction of claims and risks through a more accurate BIM model.

In the construction phase, it was pointed improvements in terms of cost estimation and quantitative take-off, reduction of project cost and duration. In concern of synchronization of procurement with design and construction, BIM helped to drive the schedule by understanding the exact coordination process to be allied with the construction phase.

5.2.4 Companies' initiatives for the pre-construction phase

During data collection, we investigated BIM adoption in the three main building life cycle phases (design, pre-construction and construction). However, the research limitation focused on understanding the improvements and the difficulties of BIM adoption in the pre-construction phase.

Findings based on professional's opinions showed BIM as a supportive tool to the pre-construction effort, helping coordination and planning through a technology-based visual manner. In Companies A and B, BIM has been mostly used to help with 3D visualization and extracting estimative and quantitative take-offs for pre-fabrication and assembly.

In the Brazilian cases, Company A did not mention any specific method dedicated to the pre-construction phase in the project studied. Company B applies a method named *"Constructabilidade"* (Constructability in English) through face-to-face meetings between design and construction teams to discuss project details and prepare for the construction. Through those meetings, design had a greater understanding of building construction details and contractors known previously the design concepts.

In the international cases, BIM enabled 3D modeling to 4D-5D (sequencing, scheduling and costing) in the pre-construction phases facilitating how to build and scrutinize the information from the schedule to validate the sequence of works and how to put them into place.

At Company C, regular-basis meetings based on project milestones of the company's internal process towards the pre-construction phase. Thus, the design is reviewed at specific design stages (30%, 50%, 70%, 80% and 100%) to confirm clash detections among disciplines and to draft strategies for the construction phase.

During the pre-construction phase, designers and contractors access the model earlier. Designers use the BIM model for 3D plans as issued in contract documents and contractors use it for quantity take-offs, and then start the coordination process between systems mainly MEP and how that interacts with structure, which takes in general, about nine months to a year. At Company D, first confirm starting planning ahead and mandating contractors to use BIM. During the coordination process, the internal design team starts to collaborate with them.

5.2.5 BIM-related changes in the design and construction interface

In the AEC industry, projects are segmented with a lot of interfaces, different scopes, and a diversity of professionals with different backgrounds and knowledge. Thus, the disconnection of the designers with the construction phase is a real gap in this industry.

Results based on the interviews showed the advantages of BIM in promoting better integration among these interfaces. The parallelism among project phases is well-known and brings a lot of risks. According to the interviewed professionals, BIM mitigates the risks of design and construction interface inconsistencies throughout project visualization and analysis by allowing projects maintain in line with the original budget.

The 3D BIM model can improve productivity, stakeholders' comprehensive understanding of the project and a collaborative assembly of a federal model (Eastman et al., 2014). However, the best way to improve the design and construction interface is to begin collaborating with the design and construction team extremely early by making a lot of sharing their models. Due to automation, professional creates expectations and skips steps. The gap is more related to the work process that needs a heavy human interface.

For Chong et al. (2016) BIM can be used to create and manage geospatial information such as site setting and transport network representation, site logistics, equipment and material usage planning, project scheduling, work progress monitoring, construction inspection and quality assurance. Once the BIM model stores all information regarding construction requirements that can be integrated into the model assists with cash flow management; and safety on site-control where simulations can show potential safety hazards.

BIM is a process that works through tools that need to be updated constantly, from the conceptual design to the construction phase. As an example, Company C involves VDC and BIM teams early in the process, engaging them in supporting the design and setting up some of the goals where a design manager will be in the day-to-day with that design team.

In conclusion, results showed that BIM changed the project scope entirely, in terms of the document, product generation speeds, and drawings in the design phase. In the construction phase, it had few changes due to the anticipations you can make with the tool. However, one of the challenges is to managing information flow during construction. A large amount of data and the changes requires someone to help lead the charge.

Lastly, corresponding to the interviewed professionals, still have designers who are designing construction documents based on 2D paper copies or PDF electronic 2D drawings. Yet, the main goal of BIM is to provide a detailed model that can be used as design deliverables but also, as a model full of data to support all phases in the building life cycle.

6 FINAL EXPLORATORY SURVEY

Critical success factors (CSFs) can help to facilitate the successful implementation of BIM by identifying key areas during the process (Antwi-Afari et al. 2018). Project teams can identify the CSFs and take measures to ensure parameters for a successful BIM implementation by having a better understanding of key areas to address appropriate strategies during BIM implementation (Ozorhon and Karahan, 2017; Liao and Teo (2017).

There is a variety of CSFs for BIM implementation in the literature, developed in different construction environments and employing different research methods. A systematic literature review carried out by Antwi-Afari et al. (2018) showed five major CSFs among thirty-four for successfully implementing BIM:

- collaboration in design, engineering, construction stakeholders,
- earlier and accurate 3D visualization of design,
- coordination and planning of construction works,
- enhancing the exchange of information and knowledge management,
- improved site layout planning and site safety.

A survey developed by Amuda-Yusuf (2018) pointed to the topmost five CSFs for BIM implementation among twenty-eight in order of importance:

- standard platforms for integration and communication;
- cost of development;
- education and training;
- standardization (product and process); and
- clear definition and understanding of users' requirements.

Chan, Olawumi, and Ho (2019) pointed other five most significant CSFs for BIM implementation developed in Hong Kong through a case study:

- client's acceptance of BIM projects,
- organizational structure to support the BIM system within the company,
- financial support from the government to set up the BIM system,
- BIM standard for the industry,
- and BIM training program for staff.

For Olawumi and Chan (2019), the three most relevant that can amplify the integration of BIM initiatives in construction projects are: (1) greater awareness; (2) experience level within the firm; and (3) increased involvement of project stakeholders. Other key CSFs identified were organization and project-related issues; industry culture; legal issues and education, knowledge, and learning.

Another case study developed by Sinoh, Othman, and Ibrahim (2020) in the Malaysian AEC industry showed intra and inter-firm coordination as important CSFs for BIM implementation. According to the authors, firms should be open to changing their management to effectively implement BIM at the intra-firm level and adapt to industry trends at the inter-firm level. Furthermore, BIM implementation should go beyond simply using new software and hardware and requires a shift in traditional building delivery processes.

Thus, to identify the key factors of BIM adoption, **the research goal was to understand BIM adoption in the design, pre-construction, and construction phases based on CSFs** as applied in bibliometrics. The purpose was to evaluate and compare the CSFs in theory and practice. Additionally, we added other CSFs in the design and construction phases.

6.1 Method

The survey research method comprises data collection from a significant sample that aims to describe, compare or explain the knowledge, attitudes, and behavior of a specific group of individuals or environments where these individuals work through quantitative and statistical analysis (Gil, 2010; Fink, 2003). According to Forza (2002), there are three types of surveys:

- Exploratory surveys: acquire a first idea about the topic to provide a basis for a more detailed questionnaire;
- Confirmatory surveys: test or explain a theory;
- Descriptive surveys: understand the relevance of a phenomenon and describe its distribution in the population to provide subsidies for the construction of theories or their refinement.

For this research, we applied an exploratory survey to obtain the data to respond to the research goal. The survey was developed through six main steps as illustrated in **Figure 29** (Fink, 2003).

First, we started by defining the research goal. After, we dedicated ourselves to planning the survey and research bibliography to base the questionnaire. Then, in step 3, we drafted the questionnaire, validated and finish the final version for data collection. In step 4, we defined the participant list and collect the data through a web-based platform. In step 5, we concentrated on data analysis and results discussion. Lastly, we conclude the research by presenting achievements, limitations and future works.

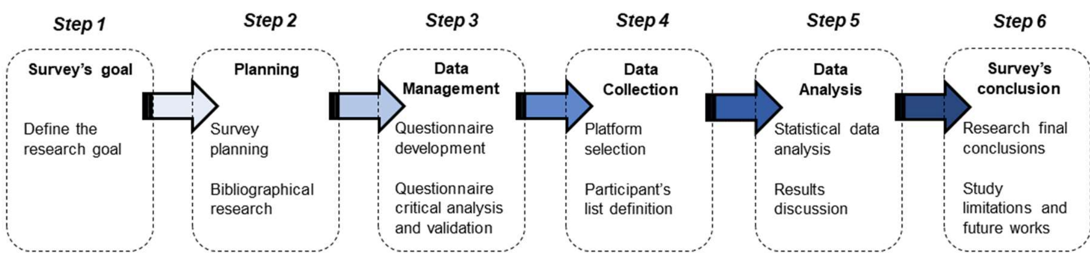


Figure 29: Survey research steps

6.1.1 Survey questionnaire

The questionnaire was structured in two versions of the language (English/Portuguese) to collect data in a direct, clear, and synthetic way. The reliability and validity of the survey questionnaire were addressed through a validation process conducted with seven professionals, three architects, and four engineers, all of them with solid knowledge of the subject and experience in construction or engineering projects.

After the validation process, we considered the respondent recommendations to improve clarity and questions comprehension. The questionnaire was developed based on the literature and the knowledge gained from the exploratory survey and the case studies during the doctorate research. We also considered the CSFs codes (Appendix B) adapted from Antwi-Afari et al. (2018) to develop questions related to the design, pre-construction and construction phases, used for content analysis in bibliometrics and the development of case studies questionnaires.

The final questionnaire version (Appendix D) was composed of 18 questions, with categorical and 7-point Likert scale questions distributed into five main sections: (1)

Participant information; (2) Company information; (3) Your BIM knowledge; (4) BIM adoption in the company and (5) BIM adoption from the design to the construction phase. **Table 11** shows the number of questions and question type per section name:

Table 11: Research questions

Section Number	Section name	Number of questions	Question type
1	Participant information	7	Categorical
2	Company information	4	Categorical
3	Your BIM knowledge	2	Categorical
4	BIM adoption in the company	2	Categorical
5	BIM adoption from the design to the construction phase	3	7-points Likert scale

6.1.2 Sample and data

The sampling process was carried out through professionals from engineering, construction, and architecture from the 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.

We collected answers from 570 respondents located in Brazil and abroad. The respondents evaluated a statement formulated to be answered in a categorial type question or a seven-point Likert perception scale question ranging from strongly disagree to strongly agree. Data analysis was performed using JMP statistical software through a distribution analysis of the sample.

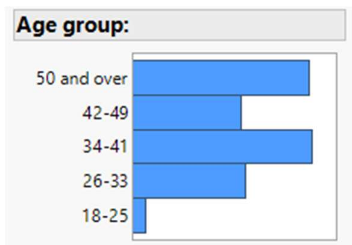
6.2 Results

Results were structured into five topics. First, we characterized the sample by showing first, the respondents' age group and gender, and then their bachelor's degree, educational level, market experience, and current job status.

Second, we presented the data discussing BIM knowledge among professionals and the BIM maturity level of the projects developed by the companies. Third, we discussed BIM separately in three main phases: design, pre-construction, and construction as established in the research goal.

6.2.1 Sample characterization

Concerning the sample characterization, findings showed the respondents 'age were first from 34 to 41 years with 172 respondents, second over 50 years with 170 respondents, third from 26 to 33 years with 109 respondents and last from 42 to 49 years (105 answers) as can be seen in **Figure 30.** Regarding to gender, male respondents were 341 against 227 female respondents (**Figure 31**).

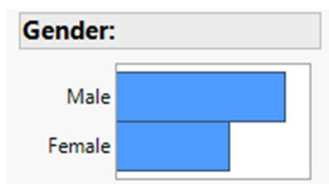


Frequencies

Level	Count	Prob
18-25	12	0.02113
26-33	109	0.19190
34-41	172	0.30282
42-49	105	0.18486
50 and over	170	0.29930
Total	568	1.00000

N Missing 0
5 Levels

Figure 30: Respondent's age group

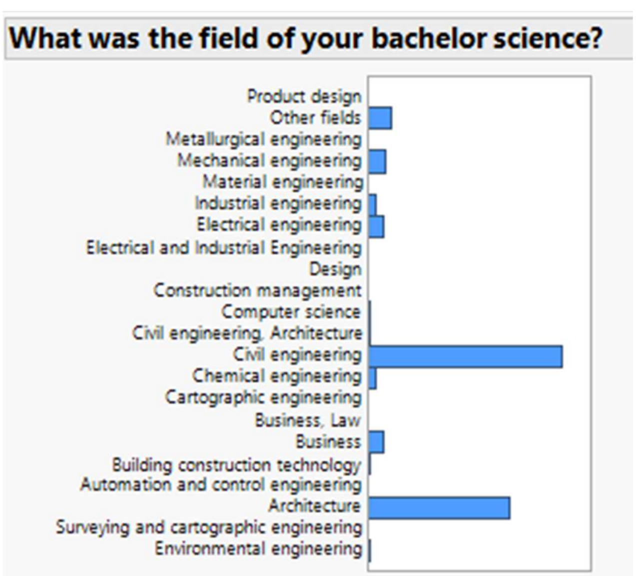


Frequencies

Level	Count	Prob
Female	227	0.39965
Male	341	0.60035
Total	568	1.00000

N Missing 0
2 Levels

Figure 31: Respondent's gender



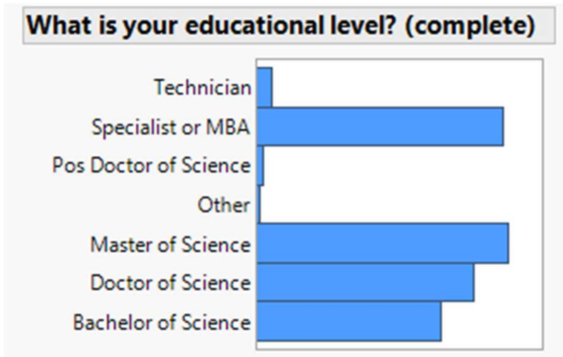
Frequencies

Level	Count	Prob
Environmental engineering	3	0.00528
Surveying and cartographic engineering	1	0.00176
Architecture	184	0.32394
Automation and control engineering	1	0.00176
Building construction technology	2	0.00352
Business	20	0.03521
Business, Law	1	0.00176
Cartographic engineering	1	0.00176
Chemical engineering	9	0.01585
Civil engineering	251	0.44190
Civil engineering, Architecture	2	0.00352
Computer science	3	0.00528
Construction management	1	0.00176
Design	1	0.00176
Electrical and Industrial Engineering	1	0.00176
Electrical engineering	20	0.03521
Industrial engineering	11	0.01937
Material engineering	1	0.00176
Mechanical engineering	22	0.03873
Metallurgical engineering	1	0.00176
Other fields	31	0.05458
Product design	1	0.00176
Total	568	1.00000

N Missing 0
22 Levels

Figure 32: Respondent's bachelor science

Findings showed that most respondents were civil engineers (251) and architects (184), respectively as illustrated in **Figure 32.** The respondent's educational level 155 answered as master of science followed by 151 as specialist or MBA and 133 as a doctor of science (**Figure 33**).



Frequencies

Level	Count	Prob
Bachelor of Science	113	0.19894
Doctor of Science	133	0.23415
Master of Science	155	0.27289
Other	2	0.00352
Pos Doctor of Science	4	0.00704
Specialist or MBA	151	0.26585
Technician	10	0.01761
Total	568	1.00000

N Missing 0
7 Levels

Figure 33: Respondent's educational level

In concern to the experience in the market, respondents mainly concluded the bachelor's degree over 20 years ago (201) followed by 10 to 15 years (110) and 5 to 10 (105) as illustrated in **Figure 34.** Lastly, respondents were mostly employed in the AEC industry compared to respondents from Academia (**Figure 35**).

Frequencies

Level	Count	Prob
0	1	0.00175
Between 1-5 years ago	53	0.09298
Between 5-10 years ago	105	0.18421
Between 10-15 years ago	110	0.19298
Between 15-20 years ago	90	0.15789
Over 20 years ago	201	0.35263
Response	1	0.00175
Up to 1 year ago	9	0.01579
Total	570	1.00000

N Missing 0
8 Levels

Figure 34: Respondent's years of experience in the market

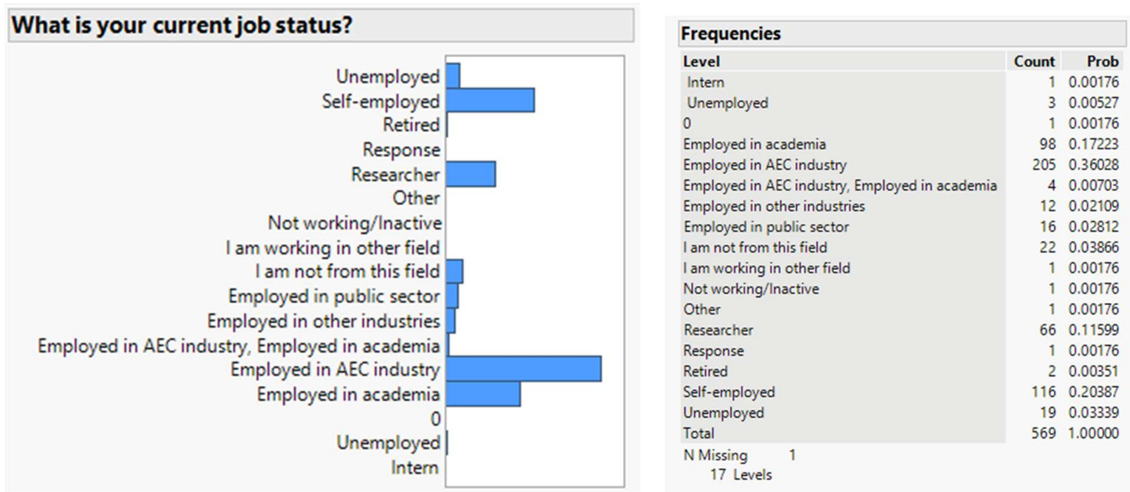


Figure 35: Respondent's current job status

6.2.2 BIM knowledge and BIM maturity level

In the final exploratory survey, findings showed the BIM knowledge of the respondents were mainly basic with 210 answers, followed by intermediate with 124 answers, none with 90 answers, advanced with 60 answers, and expert with 124 answers as can be seen in **Figure 36**.

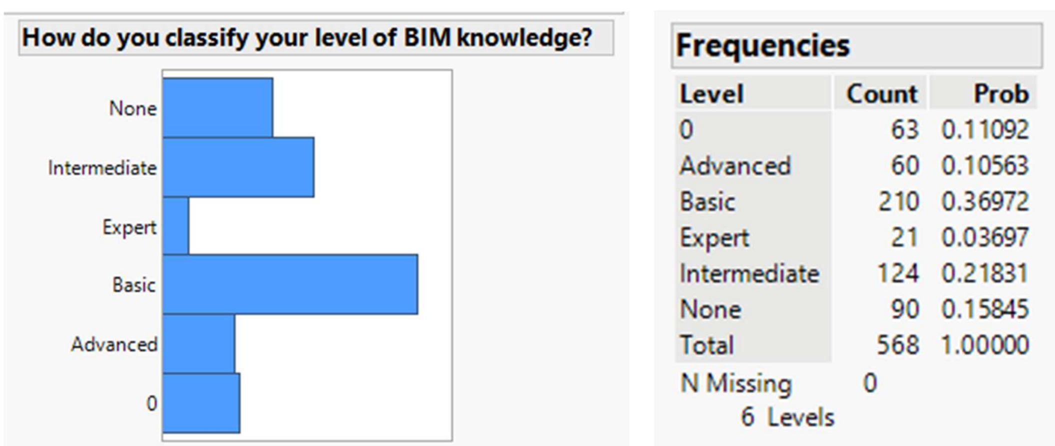
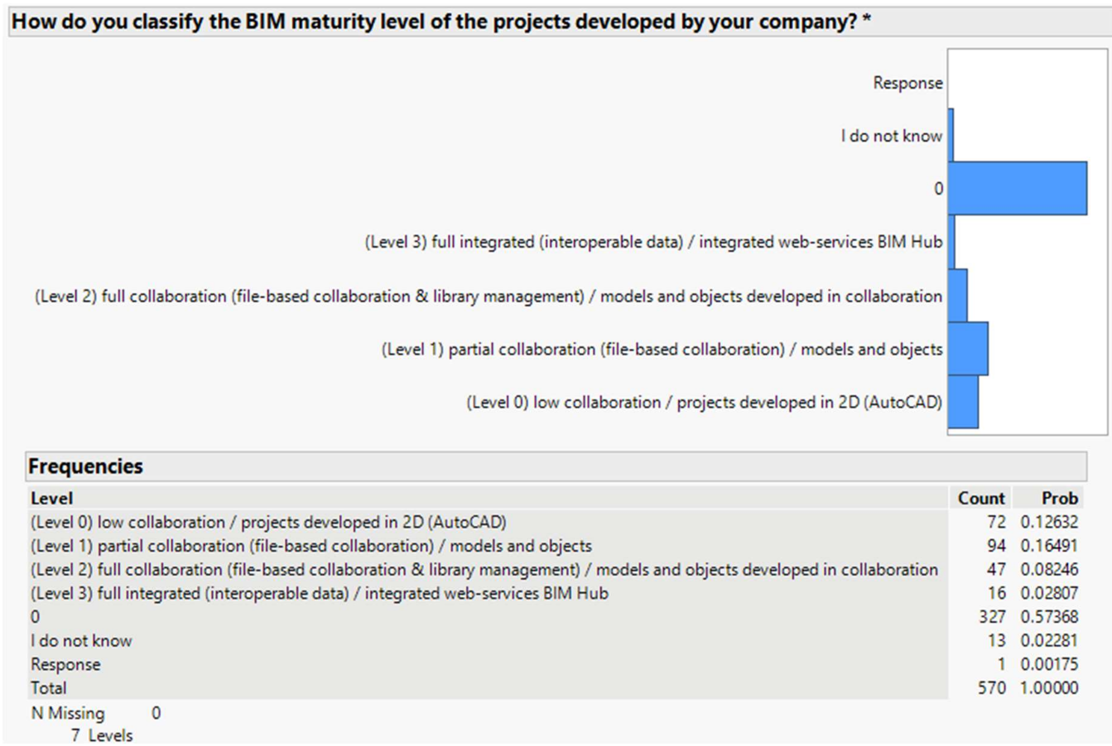


Figure 36: Respondent's BIM knowledge

In bibliometrics, we applied fourteen BIM codes to analyze the data. In two of them we analyzed the BIM stages and BIM maturity level of 119 studies. Findings showed BIM Stage 2 as the most observed stage (64%) followed by BIM Stage 3 (34%) and BIM Stage 1 (11%). Regarding the BIM maturity level, managed (57%) was the most founded level in the studied papers followed by integrated (38%) and defined (13%).

In regard to the BIM maturity level of the projects developed in the company, respondents chose in the majority of Level 1(Partial collaboration) with 64 answers, Level 0 (Low collaboration) with 72 answers, Level 2 (Full collaboration) with 47 answers, Level 3 (Full integrated) with 16 answers. Thirteen respondents answered that did not know the response and most of them selected option 0, which means they did not answer the question as illustrated in **Figure 37.**



Frequencies

Level	Count	Prob
(Level 0) low collaboration / projects developed in 2D (AutoCAD)	72	0.12632
(Level 1) partial collaboration (file-based collaboration) / models and objects	94	0.16491
(Level 2) full collaboration (file-based collaboration & library management) / models and objects developed in collaboration	47	0.08246
(Level 3) full integrated (interoperable data) / integrated web-services BIM Hub	16	0.02807
0	327	0.57368
I do not know	13	0.02281
Response	1	0.00175
Total	570	1.00000

N Missing 0
7 Levels

Figure 37: BIM maturity level of the project developed by the company

6.2.3 BIM in the design phase

BIM was evaluated based on a seven-point Likert scale ranging from strongly disagree to strongly agree. In each phase, we considered the same CSFs developed for bibliometrics, content analysis and case studies, and added another CSFs in each phase. To show the number of occurrences of each CSF, we presented the data with different colors ranging from green (less occurrence) to red (more occurrence).

Therefore, BIM in the design phase was evaluated based on 17 CSFs, twelve from bibliometrics and content analysis and five others incorporated into the design phase as illustrated in **Figure 38.** Findings showed the top-five CSFs for BIM in the design phase as strongly agreed by the respondents were:

1. Earlier and accurate 3D visualization of design;
2. Better integration among design disciplines;
3. Better design/multi-dimensional design alternatives/applications;
4. Design coordination on various elements/components;
5. Better design quality

Followed by the top-five CSFs for the design phase, other CSFs considered relevant for the respondents were: verification of consistency to the design intent, better communication among design stakeholders, and enhanced structural analysis and design. The respondents strongly agreed the CSFs mentioned before have been enhanced by BIM adoption, bringing a greater performance to the design phase.

On the other hand, some CSFs were considered neutral by the respondents, which means that BIM did not bring improvements to the design phase. The main ones were related to environmental, acoustical and thermal analysis as described below:

- Acoustical analysis and insulation
- Thermal energy analysis and insulation
- Predicting environmental analysis and insulation
- Predictive analysis of performance
- MEP analysis and insulation

Additionally, design cost, design duration, and photorealist render for marketing purposes were considered neutral by the respondents, suggesting that BIM adoption has not performed as could be. Lastly, the results may suggest that BIM adoption improved the design phase in most CSFs, considering the majority of the respondents agreed and strongly agreed that BIM adoption brought improvements to the design phase.

6.2.4 BIM in the pre-construction phase

BIM in the pre-construction phase was evaluated based on 12 CSFs, the same ones considered in bibliometrics and content analysis as illustrated in **Figure 39**. Respondents strongly agreed that BIM adoption promoted better integration and design validation (clash detection) in the pre-construction phase. Other CSFs agreed by the respondents in order of importance were:

- Model checking and validation
- Better collaboration among design and construction stakeholders
- Better exchange of information
- More effective communication among design and construction stakeholders

Regarding the neutral CSFs, respondents pointed: to providing BIM models for offsite fabrication, better implementation of lean construction; synchronization of procurement with design and construction; improved site layout and safety; integrating project documentation/bid preparation, and reduced claims and risks.

Thus, the results may suggest that half of the respondents considered BIM as neutral in the pre-construction phase and the other half agreed that BIM adoption enhanced the pre-construction phase based on CSFs.

6.2.5 BIM in the construction phase

BIM in the construction phase was evaluated based on 11 CSFs, two CSFs were added in comparison to bibliometrics and content analysis as illustrated in **Figure 40**. Respondents mostly agreed that BIM has enhanced extracting cost estimation and quantity take-off in the construction phase, followed by project constructability, a collaboration of simultaneous access of construction work, and project quality.

A significant sample of the respondents pointed to BIM as neutral in the construction phase, suggesting that BIM has not positively or negatively impacted the CSFs in the construction phase.

6.3 Discussion

Critical success factors can be considered as an important indicator of BIM adoption, identifying key areas of improvement during BIM adoption in each project phase. The final exploratory survey collected 570 answers from professionals of different ages, gender, educational level, and market experience. Additionally, it was identified their BIM knowledge and the BIM level of maturity of the projects developed by their correspondents' companies.

Findings showed BIM adoption in three different phases: design, pre-construction, and construction phases. In each phase, BIM was evaluated throughout different CSFs. Based on the respondents 'answers, we observed that BIM adoption has mostly positive impacts in the design phase compared to the pre-construction and construction phases. This result may suggest there is a need for the development of methodologies allied to BIM in the pre-construction and construction phases.

There is a gap in alternatives and solutions to incorporate BIM into the daily construction site to help the construction team to operate the 3D BIM model rather than use 2D drawings copies.

The problem is not only concerned with BIM adoption itself, yet project fragmentation between each project phase. Due to the fact that construction stakeholders usually do not collaborate with the design stakeholders in the design phase postponing collaboration to the construction phase corroborates project fragmentation.

Comparing the results of the final exploratory survey with bibliometrics and content analysis, we observed the CSFs (1) accuracy and reliability of data, and (2) design coordination of various elements/components were the principal improvements of BIM adoption in the design phase, followed by better design/multi-dimensional design alternatives/applications and earlier and accurate 3D visualization of the design.

In the pre-construction phase, we noticed (1) better collaboration among design and construction stakeholders; (2) enhancement of exchange information and knowledge management in the final exploratory survey, bibliometrics, and content analysis.

Other CSFs found in both studies were: better implementation of lean construction; improved site layout; planning and site safety and integrating project documentation/ bid preparation.

In the final exploratory survey, respondents pointed out that BIM adoption improved model checking and validation and promoted more effective communication among design and construction stakeholders in the pre-construction phase.

However, in bibliometrics, it was founded that other CSFs for BIM adoption, had impacted positively in the pre-construction phase such as improved construction project quality; reduced claims and litigation (risks); and coordination and planning of construction works.

Regarding BIM adoption in the construction phase, the exploratory survey results showed a great part of the respondents considered BIM as neutral in the construction phase, suggesting that BIM was not a driver of improvement for the construction phase based on CSFs. In bibliometrics, the studies showed that BIM has significantly improved construction project quality, followed by 4D construction scheduling and sequencing (3D+time), and Collaboration of simultaneous access of construction work.

In the design phase, do you agree that BIM adoption has enhanced:	(1) Strongly disagree	(2) Disagree	(3) Somewhat disagree	(4) Neutral	(5) Somewhat agree	(6) Agree	(7) Strongly agree
Earlier and accurate 3D visualization of design?	7	2	0	32	17	43	94
Better design/multi-dimensional design alternatives/applications?	7	2	2	32	21	50	81
Design coordination on various elements/components?	7	1	1	31	19	59	77
Verification of consistency to the design intent?	8	1	2	34	21	56	72
Predictive analysis of performance?	8	4	9	52	28	44	47
Thermal energy analysis and Insulation?	15	7	11	61	23	34	39
MEP analysis and Insulation (HVAC)?	10	7	6	48	24	43	53
Structural analysis and design?	7	4	6	46	24	46	60
Predicting environmental analysis and Insulation?	12	11	8	60	29	36	33
Acoustical analysis and Insulation	15	12	12	63	24	35	26
Photorealistic rendering for marketing purposes?	13	7	7	47	33	39	49
Accuracy and reliability of data?	7	3	6	39	31	57	50
Better design quality?	8	2	2	40	18	50	75
Better integration among design disciplines?	7	2	2	33	18	48	85
Better communication among design stakeholders?	8	2	2	35	28	52	68
Design cost reduction?	17	14	14	51	30	29	36
Design duration reduction?	20	11	10	53	27	33	36

Figure 38: BIM in the design phase

In the preconstruction phase, do you agree that BIM adoption has enhanced:	(1) Strongly disagree	(2) Disagree	(3) Somewhat disagree	(4) Neutral	(5) Somewhat agree	(6) Agree	(7) Strongly agree
The integration and design validation (clash detection)?	8	4	1	36	22	46	78
The collaboration among design and construction's stakeholders	9	3	4	39	36	58	46
The communication among design and construction's stakeholders	9	2	5	41	38	54	43
The exchange of information	8	3	1	44	26	59	52
Model checking and validation (reviewing code)	7	2	1	47	24	62	50
The reduction of claims and risks	9	4	3	50	40	49	36
The site layout, planning and site safety	11	4	3	55	30	47	40
The coordination and planning of construction works	12	2	2	43	31	59	44
The Integration of project documentation/bid preparation	9	3	4	52	32	51	42
The synchronization of procurement with design and construction	14	8	2	54	35	50	26
The provision of BIM models for offsite prefabrication	14	12	3	61	28	39	32
The implementation of lean construction	17	2	6	59	28	40	36

Figure 39: BIM in the pre-construction phase

In the construction phase, do you agree that BIM adoption has:	(1) Strongly disagree	(2) Disagree	(3) Somewhat disagree	(4) Neutral	(5) Somewhat agree	(6) Agree	(7) Strongly agree
Enhanced Collaboration of Simultaneous access of construction work?	11	6	1	55	29	54	34
Enhanced Construction duration reduction?	12	8	8	63	37	36	25
Enhanced Construction cost reduction?	12	8	4	61	40	34	30
Improved construction project performance and quality?	12	3	2	51	45	46	31
Improved Providing BIM models for shop drawings?	12	7	6	56	33	45	30
Improved 4D construction scheduling and sequencing?	12	2	5	57	27	42	42
Improved 5D cost estimation and scheduling?	14	2	7	57	28	43	38
Improved Extracting cost estimation and quantity take off?	10	4	5	48	25	49	51
Improved the project's constructability?	11	3	1	50	21	61	45
Improved Cost overrun in the design phase?	11	13	16	58	26	28	19
Improved Cost overrun in the construction phase?	14	24	16	66	16	22	12

Figure 40: BIM in the construction phase

7 CONCLUSIONS

7.1 Conclusions concerning the initial exploratory survey

The initial exploratory survey achieved the goal of evaluating BIM knowledge among professionals to delineate an overview concerning BIM adoption in the AEC industry, in Brazil. First, BIM adoption requires a significant change by the AEC firms such as software, hardware, training, process, and business investments for developing future BIM capabilities.

Based on the survey`s results, we conclude that there is a need for strong collaborative practices, as required by the increased level of design complexity, integrated delivery methods, and BIM adoption in the AEC industry. Due to the increase in design complexity, professionals must be able to deal with more collaborative and multidisciplinary solutions.

The demand for BIM education is high (Ahn and Kim, 2016). In the Brazilian context, this reality is not different. However, besides the initiative of BIM courses in undergraduate and graduate programs, education institutions must have a closer relationship with the AEC industry to understand the demands of design and construction firms. This way, education institutions can propose new learning and research opportunities to the AEC community, incrementally introducing them as a fundamental concept during the design, construction, and management phases.

Academic institutions are fundamental not only for offering the necessary knowledge during professional education. It is also a research hub, functioning as a resource to the AEC industry. Although the issue of BIM in AEC education has attracted much attention in academic literature, little is known about the current status of BIM in academia. (Becerik-Gerber, Gerber & Ku, 2011).

The academic community has been searching for more effective teaching approaches that reflect the need for strong collaborative practices, as required by the increased level of design complexity, integrated delivery methods, and information modeling adoption in the construction industry. (Becerik-Gerber, Gerber & Ku, 2011).

Another relevant aspect observed was the usage of BIM by professionals. As discussed earlier, most of the respondents understood that the notable improvement brought by BIM to the AEC industry was data management technology, where BIM has been used as a (3D) three-dimension modeling tool. This result does not bring significant advancements for the AEC industry by keeping the technology isolated as a design tool and far away from building data management.

At last, based on the notion of BIM maturity level proposed by Succar (2009), we suggested from our findings that the BIM level of maturity among professionals is between Pre BIM and BIM stage 1 (object-based modeling) in the AEC industry in Brazil.

7.2 Conclusions concerning bibliometrics

Bibliometrics provided an overview of the BIM approach in Academia in the last decade. A total of 1,378 articles were collected from the Web of Science database. Bibliometrics mapped the main clusters of BIM research and the relevant authors in the field. We performed a co-citation network, co-occurrence of keywords, and citation network by sources to identify the current status and future trends of BIM in Academia.

The content analysis focused on understanding 119 articles that represented fifty percent (50%) of the most cited publications by annual average. The articles were analyzed and codified according to twenty-six codes developed for this study, divided into three main clusters: research codes, BIM codes, and CSFs codes in the building life cycle phases. Each code had a different variety of subcodes.

As a result of the codification process, we obtained a rich amount of data which was analyzed via cross-tabulation. We performed statistical descriptive codes analysis, network codes analysis, and matrix codes analysis of the BIM codes and CSFS codes in the BLC phases.

Based on the first research question and the main research goal, we acknowledge that BIM is still a relevant topic in the field and its approach has been concentrated on understanding BIM as a technology compared to the process and people BIM macro-category. Since 2010, there has been a significant increase in research interest with a massive growth in the number of publications, from 40 to more than 280 publications in 10 years (2010-2020). The number of citations started from nearly 100 citations/year in 2010 and grew sharply up to 8,000 citations/year in 2020.

Concerning the BIM approach in Academia, the findings showed *Intelligence*, *BIM adoption in the AEC industry, and Safety* and *Sustainability* as the research topics most studied in Academia in the last decade. Concerning BIM macro-categories, *Technology* was the most representative BIM macro category followed by *Process* and *People*.

This denotes the majority of the articles analyzed were dedicated to the development of information technologies in the AEC industry. Therefore, the BIM approach has been mainly focused on topics related to interoperability; building performance; construction simulation; construction safety and code checking; energy, acoustic, and energy simulation in Academia.

IT capacity and *Tecnology management* were the most representative *Technology BIM meso-categories*. *Software funcionality, Model sharing management,* and *Compatibility* were the most notorious BIM micro-categories of the sample which corroborates *functional issues,* such as *applications, accuracy, and capability* in BIM relation in the building life cycle (Volk et al., 2014).

The second research question and research goal allowed observing the relationship of BIM macro categories with CSFs in the building life cycle phases. We noticed that *Process* had a stronger correlation with CSFs compared to *Technology and People* BIM macro categories. Particularly, we noticed 9 out of 34 CSFs had stronger link correlations with the Process BIM macro-category, five of which were related to the design phase, three to the pre-construction phase, and one to the construction phase.

In conclusion, after crossing and analyzing the data from bibliometrics, content analysis, and cross-tabulation, we suggest the importance of developing studies focused on the enhancement of BIM research related to Process and People BIM macro-categories, once the Technology BIM macro-category has been studied in the field.

In addition, data analysis also showed the relevance of studying design and construction interface with the evidence that the most significant subphases in the building life cycle were *Analysis, detailing, coordination, and specification* which is the last subphase of the design phase and, *Construction planning and construction detailing* as the first subphase of the construction phase.

7.3 Conclusions concerning the case studies

The case studies have achieved the goal to analyze BIM adoption by different companies throughout the pre-construction phase. To study BIM adoption in theory and practice, we evaluate BIM adoption in the case studies based on three main categories: technology, people, and process as we did in bibliometrics.

Findings showed that process drives technology and people enable its usage. These three are categories are dependable for the success of BIM adoption. We confirmed the problems related to technology to BIM adoption faced by the companies are mostly the same observed in theory. The main ones were: problems with software interoperability and compatibility and technology and IT capacity.

Concerning people and process categories, the principal difficulties addressed were: professionals with a lack of BIM skills, lack of collaboration among project stakeholders, work process redesign, and others. Besides, we encountered similarities in theory and practice concerning BIM adoption, we observed a great gap between the studies developed in the BIM field by Academia and the adoption of BIM faced by professionals and the construction companies.

The case studies showed that Brazilian companies are mostly working on 3D modeling and adopting a few 4D initiatives in the studied projects. On the other hand, international companies have been using 3D, 4D, and 5D BIM modeling in their projects.

This result suggests the success of BIM adoption relies not only on the process, people, and technology. Yet BIM depends on the level of maturity in the company and the level of awareness and maturity in the country.

The case studies showed that BIM is an important driver of improvement in the design compared to the pre-construction and construction phases. Undoubtedly, BIM is not sufficient to diminish the lack of integration between the design and construction interface. As said by Tzorzopoulus et al. (2014), a collaborative process is fundamental to diminish the lack of collaboration between the design and construction phases.

Thus, BIM requires changes in the design process to improve project quality and productivity.

In the AEC industry, each company works in a different field and demands different needs. For this reason, BIM cannot be considered just a digital tool, but rather a new concept designed for the AEC industry throughout the life cycle of the project (Kocaturk; Kiviniemi, 2013). BIM can be able to manage project information for collaboration, coordination, integration, simulation, design optimization, construction, and building maintenance.

The adoption of BIM by the AEC industry requires a broader framework of laws and regulations to structure the use of the technology throughout the chain of services and professionals involved in the building process. The laws and regulations are relevant mechanisms to foster a business environment for building data management, which becomes a valuable condition throughout the construction whole life cycle (Arrotéia et al., 2019).

First, it is necessary for a cultural transformation in companies based on construction team interaction and remodeling of the design process, considering a collaboration among project disciplines instead of a sequenced design process commonly developed by construction companies in Brazil.

Second, there is a constant need to update information in the three-dimensional model based on construction changes during the pre-construction and construction phases (Arrotéia, 2013).

According to Eastman et al. (2014), the 3D BIM model is not only a representation of the building through object-based parametric modeling. The elements are composed of more than just the geometry it has parameters, requirements, non-geometric information, a set of relations, and rules to control the parameters, which allows practical and automatic changes.

Thus, it is important to have a common data environment allowing the project stakeholders to manipulate the 3D BIM model not only in the design phase, yet in the pre-construction and construction phases.

However, the adoption of BIM proposes not only the training of professionals working in the civil construction industry but also the incorporation of new technological languages into the training process of new professionals.

7.4 Conclusions concerning the final exploratory survey

With the final exploratory survey, we analyzed BIM in three different phases: design, pre-construction, and construction based on 40 CSFs. We applied the same CSFs as applied in bibliometrics and content analysis and added other ones to investigate BIM in practice.

The data collected represented a relevant sample concerning the analysis of BIM in the design, pre-construction, and construction phases based on 570 professionals 'opinions from the AEC industry. Concerning the professional profile, most of the respondents were male, civil engineers, and architects with master's degrees and over 20 years of experience in the market.

The majority of the respondents classified their BIM knowledge as basic and the BIM maturity level in the projects developed by their companies between Level 0 (Low collaboration) to Level 1 (Partial collaboration) in most answers. Similarly, with the initial exploratory survey, findings suggested the BIM maturity level among professionals was between Pre BIM and BIM stage 1 (object-based modeling) in the AEC industry in Brazil.

Besides, the final exploratory survey was applied three years later after the initial exploratory survey, results suggest that BIM knowledge and BIM maturity level are closely the same. In Brazil, there is a lot of room for improvements not only regarding BIM adoption itself but also in terms of technology, people, process, and management in the AEC industry.

The success of BIM adoption relies on the management of technology, people, and process. Technology itself is useless without trained people and a well-defined process. The key to the success of BIM adoption is the employment of technology by trained people with BIM skills and information management through a well-designed process in the building life cycle. Furthermore, we understand that BIM itself does not solve the lack of integration from the design to the construction phase. We consider the main challenge is how to promote a collaborative environment among project stakeholders in all project phases.

According to the professionals ‘opinion, BIM brought more improvements in the design phase compared to the pre-construction and construction phases. In particular, BIM itself as technology does not solve the problems related to the lack of integration in the design and construction interface. The results suggest the need for the development of solutions for the management of people and processes based on the employment of innovative technologies. Furthermore, the success of BIM adoption demands a re-reading of the contractual models aligned with the project scope and project stakeholders’ roles and responsibilities.

7.5 Conclusions concerning the research questions and objectives

The general research objective was to identify CSFs for BIM in the design and construction interface for the evaluation of BIM in different projects phases. This research achieved the proposition of CSFs for BIM in the design, pre-construction, and construction phases through three different methodological approaches to evaluate BIM in theory and practice.

Before that, we first evaluated BIM knowledge among professionals to respond to the first research question RQ1: What is the level of BIM knowledge among professionals in the AEC industry in Brazil? Allied with the first research question, the first specific objective achieved the purpose to draw an overview concerning BIM knowledge and BIM education among professionals in the AEC industry in Brazil.

After we achieved the second specific research objective which was to understand an overview of BIM in theory and investigate the relationship of the BIM CSFs with technology, process, and people categories in the building life cycle phases. We developed the research through bibliometrics and content analysis to obtain answers for the second research question RQ2: How BIM has been approached in theory by Academia in terms of technology, process, and people categories?

The third specific research objective investigated the usage of BIM in four different companies throughout the pre-construction phase. To study BIM from a practical perspective, we developed a multi-case study approach with two construction companies in Brazil and two others abroad to achieve the research goal. We applied a comparative study among construction companies with different backgrounds and organizational structures, cultures, and work environments to answer the third research question RQ3: How BIM has been adopted in practice by the AEC industry from companies based in different countries?

Lastly, we accomplished the fourth specific research goal analyzing BIM through BIM CSFs in the design, pre-construction, and construction phases. We developed an exploratory survey to answer the last and following research question RQ4: How has BIM been performing in the design, pre-construction and construction phases?

Finally, we applied the CSFs in different methodological approaches, one theoretical through bibliometrics and content analysis, and two practical developing case studies and exploratory surveys. As a contribution to the academic field, we proposed the categorization of 14 different BIM codes which can be used in future works. Likewise, we applied the analysis of CSFs for BIM divided into four main phases: design, pre-construction, construction and operation with three categories: technology, people and process.

As contributions to practitioners, this research identified CSFs for BIM in the design and construction interface. The CSFs were founded in literature, classified and framed into three main phases: design, pre-construction and construction phases for the evaluation of BIM in projects.

7.6 Research limitations and further works

Despite the contributions to the field, this study has some methodological limitations. The surveys present inherent limitations as the sample is composed predominantly of Brazilian professionals with unbalance sample relating to other countries presenting geographical limitations on the findings. Likewise, in the two developed surveys, data analysis was based on respondents' perceptions, which, consequently, can be impacted by some bias. Second, the results cannot be generalized, once we apply a non-probabilistic sample.

Third, specifically in the initial exploratory survey, the sample was not stratified by different professions, sectors, firm size, and country; thus, these variables could not be investigated. These limitations can lead to future works, which include the understanding of BIM knowledge among different professionals, and the understanding of BIM in the design, pre-construction, and construction phases in different sectors, countries, and firms' sizes.

In concern to bibliometrics, the data was collected only from the Web of Science database. Second, data has limitations regarding the adoption of search strategy, search strings, and logical operators. Third, the data analysis can have some bias based on our authors 'knowledge and perception regarding the topic'. In future works, we suggest a broader investigation with other research databases adopting the codes created in this study, besides an analysis of CSFs for BIM in the building life cycle subphases to understand the potential research gaps between those subphases.

Regarding the case studies, the research applied a qualitative approach in the treatment of data analysis and results, which can be considered a limitation. The case studies cannot be generalized, once part of the data was based on professionals' viewpoints and experience concerning the research topic. Likewise, the results were obtained in a specific clipping time and are dependable on the companies' structure, size, culture, and the maturity of the AEC industry in the country.

For further works related to BIM adoption in the design and construction interface, we suggest the development of research such as:

- To create key indicators for BIM based on CSFs in the design, pre-construction and construction phases;
- To apply CSFs for the evaluation of BIM in the projects developed by the public sector;
- To develop a design management method;
- for the pre-construction phase based on BIM;
- To propose a framework for project collaboration among stakeholders in the design and construction interface.

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APPENDIX

Appendix A | Initial exploratory survey questionnaire

Survey- Pesquisa sobre BIM

1. Bem-vindo a Survey: Pesquisa sobre BIM

Este questionário é parte de uma pesquisa de doutorado em andamento realizado pela Escola Politécnica da Universidade de São Paulo.
Convidamos você gentilmente à participar da nossa pesquisa.
A sua participação é voluntária e anônima.
Seu feedback é muito importante.

Survey- Pesquisa sobre BIM

2. Sobre o seu conhecimento

1. O que é BIM?

- [ ] Nova tecnologia de representação gráfica do projeto
- [ ] Software de gestão das informações do projeto
- [ ] Software de gestão das informações do empreendimento
- [ ] Processo de gestão das informações do empreendimento
- [ ] Todas
- [ ] Nenhuma
- [ ] Outro
- [ ] Outro (especifique)

2. Na sua opinião, quais são as vantagens do BIM?

- [ ] Melhor qualidade na apresentação dos projetos ao cliente
- [ ] Melhor colaboração entre os agentes envolvidos (stakeholders)
- [ ] Melhor visualização tridimensional do projeto
- [ ] Melhor gestão das informações do empreendimento
- [ ] Redução dos erros do projeto e da construção do empreendimento
- [ ] Redução do custo e prazo da construção do empreendimento
- [ ] Extração de quantitativos mais precisos
- [ ] Todas
- [ ] Nenhuma
- [ ] Outro
- [ ] Outro (especifique)

3. E as desvantagens do uso do BIM?

- [ ] Incompatibilidade com outros softwares
- [ ] Custos indefinidos de implantação
- [ ] Alto investimento em infraestrutura, treinamento e estrutura organizacional
- [ ] Falta de definição clara sobre os papéis e responsabilidades na atualização das informações do modelo
- [ ] Falta de colaboração efetiva entre os agentes
- [ ] Falta de interesse por parte dos fornecedores
- [ ] Falta de enquadramento jurídico suficiente para adoção do BIM
- [ ] Barreiras culturais na adoção de novas tecnologias
- [ ] Todas
- [ ] Nenhuma
- [ ] Outro
- [ ] Outro (especifique)

4. Como você classifica o seu conhecimento sobre BIM?

- ○ Insuficiente
- ○ Intermediário
- ○ Bom
- ○ Avançado

Survey- Pesquisa sobre BIM

3. Sobre a empresa

5. Qual é a área de atuação da empresa no mercado?

- [ ] Desenvolvimento de projetos
- [ ] Coordenação e compatibilização de projetos
- [ ] Construção
- [ ] Operação (Facility Management)
- [ ] Consultoria
- [ ] Imobiliária
- [ ] Ensino
- [ ] Outro
- [ ] Outro (especifique)

6. Qual é o tempo de atuação da empresa no mercado?

- ◯ Menos de 1 ano
- ◯ Entre 1 a 5 anos
- ◯ Entre 5 e 10 anos
- ◯ Entre 10 e 20 anos
- ◯ Mais de 20 anos

7. Qual é o porte da empresa?

- ◯ Menos de 5 colaboradores
- ◯ Entre 5 e 10 colaboradores
- ◯ Entre 10 e 20 colaboradores
- ◯ Entre 20 e 50 colaboradores
- ◯ Mais de 50 colaboradores

8. A empresa em que você trabalha utiliza BIM?

- ◯ Sim
- ◯ Não

Survey- Pesquisa sobre BIM

4. Sobre o uso do BIM na empresa

9. Há quanto tempo a empresa trabalha com o BIM?

- ◯ Menos de 1 ano
- ◯ Entre 1 e 5 anos
- ◯ Mais de 5 anos

10. Quais software(s) BIM a empresa utiliza?

- ◯ Revit Architecture
- ◯ Vectorworks Architecture
- ◯ Bentley Architecture
- ◯ ArchiCAD
- ◯ Naviswork
- ◯ Solibri
- ◯ Tekla
- ◯ TQS
- ◯ Outro
- ◯ Outro (especifique)

11. Quais tipos de modelagens do BIM são adotado(s) pela empresa?

- [ ] 3D (Simulação tridimensional)
- [ ] 4D (Custo)
- [ ] 5D (Tempo)
- [ ] 6D (Facility Management)
- [ ] 7D (Sustentabilidade)
- [ ] Todos
- [ ] Nenhuma

12. Ter conhecimento em BIM é um fator importante na contratação de colaboradores para a empresa?

- ○ Sim
- ○ Não
- ○ Talvez

13. Você acredita que a mesma pretende implantá-lo futuramente?

- ○ Sim
- ○ Não
- ○ Talvez

14. Em caso negativo, por que?

- [ ] Incompatibilidade com outros softwares
- [ ] Custos indefinidos de implantação
- [ ] Alto investimento em infraestrutura, treinamento e estrutura organizacional
- [ ] Baixo reconhecimento do mercado/cliente
- [ ] Longo período de implantação
- [ ] Falta de profissionais capacitados em BIM
- [ ] Todas
- [ ] Nenhuma
- [ ] Outro
- [ ] Outro (especifique)

15. Na sua opinião, o que deve ser feito para a expansão do uso do BIM no mercado brasileiro?

- ○ Regulamentação de normativas e leis aliadas ao BIM por parte da alta esfera do governo
- ○ Inserção do ensino de BIM na grade curricular dos cursos de Arquitetura e Engenharia
- ○ Diminuição dos custos de implantação
- ○ Melhoria nos problemas de interoperabilidade (incompatibilidade entre softwares)
- ○ Valorização da adoção do BIM por parte do cliente
- ○ Outro
- ○ Outro (especifique)

Survey- Pesquisa sobre BIM

5. Sobre sua formação acadêmica

16. Escolaridade:

- Graduado
- Especialista
- Mestre
- Doutor
- Pós-Doutor

17. Profissão:

- Arquiteto(a)
- Engenheiro(a)
- Consultor(a)
- Professor(a)
- Outro
- Outro (especifique)

18. Tempo de atuação no mercado:

- Menos de 1 ano
- Entre 1 e 5 anos
- Entre 5 e 10 anos
- Entre 10 e 25 anos
- Mais de 25 anos

19. Você teve conhecimento sobre o uso do BIM durante a graduação?

- Sim
- Não

20. Como você classifica o seu nível de conhecimento sobre BIM obtido durante a graduação?

- Insuficiente
- Intermediário
- Bom
- Avançado

21. Você acredita que a universidade tem papel fundamental na formação do profissional sobre o uso do BIM?

- Sim
- Não
- Talvez
- Não tenho conhecimento

Appendix B | Bibliometrics content analysis codebook

Code cluster	Code number	Code name	Subcode name
Research codes	A1	Kind of study	Modeling, theoretical-conceptual, literature review, simulation, survey, case study, action-research, experimental, focus group, design science
	A2	Affiliation	University, research Institution, Company
	A3	Financial support	Yes/No
	A4	Period of Analysis	Longitudinal, retrospective, contemporary
	A5	Research Approach	Quantitative, qualitative, descriptive, predictive
	A6	Geographic scope	Regional, national, international
	A7	Analytic unit	Person, groups, organizational units, companies, design, products, process
	A8	Sources of evidence	The questionnaire, interview, document analysis, public data, press information, bibliography, big data, parametric data, algorithm
BIM codes	B1	BIM research	BIM ontology, BIM in the AEC education, BIM in the AEC industry, safety, sustainability, facility management, BIM technology applications, H-BIM, innovation, intelligence, mobile computing
	B2	BIM macro-category	Technology-focused issues, people-focused issues, process-focused issues
	B3	BIM meso-category	IT capacity, technology management, attitude and behavior, role-taking, communication, leadership, trust, learning, and experience
	B4	BIM micro-category	Software functionality, software immaturity, compatibility, model creation management, model sharing management, designer attitude, reluctance to initiate new workflows, emergence of new roles, conflicting obligations, information exchange, direct access to collaboration, organizational structure, business purposes, different requirements, third party as a leader, direct participants as a leader, trust effects, affecting trust, experience, inadequate BIM skills, learning approach, organizational learning
	B5	BIM implementation motivations	Image motives, reactive motives, project-based economic motives, cross-project economic motives
	B6	BIM relation in the building life cycle	Functional issues, informational issues, technical issues, organizational and legal issues
	B7	BIM in the building life cycle phases	Design, construction, and operation
	B8	BIM in the building life cycle subphases	Conceptualization, programming, and cost planning; Architectural, structure, and system design; Analysis, detailing, coordination and specification; Construction, planning, and construction detailing; Construction, manufacturing, and procurement; Commissioning, as-built and handover; Occupancy and operations; Asset management and facility maintenance; Decommissioning and major-programming
	B9	BIM dimensions	2D, 3D, 4D, 5D, 6D, 7D, 8D
	B10	BIM fields	Policy, process, technology

	B11	BIM stages	Pre-BIM status, BIM stage 1, BIM stage 2, BIM stage 3, Post-BIM
	B12	BIM lenses	Disciplinary lenses, scoping lenses, conceptual lenses
	B13	BIM maturity	Initial, defined, managed, integrated, optimized
	B14	Organizational scale	Macro: markets and industry; Meso: projects and their teams; Micro: organizations, units, their teams, members

CSFs related to BLC phases codes	C1	Design CSF	Earlier and accurate 3D visualization of design Better design/multi-dimensional design alternatives/applications Design coordination in various elements/components Verification of consistency to the design intent Predictive analysis of performance (energy analysis, e.g. CO2) Thermal energy analysis and simulation MEP analysis and simulation (HVAC) Structural analysis and design Predicting environmental analysis and simulation (airflow, weather) Acoustic analysis and simulation (sound) Photorealistic rendering for marketing purposes Accuracy and reliability of data (less rework and fewer document errors and omissions)
	C2	Preconstruction CSF	Integrating design validation (clash detection) Collaboration in design, construction, engineering, and facility management stakeholders Ensuring effective communication among project participants Enhancing exchange of information and knowledge management Model checking and validation (reviewing code) Reduced claims or litigation (risks) Improved site layout, planning and site safety Coordination and planning of construction works Integrating project documentation/bid preparation Synchronization of procurement with design and construction Providing BIM models for offsite prefabrication Providing better implementation of lean construction, green sustainability and IPD
	C3	Construction CSF	Collaboration of simultaneous access of construction work Reducing construction project duration Reducing construction project cost Improved construction project performance and quality Providing BIM models for shop drawings 4D construction scheduling and sequencing (3D+time) 5D cost estimation and scheduling (3D+time+cost) Extracting cost estimation and quantity take off
	C4	Operation CSF	Improved operations and maintenance (facility management) Remodeling and renovation

Appendix C | Case studies questionnaires 1 e 2

QUESTIONNAIRE 1:

BIM IMPLEMENTATION IN THE COMPANY'S ORGANIZATIONAL CONTEXT

1. When did the company become interested in BIM?
2. What were the motivations that led the company to implement BIM?
3. What were the main barriers and difficulties during the implementation process?
4. Who led the implementation? What were the main stakeholders involved?
5. What were the changes made in the company policy and processes with BIM implementation?
6. Has the design management process changed with the implementation of BIM?
7. Does the company use any kind of method or tool for the preconstruction phase that promotes a better integration between the design and construction phases?
8. Has the project documentation and bid preparation (contracting procedure) changed with BIM?
9. Among the categories (1) technology, (2) processes, and (3) people, which one do, you consider that the company has been the most impacted by BIM? Tell me about it.
10. What were the changes in technology (software and hardware) with the BIM implementation?
11. Which phase (design, construction, and operation) do you consider BIM is more effective for the company? Could you specify a subphase?
12. And contrarily, which phase (design, construction, and operation) do you consider that BIM is less effective in the company? Could you specify a subphase?
13. The usage of BIM can be changed according to the project typology/category?
14. What is the client`s feedback regarding the usage of BIM in the company`s projects?
15. On a scale of 1 to 5, how do you classify the company's BIM maturity level?

QUESTIONNAIRE 2:

BIM ADOPTION IN THE PROJECT

Concerning BIM adoption in the design and construction interface:

1. Does the company adopt any type of solution or method dedicated to the preconstruction phase to promote integration between the design and construction phases?
   1.1. 1.1 If so, talk more about the method.
   1.2. If not, do you believe that kind of solution would be important?
2. Do you believe that BIM has brought improvements to the preconstruction phase? If so, which ones?
3. Do you believe that BIM allowed the designer to “get closer” to the construction site?
4. Do you believe that BIM enhanced the project’s constructability?
5. Do you believe that BIM has improved communication between the design and construction teams?
6. In your opinion, what are the main gaps related to BIM during the design phase?
7. In your opinion, what are the main gaps related to BIM in the construction phase?
8. In your opinion, how could BIM improve the integration between the design and construction phases?

Concerning BIM adoption in the project (case study):

9. Did BIM change the project`s scope?
10. Has BIM positively or negatively interfered with the project cost and duration?
11. Did BIM improve project quality and performance? If so, could you give some examples?
12. At which project`s phase BIM has been implemented in the project life cycle?
13. Do you believe that BIM was integrated into the process in a holistic or isolated way?

Concerning the BIM model:

14. What were the main difficulties during the development of the BIM model during the design phase?

15. How did the clash detection (BIM) model verification process occur to validate information consistency across project disciplines?
16. What were the main challenges to the management of information flow during construction?
17. Does the company has continuously updated the BIM model as changes happened during construction?
    17.1 so, could you tell me more about the steps in this process?
    17.2 If so, the BIM model was updated by a specific stakeholder or team?
18. What were the BIM dimensions developed (3D / 4D / 5D / 6D / 7D / 8D) in the model?
19. On a scale of 1 to 5, how do you classify the BIM level of maturity (detailing) of the model?
20. Using the BIM model, it was possible to:
    Note: If affirmative, please cite examples:

20.1 Increase the accuracy and reliability of design data?
20.2 Collaboration in design, construction, engineering, and facility management stakeholders?
20.3 Ensuring effective communication among project participants?
20.4 Enhancing exchange of information and knowledge management?
20.5 Reduced claims or litigation (risks)?
20.6 Improve site layout, planning, and site safety?
20.7 Improve coordination and planning of construction works?
20.8 Integrating project documentation/bid preparation?
20.9 Synchronization of procurement with design and construction?
20.10 Providing BIM models for offsite prefabrication?
20.11 Providing better implementation of lean construction, green sustainability and IPD

Appendix D | Final exploratory survey questionnaire

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 company headquarters?

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

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.**

- Management
- Technology
- Policy
- Process
- 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 take off	○	○	○	○	○	○	○
Improvement of the project's constructability	○	○	○	○	○	○	○