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RESEARCH PAPER

BIM critical factors and benefits for public sector: from a systematic review to an empirical fuzzy multicriteria approach

Carlos Alejandro Díaz Schery[1], Yiselis Rodríguez Vignon[1], Rodrigo Goyannes Gusmão Caiado[1], Renan Silva Santos[1] Marcello Congro[1], Eduardo Thadeu Corseuil[1] Deane Roehl[1]

[1] Pontifical Catholic University of Rio de Janeiro (PUC), Rio de Janeiro, RJ, Brasil.

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ABSTRACT

Goal: The purpose of this study is to develop a decision support framework to select critical success factors (CSFs) and benefits for the implementation of BIM in the public works sector.

Design / Methodology / Approach: The research methodology integrates multiple fuzzy multicriteria decision making (MCDM) approaches to propose a composite framework of CSFs and benefits using qualitative and quantitative approaches, with the application of two semi-structured questionnaires with CSFs and benefits identified in previous studies, through a systematic literature review (SLR).

Results: The study identified 42 CSFs and 31 benefits for the implementation of BIM for public works, and the relative importance of the identified factors and benefits was measured according to the four main BIM perspectives: legal, people, process, and technology. The result of the applied MCDMs showed the relationship between the factors and benefits of the four most influential BIM perspectives according to the proposed framework. The most influential CSFs and benefits were: BIM adoption requires individual and group motivation in the organization, Establishment of BIM and Lean construction standards, codes, rules, and regulations, Financial support from the government to establish BIM system, Availability of quality, schedule, and cost information during construction with BIM Accuracy and reliability of documents and data and BIM provides knowledge sharing among stakeholders, Workflow, productivity, and efficiency are affected by the transition to BIM, BIM technology reduces cost and time, Conflict detection, integration, coordination, and design validation, and Creating more efficient projects with stakeholder involvement, coordination, and oversight.

Limitations of the investigation: The research sample consisted exclusively of Brazilian professionals and academics with experience in the implementation of BIM in public works.

Practical implications: The proposed framework can be applied in implementation in public construction projects that aims to implement BIM considering the selection of critical success factors and benefits.

Originality / Value: BIM methodology is widely used in the construction industry. However, there are few studies on CSFs and the benefits of BIM for the public sector, and there still lack of implementation frameworks proposal with empirical evidence.

Keywords: BIM; Critical success factors; Public sector; Framework.

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1. INTRODUCTION

Building Information Modelling (BIM) is a work methodology that integrates all project parts throughout the construction lifecycle, extracting the factual information and transforming it into digital information to create a product that optimizes the work (Eastman et al., 2011). In recent years, BIM has emerged as an innovative concept for the public works area operating in the construction industry. BIM offers a new paradigm for designing, building, operating, and maintaining a facility (Criminale et al., 2017; Freitag et al., 2017). Such a methodology is a systematic approach to the life cycle of an infrastructure (Smith et al., 2009). It is the centerpiece of the digital transformation of the industry based on collaboration between different professional groups (Jacoski et al., 2018; Stojanovska-Georgievska et al., 2022). Influencing digitization increases the industry's productivity and puts innovations in favor of the infrastructure. Implementing BIM in construction is a clear act towards digitization and is expected to generate savings of 13 to 21% in the design and implementation phase and 10 to 17% in operation and maintenance within the global infrastructure market by 2025 (Smart Market Report, 2017). Since the early 2000s, the concept of BIM has emerged as one of the most critical developments in AEC when parametric, three-dimensional modeling of buildings became more important (Eastman et al., 2011).

Succar & Kassem (2015) have established clear definitions for these terms: BIM implementation is the successful adoption of BIM tools and workflows within a single organization. On the other hand, BIM diffusion is the adoption rate of BIM tools and workflows in markets. Arayici et al. (2011) studied the implementation of BIM in an architectural firm and found several significant factors in the implementation process. (Morlhon et al., 2014) has called these factors critical success factors (CSFs), constituting essential elements for successfully implementing a new system.

Antwi-Afari et al. (2018) have identified CSFs that influence the implementation process. On the other hand, Jones & Laquidara-Carr (2016) refer to critical success factors as criteria for achieving a goal in the construction phase. According to Brito et al. (2021), studies related to CSFs for BIM adoption at the organizational level and in the context of public organizations are still lacking. To gain a deeper understanding of the critical factors for BIM, it is feasible to investigate the factors that influence its implementation. From this perspective, Park et al. (2009) reported that the analysis of CSFs, initially proposed by Rockart (1979), has been widely adopted by researchers as a top-down methodology to examine the factors affecting technological change. Lu et al. (2008) also point out that the CSF approach is an effective way to identify a few manageable but vital factors from many factors. According to Brito et al. (2021), while the factors that have been considered in the literature apply to public organizations, these organizations are confronted with other criteria that are tailored to the government context, such as regulatory structure, legislation, accountability and operation, procurement, and personnel structure.

In Brazil, between 2012 and 2014, the city of Rio de Janeiro began major processes of building modifications and alterations, driven by the sporting events of 2014 (World Cup) and 2016 (Olympic Games) (Salgado et al., 2015). Considering the need to incorporate and reconcile CSFs in BIM implementation, it is vital to establish a working method that collaboratively allows project development. Therefore, the need arises to think of the integrated design process as a way to produce sustainable buildings (Salgado et al., 2015). Decree No. 10,306, dated April 2, 2020, instituted by the Brazilian government, provides for the use of building information modeling in the direct or indirect execution of works as part of the national strategy for disseminating building information modeling. On the other hand, the governor of the state of Rio de Janeiro instituted Decree No. 46,471-2018, aiming to promote a favorable environment for investments in Building Information Modeling in the municipalities of the state of Rio de Janeiro. CSFs have recently driven developments in the construction sector concerning public works because of BIM implementation, supported by MCDM to strengthen studies. According to Tabatabaee et al. (2021), implementing BIM brings certain risks to construction projects. BIM is supplemented with information from various disciplines, faster and more accurately, affecting the assessment(Kim et al., 2015). On the other hand, the question is how to integrate and use BIM to facilitate the decision-making process. MCDM enables the integration of technical information and value from multiple stakeholders into BIM-based decision-making processes, where decision-making schemes are selected, tested, and ranked by aligning factors, benefits, or indicators to complement each other (Tan et al., 2021).

To understand current research attempts to identify factors that facilitate and motivate the implementation of BIM supported by decision support methods, this paper's objective was to answer the following research question (RQ): What are the CSFs and benefits for implementing BIM in public works? To fill the mentioned gaps, the purpose of this research is twofold: (1) to conduct a systematic literature review (SLR) to map CSFs and benefits, also identifying trends and potential gaps based on the results obtained; and then (2) to rank the main CSFs and benefits supported by fuzzy group decision-making approaches, noting the perceptions of practitioners and academics regarding their current application. Therefore, the study provides several contributions to the soft computing and industrial engineering literature. First, it examines 32 items as a bottom line from a public industry perspective. Second, the article offers a set of CSFs to facilitate the implementation of BIM and the potential benefits of this digital transformation for the construction industry. Third, the perception of multiple stakeholders (e.g., engineers and academics) is used with hybrid MCDM methods to compare 42 CSFs and 31 benefits.

Also, this work has theoretical and practical implications to operations management in the construction sector. It adds to the theory by providing a simple and straightforward methodology to assess CSFs to BIM implementation. This methodology could also be used in assessing CSFs in other aspects of construction management. From the practitioners point of view, it provides a framework which prescribes the priorities in BIM implementation as well as clearly stating the benefits reaped, so that by enabling these CSFs first, BIM implementation can be sped up and facilitated and the desired benefits achieved.

2 LITERATURE REVIEW

2.1 Critical success factors for implementing BIM in public works

With the growing acceptance of the subject to improve traditional practices (Nascimento et al., 2019), industry interest has shifted from applying BIM to determining how to successfully adopt this way of working in organizations. CSF is a concept proposed by Rockart (1979) representing a limited number of areas where satisfactory results guarantee successful competitive performance for an organization. BIM is inevitable because of its existing need for the industry (Hore et al., 2014). Significantly, the public sector recognizes the benefits that this way of working can bring. The authors warn that while this methodology does not address all concerns, it may offer opportunities for construction sectors, especially in public works, to take a step in the right direction toward a more sustainable future.

The public sector is key in guiding the industry toward BIM adoption. In recent years, the implementation of this methodology has continued to increase considerably as more and more government agencies, and non-profit organizations in various countries around the world have implemented this way of working in their projects and provided different standards and solutions on the matter at hand (Cheng et al., 2015).

One can affirm that in public works, the methodology can significantly help from the design phase to the construction (Nawari et al., 2015). Generally, the implementation of BIM enables influence during the design phase, the construction tender, and the facility management phase (Barbini et al., 2019).

2.2 Benefits of BIM implementation in public works

(Vasudevan, 2020) identified the significant benefits of BIM implementation in the construction industry, and at the same time, described the significant impact on their current practices, contract policy, and business model. They first address that "BIM is a new approach to managing building design and project data in digital format throughout the lifecycle of a construction site that provides information sharing and interoperability among stakeholders" (Ilhan & Yaman 2013).

Given the above, Al-Ashmori et al. (2020) express that the main benefits of BIM implementation are improved productivity and efficiency. That is why understanding and recognizing the value of BIM makes the decision of construction stakeholders to use BIM for their projects very easy. In addition, the government plays a leading role in promoting BIM implementation.

However, to achieve this, it is crucial to identify and convince the players of the benefits provided by the technology. That is why the government plays a leading role in promoting the implementation of BIM (Ilhan et al., 2013). The implementation of BIM in public works incorporates a variety of benefits and includes the following: technological benefits (Vasudevan, 2020), legal benefits (Nguyen et al., 2021), benefits from a process and people perspective (Siebelink et al., 2021).

2.3 The use of MCDM techniques in the context of BIM implementation

MCDM is a potent approach widely used to deal with unstructured problems that contain multiple and potentially conflicting objectives(Lee & Eom, 1990). Several MCDM techniques have been developed and are used in various fields of engineering as well as management.

In addition, multicriteria decision support methods can support decision-making in "evaluating alternatives" (Cecconi et al., 2017). According to Jalilzadehazhari et al. (2019), MCDM methods are based on "multiobjective optimization", which increases the dynamism of the decision-making requirements (Pidgeon et al., 2021; de Paula Vidal, Caiado, Scavarda, and Santos, 2022). The applied potential means this methodology can become a powerful tool to help you select your criteria and priorities in various infrastructure building problems (Jato-Espino et al., 2014). In this research, hybrid MCDM methods, such as FAHP, were used to obtain the weights based on experts' experience in evaluating CSFs for BIM implementation in public works and FTOPSIS and FVIKOR methods (to rank, order and identify all CSFs' critical success factors for BIM implementation in public works). Regarding the models for selecting factors for BIM implementation, researchers and practitioners have adopted different techniques and methodologies, summarized in Table 1. However, most research applies decision-making approaches to analyze the factors. There is a lack of work in the literature associated with understanding factor selection in BIM implementation for public works.

Table 1 - Summary of studies that have evaluated BIM factors using MCDM techniques (continue)

(Author, year)	Methods	Application
(Aminrad et al., 2022)	AHP-VIKOR	An integrated approach to building information modeling evaluation applications based on raw numbers
(Pourebrahim et al., 2014)	FVIKOR-FAHP	Application of VIKOR and fuzzy AHP for conservation priority assessment in coastal areas: case of Khuzestan district, Iran
(Gupta et al., 2017)	AHP-FTOPSIS	A framework for applying CSFs to ERP software selection: an extension of the fuzzy topsis approach
(Agrawal et al., 2022)	AHP-TOPSIS-DEMATEL	Analyzing CSFs for Sustainable Green Supply Chain Management
(Majid et al., 2012)	FVIKOR-FAHP	Project portfolio selection using fuzzy ahp and vikor techniques
(Naveed et al., 2021)	AHP	Assessment and classification of CSFs of cloud enterprise resource planning adoption using the MCDM approach
(Brito et al., 2021)	AHP	Framework for CSF-based BIM Adoption by Brazilian Public Organizations
(Firouzabadi et al., 2015)	FVIKOR	ERP software quality assessment using fuzzy VIKOR

Table 1 - Summary of studies that have evaluated BIM factors using MCDM techniques (conclusion)

(Author, year)	Methods	Application
(Rostamzadeh et al., 2015)	FVIKOR	Applying fuzzy VIKOR to evaluate green supply chain management practices
(Ashtiani et al., 2016)	FAHP-FVIKOR	Trust modeling based on a combination of fuzzy analytic hierarchical process and fuzzy VIKOR
(Ikram et al., 2020)	AHP-FVIKOR	Development of integrated management systems using an AHP-Fuzzy VIKOR approach

Source: the authors themselves.

This study chose the AHP FTOPSIS and AHP FVIKOR methods to select CSFs and benefits for BIM implementation.

Furthermore, with the hybrid fuzzy techniques selected, this framework will take a holistic approach to classify these elements properly (Lima et al., 2023).

3. MATERIALS AND METHODS

The research used a mixed methods approach. First, a systematic review was conducted to identify CSFs and benefits for BIM implementation, as well as the most suitable MCDM models for the investigation. Then an empirical study was conducted, applying a questionnaire to seven academics and five construction industry experts to assess the most relevant CSFs and benefits. Finally, hybrid multicriteria approaches were applied in groups and combined with fuzzy logic to define rankings of CSFs and benefits.

3.1 Systematic Literature Review

Systematic Literature Review (SLR) has recently become very popular among experts and researchers due to its logical and holistic approach (Karimi et al., 2021; Alves et al., 2023). In SLR, all literature relevant to a specific research question or topic area is identified, evaluated, and logically interpreted (Kraus et al., 2020). In this study, the review was performed based on the adaptation of the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) recommendation (Moher et al., 2015). The flow chart in Figure 1 summarizes the four phases described in this recommendation

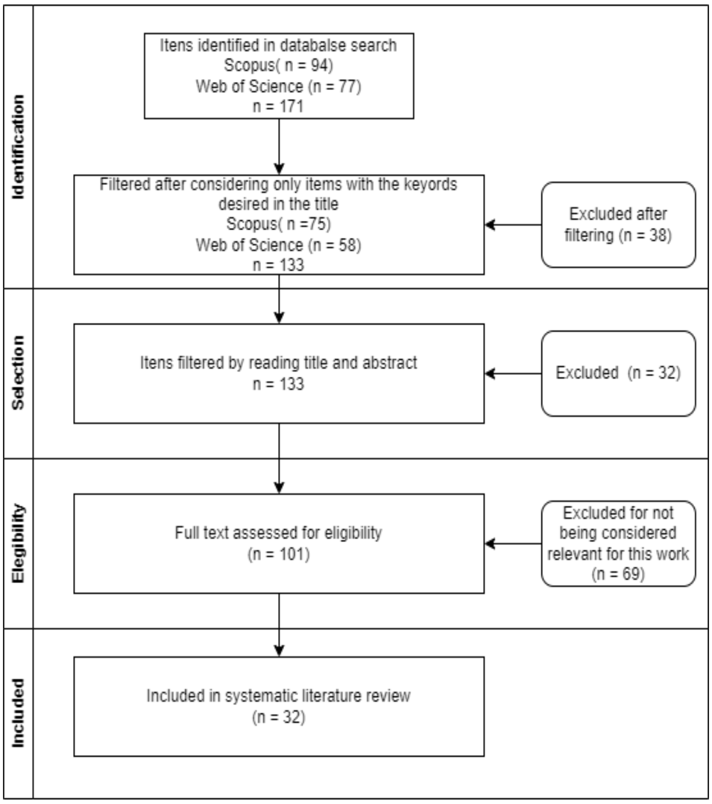

Figure 1 - Prisma Flowchart (Moher et al., 2015)

3.2 Identification

In conducting an effective systematic literature review, the starting point is formulating a specific and representative main research question, which is then supplemented by a series of sub-questions(Susca et al., 2022). In the case of this paper, the main question formulated was, “To what extent did multicriteria decision support techniques (MCDM) support the selection of best optimization strategies taking into account a framework to identify the CSFs and benefits of BIM implementation in public works”.

The Web of Science (WoS) and Scopus databases were considered to implement a robust, systematic, and comprehensive search regime. In addition, the search employed a multidimensional approach to information extraction for all two databases. The primary sources of information are journal articles written in English. To apply a consistent search regime across all databases, carefully designed keywords were used to query all databases similarly, dividing the search into two specific terms (Ruhlandt, 2018). Keyword selection was guided by combining the well-known PICO approach in the literature (Population, Intervention, Comparison, Outcome). This is a question formulation method for conducting a quantitative systematic review of the literature and was adopted by the Cochrane SPIDER Collaboration (Sample, Phenomenon of Interest, Design, Evaluation, Research Type) developed by (Tong et al., 2012). The keywords used in this article to work with the two search terms are presented below, broken down to answer the search topics:

(“CSF*” OR “critical success factor *” OR “enabler” OR “driver*” OR “trigger*” OR “promoter*” OR “CSF*” OR “BENEFITS”) AND (“building information modeling” OR bim OR “building information modeling”) AND construct*”.

("critical success factor*" OR "success factor*" OR "CSF*") AND ("multicriteria decision" OR "fuzzy" OR "multicriteria decision Making " OR “Multicriteria Decision-Analysis” OR "MCDM" OR "MCDA" OR "FUZZYTOPSIS" OR “Multi-MOORA” OR “TOPSIS” "VIKOR" OR "WASPAS" OR "FUZZYVIKOR" OR "AHP" OR "DEMATEL").

3.3 Selection

The selection phase consisted of reading the titles and abstracts of the reports obtained from the databases. Next, the documents were filtered for further research. The main reason for filtering is to identify and eliminate irrelevant articles due to missing or ambiguous definitions of keywords in the original articles.

After the initial search of the databases, in the time frame analyzed and closing the gaps on the date mentioned, the results of the two databases (Scopus: n = 141 and Web of Science: n = 30), with 171 total documents in the export format, Bibtex and CSV, respectively) were combined. Then there was a second round of keyword filtering exclusively on the document titles, reducing the total in Scopus (n = 94); Web of Science (n = 77). After screening the titles and abstracts, 133 results were excluded, following the initial inclusion/exclusion criteria presented in Table 2.

Table 2 - Initial inclusion/exclusion criteria

Exclusion Criteria	• Absence of abstract; • Papers that cannot support the authors in achieving the research objectives; • Papers not written in the English language; • Invalid articles (articles that cannot provide the online version of the full-text content)
Inclusion Criteria	• Papers written in English language; • Availability of abstracts; • Inclusion of the most recent studies

Source: the authors themselves.

3.4 Eligibility

From the full-text selection, 101 other results were excluded. After applying the filters, taking into account 101 excluded items, 32 items were left at the end. Next, the article rating scale of Ahmed & Kassem (2018), which proposes a three-point quality evaluation step, was applied: “Y=■” (denoting “Yes” with a score of 1) for quality criteria that are fully met; “P=◘”

(denoting "Partially" with a score of 0.5) for quality criteria that are partially met; and "N=□" (denoting "No" with a score of 0) for quality criteria not met, as shown in Table 3. The final set of articles selected for the study included articles that had at least one "Yes" and no more than one "No".

Table 3 - Quality criteria of the selected articles

References	Contribution	Theory	Methodology	Analysis	Score	%
(Awwad et al., 2022)	◘	◘	■	■	3	75%
(Phang et al., 2020)	◘	■	◘	■	3	75%
(Mehdipoor et al., 2022)	■	◘	■	■	3.5	88%
(Liu et al., 2021)	■	◘	■	■	3.5	88%
(Aziz et al., 2022)	■	■	■	■	4	100%
(Olawumi et al., 2019)	■	■	■	■	4	100%
(Brito et al., 2021)	■	◘	■	■	3.5	88%
(Chegu Badrinath et al., 2019)	■	■	■	■	4	100%
(Huang et al., 2022)	■	◘	■	■	3.5	88%
(Han et al., 2018)	■	◘	■	■	3.5	88%
(Chan et al., 2019)	■	◘	■	■	3.5	88%
(Dao et al., 2021)	■	■	■	■	4	100%
(Patel et al., 2021)	■	■	■	■	4	100%
(Chen et al., 2019)	◘	◘	■	■	3	75%
(Alqahtani & Rajkhan, 2020)	■	■	■	■	4	100%
(Dakhil et al., 2019)	◘	◘	■	■	3	75%
(Olugboyega et al., 2021)	■	◘	■	■	3.5	88%
(Abuelmaatti et al., 2018)	■	■	■	■	4	100%
(Gudiene et al., 2014)	■	■	■	■	4	100%
(Malik et al., 2021)	■	◘	■	■	3.5	88%
(Tsai et al., 2014)	■	■	■	■	4	100%
(Khodabakhshian et al., 2021)	■	■	■	■	4	100%
(Al-Ashmori et al., 2022)	■	□	■	■	3	75%
(Zhang et al., 2022)	■	■	■	■	4	100%
(Mangla et al., 2016)	◘	◘	■	■	3	75%
(Olanrewaju et al., 2021)	◘	◘	■	■	3.5	88%
(Maghsoodi et al., 2018)	■	■	■	■	4	100%
(Liu et al., 2019)	■	■	■	■	4	100%
(Gavali et al., 2020)	■	◘	■	■	3.5	88%
(Arrotéia et al., 2022)	■	■	■	■	4	100%
(Tan et al., 2022)	■	◘	■	■	3.5	88%
(Evans et al., 2020)	■	◘	■	■	3.5	88%

Source: the authors themselves.

3.5 Inclusion

The fourth and final step in the PRISMA methodology, taking into account their inclusion in the systematic review, was to select the articles in which CSFs and benefits for BIM implementation were identified.

3.6 Differences in CSFs and benefits

Although BIM methodology is a well-covered research topic, several studies have been conducted from different perspectives, highlighting the benefits of BIM implementation by some authors (Tan et al., 2022), where productivity and efficiency improvement are emphasized. Another view of these works relates to adopting CSFs for different BIM perspectives (Al-Ashmori et al., 2022).

3.7 Interviews with public sector experts

The data collected and related information can be obtained from experts with knowledge and experience in implementing BIM (e.g., researchers and personnel from the industrial sector). In this sense, a questionnaire was developed (https://docs.google.com/forms/d/1UWTRUV8EdEqf9kTzjMBBMhdGU_yowlRmgZ_WMiuLbZ8/edit), taking into account a 7-point Likert scale to identify the importance of each critical success factor and benefits. Respondents were asked to indicate the level of importance of each CSF and benefits considering adjustments in construction projects and BIM implementation. The following scales were considered: 1 = not at all important, 2 = not at all important, 3 = just important, 4 = neutral, 5 = moderately important, 6 = very important, and 7 = extremely important.

For this survey, the accumulated experience in working with BIM was taken into account as a scale from 1 to 5 as follows: 1 for respondents with up to 0 years of experience, 2 for professionals with less than 5 years of experience, 3 for those with experience between 5 and 10 years and 4 for those with more than 10 years of experience. Most experts claim to have less than 5 years of experience, equivalent to 60%, and the others have between 5 and 10 years of experience, equal to 40%, working with BIM. In this interview, the respondents were asked to rank the CSFs and benefits in order of importance according to the scale provided. Finally, different MCDMs are used to normalize, evaluate and aggregate the results and produce final scores for the various alternatives.

The reliability of the measuring instruments was determined by Cronbach's alpha coefficient, using SPSS software version 20, with an analysis to increase reliability. A questionnaire with 31 questions was administered in one section considering benefits and another with 42 CSF, as shown in Table 4.

Table 4 - Reliability statistics

	Cronbach's alpha	No. of elements
Q1 (benefits)	0.727	31
Q1 (CSFs)	0.958	42

Source: the authors themselves.

The analysis of the internal consistency of the questionnaires was performed using Cronbach's alpha coefficient, whose value was 0.727 and 0.958, which was acceptable in both cases.

3.8 MCDM methods

In the present study, we use the programming software R (Team, 2012) to apply FVIKOR and FTOPSIS using the R package MCDM and the Fuzzy AHP Method(Ceballos Martín, 2016) using an Excel spreadsheet. The software reduces manual calculations and therefore eliminates the potential for error.

3.9 Fuzzy AHP (FAHP)

AHP is a decision-support MCDM tool that exploits pairwise comparisons to obtain priority scales for complex criteria and constraints based on linear algebra (Saaty, 1988). Although it has multifaceted advantages such as simplicity and flexibility (da Cruz et al., 2022), the AHP can only consider a limited number of criteria and alternatives (Tan et al., 2022). The AHP has relatively stringent requirements for independence among criteria, and its results are heavily conditioned on pairwise comparisons (Jalilzadehazhari et al., 2019).

In the classic AHP, a nine-point scale (defined as the intensity of importance shown in Table 4) is the fundamental scale used in the paired comparison (Saaty, 1988). Although this scale is simple and easy to use, it does not consider the uncertainty associated with mapping a person's perception or judgment of a given value. However, in the Fuzzy Analytic Hierarchy Process (FAHP)(Agápito et al., 2019), according to this nine-point scale, five triangular fuzzy numbers $(\tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9})$ with the corresponding membership functions defined in Table 4 are used both to indicate the relative strength of each pair of elements in the same hierarchy and to establish the fuzzy decision matrix for the performance evaluation.

Table 5 - Definition and membership function of the fuzzy scale (Ayağ, 2005)

Intensity of Importance	Fuzzy number	Definition	Member Function
1	$\tilde{1}$	Equal importance (EI)	(1, 1, 2)
3	$\tilde{3}$	Moderate importance (MI)	(2, 3, 4)
5	$\tilde{5}$	Strong Importance (YES)	(4, 5, 6)
7	$\tilde{7}$	Very important (VSI)	(6, 7, 8)
9	$\tilde{9}$	Extremely important (EMI)	(8, 9, 10)

Source: the authors themselves.

This study uses the FAHP method proposed by (Ayağ, 2005) and is used to determine the weights of the evaluation criteria. The computational procedure of the method is described as follows:

(1) Compare the performance score. Triangular fuzzy numbers are used to indicate the relative strength of each pair of elements in the same hierarchy.

(2) Construct the fuzzy comparison matrix. The fuzzy judgment matrix $\tilde{A}$ is constructed using triangular fuzzy numbers according to Equation 1:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix} \tag{1}$$

(3) Solve for the fuzzy eigenvalue. A fuzzy eigenvalue, $\tilde{\lambda}$, is a fuzzy number solution to Equation 2:

$$\tilde{A}\tilde{x} = \tilde{\lambda}\tilde{x} \tag{2}$$

Where $\tilde{\lambda}_{max}$ is the largest eigenvalue $\tilde{A}$ and $\tilde{x}$ is non-zero and of dimension $n \times 1$, fuzzy vector containing fuzzy number $\tilde{x}_i$. To perform fuzzy multiplications and additions using interval and cut-off arithmetic α, the equation $\tilde{A}\tilde{x} = \tilde{\lambda}\tilde{x}$ is equivalent to Equations 3 and 4:

$$[a_{i1l}^{\alpha}x_{1l}^{\alpha}, a_{i1u}^{\alpha}x_{1u}^{\alpha}] \oplus \cdots \oplus [a_{inl}^{\alpha}x_{nl}^{\alpha}, a_{inu}^{\alpha}x_{nu}^{\alpha}] = [\lambda x_{il}^{\alpha}, \lambda x_{iu}^{\alpha}] \tag{3}$$

where:

$$\tilde{A} = [\tilde{a}_{ij}], \tilde{x}^t = (\tilde{x}_{1,\dots,}\tilde{x}_n),$$
$$\tilde{a}_{ij}^{\alpha} = [a_{ijl}^{\alpha}, a_{iju}^{\alpha}], \tilde{x}_i^{\alpha} = [x_{il}^{\alpha}, x_{iu}^{\alpha}], \tilde{\lambda}^{\alpha} = [\lambda_l^{\alpha}, \lambda_u^{\alpha}] \tag{4}$$

for $0 < \alpha \leq 1$ and all i, j, where $i = 1,2, \cdots, n; j = 1,2, \cdots, n.$

The cut-off α is known to incorporate the confidence of the experts or decision maker(s) about their preference. The degree of satisfaction for the judgment matrix $\tilde{A}$ is estimated by the optimism index μ. A higher value of the index μ indicates a higher degree of optimism. The optimism index is a convex linear combination defined by Equation 5 (Lee et al., 1999)

$$\tilde{a}_{ij}^{\alpha} = \mu a_{iju}^{\alpha} + (1-\mu)a_{ijl}^{\alpha}, \quad \forall\, \mu \in [0,1] \tag{5}$$

When α is fixed, the following matrix can be obtained after setting the optimism index, μ, to estimate the degree of satisfaction, as indicated in Equation 6, where the eigenvector is calculated by fixing the value μ and identifying the maximum eigenvalue.

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12}^{\alpha} & \cdots & \tilde{a}_{1n}^{\alpha} \\ \tilde{a}_{21}^{\alpha} & 1 & \cdots & \tilde{a}_{2n}^{\alpha} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{a}_{n1}^{\alpha} & \tilde{a}_{n2}^{\alpha} & \cdots & 1 \end{bmatrix} \tag{6}$$

(4) Calculate the consistency ratio. To ensure the consistency of the subjective perception and the accuracy of the comparison weights, the consistency ratio (CR must be less than or equal to 0.10 for an acceptable comparison) is calculated according to Equation 7:

$$CR = CI/RI, \text{ where } CI = (\lambda_{max} - n)/(n-1) \tag{7}$$

(5) Priority Aggregation. The final step in deriving the criteria weights is to aggregate the local priorities obtained at different levels of the decision hierarchy into global composite priorities.

For the application of this methodology, it is necessary that both criteria and alternatives can be structured hierarchically so that the first level of the hierarchy corresponds to the general objective of the problem, the second to the criteria, and the third to the alternatives (Marins, 2009). According to (Wernke et al., 2001), hierarchical ranking allows the decision maker to have a "view of the system as a whole and its components, as well as the interactions of these components and their impacts on the system". Thus, the use of FAHP approach provides the decision-maker with a structured view of the problem and at the same time allows to account for uncertainties in the judgements from experts.

Some researches combine FAHP, FTOPSIS, and FVIKOR methods for ranking possible alternatives since AHP can systematically weight decision criteria. In contrast, FTOPSIS and FVIKOR methods can order alternatives according to the actual situation (Patil et al., 2014). From the literature review, it was observed that three papers integrate FAHP, FTOPSIS, and FVIKOR. Undoubtedly, the FAHP-FTOPSIS-FVIKOR combination can help the decision-maker build a solid basis for evaluation. However, the existence of fuzzy information can have an imperceptible impact on accuracy, which leaves room for future improvements (Lee et al., 2019).

3.10 Fuzzy TOPSIS (FTOPSIS)

MCDM problems are those characterized by multiple conflicting criteria (attributes). Created in 1960 (Zadeh, 1965), the concept of fuzzy sets is commonly used by researchers in studies involving subjective value judgments regarding the degree of satisfaction of each of the options concerning each criterion, as well as their relative importance among the criteria themselves (Buede et al., 1995).

Appearing in 1980 (Hwang et al., 1981), the TOPSIS technique normalizes the performance scores on each criterion. Then it calculates the Euclidean distance of an alternative from the ideal and negative ideal solutions. The preferred alternative is the one that is both at the minimum distance from the ideal and at the maximum distance of the negative ideal (Buede et al., 1995). Thus, the data used in the TOPSIS technique depends on real-life situations according to the perceptions of each expert, which in turn implies preferences that cannot be estimated with an exact number (Hapsari et al., 2022).

Complementarily, in practical studies, such as (Mahpour, 2018), these techniques, when combined, allow the reduction of uncertainties concerning the experts' evaluations and simplify the way of presenting the opinions about a given theme, prioritizing the most important items in the form of ranking. In the FTOPSIS method, the scores of the alternatives and the weight of the decision criteria are defined as linguistic variables that are distinguished from one another through ranges of gradations (Lima Junior et al., 2015).

Considering one of the advantages of the TOPSIS and FTOPSIS approaches over other types of comparative approaches, such as AHP (Analytic Hierarchy Process), ANP (Analytic Network Process), FAHP, and FANP, the TOPSIS and FTOPSIS approaches allow the use of an unlimited amount of criteria for evaluating an unlimited amount of alternatives(Lima Junior et al., 2015). In addition, FTOPSIS requires less judgment than comparative techniques, fuzzy inference systems, and artificial neural networks, thus contributing to faster decision-making (Amaro et al., 2015).

The answers obtained via the questionnaire available on Google Forms were consolidated in a spreadsheet in Microsoft Excel format, where it was possible to perform the data analysis. Following the steps of (Chen, 2000), the FTOPSIS approach was applied to the obtained data. A triangular function was assigned to assign the scores on the fuzzy scale in relation to the evaluations made by the respondents, where three numbers represent each score. Tables 6 and 7 illustrate the scores assigned in this case.

Table 6 - Triangular Fuzzy Scale Scores

Score	Triangular Fuzzy Scale		
Not important at all (WP1)	0	0	0.1
Low importance (WP2)	0	0.1	0.3
Slightly important (PT3)	0.1	0.3	0.5
Neutral (PT4)	0.3	0.5	0.7
Moderately important (WP5)	0.5	0.7	0.9
Very important (WP6)	0.7	0.9	1
Extremely important (PT7)	0.9	1	1

Source: the authors themselves.

Table 7 - Triangular fuzzy scale for the levels of experience

Experience Level	Triangular Fuzzy Scale		
Level 1 (L1)	0.00	0.00	0.50
Level 2 (L2)	0.00	0.50	0.75
Level 3 (L3)	0.50	0.75	1.00
Level 4 (L4)	0.75	1.00	1.00

Source: the authors themselves.

The justificative for using the FTOPSIS approach is based on the diversity of the respondents' profiles since they come from different backgrounds, have diverse technical backgrounds, have specific professional experiences, and are from various sectors of activity (corresponding to the academic sector and the industry in which they work), which carries over a heterogeneity bias regarding the sample of respondents analyzed in this research.

Thus, as recommended by (Chen, 2000), after the data were treated utilizing the triangular fuzzy scale, the due calculations were performed as described in the following steps:

Step 1: Structuring the matrix with the obtained values (informed by the respondents) for each of the variables (Equations 8 and 9) and the matrix with the experience levels (reported by the respondents, as indicated in Equation 10),

$$\tilde{G} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \tilde{x}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \tilde{x}_{mn} \end{bmatrix} \tag{8}$$

$$\tilde{x}_{ij} = [a_{ij} \quad b_{ij} \quad c_{ij}] \tag{9}$$

$$\tilde{E} = [\widetilde{w}_1, \widetilde{w}_2, \dots, \widetilde{w}_3];\ \widetilde{w}_j = [w_1 \quad w_2 \quad w_3] \tag{10}$$

Step 2: Normalization of the matrix of values obtained for the variables (Equation 8) to obtain the matrix of scores (Equation 11). As in the present study, the analysis focuses on identifying the CSFs and benefits for BIM implementation as cited earlier; thus, the values can be normalized by applying the relationship described in Equations 11 and 12.

$$\tilde{R} = \left[\tilde{r}_{ij}\right]_{mxn} \tag{11}$$

$$\tilde{r}_{ij} = \left[\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right] \; for\ each\ C_j^* = \max(i)\, c_{ij} \tag{12}$$

Step 3: Based on the weightings performed between the values obtained for the variables' answers and the respondents' experience levels, it is necessary to generate a new matrix established by the product/multiplication between the fuzzy values obtained for the variables' answers in the normalized form and the respondents' fuzzy experience levels also in the normalized form, as indicated in Equation 13.

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{mxn} \rightarrow i = 1,2,\dots,m; j = 1,2,\dots,n\ for\ each\ \tilde{v}_{ij} = \tilde{r}_{ij}(.)\tilde{w}_j \tag{13}$$

Step 4: The obtained weighted and normalized fuzzy matrix (Equation 13) calculates the distance between each of the elements of the positive and negative ideal solutions, according to Equation 14. Additionally, the vectors referring to the positive and negative ideal solution are presented in Equations 15 and 16.

$$D(\tilde{m},\tilde{n}) = \sqrt{\frac{1}{3}\left[(m_1 - n_1)^2 + (m_2 - n_2)^2 + (m_3 - n_3)^2\right]} \tag{14}$$

$$A^* = [\tilde{v}_1^*, \tilde{v}_2^*, \tilde{v}_3^*]\ where\ \tilde{v}_j^* = [1,1,1] \tag{15}$$

$$A^- = [\tilde{v}_1^*, \tilde{v}_2^*, \tilde{v}_3^*]\ where\ \tilde{v}_j^* = [0,0,0] \tag{16}$$

Step 5: The calculation of the total distance referring to each of the alternatives to the ideal solutions (positive and negative) can be performed by summing the partial distances found in the previous step based on the application of Equations 17 and 18.

$$d_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^*) \tag{17}$$

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-) \tag{18}$$

Step 6: Finally, the Coefficient of Closeness (called CCi) can be calculated for each variable analyzed by applying Equation 19. In this case, the variables ("CSFs") are ordered in descending order. Therefore, those among the first in the ranking will be considered the main ones evaluated by the specialists.

$$CC_i = \frac{d_i^-}{(d_i^* + d_i^-)} \tag{19}$$

3.11 Fuzzy VIKOR (FVIKOR)

The VIKOR approach (Opricovic, 2011) explicitly references the Lp metric (Yu, 1973) and has been viewed as one of the best methods within MCDM for solving discrete decision problems that have non-measurable and conflicting criteria. The VIKOR method introduces a ranking index based on a specific measure of "closeness" to the optimal solution and proposes a compromise solution with an advantage rate. The fuzzy VIKOR method was developed to solve problems in a fuzzy environment, where both criteria and weights can be fuzzy sets. Triangular fuzzy numbers are used to deal with imprecise numerical quantities, one of their main advantages is their ability to obtain a solution with the highest utility trade-off (de Paula Vidal, Caiado, Scavarda, Ivson, et al., 2022). Thus, as there are explicit measurements for an acceptable advantage and for stability, FVIKOR provides a very robust decision-making approach under uncertainty. Table 8 illustrates the scores assigned in this case.

Table 8 - Triangular fuzzy scale score

Score	Triangular Fuzzy Scale		
Not important at all (WP1)	0	0	0.1
Low importance (WP2)	0	0.1	0.3
Slightly important (PT3)	0.1	0.3	0.5
Neutral (PT4)	0.3	0.5	0.7
Moderately important (WP5)	0.5	0.7	0.9
Very important (WP6)	0.7	0.9	1
Extremely important (PT7)	0.9	1	1

Source: the authors themselves.

As presented in the previous section, the respondents were grouped into experience levels. Table 9 shows the triangular fuzzy scale for the levels mentioned.

Table 9 - Fuzzy Scale of Experience Level

Experience Level	Triangular Fuzzy Scale		
Level 1 (L1)	0.00	0.00	0.50
Level 2 (L2)	0.00	0.50	0.75
Level 3 (L3)	0.50	0.75	1.00
Level 4 (L4)	0.75	1.00	1.00

Source: the authors themselves.

Extending the method to FVIKOR can help in situations with uncertain conditions (Opricovic, 2011). O procedimento passo a passo do método FVIKOR é descrito abaixo:
Step 1: Determine the ideal $\tilde{f}_i^* = (l_i^*,\ m_i^*,\ r_i^*)$ and the nadir $\tilde{f}_i^0 = (l_i^0,\ m_i^0,\ r_i^0)$ values of all criterion functions, $i = 1,2,\ldots,\mathrm{n}$ as indicated in Equations 20 and 21

$$\tilde{f}_i^* = \mathrm{M}A_j X \tilde{f}_{ij}, \tilde{f}_i^0 = \mathrm{M}I_j X \tilde{f}_{ij} \qquad \text{for} \quad i \in I^b \tag{20}$$

$$\tilde{f}_i^* = \mathrm{M}I_j X \tilde{f}_{ij}, \tilde{f}_i^0 = \mathrm{M}A_j X \tilde{f}_{ij} \qquad \text{for} \quad i \in I^c \tag{21}$$

Step 2: Compute normalized fuzzy difference $\tilde{d}_{ij}$, j =1,.., J $i = 1,2,..,n$, as indicated by Equations 22 and 23:

$$\tilde{d}_{ij} = \frac{(\tilde{f}_i^* \ominus \tilde{f}_{ij})}{(r_i^* - l_i^0)} \qquad \text{for } i \in I^b \tag{22}$$

$$\tilde{d}_{ij} = \frac{(\tilde{f}_{ij} \ominus \tilde{f}_i^*)}{(r_i^0 - l_i^*} \qquad \text{for } i \in I^c \tag{23}$$

Step 3: Compute $\tilde{S}_j = (S_j^l, S_j^m, S_j^r)$ and $\tilde{R}_i^* = (R_j^l, R_j^m, R_j^r)$, $j = 1, 2, \ldots, J$ by the relations, according to Equations 25 and 26:

$$\tilde{S}_j = \textstyle\sum_{i=1}^n \oplus(\widetilde{w}_j \otimes \tilde{d}_{ij}) \tag{24}$$

$$\tilde{R}_j = \underset{i}{\mathrm{MAX}}(\widetilde{w}_j \otimes \tilde{d}_{ij}) \tag{25}$$

Where $\tilde{S}$ is a fuzzy weighted sum, $\tilde{R}$ is a fuzzy operator MAX (To express an imprecise value, as “about m”(“approximately m”), the triangular fuzzy number (TFN) $\tilde{N} = (l, m, r)$ is used, associated with the membership triangular function defined as follows:

$$\mu_{\tilde{N}}(x) = \begin{Bmatrix} \frac{(x-l)}{(m-l)}, & x \ll m \\ \frac{(r-x)}{(r-m)}, & x \gg m \\ 0, & x \notin [l, r] \end{Bmatrix}$$

The membership function $\mu(x)$ denotes the degree of truth that the fuzzy value is equal to x within the real interval $[l, r]$. The fuzzy number $\widetilde{N}$ has the core m with $\mu(m) = 1$, and the support $[l, r]$), $\widetilde{w}_j$ are the weights of criteria, expressing the DM’s preference as the relative importance of the criteria.

Step 4: Compute the values $\tilde{Q}_j = (\tilde{Q}_j^l, \tilde{Q}_j^m, \tilde{Q}_j^r)$, $j = 1, 2, \ldots, J$ by the relation, as indicated in Equation 27:

$$\tilde{Q}_j = \frac{v(\tilde{S}_j \ominus \tilde{S}^*)}{(S^{or} - S^{*l})} \oplus \frac{(1-v)(\tilde{R}_j - \tilde{R}^*)}{(R^{or} - R^{*l})} \tag{26}$$

where: $\tilde{S}^* = \underset{j}{\mathrm{MIN}}\, \tilde{S}_j$, $S^{or} = max_j S_j^r$, $\tilde{R}^* = \underset{j}{\mathrm{MIN}}\, \tilde{R}_j$, $R^{or} = max_j R_j^r$, and v is introduced as a weight for the strategy of "the majority of criteria" (or "the maximum group utility"), whereas $1 - v$ is the weight of the individual regret. These strategies could be compromised by $v = 0.5$, and here v is modified as $v = (n+1)/2n$ (from $v + 0.5(n-1)/n = 1$) since the criterion (1 from n) related to R is included in S, too. The best values of S and R are denoted by $\tilde{S}^*$and $\tilde{R}^*$ respectively.

Step 5: "Core" ranking. Rank the alternatives by sorting the core values $Q_j^m, j = 1, 2, \ldots, J$ in decreasing order. The obtained ordering is denoted by $\{A\}_{Q^m}$

Step 6: Fuzzy ranking

The jth ranking position in $\{A\}_{Q^m}$ of an alternative $A^{(i)}$, $j = 1, 2, \ldots, J$ is confirmed if $\underset{k \epsilon J^i}{\mathrm{MIN}}\, \tilde{Q}^{(k)} = \tilde{Q}^{(j)}$ where $J^j = \{j, j+1, \ldots, J\}$ and $\tilde{Q}^k$ is the fuzzy merit of the alternative A^k at the kth position in $\{A\}_{Q^m}$. Confirmed ordering represents "exact".

Fuzzy ranking $\{A\}_{\tilde{Q}}$, although the set $\{A\}_{\tilde{Q}}$ could not be complete ordering (it may be partially ranking).

Step 7: Defuzzification of $\tilde{S}_j, \tilde{R}_j, \tilde{Q}_j, j = 1,2, \ldots, J$ by the relations indicated in Equation 28.

$$Crisp(\tilde{N}) = \frac{(2m+l+r)}{4} \tag{27}$$

Here the defuzzification method "2nd weighted mean" is applied to convert a fuzzy number into a crisp score

Step 8: Rank the alternatives, sorting by the crisp values S, R, and Q in decreasing order. The results are three ranking lists $\{A\}_S$, $\{A\}_R$, $\{A\}_Q$.

Step 9: Propose as a compromise solution the alternative ($A^{(1)}$) which is the best ranked by the measure $Q(in\ \{A\}_Q)$if the following two conditions are satisfied:

C1:"Acceptable Advantage": $Adv \geq DQ$, where: $Adv = \frac{[Q(A^{(2)}) - Q(A^{(1)})]}{[Q(A^{(J)}) - Q(A^{(1)})]}$ is the advantage rate of the alternative $A^{(1)}$ ranked first, $A^{(2)}$ is the alternative with the second position in $\{A\}_Q$, and the threshold $DQ = \frac{1}{(J-1)}$.

C2: "Acceptable Stability in decision making": The alternative A^1 must also be the best ranked by S or/and R. If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

Alternatives $A^{(1)}$ and $A^{(2)}$ if only the condition C2 is not satisfied, or

Alternatives $A^{(1)}$, $A^{(2)}$,..., $A^{(M)}$ if the condition C1 is not satisfied; $A^{(M)}$ is determined by the relation $Q(A^M) - Q(A^1)$ <DQ for maximum M (the positions of these alternatives are "in closeness").

3.12 Model Validation

The amounts of change in the use of MCDM models are visible in the traditional change framework. Still, more research is needed to describe the link between patterns in different classes with their corresponding processes (Zaehringer et al., 2015). Intensity analysis is a complex method that allows researchers to conduct more detailed research. This approach allows one to demonstrate the interactions between categorical factors and quantify the degree and intensity where changes are not uniform at different levels of detail (Enaruvbe et al., 2015).

In this research, two indexes of percent change (Equation.29) and intensity of change (Equation.30) were used to evaluate and compare the results of the models with each other (Ameri et al., 2018):

$$\Delta P = \frac{N - N_{constant}}{N} \times 100 \tag{28}$$

$$\Delta I = \frac{\sum_{i=1}^{N} \frac{rank\ i\ (r1)}{rank\ i\ (r2)}}{N} \tag{29}$$

Where ΔP is the percentage of change, N is the number of alternatives, and $N_{constant}$ is the number of alternatives with the same rank. ΔI is the intensity of changes, $rank\ i\ (r1)$ is the rank of alternative in the first method, $rank\ i\ (r2)$is the rank of alternative in the second method.

4. RESULTS AND DISCUSSION

4.1 Identifying critical success factors for BIM implementation

This section briefly presents the results of identifying CSFs for BIM implementation in public works. The CSFs obtained about BIM perspectives are used to evaluate the relative weights of the BIM perspectives. Then, FTOPSIS and FVIKOR are used to select the CSFs for BIM implementation.

4.2 FAHP results

AHP was used to calculate the weights of the initially listed levels of expertise (N1, N2, N3, and N4) according to Tables 6 and 8 (from the previous section) for each expert selected in this study. A comparison was performed between the experts concerning the level of expertise. A value of 4 of the experts' level of knowledge was taken for each pairwise comparison in matrix format, as shown in Table 10.

Table 10 - Comparison in pairs of experts according to the level of specialization

CRI		E1			E2			E3			E4			E5	
E1	1.00	1.00	1.00	0	0.5	0.75	0.5	0.75	1	0.75	1	1	0.75	1	1
E2	1.33	2.00	1.00	1.00	1.00	1.00	0.5	0.75	1	0.75	1	1	0.75	1	1
E3	1.00	1.33	2.00	1.00	1.00	1.33	1.00	1.00	1.00	0.75	1	1	0.75	1	1
E4	1.00	1.00	1.33	1.00	1.00	1.33	1.00	1.00	1.33	1.00	1.00	1.00	0.75	1	1
E5	1.00	1.00	1.33	1.00	1.00	1.33	1.00	1.00	1.33	1.00	1.00	1.33	1.00	1.00	1.00

Source: the authors themselves.

In this step, the geometric mean of the fuzzy comparison value($\tilde{r}_1$) was calculated and proceeded to calculate the fuzzy weights for each expert, where the set of fuzzy weights is essential not only for fairness and straightforward interpretation but also to arrive at a unique solution for some methods, as shown in Table 11.

Table 11 - Geometric mean of the fuzzy comparison value ($\tilde{r}_1$) and Fuzzy Weight Distribution

Fuzzy geometric mean				(Fuzzy weight)				
CRI		r_i			Wi			**Rank**
E1	0.000	0.869	5	0.000	0.096	0.138	0.000	5
E2	0.869	1.060	4	0.076	0.118	0.144	0.076	4
E3	0.921	1.042	2	0.081	0.116	0.166	0.081	2
E4	0.960	1.000	3	0.084	0.111	0.163	0.084	3
E5	1.000	1.000	1	0.088	0.111	0.170	0.088	1
Total	3.750	4.971	5.420					
P (-1)	0.267	0.201	0.185					
INCR	0.088	0.111	0.144					

Source: the authors themselves.

As a result of the above, the order of importance of the experts is clearly shown, considering the pairwise comparisons using a preference scale, which will contribute to the selection of CSFs and the benefits of implementing BIM in public works.

4.3 FTOPSIS and FVIKOR results

After obtaining the weightings of each researcher, it was built a matrix where the experts are related according to the benefits that drive the implementation of BIM in public works, and another intended to identify the degree of importance of the factors for the implementation of BIM from the questionnaire applied as mentioned above. The research tries to estimate the best alternative (benefits) and the importance of the factors for implementing BIM. The prioritization and selection of the most feasible alternatives are performed using the FVIKOR and FTOPSIS methods, with the R Studio tool using the FuzzyMCDM package. The data for FVIKOR and FTOPSIS were collected from the processing of the interviews (questionnaires), in which the experts ranked the main advantages and factors on a Likert scale (1-7), as the results are shown in Tables 12 and 13.

Table 12 - CSF Evaluation by respondent

	E1			E2			E3			E4			E5		
CSF1	0.7	0.9	1	0.9	1	1	0.9	1	1	0.1	0.3	0.5	0.9	1	1
CSF2	0.5	0.7	0.9	0.5	0.7	0.9	0.5	0.7	0.9	0.5	0.7	0.9	0	0.1	0.3
CSF3	0.7	0.9	1	0.5	0.7	0.9	0.9	1	1	0.5	0.7	0.9	0.7	0.9	1
CSF4	0.9	1	1	0.7	0.9	1	0.9	1	1	0.5	0.7	0.9	0.7	0.9	1
CSF5	0.7	0.9	1	0.5	0.7	0.9	0.9	1	1	0.5	0.7	0.9	0.7	0.9	1
CSF6	0.5	0.7	0.9	0.7	0.9	1	0.7	0.9	1	0.5	0.7	0.9	0.7	0.9	1
CSF7	0.5	0.7	0.9	0.9	1	1	0.9	1	1	0.5	0.7	0.9	0.9	1	1
CSF8	0.9	1	1	0.7	0.9	1	0.9	1	1	0.1	0.3	0.5	0.9	1	1
CSF9	0.5	0.7	0.9	0.7	0.9	1	0.9	1	1	0.1	0.3	0.5	0.7	0.9	1
CSF10	0.9	1	1	0.7	0.9	1	0.7	0.9	1	0.5	0.7	0.9	0.3	0.5	0.7
.....	......			.....			.....			......			.....		

Source: the authors themselves.

Table 13 - Benefits evaluation by respondent

	E1			E2			E3			E4			E5		
B1	0.9	1	1	0.7	0.9	1	0.7	0.9	1	0.7	0.9	1	0.5	0.7	0.9
B2	0.7	0.9	1	0.7	0.9	1	0.7	0.9	1	0.7	0.9	1	0.7	0.9	1
B3	0.5	0.7	0.9	0.9	1	1	0.9	1	1	0.7	0.9	1	0.5	0.7	0.9
B4	0.5	0.7	0.9	0.5	0.7	0.9	0.5	0.7	0.9	0.7	0.9	1	0.5	0.7	0.9
B5	0.3	0.5	0.7	0	0.1	0.3	0.5	0.7	0.9	0.7	0.9	1	0.5	0.7	0.9
B6	0.7	0.9	1	0.9	1	1	0.7	0.9	1	0.9	1	1	0.5	0.7	0.9
B7	0.7	0.9	1	0.5	0.7	0.9	0.5	0.7	0.9	0.9	1	1	0.5	0.7	0.9
B8	0.9	1	1	0.7	0.9	1	0.5	0.7	0.9	0.7	0.9	1	0	0.1	0.3
B9	0.9	1	1	0.5	0.7	0.9	0.3	0.5	0.7	0.7	0.9	1	0.7	0.9	1
B10	0.7	0.9	1	0.9	1	1	0.3	0.5	0.7	0.5	0.7	0.9	0.3	0.5	0.7
...	.....			.....			.....			.....			.....		

Source: the authors themselves.

Once the factor weights and the comparison matrix of the alternatives were obtained, the FVIKOR methodology was applied using R (FuzzyMCDM package). Tables 14 and 15 show the results of the FVIKOR analysis calculated in R.

Table 14 - Summary of CSF for FVIKOR analysis

Alternatives	Def_S	Def_R	Def_Q	Ranking
Financial support from the government to set up BIM system	0.035	0.024	0.001	1
Establishing BIM and LC standards, codes, rules and regulations	0.036	0.024	0.001	2
BIM adoption requires individual and group motivation in the organization	0.038	0.025	0.007	3
Availability of quality, schedule, and cost information during construction with BIM	0.049	0.024	0.015	4
Ensuring effective communication among project participants	0.049	0.024	0.015	5

Source: the authors themselves

In the FVIKOR application, the increasing order of rankings for the CSFs was obtained as follows: CSF37 > CSF35 > CSF12 > among others. Out of a total of 42 CSFs, 10 were identified as the most feasible and efficient CSFs for BIM implementation.

Table 15 - Summary of benefits for FVIKOR analysis

Alternatives	Def_S	Def_R	Def_Q	Ranking
BIM provides knowledge sharing between stakeholders	0.091	0.026	0.007	1
Workflow, productivity, and efficiency are affected by the transition to BIM	0.086	0.038	0.028	2
BIM technology reduces cost and time	0.096	0.038	0.038	3
Creating more efficient projects with the participation, coordination, and supervision of the stakeholders	0.104	0.045	0.061	4
Enhancing exchange of information and knowledge management	0.134	0.038	0.075	5

Source: the authors themselves.

In applying the FVIKOR method, following the ascending order, where the classifications obtained of the main benefits for implementing BIM in public works, the following result was obtained: B2 > B6 > B1> among others. Out of 31, the 10 most feasible and efficient benefits for implementing BIM in public works were identified.

In the FTOPSIS model, once the factorial weights and the alternative comparison matrix were obtained to identify the degree of importance of the factors for BIM implementation, the FTOPSIS methodology was applied using R, as shown in Table 16.

Table 16 - Summary of CSF for FTOPSIS analysis.

Alternatives	Code	R.1	R.2	R.3	Def_R	Ranking
BIM adoption requires individual and group motivation in the organization	CSF12	0.358	0.950	2.792	1.159	1
Establishing BIM and LC standards, codes, rules and regulations	CSF 35	0.324	0.941	2.647	1.122	2
Financial support from the government to set up BIM system	CSF 37	0.335	0.939	2.633	1.121	3
Availability of quality, schedule, and cost information during construction with BIM	CSF 4	0.298	0.914	2.716	1.112	4
Accuracy and reliability of documents and data	CSF 34	0.298	0.914	2.716	1.112	5

Source: the authors themselves.

In applying the FTOPSIS method, choosing an ascending order of classification for the CSF, the following structure was obtained: CSF12> CSF35> CSF37> among others, as can be seen, because the list is quite long. The 10 CSFs were identified as the most feasible and efficient for BIM implementation in public works.

Regarding the benefits of the same method, taking into account the degree of importance of the benefits for BIM implementation, the FTOPSIS approach was applied using R, as shown in Table 17.

Table 17 - Summary of benefits for FTOPSIS analysis (continue)

Alternatives	Código	R.1	R.2	R.3	Def_R	Ranking
BIM provides knowledge sharing between stakeholders	B2	0.578	0.881	1.328	0.905	1
Clash detection, integrating, coordinating and validating design	B25	0.580	0.880	1.309	0.902	2

Table 17 - Summary of benefits for FTOPSIS analysis (conslusion)

Alternatives	Código	R.1	R.2	R.3	Def_R	Ranking
Workflow, productivity, and efficiency are affected by the transition to BIM	B6	0.663	0.857	1.151	0.874	3
Reducing construction project duration	B19	0.672	0.856	1.142	0.873	4
BIM technology reduces cost and time	B1	0.552	0.829	1.125	0.854	5

Source: the authors themselves.

In applying the FTOPSIS method, following ascending order of BIM in public works, an analysis of the 10 most influential was performed, as below: B2 > B25 > B6, among others. The 10 benefits were identified as the most feasible and efficient for BIM implementation in public works.

Table 18 summarizes the results showing the top 5 CSFs by aggregating FAHP-TOPSIS and FAHP-VIKOR with the Borda method.

Table 19 does the same for the benefits identified.

Table 18 - Aggregation of the FTOPSIS and FVIKOR Rankings by the Borda Method for the CSFs

CSF	Code	Ranking FTOPSIS	Ranking FVIKOR	Ranking Borda
BIM adoption requires individual and group motivation in the organization	CSF12	1	3	1
Establishing BIM and LC standards, codes, rules and regulations	CSF35	2	2	2
Financial support from the government to set up BIM system	CSF37	3	1	3
Availability of quality, schedule, and cost information during construction with BIM	CSF4	4	4	4
Accuracy and reliability of documents and data	CSF34	5	5	5

Source: the authors themselves.

Table 19 - Aggregation of the FTOPSIS and FVIKOR Rankings by the Borda Method for the Benefits

Benefits	Code	Ranking FTOPSIS	Ranking FVIKOR	Ranking Borda
BIM provides knowledge sharing between stakeholders	B2	1	1	1
Workflow, productivity, and efficiency are affected by the transition to BIM	B6	3	2	2
BIM technology reduces cost and time	B1	5	3	3
Clash detection, integrating, coordinating and validating design	B25	2	7	4
Creating more efficient projects with the participation, coordination, and supervision of the stakeholders	B3	7	4	5

Source: the authors themselves.

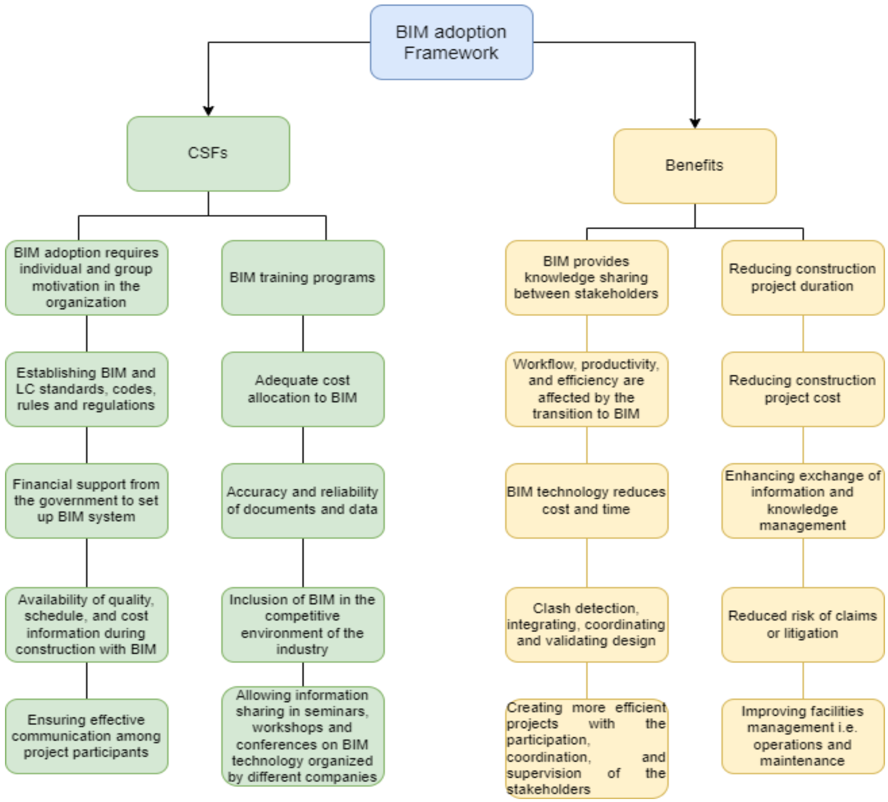

Figure 2 - Framework based on CSFs and benefits of BIM for adoption in public works.

Table 18, 19 and its relationship with Figure 2 reveal that most factors, such as CSF4, CSF34, and CSF37, maintained an attachment to the BIM process strategy, which strongly impacts the success of a complete digital transformation of processes, culture, and technology. On the other hand, CSF35 is oriented towards the legal plane, where it facilitates collaboration during the BIM process, supported by agreements and "legal and political contractual" considerations, while CSF12 being the first in the ranking, its impact is linked to the BIM people strategy, which is a challenge in the balance and strength of the digital transformation, where its basis is in people, and they are ultimately those who are at the center of this transformation.

The other section is the benefits, which highlights its incidence the B3, B6, and B25, and its strong inclination towards processes, then B1 and B2 is related to technology and people, in addition to the results of the Borda Method for the Benefits B2 is the most significant benefit. There is great dominance towards this strategy of BIM in a people perspective according to the ranking obtained, revealing that the implementation of BIM is a process of change management, where people focus attention and their competencies in view of this.

Based on the framework presented, practitioners who deal with BIM in public works can prioritize CSFs and reap the benefits. For instance, the manager of a construction project can prioritize the training of the personnel involved in BIM, and allocate costs to BIM information quality to ensure accuracy and reliability, among others CSFs, in order to facilitate obtaining benefits such as reduced project duration and costs.

4.4 Model Validation

The results of the evaluation of the methods by percent variation and intensity of variation are shown in Table 20.

Table 20 - Percentage of changes

	Percentage of Change	Intensity of change
Benefits	84	1.16
CSF	76	1.06

Source: the authors themselves.

The results in the Table indicate that the percent change is 84 (Benefits) and 76 (CSFs)

Moreover, the change intensity evaluation results showed that the Benefits evaluation model had a higher change rate of 1.16), while the CSF ranking had an intensity of change of 1.06. Thus, it can be seen that although both rankings significantly differ, the intensity of change is low.

5. CONCLUSIONS

The transformation to BIM as a new digital technology is crucial in creating and reinforcing disruptions with solid consequences for digital transformation performance. Moreover, with the developed range of digital technologies, guidelines must be established in digital transformation to implement them correctly to maximize their transformation impacts in construction. For achieving full BIM implementation, government application of BIM, as a driver for the required change in public works, is needed. Identifying CSFs has been considered important, especially when implementing BIM in public works. Therefore, this research reviewed many papers from the literature (171) to identify CSFs for BIM implementation. It can be deduced from the literature that there is a good set of CSFs for BIM implementation in public works, which has been considered as the basis for the study. In this paper, several CSFs in BIM have been identified from various previous research. Initially, a total of 42 CSFs were identified and classified into four main groups: (1) technological, (2) processes, (3) legal, and (4) people; through literature review, finally, each CSF was grouped according to the classification obtained in the selected model with higher accuracy. The AHP, TOPSIS, and VIKOR methods were used, all robust with fuzzy logic, which allows for eliminating uncertainty in the results. This study provides a list of CSFs with priority that require significant attention in implementing BIM in public works.

Additionally, each factor was grouped within the corresponding dimension perspectives of BIM. The result provides a greater understanding of selecting CSFs for BIM implementation in public works from the search for best practices. The proposed framework can be more effective and efficient than conventional approaches as it reveals the best alternatives among CSFs and benefits for BIM implementation in public works.

BIM methodology is developing rapidly, but its effective use and speed in its practical implementation are not without limitations. In this research, aiming at the selection of CSFs and benefits for BIM implementation through the proposal of a framework, several limitations are managed, of which a future study is suggested to develop a computerized knowledge-based software model for BIM implementation in public works, and one with an optimal alignment in terms of requirements and constraints based on the CSFs and the identified benefits. In addition, 42 CSFs and 31 benefits were identified for implementing BIM in public works, which can be extended and applied in future studies.

Lastly, as this work focuses on public works, the experts interviewed are from public sector or work in public construction projects. Future work could assess the CSFs and benefits from the point of view of private companies stakeholders and compare these views to identify patterns or significant disagreements.

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Author contributions: CADS: Conceptualization, Methodology, Software, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Funding Acquisition; YRV: Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Writing – Original Draft; RGGC: Validation, Resources, Writing – Review & Editing, Supervision, Project administration, Funding Acquisition; RSS: Validation, Data Curation, Writing – Review & Editing, Visualization; MC: Validation, Resources, Writing – Review & Editing, Supervision, Project administration, Funding Acquisition; ETC: Validation, Resources, Writing – Review & Editing, Supervision, Project administration, Funding Acquisition; DR: Validation, Resources, Writing – Review & Editing, Supervision, Project administration, Funding Acquisition.