

Research paper

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Analysis and prioritisation of critical delay factors in construction projects: A Colombian case

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Abstract: The factors causing delays in construction projects continue to be studied, yet Colombia's construction sector remains plagued by excessive deadlines, cost overruns, and disputes among the parties involved. This study aims to analyze and prioritize the critical factors that cause delays in construction projects. The proposed methodological framework begins with identifying delay factors from the literature review. Essential factors are determined using the Failure Mode and Effects Analysis (FMEA) technique, considering expert opinions. Then, a structural analysis of these factors is performed using the Matrix of Cross-Impact Multiplications Applied to Classification (MICMAC) technique to determine the key factors and their driver-dependent correlations. Finally, a multi-criteria analysis is conducted using the Fuzzy Analytic Hierarchy Process (FAHP) technique to establish the hierarchy of critical factors. The study found that the two most critical factors causing delays in construction projects are schedule adherence and the variation of execution times versus planned times. Additionally, the sequential integration of the three techniques allowed for effectively identifying and prioritizing critical factors, making the proposed methodological framework suitable for application in similar contexts. The results can help project managers focus on these factors, develop realistic plans, and strengthen project stakeholder management to mitigate the effects of delays in future projects.

Keywords: FMEA, MICMAC, FAHP, construction projects, influencing factors, lag factors, structural analysis

1 Introduction

Delays in construction projects are a considerable source of claims and litigation due to the extension of deadlines beyond what was initially planned. A delay in a construction project is defined as a time overrun, either beyond the date that the parties agreed upon for the delivery of the project or beyond the date that the project stakeholders consider reasonable for the delivery of the project. These delays can generate various impacts such as loss of productivity, cost overruns and disputes amongst stakeholders (Yusuwan and Adnan 2013). Identifying the critical path affected by these delays is crucial, as it directly impacts the project's completion (Palaneeswaran and Kumaraswamy 2008). Schedule delay analysis is often conducted to demonstrate the cause-effect relationships of time-related conflicts in construction projects (Arditi and Pattanakitchamroon 2006). Understanding these factors is essential to minimising negative effects and implementing the necessary measures to mitigate delays and cost overruns (Gonzalez et al. 2014).

Therefore, this study proposes an analysis of the factors that cause delays in construction projects, focusing on identifying and prioritising the critical factors. This study aims to provide insights to assist decision-makers in the planning and execution of construction projects, particularly within the Colombian context, enabling them to make informed decisions regarding time management.

Extensive research has been conducted in two main areas: studies focussed on identifying and categorising delay factors in construction projects and qualitative studies that apply methodologies for structural analysis, multi-criteria analysis and risk analysis, especially those involving expert opinions. These studies have revealed varying patterns in the factors included in each category by different authors and their respective weights in construction projects (Rudeli et al. 2018). This variability presents a challenge in identifying a single root cause but

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offers the opportunity to pinpoint a group of factors with the most significant influence on delays.

For instance, Zemra et al. (2019) concluded that owner-related causes are the most significant sources of delay, while Zidane and Andersen (2018) identified 10 universal delay factors, including design changes, payment delays, poor planning and resource shortages. Similarly, Al-Gheth and Ishak (2020) identified management and financial factors as the primary causes of delays in both the global construction sector and the United Arab Emirates. Durdyev and Hosseini (2019) highlighted the efforts in developing countries to identify delay causes, listing 10 common causes worldwide such as weather conditions, poor communication and material shortages. In Egypt, Elshaboury et al. (2021) found the financial problems of contractors and price fluctuations to be the main causes of delays. Fakunle and Fashina (2020) emphasised that delay causes vary by country and project type. Arantes and Ferreira (2020) identified six central universal factors from a literature review: inadequate planning, poor consultant performance, ineffective site management, owner influence, bureaucracy and low-quality contracts.

Despite extensive research on delay factors in construction projects in different regions of the world, such as India, Egypt and the United Arab Emirates, there is no specific attention given to the Colombian context. For example, studies by Doloi et al. (2012) in India and Elhusseiny et al. (2021) in Egypt highlight the delay factors in

those countries. This lack of specific studies for Colombia underscores the need for and contribution of our research.

Our research contributes to filling this gap by identifying critical factors in the Colombian context and proposing a methodological framework combining failure mode and effects analysis (FMEA), MICMAC and fuzzy analytical hierarchy process (FAHP) techniques. These techniques allow for the effective prioritisation of critical factors. Consequently, the results may be useful for project managers in developing realistic plans and improving stakeholder management to mitigate future delays. The structure of this document is divided into the following sections: Section 2 presents the methodology and materials used, Section 3 presents the results obtained and Section 4 outlines the main conclusions and suggests future research directions.

2 Materials and methods

This section presents the methodological framework and resources used in the research. Figure 1 shows how, through an input-process-output (IPO) approach, the three analysis techniques that led to the results were integrated.

The analysis techniques used, as well as the profile of the experts, are described in the following sections.

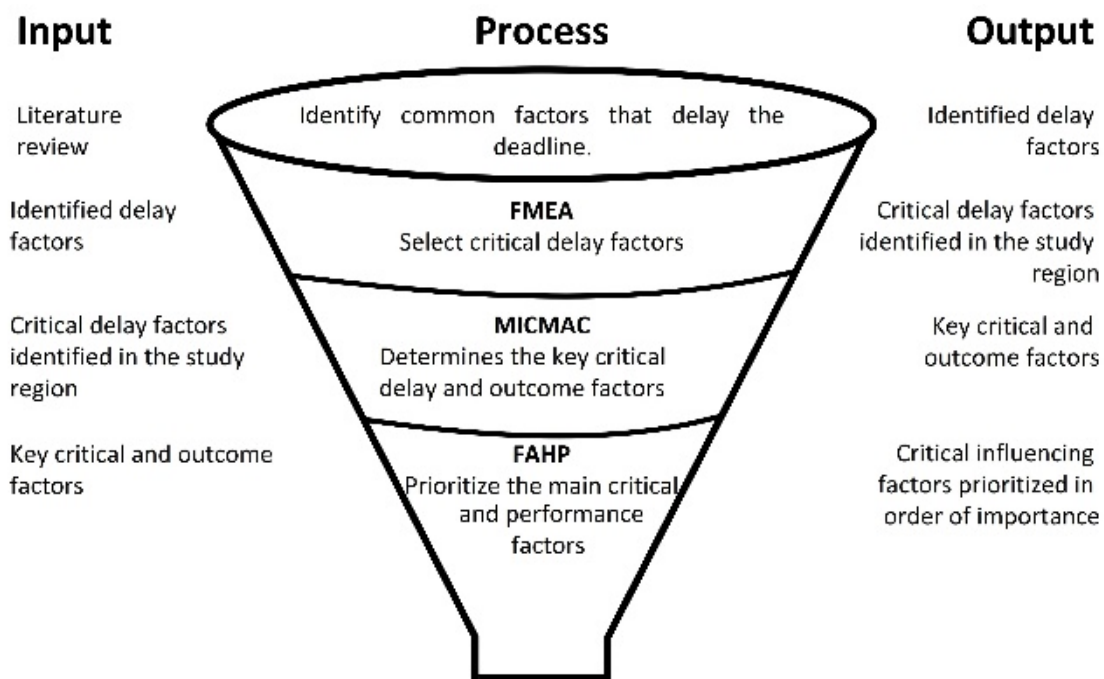


Fig. 1: Methodological framework. Source: Own 2023.

2.1 FMEA method

FMEA is, in principle, a risk assessment technique whose main interest is to highlight the critical points to eliminate them or establish a preventive system (corrective measures) to avoid their occurrence or minimise their effects (Delgado Silveira et al. 2012). This technique has been used in multiple studies in different fields: production (Santos and Cabral 2008), civil engineering (Lee and Kim 2017) and occupational health and safety (Mete 2019), amongst others. This study uses the technique to select the critical factors that generate delays in construction projects in Colombia. The procedure is summarised in the following steps:

- Step (1): Identify the critical factors that delay construction projects through a literature review combined with a field survey.
- Step (2): Categories of factors that cause delays are defined.
- Step (3): Identify the potential effects.
- Step (4): Identify the factors causing the delays.
- Step (5): The factors of occurrence (O), severity (S) and detection (D) are scored. The scores for these three factors typically range from ‘1’ to ‘10’. It is assumed that the components of the system being evaluated that have a high-risk priority number (RPN) are more critical than those with lower values (Abdelgawad and Fayek 2010). The scoring is carried out by 26 experts who participated in the study through surveys, resulting in a response rate of 73.07%, equivalent to 19 completed questionnaires.
- Step (6): The RPN is calculated by multiplying the scores of the risk factors, such as O, S and D, i.e.:

$$RPN = O * S * D$$

2.2 MICMAC method

MICMAC, a structural analysis technique used to structure ideas and as a forecasting method created by Michel Godet (1987), can be considered a qualitative approach to system dynamics (Mirakyan and De Guio 2015) and is used here to determine the key critical and outcome factors (Ocampo et al. 2022). In general, it allows the description of a system/model by filling up a matrix that is oriented vertically to describe the degree of influence and horizontally to describe the degree of dependence of each of the variables foreseen for it. The MICMAC starts with (and is adapted from) its three main steps.

- Step (1): Identifies all those variables that, in principle, can be significant for the behaviour of the system under study (Dema and Barberá 2010); in this case, they are the critical factors identified in the FMEA analysis.
- Step (2): The structural analysis matrix is constructed, which shows the direct relationships of mobility and dependence relationships between the internal variables of the system and its environment, which are also equivalent to all the critical factors. The cells store the degree of influence between each variable i and j : (0) no influence, (1) weak influence, (2) medium influence, (3) strong influence and P potential. The group of experts fill this matrix.
- Step (3): Consists of identifying the key and outcome factors in a Cartesian plane called the influence-dependence plane, as shown in Figure 2. According to the objective of the MICMAC technique, the key factors are chosen because they are the most influential and dependent, and the outcome factors are chosen because they are considered potential key factors (Barati et al. 2019). The main output of this phase is an $m \times n$ matrix that we call matrix R, where m is the number of classification types.

2.3 Fuzzy analytical hierarchy process

The FAHP is a technique that was developed to overcome the AHP developed by Saaty (1980). According to Yang and Chen (2004), the ambiguity associated with the judgement of the decision-makers with respect to numerical values has not been considered by AHP. Moreover, personal preference and judgement of the decision maker greatly affect the outcome of AHP. To overcome these problems, researchers such as Buckley 1985 and Chang 1996 modified and fuzzified Saaty’s AHP to formulate and control uncertainty. Thus, fuzzy logic combined with AHP becomes a powerful tool that is very useful for multi-criteria decision-making. It converts the problem undertaken into a hierarchical structure consisting of several defined levels, such as the objective, criteria and sub-criteria, and delivers the alternative according to their weight obtained in the form of a priority after synthesising the value judgements made (Singh and Nachtnebel 2016; Liu et al. 2020).

This study uses the geometric mean FAHP method of Buckley (1985) since the extended analysis method of Chang (1996) could not make full use of all the information in the fuzzy comparison matrix (Rashid et al. 2020; Segura Dorado et al. 2023).

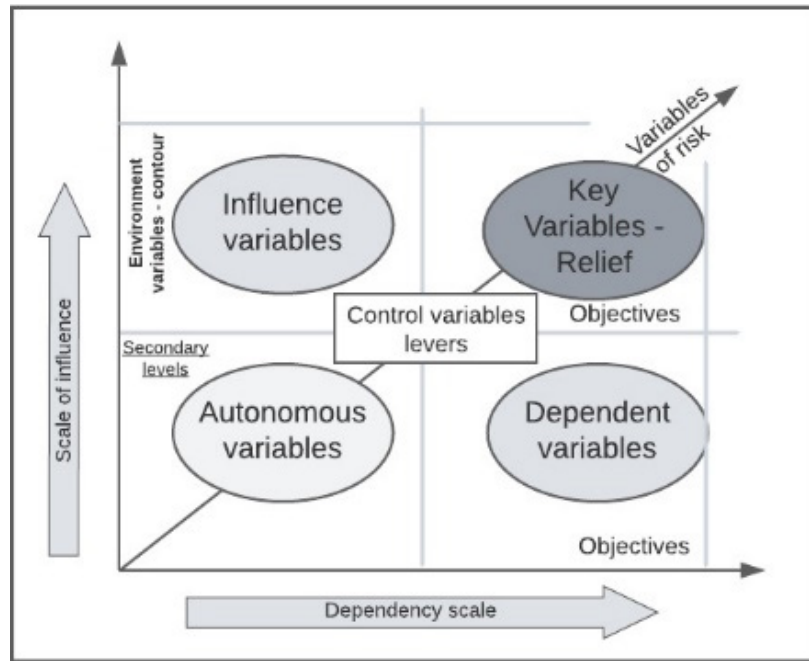


Fig. 2: Influence-dependence plane. Source: (Villacorta et al. 2014).

Before applying the FAHP method, we relied on the Analytic Hierarchy Process (AHP) method to check the consistency of the judgements made by the consulted experts. The consistency ratio (CR) was calculated as $CR = CI/RI$, where CI is the consistency index and RI is the random index, CI is defined as $CI = \frac{\lambda_{\max} - n}{n - 1}$ with $\lambda_{\max}$ is the maximum eigenvalue and n is the number of factors in the judgement matrix. Judgements are consistent if the CI value is < 0.1 (Chroust 2015; Anacona Mopan et al. 2023).

The application of the FAHP follows the following steps:

- Step (1): A hierarchical diagram is established for the problem; the top level represents the objective or goal, the intermediate level represents the criteria and the lower level represents the alternatives. In this research, there are no alternatives because the aim is to prioritise the criteria, which are the critical factors derived from the MICMAC method.
- Step (2): We scaled the data resulting from the pairwise comparison of expert judgement according to the scale of Saaty (1980) to the triangular fuzzy number scale, as shown in Table 1.

Then, the pairwise comparison matrix is constructed as follows, where d_{ij}^k indicates the k^{th} decision maker's preference of i^{th} criterion over j^{th} criterion by fuzzy triangular

Tab. 1: Fuzzy conversion scale of FAHP.

AHP preference number	AHP linguistic variables	TFNs scale	TFNs reciprocal scale
1	EI	(1,1,1)	(1,1,1)
3	MMI	(2,3,4)	(1/4, 1/3, 1/2)
5	SMI	(4,5,6)	(1/6, 1/5, 1/4)
7	VSMI	(6,7,8)	(1/8, 1/7, 1/6)
9	EMI	(9,9,9)	(1/9, 1/9, 1/9)

EI, equally important; EMI, extremely more important; FAHP, fuzzy analytical hierarchy process; MMI, moderately more important; SMI, strongly more important; TFNs, Triangular fuzzy numbers; VSMI, very strong more important.

number (l, m, u). This matrix, of size $(m \times n)$, can be represented by the following equation:

$$\begin{matrix}
 \tilde{d}_{11}^k & \tilde{d}_{12}^k & \dots & \dots & \tilde{d}_{1n}^k \\
 \tilde{d}_{21}^k & \tilde{d}_{22}^k & \dots & \dots & \tilde{d}_{2n}^k \\
 \tilde{d}_{31}^k & \tilde{d}_{32}^k & \dots & \dots & \tilde{d}_{3n}^k \\
 \vdots & \vdots & \ddots & \ddots & \vdots \\
 \tilde{d}_{n1}^k & \tilde{d}_{n2}^k & \dots & \dots & \tilde{d}_{nn}^k
 \end{matrix} \quad (1)$$

- Step (3): If the number of decision-makers is greater than 1, the preferences of each of them are averaged according to the following equation:

$$d_{ij} = l_{ij}, m_{ij}, u_{ij}$$

$$d_{ij} = \left(\min(l_{ij}^k), \text{average}(m_{ij}^k), \max(u_{ij}^k) \right) \quad (2)$$

Therefore, the pairwise comparison matrix is modified as the following matrix:

$$\tilde{A} = \begin{bmatrix} \tilde{a}_{11} & \dots & \tilde{a}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \dots & \tilde{a}_{nn} \end{bmatrix} \quad (3)$$

- Step (4): To calculate the geometric mean of the fuzzy comparison values for each criterion, the following equation provides the fuzzy geometric mean:

$$\tilde{r}_i = \left(\prod_{j=1}^n \tilde{a}_{ij} \right)^{\frac{1}{n}}, i = 1, 2, \dots, n. \quad (4)$$

- Step (5): To calculate the aggregate fuzzy weight of each criterion, the following equation provides the fuzzy weight:

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \dots \oplus \tilde{r}_n)^{-1} = lw_i, mw_i, uw_i \quad (5)$$

- Step (6): De-fuzzified the fuzzy weight, $\tilde{w}_i$, by applying the area centre method since $\tilde{w}_i$ is still a fuzzy triangular number. The calculation of de-fuzzified can be performed using the following equation:

$$M_i = \frac{lw_i + mw_i + uw_i}{3} \quad (6)$$

- Step (7): Calculate the relative weight and rank the real alternatives. Since M_i is a non-fuzzy number, it must be normalized. The relative weight N_i is calculated by dividing each M_i by the sum of all M_i values, ensuring that the sum of all N_i equals 1. This allows for the ranking of the alternatives based on their relative weights. The relative weight calculation and the alternatives' ranking are given in the equation as follows, where, $\sum_{i=1}^n N_i = 1$.

2.4 Expert profile

For the qualification of each of the factors, experts with extensive experience as owners and employees of companies in the construction sector were selected. The characteristics or requirements to be met by each participant are as follows:

- Experience: It includes management, direction and execution in all phases of construction projects, with

specific experience in the types of projects under consideration (e.g., residential, commercial and infrastructure).

- Education: It includes professionals with degrees in project management, civil engineering, industrial engineering, architecture, or related fields such as construction management and environmental engineering. This broader inclusion ensures a diverse skill set that can contribute to various aspects of project evaluation.
- Experience duration: It includes 5 years of practical experience in the construction industry, both as an owner of construction companies and as an employee. This experience must involve hands-on participation in planning, execution and project management, ensuring practical, on-the-ground expertise.
- Positions: It includes construction manager, resident architect, draftsman, equipment machinery resident, construction consultant, resident planning and programming engineer and other related roles. The list has been expanded to include specialists in sustainability, safety and technology integration.
- Certifications and professional memberships: This includes relevant certifications and memberships in professional associations related to construction project management (e.g., PMP, PMI, and AACE). This ensures experts have up-to-date knowledge of industry best practices.
- Geographical experience: Preferably, it includes experts with experience in the specific region where the projects are located. Local expertise can provide insights into regional regulations, environmental considerations and community dynamics affecting project success.
- Ongoing professional development: A requirement for experts to demonstrate continuous professional development, such as attending relevant conferences or workshops, ensures their knowledge remains current in a rapidly evolving industry.
- Interdisciplinary collaboration: It involves the encouragement of a multidisciplinary team approach, allowing collaboration amongst experts with complementary skills to enhance the overall project evaluation through diverse perspectives.
- Random selection factor: To mitigate potential biases in expert selection, a random selection factor is considered. This involves selecting a certain percentage of experts from a pool of qualified candidates through a random draw, ensuring diverse representation and reducing the likelihood of unintentional biases in the selection process.

By incorporating these improvements, the classification of experts becomes more nuanced, ensuring the selected experts possess a comprehensive set of skills, relevant experience and up-to-date knowledge to effectively evaluate the various factors influencing construction projects.

3 Results

3.1 Identification and selection of critical delay factors using the FMEA

Table 2 shows the results obtained through the FMEA. Column 1 shows the six categories that were identified as causing delays. Column (2) shows the potential effects of each of the categories. Column (3) shows the 36 delay-causing factors. Column (4) shows the score assigned by the experts to each factor (occurrence (O), severity (S) and detection (D)), and the last column describes the RPN of each delay-causing factor calculated using Eq. (1).

Table 2 and Figure 3 show a ranking of the 20 most important factors that cause delay. It is worth noting that the factors of financial difficulties, as well as the contractor's inaccurate planning, are the factors with the highest RPN (432).

The following section determines the key delay and outcome factors using the MICMAC method based on the 20 factors filtered with the FMEA analysis method.

3.2 Determination of key delay and outcome factors (MICMAC)

- Step (1), Identification of variables: In this case, they are the delay causal factors selected by their criticality score obtained through the modified FMEA. Table 3 shows the acronyms associated with each element, whose name was adjusted as a variable.
- Step (2), Construction of the structural analysis matrix: This activity delivers the structural analysis. Initially, the 20 critical factors were organised in the structural analysis matrix. Then the structural analysis matrix was constructed. For its construction, based on structured surveys and semi-structured interviews, the experts gave a score of (0) zero, (1) low, (2) medium, (3) high or (P) to the potential influence that each factor recorded in the first column exerts on the other factors in the other columns. It is understood that there are no influences on the diagonal of the matrix. For example, the ranking factor (F01)

exerts a high influence on the ranking factor (F02) by assigning it the value 3 in the cell of its intersection. For this purpose, about 16 surveys were sent to officials of companies involved in construction, of which 10 were completed, with a response rate of 62.5%. The results are shown in Figure 4.

- Step (3), Identification of key and result factors: Finally, with the double-entry matrix filled out and the use of MICMAC software, the influence-dependence plane was structured and obtained, which was used to identify the key causal and outcome factors (Figure 5).

The key causal factors are in the upper right quadrant of the influence-dependence plane, and the outcome factors are in the lower right quadrant. These factors are regrouped according to the category to which they are assigned, as shown in Table 4.

3.3 Prioritisation of key and performance factors

In this section, the seven factors resulting from the MICMAC method were taken and prioritised using the FAHP method, so that the hierarchy was structured with three levels: objective, categories and factors. An analysis of the judgements made by the experts consulted found that their answers were consistent with a CR of <0.1. Steps 1–7 show the application of the geometric mean for which the fuzzy technique was implemented.

- Step 1: A hierarchical structure diagram for the causal factors of delays of key construction projects and outcomes is presented in Figure 6.
- Step 2: Scale the matrix using the relative scaling measure and construct the criteria matrix by varying it from 1 to 9. See Table 1.
- Step 3: As the consultation was made with several experts, it was necessary to average the preferences of each expert using Eq. 2. Table 5 shows the comparison matrix of the factors after averaging.
- Step 4: Calculate the diffuse geometric mean. The calculation for F01 using Eq. (4) is shown below. The same procedure is repeated for each factor.

$$\tilde{r}_1 = \left[\left(1 \cdot 1 \cdot \frac{1}{4} \cdot \frac{1}{2} \cdot 4 \cdot 2 \cdot \frac{1}{5} \right)^{\frac{1}{7}} \right], \left[\left(1 \cdot 2 \cdot \frac{1}{5} \cdot 3 \cdot 5 \cdot 3 \cdot \frac{1}{4} \right)^{\frac{1}{7}} \right], \\ \left[\left(1 \cdot 3 \cdot \frac{1}{6} \cdot 4 \cdot \frac{1}{6} \cdot 4 \cdot \frac{1}{3} \right)^{\frac{1}{7}} \right] = (0.96, 1.24, 1.48)$$

Tab. 2: FMEA Criticality Score Matrix for Delay Factors.

Categories	Potential effects	Factors causing delay	O	I	D	RPN
Lack of approval of the owner's advisory service	Failure to meet project deadlines Cost overruns due to reprocessing	Design changes	8	9	4	288
		Delay in the approval of shop drawings and material samples	5	7	4	140
		Quality of project equipment	5	7	4	140
		Quality of raw materials for the project	4	7	4	112
		Lack of expertise and/or experience in the contracted consulting service	5	8	5	200
Non-compliance of labour	Failure to meet project deadlines Occupational accidents Cost overruns due to changes in contract extensions	Absenteeism	5	7	5	175
		Labour shortage	4	7	4	112
		Low labour productivity	7	8	5	280
Incidents with materials and equipment	Failure to meet project deadlines Cost overruns due to price changes and substitutions	Non-compliance with construction material suppliers	6	8	5	240
		Non-compliance of equipment suppliers	6	8	5	240
		Shortage of construction materials on the market	5	8	5	200
		Changes in material specifications during the execution of the project	7	8	5	280
		Unavailability of equipment	5	7	4	140
		Inadequate equipment/obsolete equipment	5	7	4	140
Problems with contractors	Failure to meet project deadlines	Discussion or discomfort during the workday.	4	5	5	100
		Contractor's financial difficulties	8	9	6	432
		Inadequate experience on the part of the contractor	7	8	6	336
		Poorly qualified work of the contractor's technical team	7	7	5	245
		Inaccurate planning and/or scheduling	9	8	6	432
Delays due to external conditions.	Failure to meet project deadlines	Adverse weather conditions	5	6	6	180
		Environmental restrictions	5	6	6	180
		Delay in the completion of the final inspection and certification by a third party	5	6	5	150
		Accidents during construction	5	6	6	180
		Force majeure (war, riots, strikes, earthquakes, etc.)	4	5	6	120
		Inflation/price fluctuations for materials or equipment	4	7	6	168
		Problems with neighbours	4	5	5	100
		Government intervention	4	6	6	144
		Unforeseen ground conditions	5	7	7	245
Problems with the owner	Failure to meet planned project dates Cost overruns due to rework	Late management of the owner's responsibilities	6	7	5	210
		Project financing problems	7	8	6	336
		Stop the work order by the owner.	5	7	5	175
		Owner's lack of construction experience	7	6	5	210
		Lack of a capable representative for the owner	6	7	5	210
		Inadequate project feasibility study	7	8	4	224
		Change of customers/change of scope	7	8	5	280
		Setting of unrealistic project duration deadlines	8	8	4	256

FMEA, failure mode and effects analysis; RPN, risk priority number.

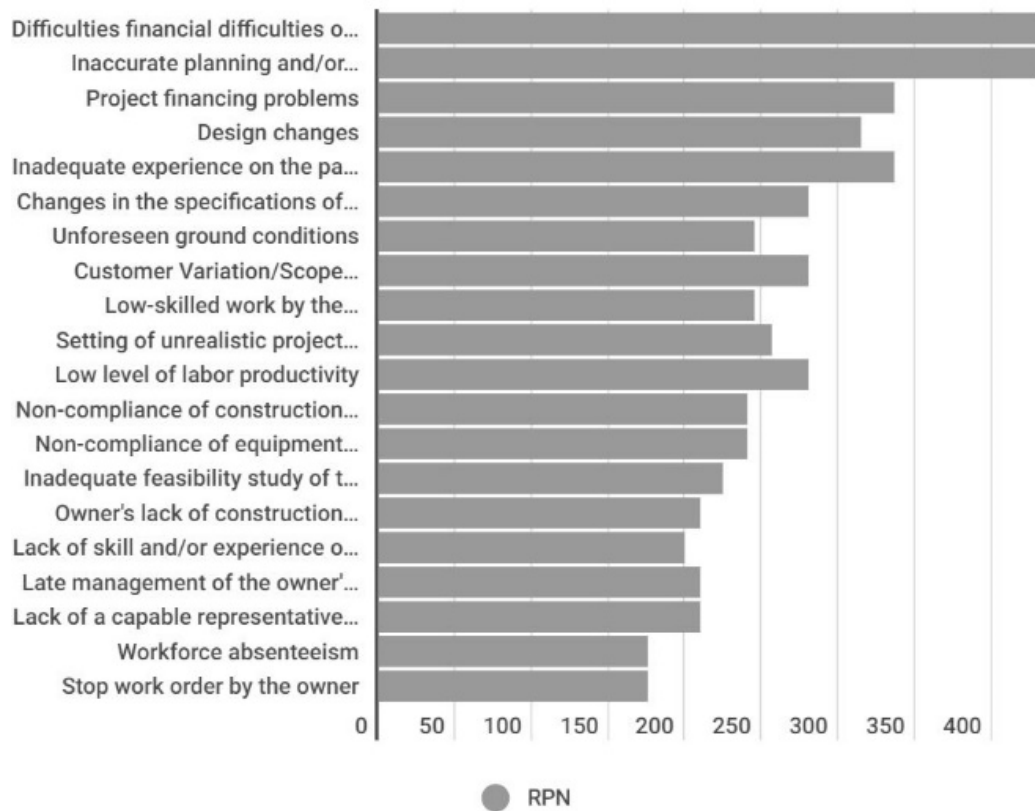


Fig. 3: Ranking of critical factors causing delays. Source: Own 2023.

Tab. 3: Definition of the variables associated with the critical factors.

Nº	Factor	Abbr.
1	Difficulties financial difficulties of the contractor	F01
2	Inaccurate planning and scheduling	F02
3	Project financing problems	F03
4	Design changes	F04
5	Inadequate experience on the part of the contractor	F05
6	Changes in the specifications of materials during the execution of the work	F06
7	Unforeseen ground conditions	F07
8	Customer variation/scope change	F08
9	Low-skilled work by the contractor's technical team	F09
10	The setting of unrealistic project duration time frames	F10
11	Low level of labour productivity	F11
12	Non-compliance with construction material suppliers	F12
13	Non-compliance of equipment suppliers	F13
14	Inadequate feasibility study of the project	F14
15	Owner's lack of construction experience	F15
16	Lack of skill and experience on the part of the consulting service hired by the owner.	F16
17	Late management of the owner's responsibilities	F17
18	Lack of a capable representative for the owner	F18
19	Workforce absenteeism	F19
20	Stop the work order by the owner.	F20

Table 6 shows the geometric mean of the fuzzy comparison values for each factor $\tilde{r}_i$, the vector sum of each $\tilde{r}_i$ and the inverse power of the vector sum in their increasing order.

- Step 5: To calculate the fuzzy weight of each factor, $\tilde{w}_i$ using Eq (5), the calculation of the fuzzy weight for F01 is shown below.

$$\begin{aligned}\tilde{w}_1 &= [(0.969 \cdot 0.11), (1.240 \cdot 0.13), (1.486 \cdot 0.16)] \\ &= (0.103, 0.160, 0.233)\end{aligned}$$

The same process is repeated for the calculation of the fuzzy weight for each factor. Table 7 shows the fuzzy weight $\tilde{W}_i$, the weight $\tilde{M}_i$, the relative weight of $\tilde{N}_i$ and the rank for each factor.

As a result, the 'Compliance with project schedule and/or planning in the contractors' category was the highest priority, with a score of 21.6%. The second and third highest priorities were the factors 'Technical suitability of the contractor's equipment' and 'Continuity of the execution of the works by the owner', with scores of 19% and 17%, respectively, located in the 'Owner' and 'Contractors' categories. Finally, the IPO funnel diagram in Figure 7 shows the partial and consolidated results.

	F01	F02	F03	F04	F05	F06	F07	F08	F09	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	X
F1		3	3	2	0	3	0	2	3	3	P	3	2	2	0	0	P	2	3	3	34
F2	3		P	3	P	3	2	3	2	3	3	3	3	3	0	2	3	2	P	3	41
F3	3	3		3	2	3	0	3	2	3	2	2	3	1	1	2	1	2	P	3	39
F4	3	3	2		2	3	1	3	2	3	3	2	1	3	2	1	3	0	1	3	41
F5	3	3	0	3		2	2	2	3	3	3	2	1	1	3	P	0	0	0	P	31
F6	3	2	1	2	0		0	3	0	3	3	2	3	2	0	0	2	0	2	2	30
F7	3	2	2	0	0	0		2	0	3	2	0	2	3	0	0	P	0	0	3	22
F8	3	3	2	0	3	2	1		0	3	3	3	3	P	0	0	2	0	1	3	32
F9	3	2	0	3	1	0	3	3		3	2	2	2	2	P	3	1	1	3	2	36
F10	3	3	3	P	1	0	3	P	P		3	3	3	3	0	0	1	0	3	3	32
F11	3	2	P	0	3	2	2	1	3	3		3	3	3	0	0	2	0	3	P	33
F12	3	2	P	0	3	0	3	0	3	3	P		0	1	0	0	0	0	0	3	21
F13	3	2	0	0	0	0	3	0	3	3	0	3		2	0	0	0	0	1	2	22
F14	3	3	3	0	2	0	3	0	3	2	3	3	3		0	1	3	0	0	3	35
F15	3	3	3	2	3	0	3	0	3	2	0	0	3	0		3	3	2	0	3	36
F16	3	3	3	3	3	0	3	P	3	1	1	1	3	3	2		3	3	0	3	41
F17	3	3	3	0	2	0	3	0	3	0	1	1	3	3	3	0		2	0	3	33
F18	3	3	2	0	0	0	3	0	2	0	0	0	3	2	2	2	0		0	2	24
F19	3	3	1	1	0	2	2	1	3	3	2	0	1	0	0	1	0	P		2	25
F20	3	3	2	1	2	0	3	0	3	0	0	0	3	3	2	3	0	P	1		29
Y	57	51	30	23	27	20	40	23	41	44	31	33	45	37	15	18	24	14	18	46	

Fig. 4: Structural analysis matrix. Source: Own 2023.

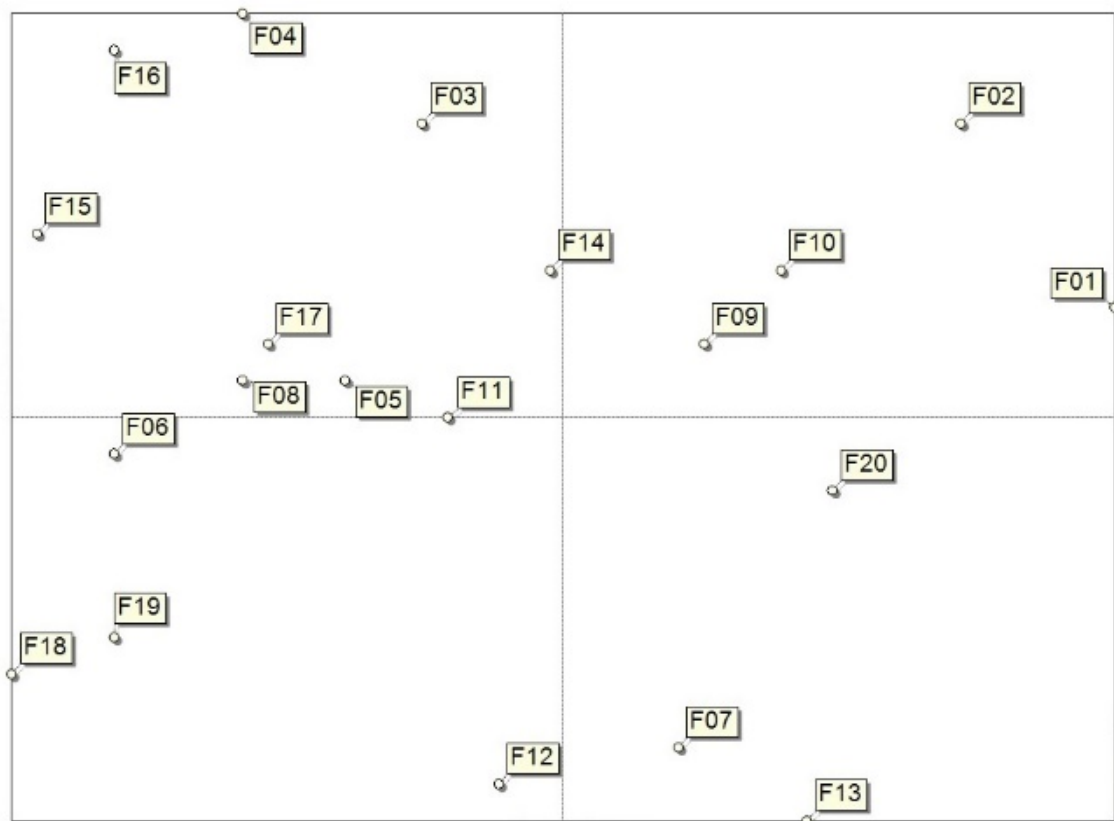


Fig. 5: Influence-dependence plane. Source: Own 2023.

Tab. 4: Causal factors of the main delays and results.

Category	Key causal factors	Abbr.
Contractor	Contractor's financial situation	F01
Contractor	Technical suitability of the contractor's equipment	F09
Contractor	Compliance with project schedule and/or planning	F02
Contractor	Soil conditions	F07
Materials and equipment	Equipment supplier compliance	F13
Proprietor	Continuity of the execution of the works by the owner	F20
Proprietor	Variation of execution times with respect to estimates	F10

4 Discussion

This investigation identified the main factors causing delays in the construction sector in Colombia. To achieve the objectives, a methodological framework was structured based on a funnel diagram (IPO) that integrates and sequences a series of approaches to address the problem. The different methods allowed us to identify, select and classify the delay factors in a complementary and quantified way. Of the 36 factors initially identified, 35 coincide with those identified by Vidyasagar Reddy and Rao (2022) in their study, 'analysis of critical factors for construction projects in India'. Unlike our research, they considered factors such as corruption and the priorities

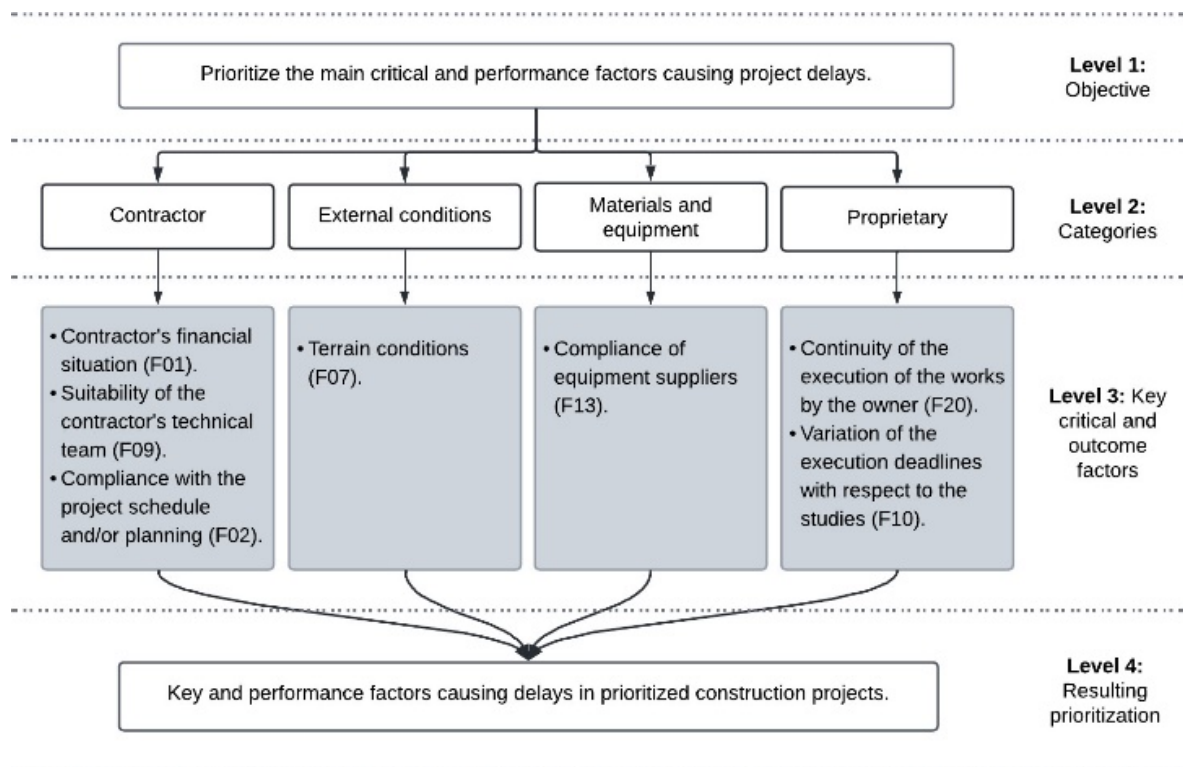


Fig. 6: Diagram of the hierarchical structure of causal factors of key delays and results. Source: Own 2023.

Tab. 5: Factor comparison matrix.

	F01	F09	F02	F07	F13	F20	F10
F01	(1, 1, 1)	(1, 2, 3)	(1/4, 1/5, 1/6)	(2, 3, 4)	(4, 5, 6)	(2, 3, 4)	(1/5, 1/4, 1/3)
F09	(1/3, 1/2, 1)	(1, 1, 1)	(4, 5, 6)	(4, 5, 6)	(2, 3, 4)	(1/7, 1/6, 1/5)	(2, 3, 4)
F02	(6, 5, 4)	(1/6, 1/5, 1/4)	(1, 1, 1)	(8, 9, 10)	(7, 8, 9)	(1/9, 1/8, 1/7)	(4, 5, 6)
F07	(1/4, 1/3, 1/2)	(1/6, 1/5, 1/4)	(0, 1/9, 1/8)	(1, 1, 1)	(2, 3, 4)	(6, 7, 8)	(3, 4, 5)
F13	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	(1/9, 1/8, 1/7)	(1/4, 1/3, 1/2)	(1, 1, 1)	(1, 2, 3)	(2, 3, 4)
F20	(1/4, 1/3, 1/2)	(5, 6, 7)	(7, 8, 9)	(1/8, 1/7, 1/6)	(1/3, 1/2, 1)	(1, 1, 1)	(6, 7, 8)
F10	(3, 4, 5)	(1/4, 1/3, 1/2)	(1/6, 1/5, 1/4)	(1/5, 1/4, 1/3)	(1/4, 1/3, 1/2)	(1/8, 1/7, 1/6)	(1, 1, 1)

of government political leaders as additional factors. It keeps the door open for studying the critical factors that delay public works projects, where political intervention and corruption are relevant in Colombia and other Latin American countries.

Therefore, of the 36 factors identified through the literature review using the FMEA methodology, an initial prioritisation was made based on their criticality, resulting in 20 factors. This volume resulted in the use of the MICMAC, through which the seven most predominant and dependent key and result factors were obtained, indicating the factors to which more attention should be paid. Finally, using the FAHP methodology was justified, resulting in the highest priority factors being 22.22% of the initial sample. The following is a detailed analysis of the three essential factors prioritised by the FAHP.

4.1 Inaccurate planning and scheduling by contractor (F02)

The planning and programming of a construction project are summarised in the management, coordination and preparation of all the resources that the contractor requires to operate the project. According to Serna et al. (n.d.), when planning is good, time variations are lower;

Tab. 6: Causal factors of the main delays and results.

Factors	$\tilde{r}_i$
F01	(0.969, 1.240, 1.486)
F09	(1.173, 1.520, 1.970)
F02	(1.583, 1.723, 1.860)
F07	(0.763, 0.934, 1.140)
F13	(0.420, 0.557, 0.727)
F20	(1.118, 1.346, 1.706)
F10	(0.360, 0.440, 0.560)
Total	(6.39, 7.76, 9.45)
Inverso	(0.11, 0.13, 0.16)

this statement is statistically supported in their study since a p -value of <0.05 was found using the Wilcon method. However, the authors mention that no significant differences are found when comparing cases of poor planning, which agrees with the findings of Sambasivan and Soon (2007), Doloi (2013), Assaf and Al-Hejji (2006) and Marzouk and El-Rasas (2014). These authors emphasise that poor planning and scheduling by contractors is one of the most important causes of delays.

4.2 Poorly qualified work of the contractor's technical team (F09)

According to Muhwezi et al. (2014), this factor may be due to two causes, and the first could be that the contractor prefers to pay cheap unskilled labour so that the savings in these costs are reflected in the profit. But according to Gómez Moreno (2015), the second cause may be related to the shortage of skilled labour in Colombia. He also points out that in the next 5 years, Colombia is expected to execute essential infrastructure works, and contractors will have to face the insufficiency of sufficient skilled labour to ensure the viability and quality of the results. Therefore, this factor shows the importance of the problems Colombia is going through so that not only the labour needs of the projects can be anticipated, but also contribute to the planning and management of construction projects (Giraldo Arcila et al. 2013).

4.3 Suspension of work by the owner

It is highlighted that there is a difference between the concept of delays and the concept of work stoppage. According to Giraldo Arcila et al. (2013) and Gordo Barreiro et al. (2017), the work stoppage of the results comes from a direct order from the project owner that stops the total or partial progress of the activities; when this event occurs, the project work, either in whole or in section, is paralysed until the project owner lifts said suspension. On

Tab. 7: Diffuse weight, weight, normal weight and rating of each factor.

Categories	Factor	Fuzzy weight $\tilde{W}_i$	Weight $\tilde{M}_i$	Normal weight $\tilde{N}_i$	Ranking
Contractor	F01	(0.103, 0.160, 0.233)	0.165	0.157	4
Contractor	F09	(0.124, 0.196, 0.309)	0.21	0.199	2
Contractor	F02	(0.168, 0.222, 0.291)	0.227	0.216	1
Contractor	F07	(0.081, 0.120, 0.179)	0.127	0.12	5
Materials and equipment	F13	(0.044, 0.072, 0.114)	0.077	0.073	6
Proprietor	F20	(0.118, 0.173, 0.267)	0.186	0.177	3
Proprietor	F10	(0.038, 0.057, 0.088)	0.061	0.058	7

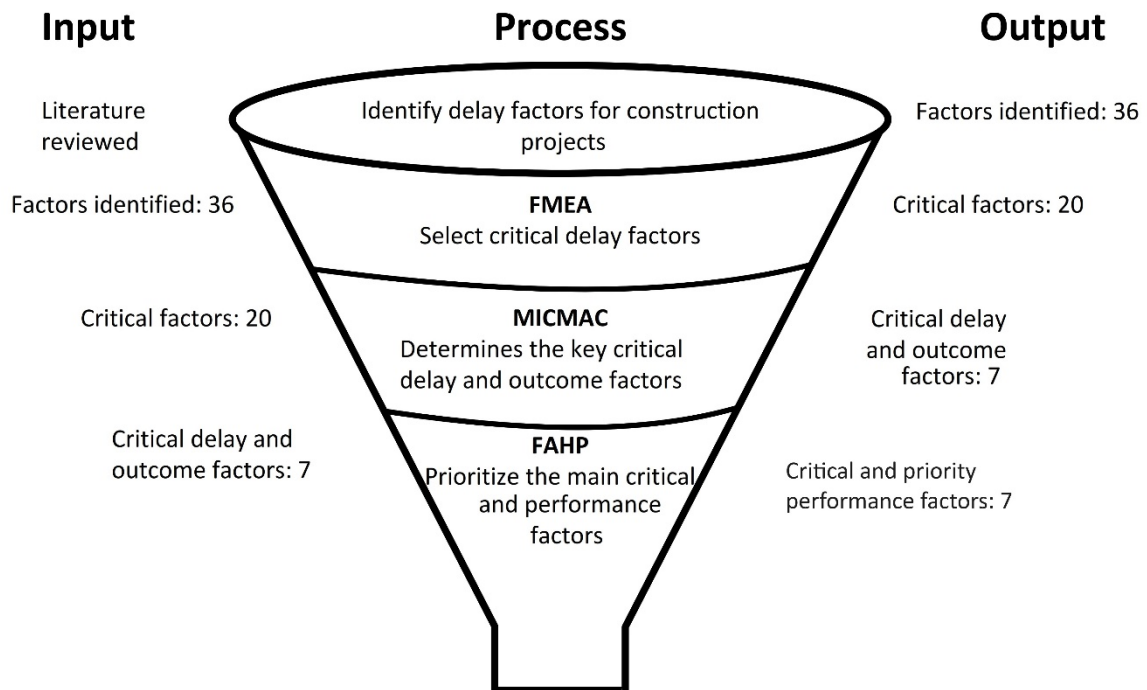


Fig. 7: Results of the IPO funnel diagram. IPO, input-process-output. *Source:* Own 2023.

the other hand, the delay is not subject to orders from the project owner or, where appropriate, from the contracting entity. Therefore, determining its causes involves many aspects that must be analysed (Henschel and Hildreth 2007). In the private sector, several contracts have clauses that allow owners to suspend work on a project under specific circumstances; the ability to suspend work is in most government contracts (Curren 2014), so the suspension may cause project delays and may result in compensable damages.

Finally, two standout contributions resulting from the research emerge: one is the combination of FMEA tools with a structural analysis tool (MICMAC) and a multicriteria analysis tool (FAHP) to prioritise the factors causing delay in the construction sector. The second contribution is the application of this methodology to the Colombian case, where the industry will have elements of analysis and improvement of the causes of project delays.

5 Conclusions

Time management in construction projects is a dimension whose performance has an impact not only on schedule adherence but also on execution costs. This research aimed to analyse and prioritise the critical factors that

cause delays in construction projects. One of the contributions of this research is the complementarity of the three approaches used to address the methodology. The literature review identified 36 factors affecting the schedule, which were the input to determining the critical delay factors categorised by the adapted FMEA technique. The second contribution is its application to a case in the Colombian context. Using the MICMAC technique, seven critical outcome factors were determined by analysing delay factors in the planning phase. To determine more specifically the priorities in the seven critical key factors, the multi-criteria FAHP technique was used. These factors were grouped into four categories, where the 'Contractors' and 'Owner' categories contain the five factors requiring the most attention to control the project schedule. The three most critical factors causing delays in construction projects were found to be: inaccurate planning and scheduling by the contractor, unskilled work by the contractor's technical team and stoppage of work by the owner. This information allows the agents of the construction system in the region in question to plan projects with preventive elements and to make specific improvements. However, a systemic-dynamic study with a simulation approach can be carried out in the future to identify the interrelationships between factors and validate this result as a support point.

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