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Identifying the Causes of Delay Using the Analytic Hierarchy Process (AHP) Method in Brazilian Public Road Infrastructure Projects

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Abstract

The highway infrastructure system plays an important role in a country whose continental extensions require an adequate transportation system to connect people and places and boost the economy. Delayed delivery of these projects is one of the most significant problems in the road construction industry and poses challenges to project success in terms of time, cost, quality, and safety. Some studies have carried out literature reviews, applied questionnaires and performed expert interviews, or used analytical methods such as machine learning and AHP (Analytic Hieraquircal Process) to identify factors that cause delays. The objective of this study was to identify the main delay factors in road infrastructure projects using the AHP analytic hierarchy process approach in the context of public works management in Brazil. This study consisted of two stages, the first being a search in databases and search engines, using keywords that point to studies on delay factors in road construction projects. After this, the criteria and sub-criteria were examined and classified, and the factors and causes of delays were ranked based on discussions with an expert and the application of a questionnaire, according to the AHP methodology. The supporting software used was SuperDecisions. The main factors (criteria) and sub-factors (sub-criteria) that influence delay were categorized according to the literature. The main factors were compiled into five criteria called: principal contractor, designer, manager, material/manpower/equipment, and external factors. Within these groups, 24 sub-factors that most influenced delay were initially selected. But after the consistency tests were not acceptable, a new selection was made, which considered in the analysis the 15 most influential sub-factors. According to the experts, the order of importance was: Contractor>External Factors>Materials>Manpower and Equipment>Manager>Designer. The most important sub-criterion according to the specialists in causing delays in Brazilian road infrastructure projects was climate. The study pointed out which factors should have priority in decision-making to avoid delays in public, government-funded road transportation projects in Brazil. By applying it, one can arrive at the variables that can be used to develop a prediction model that helps mitigate the risks of delay in public road infrastructure projects.

Keywords: highway infrastructure, public works projects, AHP method, project delays, civil construction

1. Introduction

Highway infrastructure has been considered necessary for the economic development of any country since its very early days (Pai et al., 2018), contributing to its growth, efficiency, and the productivity of other industrial sectors, including construction. For this purpose, many investments are being made worldwide, and it is estimated that 25 million km of new paved roads will be built by 2050, enough to circle the planet 600 times (Alamgir et al., 2017).

The characteristics of road infrastructure require a long period of planning and construction (Park, 2021), and most road infrastructure projects are managed by the public sector (Karunakaran, Malek, & Ramli, 2019) in order to improve a country's social and economic activities (Kassa, 2020), such as access to markets, production, jobs, healthcare, and other social services (Al-Hadithi, 2018).

In Brazil, highways are the principal means of transportation. This mode of transport facilitates the mobility of products and services, the movement of cargo and passengers, as well as commercial activities in the surrounding areas. The National Department of Transportation Infrastructure (DNIT) is the agency responsible for the construction, restoration, conservation, and maintenance of the federal inter-urban transport routes, and is linked to the Ministry of Infrastructure (MInfra). Currently, DNIT is responsible for a federal paved road network of 65.3 thousand km. This agency is also responsible for the management of the highways, providing increased safety and comfort to users throughout the road network under the agency's jurisdiction (DNIT, 2021).

The stages of design preparation and execution for road infrastructure projects are recurring challenges. These are divided into these principal stages: planning and definition, design, procurement, and construction (Rivera, Baguec Jr., & Yeom, 2020), which must be well-executed and concluded. Within these are factors that can lead to a delay in their use, that is, a delay in being able to fully utilize them. According to Yap et al. (2021), these may be related to clients, contractors, consultants, labor, equipment, and materials. They can also occur at different stages, depending on project size, construction duration, contract volume, and technical and managerial know-how (Mahamid, Bruland & Dmaidi, 2012), as well as the location of the construction site (Cabahug et. al, 2018).

Delays in the delivery of public road infrastructure are a consequence that can be linked to the bidding stage through the selection of the lowest bidder (Bekr, 2015; Islam et al., 2015; Santoso & Soeng, 2016), to inadequate planning and design (Mejía et al., 2020), to inadequate project execution (Mohajeri Borje Ghaleh et al., 2021), or to a lack of sufficient resources (Noulmanee et al., 1999) that include labor, equipment, construction facilities and machinery, materials, money, and time (Danial & Misnan, 2022).

Designing and constructing road projects is always a challenge. Delay in completion is one of the most significant problems in the road construction industry and limits the success of these projects in terms of time, cost, quality, and safety (Mahamid, Bruland, & Dmaidi, 2012; Mahamid, 2017; Bounthipphasert et al., 2020; Rivera, Baguec Jr., & Yeom, 2020). This delay in the ability to use infrastructure further reduces the social benefits that it should provide (Eriksson, Larsson, & Pesämaa, 2017). This implies that, without efficient transportation infrastructure, economic and social development could be severely hampered (Amoatey & Ankrah, 2017).

In developing countries, public construction projects are of particular importance because of their connection with the extension of infrastructure (Bagaya & Song, 2016). Brazil, as a developing country, is still greatly affected by the inadequacy of design and execution, which leads caused delays in construction with social and economic impacts. The goal of the government, through DNIT, is to serve the public by provisioning roads in a timely manner, because delays during road construction lead to excessive costs and obstacles for users, such as increased travel time.

Researchers have sought to identify the variables that cause delays in road projects, and have highlighted some causes and factors that lead to poor cost and time performance in developed and developing countries (Melaku Belay et al., 2021). Most of these studies were performed through an analysis of the literature coupled with questionnaires, as well as with analysis methods such as the Importance Index, Frequency Index, and Severity Index (Mohajeri Borje Ghaleh et al., 2021; Negesa, 2022; Purushothaman & Kumar, 2022; Subedi & Joshi, 2020; Mejía et al., 2020; Rivera, Baguec, & Yeom, 2020).

One approach that has been gaining space in the analysis of delay factors is the Analytic Hierarchy Process (AHP) (Khademi et al., 2012; Asadabadi, Chang, & Saberi, 2019; Razi, Ali, & Ramli, 2019; Tavassolirizi et al., 2020; Lin, Fan, & Chen, 2022). The AHP method is an approach to multicriteria decision-making proposed by Saaty (1980), which has been used by transportation researchers (Rabbani & Rabbani, 1996; Tavassolirizi et al., 2020; Lin, Fan, & Chen, 2022) to systematize complex problems through a hierarchical structure and to build an attribute comparison matrix to determine the weightings among the criteria.

The application of the AHP method to identify delay factors, according to Tavassolirizi et al. (2020), can begin from the existing literature, and then, through interviews with experts, the factors can be prioritized. This application follows the hierarchical construction, which can be established and represented by a selection of main groups (criteria), where each criterion can be divided into sub-criteria.

While there are many studies, as can be seen from the literature review, and while several studies have investigated the causes and effects of delays in the construction sector, very few have focused on road construction (Amoatey & Ankrah, 2017). Even though these studies have been applied and made a contribution to the scientific and professional community, the occurrence of delays in the delivery of road projects is still very common and requires further investigation (Sanni-Anibire, Zin, & Olatunji, 2021). Despite the contributions from these studies, in Brazil, there has been no research focused on delays in public road projects.

According to Macedo (2020), in the Brazilian context, the great difficulty regarding road management is the lack of data on road projects (CNM, 2018). The lack of basic data on road projects is attributed to the particular characteristics of Brazilian traffic, which causes difficulties in using studies, models, and data from other countries as reference sources (Macedo, 2020). It can be seen that there is a significant relationship between the factors that cause delays in road projects and the involvement of particular circumstances.

Given the reality that, in Brazil, there are still no studies identifying the factors that cause delays in road projects and, given that the lack of investment is a result of economic difficulties, this study sought to validate the use of the AHP method, the factors of which are considered important by experts, for publicly-funded road infrastructure projects. Because of the importance of the numerous impacts that arise from delays, it is necessary to investigate and analyze their factors, with the hierarchization of the causes of delay being an important aid to decision-making.

1.1 Delays in Road Infrastructure

In a study by Amoatey and Ankrah (2017), when explaining concepts of delay, the authors indicated that several studies point out that delays occur in all construction projects. While the significance of this delay varies considerably from project to project, they suggest that a delay in project delivery is the most common, complex, and universal phenomenon in construction.

Because highway projects are heavy construction activities with a high degree of mechanization that require large volumes of materials, failures and shortages of these resources are potential delay factors (Mejía et al., 2020). Not limited to the construction process, factors such as inefficient decision-making, lack of team qualification, and conflicts between parties are also integral to these projects (Khair et al., 2018).

According to Williams (2003), a three-month delay during design can lead to a one-year delay in execution, resulting in substantial costs (Danial & Misnan, 2022). In the study conducted by Kassa (2020) in Ethiopia, it was revealed that 88% of road construction projects had been delayed and 80% of them cost more than originally planned. According to Mpofu et al. (2017), the causes of delay vary for each country and are associated with social, economic, and cultural issues.

There are several causes for delay or related factors that have been identified by project researchers in highway construction, as stated by Danial and Misnan (2022), in which some of the researchers categorized them into major groups. Aziz and Abdel-Hakam (2015) classified delays into the following groups:

(1) Factors related to the owner, including the owner's financial difficulties and late payments for completed construction work.

(2) Factors related to contractors, which include: poor site management and supervision, contractor's financial difficulties, obsolete or inadequate construction methods, inaccurate estimates, incompetent subcontractors, and errors during construction.

(3) Factors related to consultants, including poor project management assistance, poor contract management, slow inspection of completed construction sites, and design errors.

(4) Design-related factors, which include design changes, additional work, and the slow flow of information between the parties involved.

(5) Factors related to materials and manpower, which include material shortages and skilled labor shortages.

(6) External factors, including unforeseen site conditions, price fluctuations, bad weather, and government obstacles.

With clustering, the causes of delay are categorized according to their main group (Le-Hoai, Lee, & Lee, 2008; Mahamid, Bruland, & Dmaidi, 2017), allowing mitigation actions to be implemented to avoid project delays (Zidane & Andersen, 2018). Identifying the factors and causes of road project delays makes it possible to see their effects and mitigation actions.

To develop this paper, data were collected from 55 studies conducted in many different countries, which are shown in Table 1.

Table 1. Literature used for data collection

Source/Author	Location	Project Type	Number of delay factors identified	Year
Noulmanee et al.	Thailand	Highway	4	1999
Vidalis & Najafi	Florida	Highway	4	2002
Ellis &Thomas	California/ Florida/Georgia/New York/South Carolina/Wisconsin	Highway	10	2003
Le-Hoai, Lee & Lee	Vietnam	Road	5	2008
Kaliba, Muya & Mumba	Zambia	Road	13	2009
Chileshe & Berko	Ghana	Road	7	2010
Nasir, Gabriel & Choudhry	Pakistan	Highway	20	2011
Mahamid, Bruland & Dmaidi	Palestine	Highway and Road	5	2012
Wijekoon & Attanayake	Sri Lanka	Road	5	2012
Kamanga & Steyn	Malawi	Road	10	2013
Ezeldin & Abdel-Ghany	Egypt	Road + Engineering projects	13	2013
Alinaitwe, Apolot & Tindiwensi	Uganda	Road + Engineering projects	5	2013
Patil et al.	India	Road	6	2013
Ondari & Gekara	Kenya	Road	3	2013
Hasan, Suliman & Malki	Bahrain	Road	17	2014
Atibu	Kenya	Road	5	2015
Islam et al.	Bangladesh	Road + Engineering projects	10	2015
Bekr	Iraq	Road + Engineering projects	10	2015
Al-Hazim & Salem	Jordan	Road	4	2015
Honrao & Desai	India/Bahrain	Highway	15	2015
Santoso & Soeng	Cambodia	Road	10	2016
Aziz & Abdel-Hakam	Egypt	Road	20	2016
Elawi, Algahtany & Kashiwagi	Saudi Arabia	Road and Bridge	10	2016
Tesfa	Ethiopia	Asphalt road	10	2016
Aforla, Woode & Amoah	Ghana	Highway	10	2016
Ekanayake & Perera	Sri Lanka	Highway	5	2016
Khalid et al.	Sudan	Road	20	2017
Mahamid a	Saudi Arabia	Road	5	2017
Mahamid b	West Bank in Palestine	Road	5	2017
Amoatey & Ankrah	Ghana	Road	5	2017
Venkateswaran & Murugasan	India	Road over Bridge	5	2017
Alfakhri et al.	Libya	Road	5	2017
Lozano Serna et al.	Colombia	Road	10	2018
Cabahug et al.	Philippines	Road	4	2018
Rudeli et al.	Ecuador	Road	7	2018
Thapanont, Santi & Pruethipong	Thailand	Highway	5	2018
Pai et al.	India	Highway and Road	5	2018
Al Hadithi	Iraq	Highway	7	2018
Alfakhri, Ismail & Khoiry	Libya	Road	7	2018
Karunakaran, Malek & Ramli	Malaysia	Highway and Road	12	2019
Rachid, Toufik & Mohammed	Algeria	Highway	5	2019

Sohu & Chandio	Pakistan	Highway	10	2019
Kumar	India	Highway and Expressway	5	2020
Kassa	Ethiopia	Federal Road and Railway Construction	10	2020
Al Hinai, Widyarto & Bhuiyan	Oman	Road	4	2020
Bounthipphasert et al.	West Bank in Palestine	Road	5	2020
Melaku Belay et al.	Ethiopia	Road	9	2020
Rivera, Baguec & Yeom	***	Road	10	2020
Mejía et al.	Africa and Asia	Road	20	2020
Subedi & Joshi	Nepal	Road	13	2020
Mohajeri Borje Ghaleh et al.	Iran	Road	6	2021
Stević et al.	Republic of Benin	Road	5	2022
Purushothaman & Kumar	New Zealand	Road	8	2022
Danial & Misnan	Malaysia	Road site	5	2022
Negesa	Ethiopia	Road	10	2022

Note. *** more than 25 developing countries.

Several different studies have found factors that cause delays in road infrastructure projects. These were noted by researchers on every continent: Asia, Oceania, South America, Africa, North America, and Europe (Vidalis & Najafi, 2002; Aforla, Woode, & Amoah, 2016; Cabahug et al., 2018; Rudeli et al., 2018; Purushothaman & Kumar, 2022; Mejía et al., 2020). Asia featured the most research on delays in road infrastructure construction, followed by Africa. By country, the greatest number of delay factors were recorded in Ethiopia (39) (Tesfa, 2016; Kassa, 2020; Melaku Belay et al., 2020; Negesa, 2022), followed by India (36) (Patil et al., 2013; Venkateswaran & Murugasan, 2017; Pai et al., 2018; Kumar, 2020; Honrao & Desai, 2015) and Egypt (33) (Ezeldin & Abdel-Ghany, 2013; Aziz & Abdel-Hakam, 2016) (Figure 1).

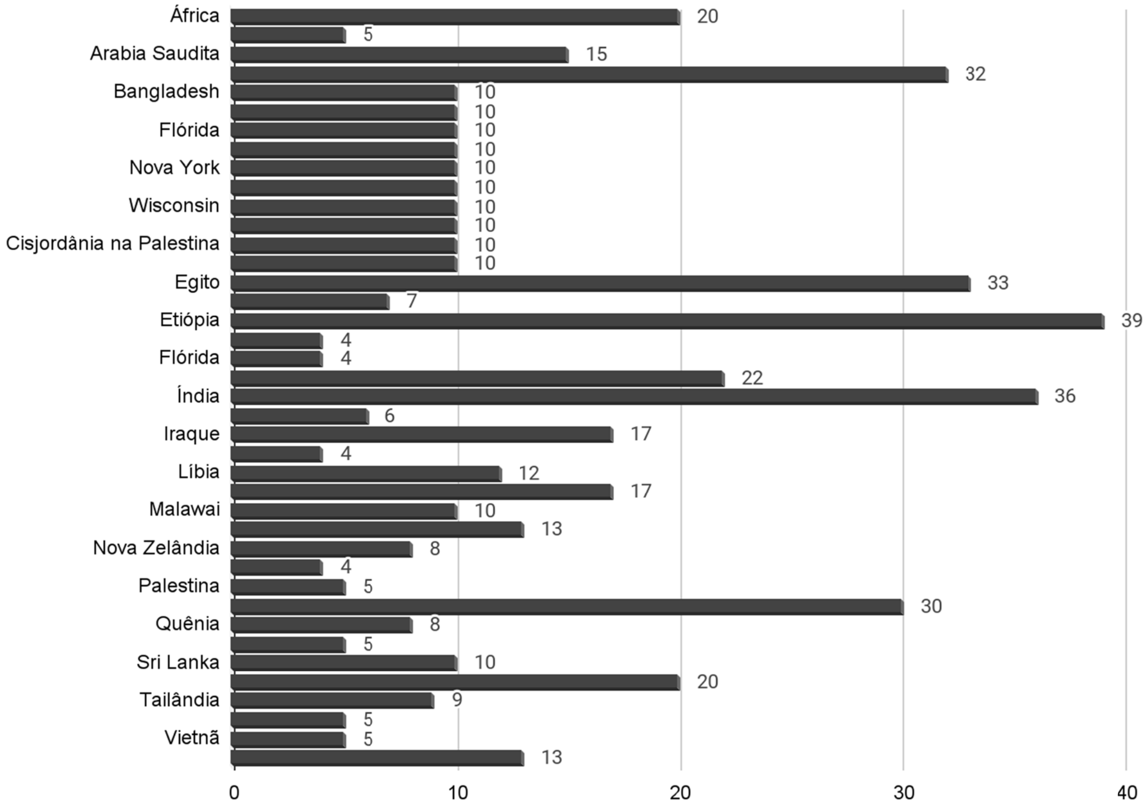

Figure 1. Number of delay factors identified per country

1.2 AHP Method Applied to Studies on Road Project Delay

The AHP, or analytic hierarchy process method, systematizes complex problems using a hierarchical structure (Lin, Fan, & Chen, 2022), where the importance of the attributes being investigated is identified. The weightings identified for the different attributes are determined by experts (specialists) who will conduct pairwise comparisons regarding the importance of the various criteria evaluated (Kimura & Suen, 2003). This method therefore divides the decision-making elements into multiple dimensions, hierarchically structuring a large and complex problem by dividing it into several small sub-problems, and then evaluating these sub-problems individually.

In this study, the AHP method was used as a tool to identify, through prioritization, the delay factors appropriate to the Brazilian reality, based on the analyses made by the specialists. The articles selected for the development of this study, which utilized this method, were:

Table 2. Studies that applied the AHP method to road projects

Source/Author	Methodology/Techniques Applied	Results
Lin, Fan, & Chen (2022)	Five dimensions and nineteen factors were established from the AHP-ANN (artificial neural network) combination and a model was developed to predict the main factors of construction risk and quality. Their influence on the public construction management of Taiwan's central government was analyzed.	The results can be used as a reference to develop decision-making strategies for management.
Mohajeri Borje Ghaleh et al. (2021)	The Ishikawa (cause-effect) diagram was used to organize the factors qualitatively, to identify and prioritize the delay risks with the AHP method by assigning weights to the delay factors for road construction projects.	This study presents the framework for identifying and prioritizing delay risks for road construction projects with the AHP method. It showed that financial and credit problems, land financing, management problems, technical problems, and natural disasters have the highest risk among the main criteria.
Tavassolirizi et al. (2020)	The causes of delays for rail transportation projects were identified from the existing literature and these factors were evaluated and prioritized using an AHP-based multi-criteria decision-making (MCDM) approach.	Of the four major factor categories identified, the management factor had the highest weight, with financial, design, and implementation factors ranked second through fourth, respectively. The sub-factors included: having numerous parties involved, lack of centralized supervision, and poor supervision by project managers.
Razi, Ali, & Ramli (2019)	Seven delay factors and twenty-two sub-factors were identified from a literature review and from consultations with roadway experts. The weights were determined based on a peer-assigned questionnaire distributed to a road project team, and subsequently, the prioritization of the delay factors was performed according to the AHP method.	They concluded that the top five highest priority factors were: technical, natural risk, economic and financial, contractual, and socio-political. The top five highest priority sub-factors were determined to be: financing risk, flood risk, heavy rainfall, soil conditions, and existing utility problems.

It can be seen in the selected articles that the results from the AHP method can assist decision-makers in selecting the best solutions. The present study, therefore, adopted this method for the selection of the factors, arriving at the criteria and sub-criteria, in other words, the main factors and their respective sub-factors. In this manner, it is possible to arrive at consistent variables that influence delays.

2. Materials and Methods

The methodology developed in this study combined a search of the literature for factors/variables of the main causes of delay in road infrastructure projects in Brazil and in the world with a subsequent questionnaire administered to experts with experience in road infrastructure projects, in order to prioritize the causes of delay in public infrastructure projects in Brazil using the AHP methodology. The phases developed are presented in the flowchart in Figure 2.

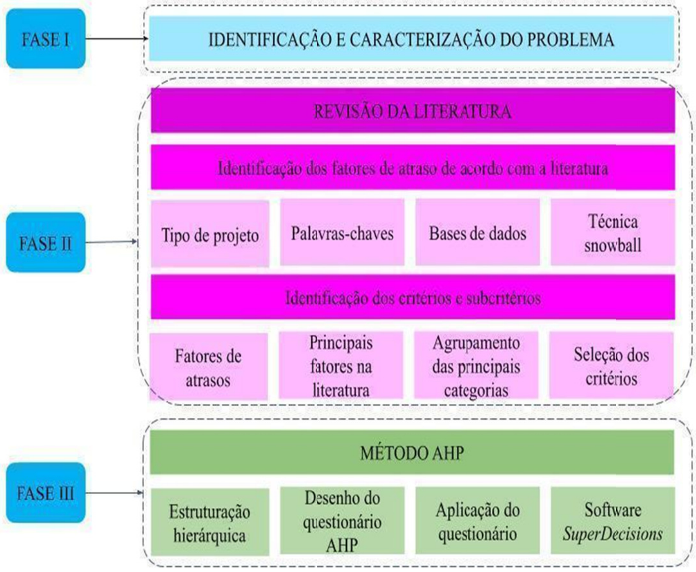

Figure 2. Flowchart of the methodology adopted

2.1 Phase 1 – Identification and Characterization of the Problem

Once the problem was identified and the scope of the study delimited, a literature investigation was prepared, which can be characterized as a descriptive study to determine and characterize the variables in a particular situation that approximated an exploratory study of the fundamentals important to develop a better understanding of the problem under study (Cavana, Delahaye, & Sekeran, 2001). This, in turn, included studies in the literature related to road infrastructure delays. A questionnaire was applied to experts in order to identify the factors for the local context. Finally, the analytic hierarchy process (AHP), a multicriteria decision-making (MCDM) approach, was applied to select factors that match the reality of the local context.

2.2 Phase 2 – Literature Review

The review was conducted through a survey of articles published on road infrastructure delay factors in indexed journals and scientific conferences. The search was conducted in the databases, and Google Scholar was also used. For data collection, the keywords “delay,” “road infrastructure,” “schedule delays,” “road construction project,” and “public construction” were used to find studies in the field of road infrastructure. Then, the terms “construction industry,” “road infrastructure construction project”, and “delays road infrastructure,” directed the searches to all titles, abstracts, and keywords. The intent was intended to reach the maximum number of publications that referred to these parameters, to discover a greater number of road transport infrastructure delay factors.

In order to analyze academic papers that meet the objectives of this study, the abstracts of all of the papers found were read, and the following inclusion criteria were adopted: being available in full, containing information on highway infrastructure projects, and identifying delay factors in highway projects. Course completion papers, dissertations, and theses were not considered, and replicated studies were discarded. After obtaining the total number of studies, articles that did not refer to road transport infrastructure were excluded.

To reach the representative number, the snowball technique was used, which uses reference networks to identify studies that were cited in the selected articles obtained from the search terms (Thomé, Scavarda, & Scavarda, 2016).

From the analysis of and extraction of information from the articles in the literature review on studies that focused on causes of delay in road infrastructure, the factors that contribute to delay were selected, resulting in 472 factors that were organized according to the various studies.

2.3 Phase 3 – AHP Method

To model the problem according to the AHP method, it is first necessary to choose some criteria so that the hierarchical structure can be constructed. Taking the literature review as a base and synthesizing the information, a list with the selected factors was created. The list was homogenized with similar factors. From this, the frequency of repeated road infrastructure delay factors could be realized. The selected factors then served as sub-criteria and a preliminary list was defined. This list of sub-criteria was revised through discussions with specialists and academics, in order to fit the reality of government-funded road infrastructure projects in Brazil. These factors were grouped according to their characteristics, with each main group serving as a criterion. The different criteria were grouped according to the part or factor involved in the delay. The four main procedures are shown below (Figure 3):

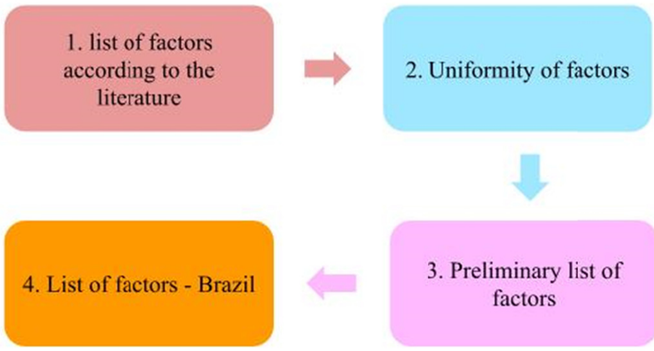

Figure 3. Flowchart of the criteria selection process

The decision was made to group the list of factors into the following five criteria: contractor; designer; manager; materials, manpower, and equipment; and external factors. A list of delay factors (sub-criteria) and their related groups (criteria) were therefore structured, in order to later select the factors to be used in the AHP questionnaire.

2.3.1 Design of the AHP Questionnaire

A questionnaire was designed based on the delay factors under consideration, which were selected and adapted for public road infrastructure projects in Brazil. The use of the questionnaire served as a qualitative approach (Cavana, Delahaye, & Sekaran, 2001) to obtain and analyze data that could be relevant or significant. The structuring was performed based on the AHP model with the data input being the list of criteria (Brazil) that served as the basis for the questionnaire. To organize the criteria and sub-criteria, the AHP method was simplified, using the SuperDecisions 3.2 software to create a hierarchical factor structure.

To inform the respondents of the questionnaire's purpose, the research objective was presented: to identify the causes of delay in road transportation infrastructure projects that the specialists considered relevant, as well as the factors that drive them the most, along with identifying which factors should have priority in decision making, in order to avoid or mitigate delays in future public road transportation projects in Brazil. Next, the sections of the questionnaire were explained. These sections are as follows:

Section A: General respondent information.

Section B: Expert opinion on various criteria as to their importance in relation to each other (contractor; designer; manager; materials, manpower, and equipment; and external factors), as well as their sub-criteria.

Section C: Expert opinion of which other criteria they believed were relevant and that had not been mentioned in the questionnaire.

The first part consisted of general questions, such as the respondent's professional field, highest level of education achieved, current occupation, years of experience in public infrastructure projects, project management techniques used, and the frequency of technological use in design, planning, scheduling, and project control activities (never, rarely, eventually, frequently, or very frequently).

The second part was designed as a peer questionnaire on the importance of delay factors in road infrastructure projects, with respondents being asked to grade the factors using the AHP model on a scale of 1 to 9. The questions asked which criterion (factor) was more important in relation to another and, among the selected criteria and sub-criteria, how much more each one contributed in relation to another towards delay in the construction of public road infrastructure projects in Brazil. The difference in importance between the factors was graded using the Likert scale for the dimensions (1, 3, 5, 7, and 9) and was categorized as follows: equal importance (1), small difference (3), great difference (5), very great difference (7), and extreme difference (9), according to Saaty's scale for determining the weights of each dimension and the importance of each factor (criterion) and sub-factor (sub-criterion).

2.3.2 Application of the AHP Questionnaire

After designing the questionnaire and selecting the experts, the questionnaires were sent out. They were developed to obtain expert opinions from experienced professionals in road infrastructure projects in Brazil. It was made available via Google Forms as a free online survey tool. The supporting software was SuperDecisions 3.2, a practical and fast decision support analysis tool that implements AHP to analyze the results of the questionnaire applied to the experts.

2.3.3 Multi-Criteria Analysis

With the AHP method, a problem is structured into hierarchical levels where the criteria and sub-criteria are ranked to assess technological options and where expert judgment is required to define the importance of each criterion and sub-criterion through peer-to-peer comparisons, according to the preferences established between them. The importance of one attribute over another is represented by fuzzy triangular numbers. These numbers are calculated according to expert judgment using linguistic terms based on the Saaty scale in 9 levels (Table 3).

Table 3. Fundamental Saaty scale

Numerical Scale	Verbal Scale	Explanation
1	Both elements are of equal importance	Both elements contribute to the property equally
3	Moderate importance of one element over the other	Experience and opinion favor one element over the other
5	Strong importance of one element over the other	One element is strongly favored
7	Very strong importance of one element over the other	One element is very strongly favored over the other
9	Extreme importance of one element over the other	One element is favored with at least an order of magnitude difference
2, 4, 6, 8	Intermediate values between adjacent opinions	Used as consensus values between opinions
0.1 increments	Intermediate values at the finest gradation of 0.1	Used for finer grades of opinions

The next step is to construct a set of square matrices for the paired comparison (Figure 4). This is constructed by comparing each element at a higher level with the elements at the level just below, using the fundamental importance scale. The weights of the factor for each level relative to an adjacent factor at the top level are calculated as the components of a normalized eigenvector, associated with the largest eigenvalue from its comparison matrix. Then, for each element at the level below, the weighted values were totaled and their local and global priorities were obtained. The composite weights of the decision alternatives were then determined by aggregating the weights through the hierarchy (Rabbani & Rabbani, 1996; Hossein, Kang, & Kim, 2015; Tavassolirizi et al., 2020; Lin, Fan, & Chen, 2022).

$$
\begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_m \end{array}
\begin{array}{c} \begin{array}{cccc} \quad c_1 \quad & \quad c_2 \quad & \cdots & \quad c_n \quad \end{array} \\
\begin{bmatrix}
(1,1,1) & (1/a_{1[1,2]}, 1/a_{2[1,2]}, 1/a_{3[1,2]}) & \cdots & (1/a_{1[1,n]}, 1/a_{2[1,n]}, 1/a_{3[1,n]}) \\
(1/a_{3[1,2]}, 1/a_{2[1,2]}, 1/a_{1[1,2]}) & (1,1,1) & \ddots & \tilde{x}_{2n} \\
\vdots & \vdots & \vdots & \vdots \\
(1/a_{3[1,n]}, 1/a_{2[1,n]}, 1/a_{1[1,n]}) & \cdots & \cdots & (1,1,1)
\end{bmatrix}
\end{array}
$$

Figure 4. Pairwise Comparison Matrix

The consistency analysis of the pairwise comparison matrices can be done using the consistency index (CI). The consistency ratio (CR) is the ratio between the consistency index of the judgment set and the random index (RI), as shown in Equation 1, of the corresponding random matrix in the AHP method.

$$CI = RC/RI \tag{1}$$

The consistency ratio (CR) is used to estimate the consistency of the pairwise comparisons, i.e., a CR value greater than 10% indicates that the judgments are at the limit of inconsistency and the weights may lead to inaccurate conclusions. Saaty (2003) proposed this method to measure inconsistencies, by first estimating the consistency index (CI), where CR should not be greater than 0.10. Otherwise, the result of the pairwise comparison should be rejected and the comparison matrix should be revised (Equation 1). In this case, the pairwise comparisons must be reviewed and updated by the decision maker.

The consistency index (CI) of the pairwise comparison matrix was calculated from the ratio between the size of the matrix (n) and its largest eigenvalue (λ_{max}), as shown in Equation 2:

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{2}$$

The random consistency index (RI) was determined empirically by considering a randomly generated sample of 500 positive reciprocal matrices (Phuangpornpitak & Tia, 2013).

The values assigned to RI by Saaty and Vargas (2012), according to the order of the matrix n, are shown in Table 4.

Table 4. Empirical Values for the Random Consistency Index

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

The consistency index (CI) of the pairwise comparison matrix was calculated from the ratio between the size of the matrix (n) and its largest eigenvalue (λ_{max}), as shown in Equation 3:

$$CI = (\lambda max\ -\ n)/(n-1)CI = \frac{\lambda_{max} - n}{n-1} \tag{3}$$

The decision matrix was then filled in to normalize the values assigned to the compared criteria. The weightings for the criteria were determined through pairwise comparison. A total of (n-1) comparisons are required. As proposed by Macedo et al. 2020 and according to Sánchez-Lozano, García-Cascales, and Lamata (2016), the weights were obtained as shown in Equation 4:

$$(w_{C_{ia}}, w_{C_{ib}}, w_{C_{ic}}) = \left[\frac{C_{ia}}{\sum_{i=1}^{n} \quad C_{ic}}, \frac{C_{ib}}{\sum_{i=1}^{n} \quad C_{ib}}, \frac{C_{ic}}{\sum_{i=1}^{n} \quad C_{ia}}\right] \tag{4}$$

Where: w_{ci} represents the experts' weighting of the criteria I, i = 1, 2, 3, and C_i are the pairwise comparisons between the criteria.

The priority vectors for each factor at each level are known as local weights, and the global weights are calculated by multiplying the local weights by factors, subfactors, and sub-subfactors (Alsuwehri, 2011; Hossein, Kang, & Kim, 2015).

From the linguistic terms and their respective fuzzy values, a decision matrix $\tilde{D}$ was constructed (Figure 5). In matrix $\tilde{D}$, x_{ij} represents the value of alternative A_i with respect to criterion C_j, W = [w_1, w_2…, w_{10}] is the weighting vector associated with the criterion, A_m are the alternatives, and x_{mn} are the values determined by the experts.

$$\begin{array}{cc} & \begin{array}{cccc} w_1 & w_2 & \cdots & w_n \\ c_1 & c_2 & \cdots & c_n \end{array} \\ \tilde{D} = \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_m \end{array} & \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \end{array} \qquad i = 1, 2, \ldots, m; j = 1,2, \ldots, n$$

Figure 5. Decision matrix – AHP method

Matrix $\tilde{D}$ was normalized so that the scale would be the same for all criteria (Equation 5). The weightings of the criteria in decision-making problems do not have the same average and not all of them are equally important. The normalized weighted value v_{ij} was calculated using Equation 6.

$$\underline{n}_{ij}, = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} \ (x_{ij})^2}} \qquad j = 1, 2, \dots, n; i = 1, 2, \dots, m \tag{5}$$

$$\underline{v}_{ij}, = w_{ij} \otimes \underline{n}_{ij} \qquad j = 1, 2, \dots, n; i = 1, 2, \dots, m \tag{6}$$

The positive (PIS, A +) and negative (NIS, A-) fuzzy ideal solutions are determined according to Equation 7 and Equation 8, respectively.

$$A^+ = \{\tilde{v}_1^+, \tilde{v}_2^+, \dots, \tilde{v}_m^+\} \tag{7}$$

$$A^- = \{\tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_m^-\} \tag{8}$$

Where: $\tilde{v}_1^+ = (1, 1, 1)$ and $\tilde{v}_1^- = (0, 0, 0)$.

The distances for PIS (D+) and for NIS (D-) were calculated by Equation 9 and Equation 10, respectively.

$$D_i^+ = \sum_{j=1}^{n} \quad d_v\left(\underline{v}_{ij}, \tilde{v}_j^+\right) \tag{9}$$

$$D_i^- = \sum_{j=1}^{n} \quad d_v\left(\underline{v}_{ij}, \tilde{v}_j^-\right) \tag{10}$$

Finally, the approximation coefficients CC_i were calculated for each of the alternatives evaluated, according to Equation 11. The CC_i values vary between 0 and 1. The closer to 1, the higher the priority for that alternative. From this, the final ranking of the alternatives was defined from the CC_i values.

$$CC_i = D_i^- / (D_i^+ + D_i^-) \tag{11}$$

With the results obtained, further analysis is presented in the following sections.

3. Results

This section provides an overview of Brazilian public road infrastructure delay factors. Based on the literature and discussions with experts, two levels of delay factors were found that are most responsible for driving delays in public road infrastructure projects and works in Brazil. The two levels were categorized as main factors (criteria) and sub-factors (sub-criteria). These are believed to be the main causes of delays in road infrastructure and construction projects.

3.1 Selection of Road Infrastructure Delay Factors

Based on the literature review and discussions with experts and academics, the information was synthesized, criteria were selected, and a preliminary list of factors was defined. The first level consists of five main factors: principal contractor; designer; manager; materials, manpower, and equipment; and external factors. This list of criteria was designed according to the 473 factors obtained from articles in the literature that focused on road infrastructure delays. From the selected studies, similar factors that had the same meaning were standardized.

In this process, repeated factors were excluded, leaving a total of 220 factors for road infrastructure delays. From the selected studies, factors that had the same meaning were consolidated into a list of 35 factors. However, many of these factors do not fit the reality of Brazilian road projects. Therefore, these factors would need to be filtered according to the requirements of local projects.

It was clear from this literature review that delays are commonly found in transportation infrastructure projects all over the world. Table 5 contains a list of the top ten delay factors based on the frequency of occurrence and their respective groups.

Table 5. Ranking of the top ten delay factors in road infrastructure projects

nº	Factor	Main Group	Source/Author
1.	Delayed payments to the contractor by the owner	Owner	Nasir, Gabriel & Choudhry (2011) Bekr (2015) Honrao & Desai (2015) Tesfa (2016) Alfakhri, Ismail & Khoiry (2018) Al Hadithi (2018)
2.	Poor/ineffective planning and scheduling	Contractor	Rachid, Toufik & Mohammed (2019) Al Hinai, Widyarto & Bhuiyan (2020) Melaku Belay et al. (2021) Danial & Misnan (2022)
3.	Adverse weather conditions	External	Ellis & Thomas (2003) Nasir, Gabriel & Choudhry (2011) Hasan, Suliman & Malki (2014)
4.	Financial difficulties of the contractor	Contractor	Le-Hoai, Lee & Lee (2008) Kaliba, Muya & Mumba (2009) Nasir, Gabriel & Choudhry (2011)
5.	Problems in the land acquisition process	Owner	Wijekoon & Attanayake (2012) Ekanayake & Perera (2016) Pai et al. (2018) Mohajeri Borje Ghaleh et al. (2021)
6.	Unrealistic schedule	Contractor	Alfakhri, Ismail & Khoiry (2018) Lozano Serna et al. (2018)
7.	Inadequate contractor experience	Contractor	Sohu & Chandio (2019) Bekr (2015) Aziz, Abdel-Hakam (2015) Tesfa (2016)
8.	Lack of construction materials on site	Mat./manpower/equip.	Aforla, Woode & Amoah (2016) Lozano Serna et al. (2018) Karunakaran; Malek; Ramli (2019)
9.	Poor site management and supervision	Contractor	Mejía et al. (2020) Le-Hoai, Lee & Lee (2008) Hasan, Suliman & Malki (2014)
10.	Inadequate design	Designer	Vidalis & Najafi (2002) Chileshe & Berko (2010) Tesfa (2016)

Table 5 shows the top ten factors most frequently found in the literature. The main group for these factors was identified according to some researchers such as Le-Hoai, Lee and Lee (2008); Aziz and Abdel-Hakam (2015); and Mahamid, Bruland and Dmaidi (2017), who classified delays into main groups.

Most of these studies made use of questionnaires and analytical approaches such as the Importance Index, Frequency Index, and Severity Index. The group related to contractors and the group related to owners were the groups that contained the most delay factors.

The results, with regard to frequency according to the literature, provided insight into the delay factors in road infrastructure.

3.1.1 Selection of Criteria

Based on an evaluation of the local context, a new list of criteria was established for public road projects. The criteria were separated into main groups, and selected and adapted for road infrastructure projects in Brazil.

The contractor; designer; manager; materials, manpower, and equipment; and external factors were seen as the main factors in road infrastructure projects that play central roles in the construction phase of these projects in Brazil.

Taking into account the importance and the control mechanisms of the design and construction phases for road transportation infrastructure, this study considered the first level for structuring the hierarchical model to have five main factors: contractor, designer, manager, materials/manpower/equipment, and external factors.

3.1.2 Selection of Sub-Criteria

Following the selection of the factors from the literature and from discussions with experts, the 24 sub-factors (or sub-criteria) were defined and related to public road infrastructure projects in Brazil. These 24 were associated with the main groups as follows: five with the principal contractor; five designer; five manager; four materials, manpower, and equipment; and five external factors. Table 6 shows the name of each factor and sub-factor with its abbreviated ID code.

Table 6. Principal delay factors, according to the experts, in public road infrastructure projects and works in Brazil

Objective	**Main Factors (Criteria) level 1**	**Subfactors (Sub-criteria) level 2**	**ID**	**Code**
Criteria for selection of variables for the causes of delays in road infrastructure projects	Contractor (C)	Unrealistic schedule	Time	C1
		Inaccurate project cost estimate	Cost	C2
		Lack of coordination between construction parties / Poor inspection and/or supervision of contractor / Shortage or lack of qualification of contractor's technical staff / Delay in mobilization of construction site by contractor	Coordination	C3
		Contractor's cash flow problems	Cash Flow	C4
		Operation and operating licenses	License	C5
	Designer (P)	Inadequate experience of the project/design team / Inadequate experience of the consultant/supervisor / Delay in the review and approval of the project/design	Experience	P1
		Design changes requested by consultants/designers	Alterations	P2
		Design changes during construction	Design	P3
		Change of consultant/designer during project execution	Team Changes	P4
		Use of BIM-related technologies in project design	BIM	P5
	Manager (G)	Additional Work / Extra Work / Rework	Work	G1
		Low knowledge of project documents by staff / Lack of database and little experience planning/managing the project	Planning	G2
		Physical characteristics/type of project	Characteristics	G3
		Poor communication and coordination between planner/designer	Communication/coordination	G4
		Specification mismatch (non-conformity)	Inconsistency	G5
	Materials / Manpower / Equipment (MME)	Lack of construction materials on-site / Delayed/slow delivery of materials	Material	MME1
		Scarcity of skilled and unskilled labor / Low labor productivity	Manpower	MME2
		Lack of equipment	Equipment	MME3
		Frequent equipment breakdowns	Defects	MME4
	External Factors (FE)	Adverse weather conditions	Climate	FE1
		Political situation	Politics	FE2
		Economic instability (currency, inflation, etc.)	Economy	FE3
		Delayed response from utility agencies	Public Service	FE4
		Environmental and Natural Resource Issues	Environment	FE5

3.2 Multi-Criteria Analyses – AHP

The questionnaire was applied to three experts. SuperDecisions software was used in this study to help structure the problem by performing a pairwise comparison between the criteria and sub-criteria of the same group (or clusters) in order to obtain the priorities mathematically.

The results from the previous step gave rise to a list of criteria and sub-criteria to be hierarchized in order to apply the model.

3.2.1 Experts

The experts consulted for this study were professionals involved in the public sector, academia, and the execution of Brazilian road infrastructure projects. These experts have experience in publicly-bid road infrastructure projects of between 8 and 15 years, making it possible for the discussions to reflect real project scenarios.

The order of importance of the criteria and sub-criteria based on expert assessment is shown in Table 7, according to the criteria and sub-criteria presented earlier in Table 6.

Table 7. Order of importance of the criteria according to experts

Specialist	Order of importance of criteria	Order of importance of sub-criteria
E1	G>FE>C>P>MME	MME2>FE2>P1>G2>C2>C1>P2>G1>MME4>FE4>G5>C3>P4>FE3>C4>G4>C5>G3>P3>MME1=MME3>FE5>P5
E2	C>MME>P>FE>G	G3>C2>MME1>MME4>G4>FE1>C1>P2>FE4>P33>FE3>P1>P5>MME2>FE2>C5>P4>C3>G5>FE5>MME3>C4>G2>G1>
E3	FE>C>G>MME>P	MME2>G2>C5>P5>FE5>P4>FE4>MME3>FE2>C2>C1>C4>P1>G5>P2>P3>FE3>G1=G3=G4>MME1>FE1>C3>MME4

It is important to note that the three experts differ with regard to the order of importance of the criteria, but both experts 1 and 3 pointed out that the lack of manpower sub-criterion, which belongs to the Materials / Manpower / Equipment (MME) criterion, is one of the most important factors in the cause of delays in Brazilian road infrastructure.

The final priority analysis of the order of importance of the criteria and sub-criteria from the experts' evaluation is presented in Table 8.

Table 8. Final priority of criteria and sub-criteria according to the three experts

Specialist	Order of importance of criteria	Order of importance of sub-criteria
E1, E2, E3	FE>C>G>MMR>P	MME2>G2>FE2>C2>P1>C5>P5>C1>FE4>FE5>G3>MME4>P2>P4>MME1>G4>MME3>FE3>FE1>G1>P3>G5>C3>C4

The experts considered the External Factors criterion to be the most important. Among the sub-criteria in this group are: difficulties with adverse weather conditions, political situation, economic instability (currency, inflation, etc.), delay in response from public service agencies, and issues related to the environment and natural resources.

For the choice of sub-criterion, manpower was pointed out as the most important factor for the problem of delay in Brazilian public road infrastructure. The shortage of skilled and unskilled labor and low labor productivity can be reduced with the proper qualification of the professionals who participate in this sector.

Once the decision rule for each scenario was established, the pairwise comparison between the criteria could be performed. The consistency ratio (CR) for each expert, the highest eigenvalues (λ_{max}) found, and the consistency indices of the judgments (CI) are shown in Table 8.

Table 9. Consistency ratios of the criteria matrices.

Dimension	E1				E2				E3			
		CR	λ_{max}	CI		CR	λ_{max}	CI		CR	λ_{max}	CI
Contractor	0.0927				0.029				0.029			
Designer	0.012				0.015				0.012			
Manager	0.001				0.000				0.000			
Materials/ Manpower/ Equipment	0.009	0.058	5.25	0.06	0.008	0.058	5.43	0.05	0.008	0.05 6	5.28	0.06
External Factors	0.047				0.048				0.051			

3.2.2 Analysis After Adjusting the Sub-Criteria Because of Data Inconsistency

After organizing the criteria hierarchically, the vectors were obtained from the priority and consistency evaluation for the criteria and sub-criteria using the AHP method. In the comparison matrix for the five groups, inconsistencies were present, with some values greater than 0.1. In this case, the questionnaire needs to be revised, since, as Saaty (1980) suggests, inconsistency rates higher than 0.1 are considered unacceptable. One of the possible causes for this result may have been the large number of sub-criteria, which could have been confusing to the experts. The solution adopted was to reduce the number of variables.

A new selection of sub-criteria was performed, which were distributed as follows: three for main contractor; three designer; three manager; three materials, manpower, and equipment; and three external factors, as shown in Table 10.

Table 10. Revised delay factors related to highway infrastructure projects

Objective	**Main Factors (Criteria) level 1**	**Subfactors (Sub-criteria) level 2**	**ID**	**Code**
Criteria for selection of variables for the causes of delays in road infrastructure projects	Contractor (C)	Unrealistic schedule	Time	C1
		Inaccurate project cost estimate	Cost	C2
		Lack of coordination between construction parties / Poor inspection and/or supervision of contractor / Shortage or lack of qualification of contractor's technical staff / Delay in mobilization of construction site by contractor	Coordination	C3
	Designer (P)	Inadequate experience of the project/design team / Inadequate experience of the consultant/supervisor / Delay in the review and approval of the project/design	Experience	P1
		Design changes during construction	Design	P3
		Use of BIM-related technologies in project design	BIM	P5
	Manager (G)	Additional Work / Extra Work / Rework	Work	G1
		Low knowledge of project documents by staff / Lack of database and little experience planning/managing the project	Planning	G2
		Physical characteristics/type of project	Characteristics	G3
	Materials / Manpower / Equipment (MME)	Lack of construction materials on-site / Delayed/slow delivery of materials	Material	MME1
		Scarcity of skilled and unskilled labor / Low labor productivity	Manpower	MME2
		Lack of equipment	Equipment	MME3
	External Factors (FE)	Adverse weather conditions	Climate	FE1
		Political situation	Politics	FE2
		Economic instability (currency, inflation, etc.)	Economy	FE3

A new evaluation was performed using Superdecisions. Because the CR values are less than 0.10 for all experts, the estimated values of the sub-criteria are confirmed to be consistent. By performing another factor selection, new weightings were assigned to the criteria and sub-criteria, based on the expert evaluation of the importance of the evaluated items.

In order to unify the weightings for the obtained criteria and sub-criteria, a homogeneous aggregation was performed. In other words, all experts were considered equally important in the decision. The arithmetic mean was used as an aggregation measure. The criteria and sub-criteria weightings obtained from the homogeneous aggregation are shown in Table 11.

Table 11. Criteria weightings obtained from homogeneous aggregation

Dimension	E1/E2/E3	Sub-criterion	E1/E2/E3
Contractor	0.41638	C1	0.29686
		C2	0.6175
		C3	0.08563
Designer	0.04723	P1	0.33252
		P3	0.13965
		P5	0.52784
Manager	0.15950	G1	0.13501
		G2	0.58416
		G3	0.28083
Materials/Manpower/Equipment	0.16778	MME1	0.73064
		MME2	0.18839
		MME3	0.08096
External Factors	0.20911	FE1	0.74705
		FE2	0.11939
		FE3	0.13356

For this new final priority analysis of the experts' results, the order of importance of the criteria and sub-criteria is presented in Table 8. The order of importance, according to the specialists, was: Contractor>External Factors, Materials, Manpower, and Equipment>Manager>Designer. The indices, in order, were: 0.41638, 0.20911, 0.16778, 0.15950, and 0.04723, respectively.

A new order of importance for the criteria and sub-criteria, based on the experts' evaluations was determined, and this is presented in Table 11, using the same criteria and sub-criteria previously presented in Table 9.

Table 12. New final priority order of importance of the criteria and sub-criteria, according to the three experts

Specialist	Order of importance of the criteria	Order of importance of the sub-criteria
E1, E2, E3	C>FE>MME>G>P	FE1>MME1>C2>G2>P3>P1>C1>G3>MME2>P2>G1>FE3>FE2>C3>MME3

The criterion most responsible for the problem of delay is that related to the Contractor. With regard to sub-criteria, climate, specifically adverse weather conditions, is one of the most important factors in causing delays in Brazilian road infrastructure.

3.2.3 Discussion on the Importance of the Sub-Criteria Within Their Groups

Discussions were realized based on the final priority order of importance of the sub-criteria, as shown in Table 11, and the respective weightings, shown in Table 10.

For the sub-factors related to the Principal Contractor, the classification obtained was: Cost>Time>Coordination. This result reveals that the Cost delay factor, inaccurate project cost estimation, had the highest importance. This result agrees with Honrao Desai (2015) and Tesfa (2016), whose studies were carried out in the contexts of India/Bahrain and Ethiopia.

One point that can be highlighted is that delay directly impacts costs (Karunakaran, Malek, & Ramli, 2019). In Odeck's (2004) study, using data from Norwegian road construction projects over the years 1992–1995, the discrepancy between estimated and actual cost was found to have an average of 7.9%, ranging from 5.9% to 183%. Kassa (2020) estimated that approximately 80% of road construction projects exceed the estimated completion cost. Delays will cause negative impacts on both the contractor and the contractees (Thapanont, Santi, & Pruethipong, 2018), which, in this scenario, could be the manager or the designer. However, inaccurate estimates may be a sign of poor management with poor communication and/or coordination between the planner/designer.

For the sub-factors related to External Factors, the classification determined was: Weather>Economics>Politics. Climate, specifically adverse weather conditions, was the most important within this group. This is because road project activities are more exposed to the weather than other construction projects, dealing with extreme temperatures and flooding rains, among others. This result agrees with the study conducted by Siddiqui & Faheem (2021).

For the factors related to Materials, Manpower, and Equipment, the classification was:

Material>Manpower>Equipment. Material was considered the most important factor. Lack of construction materials on site, and delayed or slow delivery of materials, were seen in studies investigating the causes of delays in road construction projects (Purushothaman & Kumar, 2022).

Mejía et al. (2020) pointed out, with regard to materials issues, that an effective supply chain management strategy will be integrated early in the project life cycle, will properly define the suppliers and materials needed, and will properly plan for procurement, transportation, storage, and access to construction materials (Eriksson, 2015; Khair et al., 2017; Oyegoke & Al Kiyumi, 2017).

For the factors related to the Manager, the classification obtained was: Planning>Characteristics>Work. Planning was considered to be the most important. Insufficient knowledge of project documents by the team, lack of a database, and limited experience in project planning and management are the factors that cause the most delay for managers and professionals. A point that can be highlighted is that the problem of inadequately qualified professionals can be reduced through appropriate training of the managers, which can improve planning and reduce deficiencies.

Regarding the factors related to the Designer, the classification obtained was: BIM>Experience>Design. BIM was the most important, because the use of BIM-related technologies in the preparation of projects can assist in resolving project planning problems, design problems, and defining project characteristics (Costin et al., 2018). To reduce delay, the use of Building Information Modeling technologies to check interference between underground utility lines (Sanchez-Rivera et al., 2017; Costin et al., 2018) and to support planning activities can be highlighted.

In this way, it is possible to see several factors (criteria or sub-criteria) in the AHP method that influence delay in road projects. Pairwise comparisons are performed between the factors to determine the weight and decision-making priority of each problem. The results for the AHP can therefore assist managers in selecting a better solution. The AHP can be used to process uncertain or subjective data and to develop a hierarchical structure based on logical relationships. This structure makes it possible for managers to understand the relationships between each relevant factor, which enables the analysis of additional criteria and the calculation of factor weightings.

4. Discussion

The use of the AHP method, as a tool to identify and prioritize delay factors, can make this process more efficient, rational, and clear for public road infrastructure projects in Brazil. Due to the significance of delays, it is necessary to investigate and analyze the factors that cause them. Although delay cannot be completely avoided, it can be reduced with the necessary precautions.

The hierarchization of the causes of delay provides a mathematical basis to assist in decision-making, reduce associated errors, and improve the overall process. There are several causes or delay factors that have been identified by project management researchers related to highway construction. However, these are characterized in local contexts.

The results of this study show that, in the perception of experts, the Contractor criterion is the most significant in causing delays in Brazilian public road infrastructure projects, followed by External Factors; Materials, Manpower, and Equipment; Manager; and Designer.

The most significant causes of delay that were identified are related to the factors of inaccurate project cost estimation; adverse weather conditions; lack of construction materials on site, late and slow delivery of materials; inadequate knowledge of project documents by the team, lack of a database, and limited experience in project planning and management; and the use of BIM-related technologies in project design.

In this study, the causes of delays in road infrastructure projects were presented based on a literature review, and these causes were identified and prioritized using the AHP method. The framework discussed the delays in the Brazilian public road infrastructure system from the point of view of management, with the AHP method serving as a tool to analyze the experts' answers and decrease the resulting inconsistency rate.

With so many factors attributed to the causes of delay in infrastructure projects, it is necessary to determine those that are most responsible for the delay in project completion. These factors may be responsible for the overall success or failure of this type of project.

In this study, the factors can be mitigated with actions that include the non-acceptance in the bidding process of incomplete projects, which generate erroneous impacts on the estimation of quantities, reflected in the planning. Another recommendation is to invest in the qualification of managers and professionals involved, with better systems and the use of technologies, methodologies, and techniques to reduce the deadline for public works.

In this study, the factors can be mitigated with actions that include the non-acceptance of incomplete projects in the bidding process, which generate errors in the estimation of quantities, which affects the planning. Another recommendation is to invest in the qualification of the managers and professionals involved, with better systems and with the use of technologies, methodologies, and techniques that help public projects meet their deadlines.

As suggestions for future studies, it is recommended that emerging technologies be used to solve these factors through machine learning, with the implementation of prediction models. Another suggestion would be the use of BIM to help minimize errors at various stages of development and replace manual "paper-based" processes with digitized workflows from start to finish, using information from intelligent three-dimensional models.

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