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A Fuzzy Logic Application to Manage Construction-Cost Escalation

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Abstract: In large-scale projects, such as transport infrastructures, the cost-planning phase stands out as one of the most crucial for the project's success. Cost and time overruns, during the construction phase, are often the cause of project failure. A meticulous, conscious, and accurate ex-ante analysis of cost and time assessment can greatly contribute to the efficient and effective completion of a project. Various approaches have been developed to estimate and mitigate cost overruns. Such mitigation is subject to careful analysis of project risks, encompassing construction, environmental, social acceptance, and market risks. In this contribution, we propose the implementation of the risk-assessment tool, suggested by the National Anti-Corruption Authority (ANAC), using fuzzy logic to enhance its effectiveness. Thanks to the implementation of fuzzy prioritizations, the risk matrix and the associated risk levels, which are obtained by combining the event's probability of occurrence and its expected impact on costs, have been clearly and structurally defined. This tool can facilitate risk ranking and, therefore, the implementation of their management strategies during the design and construction phases as well as the consensus-creation process. This application can therefore be used by public authorities as a transparent and manageable tool to assess expected risk during the design and implementation phases of the project.

Keywords: fuzzy logic; multicriteria; cost escalation; risk management; infrastructure projects

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Citation: Canesi, R.; D'Alpaos, C. A Fuzzy Logic Application to Manage Construction-Cost Escalation. *Buildings* **2024**, *14*, 3015. https://doi.org/10.3390/buildings14093015

Academic Editor: Irem Dikmen

Received: 9 August 2024
Revised: 10 September 2024
Accepted: 16 September 2024
Published: 23 September 2024

1. Introduction

In the EU and USA, governments and public administrations are facing nowadays an unprecedented challenge in providing public works and services due to ever more stringent budget constraints, on the one hand, and increasing demand for public works, goods, and services, on the other [1]. Consequently, the public sector is required to become more effective and efficient in procurement to deliver the "best value for money" [2,3]. Procurement design and management are inherently complex, requiring strategic decisions by public buyers, suppliers, and third parties to address contractual, competition, and risk-sharing issues [3–5]. The procurement process typically involves two key phases: awarding and executing the contract. While these phases are closely related, they are often managed separately [6]. Since the work of Laffont and Tirole [4], research has extensively explored procurement efficiency and its challenges, such as cost escalation and time overruns, focusing on information asymmetry, contract incompleteness, and uncertainty in construction or production costs.

Cost escalation and time overruns are indeed a major issue in procurement in Italy as they affect the majority of contracts awarded regardless of the presence of penalties for delays [7–11]. Nonetheless, the economic and engineering literature addresses cost uncertainty differently. Economists consider it as a major cause of contract inefficiency due to information asymmetry. The latter, on the other hand, investigates primarily the effect of cost uncertainty on the supplier's pricing strategy [10]. In detail, uncertainty in estimated investment costs can generate simultaneously significant risks and opportunities, prompting suppliers to adopt opportunistic behaviors, in the form of strategically underpriced bids. This often results in cost escalation and time overruns during the contract-execution phase. This issue is particularly relevant in Italy as testified in the literature [9,12–17]. There is indeed a close relation between court inefficiency and contracts breaches [3,7,18–20]. As previously mentioned, procurement contracts typically include penalty fees for delays. Nonetheless, whether or not these penalties are enforced depends both on the fee and the efficiency of the judicial systems (i.e., the potential duration of court trials). Whenever penalty fees are underestimated, contract renegotiation is costly for public buyers, or courts of law are inefficient (i.e., "justice delayed is justice denied"), evidence shows that procurement contracts often face cost escalation and time overruns. An analysis conducted on a dataset of 45,370 fully completed public-works procurement contracts in Italy during the period 2000–2006 revealed that about 78% of these contracts matured delays. The average delay was about 157 days and the maximum delay exceeded 1500 days and related to transport infrastructures [10]. Similar results were found by other authors [9,12,14,15,17,21,22].

Time and cost overruns are significant in public works related to transport infrastructures [11,23–26]. In this respect, we conducted an analysis on the dataset of 141,526 public procurement auctions for transport infrastructures provided by the Italian National Anti-Corruption Authority (ANAC) over the period 2008–2021 [27]. The dataset comprises information on the reserve price, awarding mechanism, entry restrictions, awarding price, awarded supplier, and details on contract execution (e.g., suspensions, if any, the reason for the suspension, time overruns, and cost overruns). We firstly considered the entire set of observations: (a) the median reserve price is equal to EUR 158,332.8, whereas the mean reserve price is equal to EUR 2,210,893 due to the presence of very large contracts; (b) the median awarding price amounts to EUR 136,655, whereas the mean is equal to EUR 1,800,155.

Since full data are not available for the entire dataset, we divided it into two subsets of contracts. The first subset includes 58,057 observations. It reports the reserve price, the awarding price, the execution time set by the contract, and the final price paid to the supplier. The second subset consists of 49,451 observations. In addition to the information provided in the first subset, it also includes the work's starting date and the work's completion date. We then calculated for the larger subset the median and mean reserve prices, which amount to EUR 158,620 and EUR 392,357, respectively, as well as the median and mean expected contract duration, which are equal to 90 days and 141 days, respectively. The median and mean prices actually paid by the buyer (i.e., the contracting authority) are EUR 175,869 and 414,653, respectively. Consequently, the median and mean cost escalations compared to the reserve price are equal to 12.9% and 15.3%, respectively. Finally, we considered the second subset of contracts, and calculated the following: (a) the actual median and mean contract duration, which are equal to 146 days and 209 days, respectively, and (b) the median and mean delays, which are equal to 17 days and 36.5 days, respectively. It emerged, though, that 30% of the contracts, in the second subset, were completed before the contractual date, possibly due to premium fees for early completion. Only 14% of the contracts were completed on time, while 56% experienced delays. It is worth mentioning, though, that avoiding time and cost overruns is nowadays a major and challenging goal for Italian contracting authorities. This is particularly relevant for public works included in the National Recovery and Resilience Plan (NRRP) and financed via the Next Generation EU funding program. As previously mentioned, estimates on expected investment costs of public works and infrastructures are largely affected by uncertainty, which in turn affects the project riskiness. The higher the volatility of construction costs, the higher the project riskiness and the higher the probability of cost and time overruns. Construction companies operate in risky environments due, for example, to climate conditions, contingencies which may arise at the construction site, and improper infrastructure design. To prevent time and cost overruns, if the efficiency of the judicial system improves and penalty fees are actually enforced, both contracting authorities and construction companies should properly assess (and manage) project risks. Effective risk management is crucial to reduce and control risk [28]. To implement effective risk-management strategies, the identification of risk factors is fundamental and preliminary to the assessment and responding phase [29].

Nonetheless, very often, due to poor design or limited information, and uncertainty during the infrastructure-construction phase, the identification of risks, which may lead to time and costs overrun, is challenging and complex.

The aim of this paper is to provide a formal model, though operative, easy to use, and transparent, to assess the project's risk and its related risk components throughout the design and execution phases of construction projects, and specifically public works. In fact, regardless of the different theoretical methods proposed in the literature, in real-world situations risks are generally identified through experts' (i.e., practitioners and professionals) past experience. In this context, the adoption of the risk matrix proposed by ANAC offers useful insights into potential risks associated with cost estimates and their robustness. This matrix considers the probability of occurrence and the impact at different scales of various cost categories usually included in offers for the awarding of public works procurement contracts. The ANAC matrix, firstly introduced in 2015 by ANAC, was later regulated by Legislative Decree no. 50/2016, and subsequently updated in 2018 and 2023 by ANAC [29,30]. In this paper, we propose a theoretical and methodological framework that draws from the ANAC matrix to rank risk components, from more impactful on cost escalation to less [31]. Considering the presence of multiple evaluation criteria within the ANAC matrix and the need to assess multiple risk categories associated with a complex project, categories that are significantly influenced by the uncertainty and vagueness inherent in the initial project phases, it was decided to employ a multicriteria approach, specifically the Fuzzy Analytic Hierarchy Process (FAHP) model introduced by Van Laarhoven and Pedrycz in 1983 [31]. This model is particularly suited for situations where uncertainty arises from human preferences. The remainder of the paper is organized as follows. Section 2 clarifies the methodological background and offers an insight into the AHP and FAHP; Section 3 provides the description of the FAHP model; in Section 4 the model results are presented and discussed along with an application to a real-world case study; finally, Section 5 concludes the paper.

2. Methodological Background

The AHP has emerged as one of the most widely used methods for multi-criteria decision-making [32,33]. The AHP has been in widespread use in risk evaluation processes, particularly in the construction sector, due to its flexibility and adaptability throughout the life cycle of a construction project [28,34–38]. AHP decomposes decision-making problems into a hierarchical tree consisting of a goal, attributes (or criteria), and alternatives. AHP operates through pairwise comparisons, and the definition and synthesis of priority vectors. Many decision-making tasks resist quantification due to their inherent complexity. Considering these complexities, it is well known that the conventional AHP struggles with evaluating and interpreting uncertainty and vague information during decision-making. Nonetheless, the human mind is capable of managing complex problems by utilizing imprecise knowledge instead of exact information. To address these limitations, the Fuzzy Analytic Hierarchy Process (FAHP) was introduced, combining Fuzzy Set Theory (FST) with AHP [31]. This method employs fuzzy numbers to handle uncertainties, effectively translating human preferences into scores while considering various criteria in the selection process [39].

FST was proposed by Zadeh to mimic human reasoning by making decisions based on approximate information and uncertainty [40]. FST's main objective is to mathematically model uncertainty and vagueness, providing a structured framework for managing "fuzziness". Zadeh defined a fuzzy set as a class of elements with a continuum of grades of membership. Each element (also known as set) is assigned a membership value between zero and one through a membership function. A series of properties and relationships are established for the sets, such as union, intersection, complement, and convexity. Considering the latter feature, the separation theorem is validated without requiring the fuzzy sets to be disjoint. Precisely, these overlapping and non-disjoint conditions allow FST to address the vagueness inherent in human thinking, managing to bypass precise and unambiguous information required by traditional mathematical approaches, often absent in real-world scenarios. FST allows the articulation of complex problems using descriptive linguistic expressions, thus offering interpretive capacity in the answers. As a result, respondents can articulate their opinions more clearly than when providing crisp numerical answers. Thus, the FAHP was developed to address hierarchical issues, effectively managing the uncertainty and imprecision inherent in human judgments.

As said, multicriteria decision-making has been widely applied in the risk evaluation of construction projects. The concept of risk has always been associated with vagueness, leading to various and different definitions by famous economists of the early 20th century such as Keynes, Knight, Kolmogorov, and Von Mises [41–44]. Despite the differences, these definitions commonly link the concept of risk with exposure, probability, and uncertainty [45]. The inherent characteristics of the risk concept render FAHP approaches especially suitable for assessing its effects in complex construction projects, where numerous unknown risk sources exist and decision-making hinges on subjective judgment to be supported by solid logical analysis [46–51].

In the construction sector, risk management is generally divided into four stages: risk identification (i), risk assessment (ii), risk management (iii), and risk monitoring (iv) [52]. The first stage (i) involves drawing up an all-encompassing list of possible risks that could influence and impact the construction project. Many authors divide these lists into groups of risks that share common characteristics, such as financial, economic, market, administrative, political, environmental, and social risks [48,53–57]. Grouping risks according to categories or measures of their probability and likely impact, with a focus on remediations, is widely recommended in the literature [37]. This approach can help support stages (iii) and (iv).

Our study focuses on the second phase (ii), which concerns risk assessment. This phase plays a crucial role in strategic decision-making by offering both quantitative and qualitative evaluations of project risks identified in the previous phase. Numerous advanced techniques, taking advantage of the recent Industry 4.0 revolution coupled with the rapid advancements in data science disciplines, have been designed to tackle cost overruns, including structural equation modeling, Monte Carlo simulations, decision support systems, and multi-criteria decision modeling, enhanced and supported by data-driven methods and by the implementation of artificial intelligence-based models, such as integrated BIM-Augmented Reality [58–65]. Specifically, various multicriteria approaches have been applied in the literature to establish a hierarchical risk-breakdown structure for classifying the diverse selected risks [66]. Among the above-cited approaches, AHP and FAHP, introduced earlier in this section, provide significant support for decision-makers [67,68]. Such approaches are also widely used in the field of construction risk management, particularly for identifying potential risks, ranking them, and estimating the cost and time overruns they may cause. Recently, several studies have applied these models to the domain of large-scale projects. Fuzzy logic has been employed to rank, in construction projects, top risks objectively by establishing criteria for experts based on cost impact and probability. These studies consider factors such as the cost impact of risks, the type of project, its location, the contract type, the project's evolution over time, and other construction-related risks [69–72]. To determine the probability of risk occurrence, along with making predictions about cost and time overruns, methods such as FAHP (Fuzzy Analytic Hierarchy Process), Monte Carlo Simulations, and the Program Evaluation Review Technique (PERT) have been applied in combination [73]. However, the Risk Probability and Impact Severity Matrix proposed in some of these studies does not account for the systematization and distribution of the severity of impacts. Our study addresses this gap by providing a structured and rigorous definition of the impact–probability matrix, bringing clarity and accuracy to the risk severity distributions previously suggested by other studies. Regarding FAHP approaches, the most common ones include interval, triangular, and trapezoidal FAHP [49,74]. The interval approach uses an interval number to express the relative importance of a factor, unlike the crisp number used in the classic AHP approach. Similarly, the triangular and trapezoidal FAHP approaches use a triangular or trapezoidal number to express relative importance in pairwise comparisons. In the triangular approach, the central number represents the most likely value, while the two base values represent minimum, on the left, and maximum, on the right, potential values. Due to its nature of associating a value with a probability of occurrence and a possible range, the triangular fuzzy AHP is well-suited for risk assessment in construction projects [75].

Finally, the third and fourth stages (iii and iv) focus on risk management and monitoring, particularly in the areas of safety, cost, and timing within construction projects. Numerous studies have proposed comprehensive and systematic risk-management frameworks covering all phases of construction projects, describing the cause-and-effect relationships among the identified risk factors [74,76–80].

Despite the expanding body of research on employing FAHP for risk assessment in the construction sector, three primary concerns persist [48]. Firstly, risk is often not evaluated as the combination of its probability of occurrence and its impact on projects [47,48,81]. Secondly, consistency analysis of FAHP matrices is frequently neglected in practical applications [46,82–84]. Lastly, the complex algorithms used in FAHP pose challenges for practical implementation [82,85]. Our contribution aims to address the first issue specifically, by applying an impact–probability matrix for assessment, as described in the following section.

3. The Model

Based on the contractor's objective of minimizing the potential for cost escalation in the project, a decision aid model is developed. The decision problem is formulated as a classification issue. Essentially, any decision problem involves partitioning a set of actions—specifically, in our case, the matrix combination of risks associated with the construction development project—based on certain properties and reducing it to the aggregation of ordering relations applied to the set. To establish the ranking of the identified risks, we utilized a Fuzzy AHP model to consolidate preferences and derive an overall ranking structure for each risk alternative as defined in a risk matrix table.

As previously specified, a Fuzzy Analytic Hierarchy Process (FAHP) is an extension of the traditional Analytic Hierarchy Process (AHP) that incorporates fuzzy logic to handle the uncertainty and vagueness associated with decision-making problems. AHP is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. It involves structuring the decision problem as a hierarchy tree, pairwise comparison formulation for each hierarchy level, and ranking calculation.

Fuzzy logic deals with reasoning that is approximate rather than fixed and exact. Unlike binary logic where variables must be true or false, fuzzy logic variables may have a truth value that ranges between 0 and 1.

Fuzzy AHP combines the strengths of AHP and fuzzy logic to provide a robust decision-making framework that can effectively handle the complexity and ambiguity inherent in many real-world problems. The FAHP is therefore a hybrid method which is developed according to the steps presented in Figure 1, which combine AHP and fuzzy approach flow charts proposed by De Felice et al. and Liu et al. [86,87].

The development of a fuzzy AHP model mirrors the general process of an AHP approach but with some differences, particularly in the judgment-formulation phase and the calculation of fuzzy weights. The white and light gray boxes indicate the common steps between AHP and FAHP; however, different techniques are applied in the calculation steps shown in the light gray boxes. Otherwise, the dark gray box represents steps unique to FAHP, not present in AHP. We will now illustrate the phases of FAHP, specifically using the Triangular Fuzzy Number (TFN) approach:

- Phase I: Problem structuring.
- Phase II: Definition of the expert team.
- Phase III: Construction and validation of the hierarchy.
- Phase IV: Fuzzy pairwise comparisons and aggregation of experts' judgments; calculation of the fuzzy weights for each criterion, subcriteria, and ratings; defuzzification of the fuzzy weights.

- Phase V: Consistency index calculation.
- Phase VI: Final ranking of alternatives and sensitivity analysis.

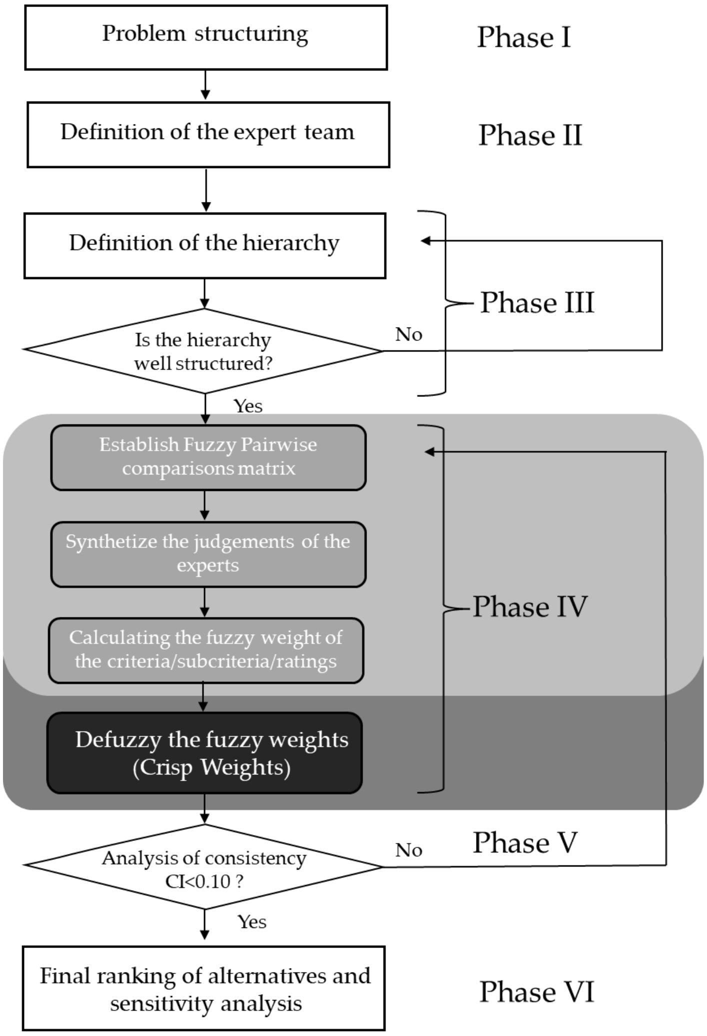


Figure 1. Fuzzy AHP flowchart.

In this study, we implement an FAHP approach to rank risks in construction development projects from most risky to least risky. This tool offers significant potential value for both contracting authorities and contractors in managing risks and therefore potential cost escalation in construction projects; in large-scale projects in particular, mismanagement can lead to exponential increases in time and costs. In detail, we developed and implemented an FAHP absolute model to rank twenty risk levels (from r1 to r20), as detailed in Table 1. These 20 alternatives represent the twenty different possible arrangements given by the combination of five levels of probability of occurrence and four levels of impact on costs. In a previous study by Gallo and Canesi [29], the list of risks and an approach for their assessment proposed by the National Anti-Corruption Authority (ANAC) were considered. Building on that study, our research draws on the same risk-classification and risk-assessment matrix associated with a construction project. In their study, the authors addressed the stochastic nature of events by assessing risks probabilistically. They evaluated potential unfavorable outcomes compared to initial forecasts, using a matrix (reproduced here in Table 1) that categorizes risks into five levels of occurrence probability and four impact categories on costs. The levels of specific risk occurrence probabilities were defined as follows: quite impossible (P_a) ∈]0%,1%[; unlikely (P_b) ∈ [1%,25%[; likely (P_c) ∈ [25%,50%[; very likely (P_d) ∈ [50%,75%[; and almost certain (P_e) ∈ [75%,100%[. The impact on cost categories corresponds to a possible percentage increase in the estimated base cost. Impact Levels are classified as light (I_a) implying an increase in costs of [0%,5%[; mediocre (I_b) implying an increase in costs of [5%,10%[; severe (I_c) implying an increase in costs of [10%,20%[; and critical (I_d) implying an increase in costs of [20%,∞[. In the study by Gallo and Canesi [29], risk levels based on the combination of probability and impact were visually assigned using colors across the 20 positions in the contingency table. In contrast, our current research employs the FAHP absolute model to rank these 20 potential risk level combinations (Table 1). This approach enables us to assign weights to each identified risk in a construction project, thereby creating a prioritized list from the most risky to the least risky.

Table 1. Risk matrix codes representing the alternatives (from r1 to r20).

Risk Matrix Code				**Impact on Costs**			
				Light **I_a** **[0%,5%[**	**Mediocre** **I_b** **[5%,10%[**	**Severe** **I_c** **[10%,20%[**	**Critical** **I_d** **[20%,∞[**
Probability of risk occurance	Quite impossible	P_a	]0%,1%[	r1	r2	r3	r4
	Unlikely	P_b	[1%,25%[	r5	r6	r7	r8
	Likely	P_c	[25%,50%[	r9	r10	r11	r12
	Very likely	P_d	[50%,75%[	r13	r14	r15	r16
	Almost certain	P_e	[75%,100%[	r17	r18	r19	r20

As outlined previously, the FAHP approach is articulated into six stages (Figure 1). The initial stage involves problem structuring to delineate the decision problem statement (i.e., ranking problem) and establishing the hierarchy's objective. Phase II involves identifying actors, stakeholders, objectives, perspectives, and alternatives.

In Phase III, the expert team structured the risk hierarchy, including criteria ratings (Figure 2). The top tier of this hierarchy represents the overarching goal: ranking risk levels based on their potential probability of occurrence and impact on construction cost escalation. The criteria (Probability of Occurrence and Impact on Cost) and their respective ratings (five levels for probability and four for impact) were defined. These ratings correspond to the different levels of probability and impact previously identified in Table 1. Ultimately, at the base of the hierarchical structure are the alternatives under investigation, namely the twenty risk levels (from r1 to r20). This hierarchy was validated by both the decision-maker and a panel of experts.

After structuring the hierarchy, Phase IV follows. It involves establishing fuzzy pairwise comparison judgments and synthesizing them. Specifically, the hierarchical structure establishes relationships and determines the relative importance of criteria, sub-criteria, and ratings through pairwise comparisons. At each hierarchical level, elements are compared in pairs based on their control criterion or sub-criterion. In traditional AHP, these pairwise comparisons are made using a ratio discrete scale known as Saaty's fundamental scale [33]. Although Saaty's scale is simple and easy to use, it does not account for the uncertainty associated with mapping one's perception or judgment to a number [88]. As previously mentioned, triangular membership functions have been effectively used in construction risk analysis [46,48,85,89]. Fuzzy logic uses the triangular fuzzy scale to extend classical logic to handle the concept of uncertainty. Unlike traditional binary logic where variables are either true or false, fuzzy logic allows for values between 0 and 1, representing varying degrees of truth. This is particularly useful when dealing with imprecise or ambiguous information. By using fuzzy numbers, you can capture a range of opinions and preferences. Triangular membership functions are therefore adept at handling the imprecision of assessments using linguistic variables in FST modeling [90]. Therefore, to account for this vagueness and improve upon the conventional nine-point

Saaty scale, we applied a fuzzy approach by converting semantic judgments into triangular fuzzy judgments ($\tilde{1}$ to $\tilde{9}$), see Table 2.

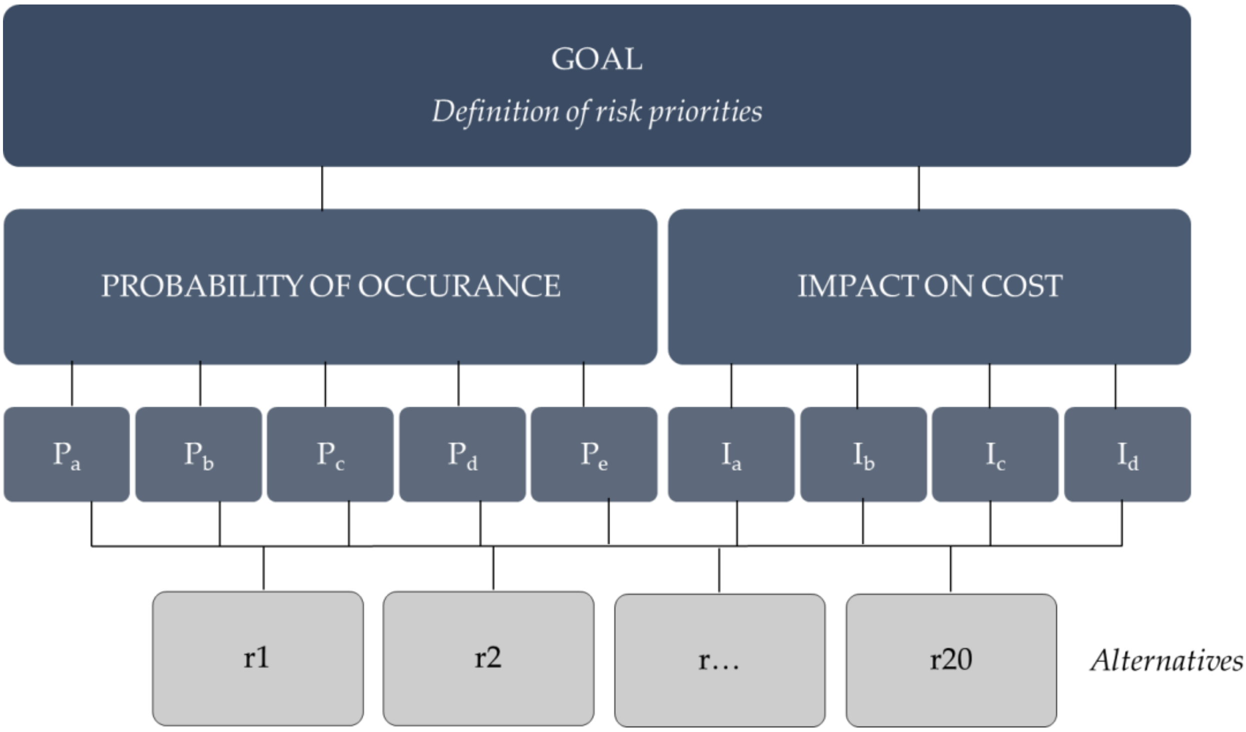


Figure 2. FAHP absolute model hierarchy. Authors' elaboration.

Table 2. Triangular fuzzy scale. Authors' elaboration from Huang et al. and Hu et al. [91,92].

Crisp Number	Definition	Explanation	Triangular Fuzzy Number (TFN)	Reciprocal TFN's
1	Equal importance	Two activities contribute equally to the objective	(1, 1, 1)	(1, 1, 1)
3	Moderate importance	Experience and judgment strongly favor one activity over another	(2, 3, 4)	(1/4, 1/3, 1/2)
5	Strong importance	Experience and judgment strongly favor one activity over another	(4, 5, 6)	(1/6, 1/5, 1/4)
7	Very strong or demonstrated importance	An activity is strongly favored, and its dominance demonstrated in practice	(6, 7, 8)	(1/8, 1/7, 1/6)
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation	(8, 9, 10)	(1/10, 1/9, 1/8)
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed		

To account for the imprecision inherent in human qualitative assessments, nine TFNs have been defined, each with its corresponding membership function, as illustrated in Figure 3.

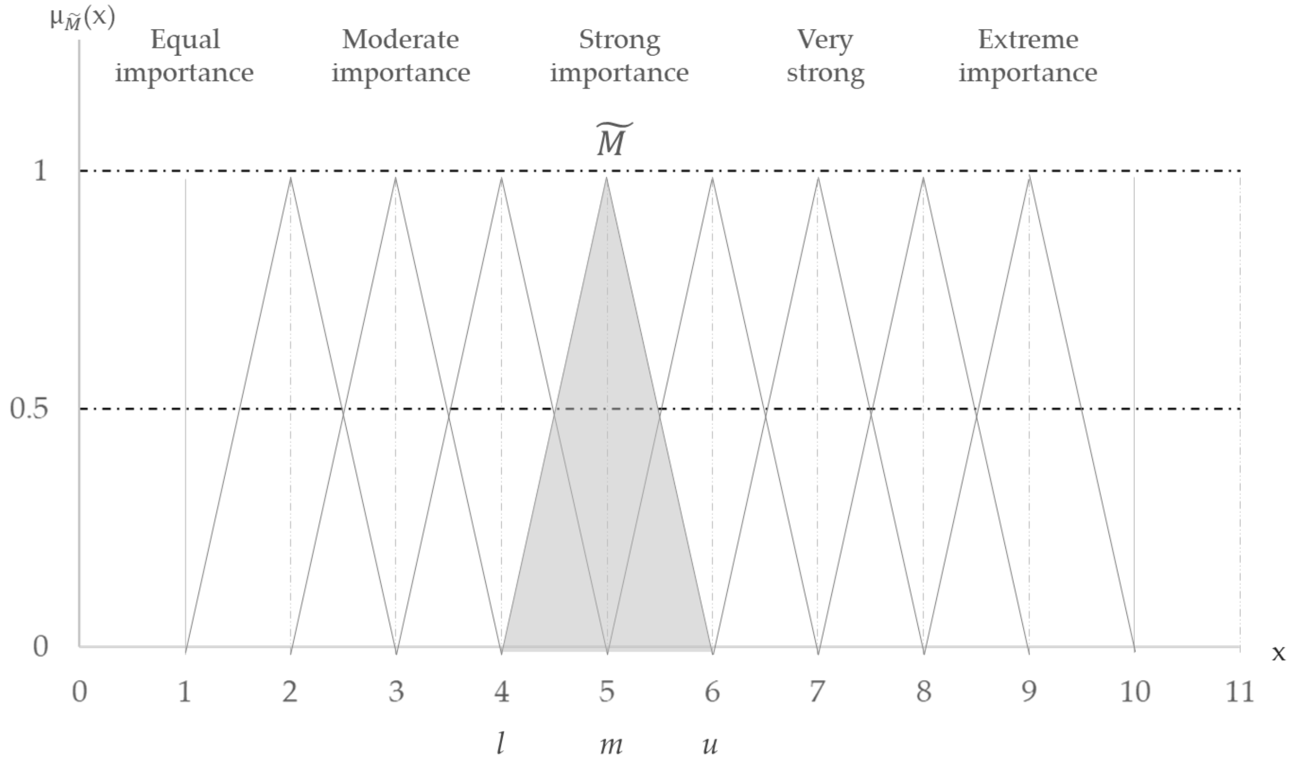


Figure 3. Triangular membership function representation of triangular fuzzy numbers $\tilde{1}, \tilde{2}, \tilde{3}, \tilde{4}, \tilde{5}, \tilde{6}, \tilde{7}, \tilde{8}, \tilde{9}$. Authors' elaboration from Liang et al. [93].

A TFN on $\mathbb{R}$, according to Pedrycz [90], can be indicated as $\tilde{M} = (l,\ m,\ u)$, where $l < m < u$. The membership function $\mu_{\tilde{M}}(x)$ of $\tilde{M}$ is an isosceles triangle with base within the interval $[l, u]$ and vertex at $x = m$. The membership can therefore be defined as follows (1):

$$\mu_{\tilde{M}}(x) = (l\ ,u) = \begin{cases} \frac{x-l}{m-l},\ l \le x \le m \\ 1,\ x = m \\ \frac{u-x}{u-m},\ m \le x \le u \\ 0,\ otherwise \end{cases} \tag{1}$$

Further, the Fuzzy Reciprocal Number is represented by (2):

$$(l,\ m,\ u)^{-1} \approx \left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l},\right) \tag{2}$$

Phase IV also includes calculation of the fuzzy weight of each hierarchy level, incorporating ratings, and concludes with defuzzification, to convert the defined fuzzy weights into crisp weights. Similar to Saaty's AHP eigenvector calculation, in FAHP, TFNs are used in the judgment matrices as interval arithmetic to solve the fuzzy eigenvector [94]. Squared Fuzzy Comparison Matrixes (FCMs), by using FTNs, are defined as follows:

$$\tilde{M} = \tilde{m}_{ij} = \begin{array}{c|cccc|} & \tilde{M}_1 & \tilde{M}_2 & \dots & \tilde{M}_n \\ \tilde{M}_1 & 1 & \tilde{m}_{12} & \dots & \tilde{m}_{1n} \\ \tilde{M}_2 & \frac{1}{\tilde{m}_{12}} & 1 & \dots & \tilde{m}_{2n} \\ \dots & \dots & \dots & \dots & \dots \\ \tilde{M}_n & \frac{1}{\tilde{m}_{1n}} & \frac{1}{\tilde{m}_{2n}} & \dots & 1 \end{array} \tag{3}$$

The value of $\widetilde{m}_{ij}$ relates to the relative importance (using TF Scale) of a specific criterion, sub-criterion, or rating $\widetilde{M}_i$ when compared to another criterion, sub-criterion, or rating $\widetilde{M}_j$. The comparisons on the main diagonal are set to 1, reflecting the inherent preference relation, while the elements in the lower part of the matrix are reciprocals of the TFNs in the upper triangle, as illustrated in Table 2. After defining the FCM, pairwise comparisons are used to fill the matrixes. Finally, in Phase IV, the fuzzy eigenvectors are calculated for each row *i*, following their defuzzification and normalization. Defuzzification is an essential step following fuzzification because it translates fuzzy results into a clear, actionable number, called crisp value. Since, practical applications require specific numeric values for implementation, e.g., you might need a precise risk score to allocate resources or prioritize actions, defuzzification provides a single, clear value that simplifies the decision-making process.

Conclusively, before defining the final ranking of alternatives and performing the sensitivity analysis, the consistency analysis needs to be performed in Phase V. To check the judgements' consistency, the consistency index (CI) is calculated as follows:

$$\mathrm{CI} = \frac{(\lambda_{max} - n)}{(n-1)} \tag{4}$$

where λ_{max} is the maximum defuzzied eigenvalue and n is the number of elements of the FCM ($\widetilde{M}$). For consistency to be satisfied, CI < 0.1. The closer λ_{max} is to n, the smaller the deviation index is, leading to more consistent results.

Finally, the alternatives are ranked according to their global priorities (or global weights; in the case of FAHP, they are called Crisp Priority Values) by applying a weighted-sum aggregation method across the hierarchical levels. All the above-mentioned phases were conducted through focus group discussions. The experts involved in the focus group included stakeholders from both sides, i.e., the contracting authority and the contractors. This group was intentionally composed of professionals with diverse expertise across various fields, ensuring that a broad range of perspectives and insights could be considered during the discussions. By involving individuals with different areas of specialization, the focus group aimed to comprehensively address the complexities of research and foster a more holistic approach to problem-solving. In this phase, brainstorming sessions were favored over individual interviews because they facilitated consensus building based on the final set of weights. These weights were determined by calculating the geometric means of expert judgments in line with group decision-making theory.

4. Results and Discussion

Implementing phase IV of the Crisp Value Priority Vector calculation, we calculated the geometric mean to synthesize the experts' judgments into local priorities, using the fuzzy eigenvalue approach, as described in the Methods Section. This phase also involved aggregating the group local priorities to establish global Crisp Value Priorities among criteria and sub-criteria, as detailed in Table 3.

In the process of determining global priorities, we utilized the weighted geometric mean aggregation method to capture and embed preference data derived from the local pairwise comparison matrices of each criterion and rating.

As shown in Table 3, The criterion "Probability of Occurrence" plays a major role, with priority of 0.644. The ranking underscores that events with high probabilities but minimal impact on project forecasts should warrant great consideration in mitigation strategies and risk assessments. This outcome underscores how the stochastic nature of the concept of risk is embedded in the judgments expressed by the focus group's stakeholders. Table 3 also indicates that higher ratings (Probability of Occurrence and Impact on Cost) correspond to higher Crisp Value Priority Vectors. Finally, in Table 4, we present the Crisp Priority Vectors for the 20 risk alternatives. The Crisp Priority Vector for each Alternative was calculated, as presented in Table A1 (Appendix A), by adding the weight priorities for each rating (P_x e I_x) associated with each alternative.

Table 3. Criteria and sub-criteria Crisp Value Priority Vectors.

	Criteria	**Crisp Value Priority Vector (Normal)**	**Ratings**	**Crisp Value Priority Vector (Normal)**	**Crisp Value Priority Vector (Ideal)**	**Weighted Priorities**
Goal	Probability	0.6439	P_a	0.059	0.126	0.081
			P_b	0.077	0.165	0.107
			P_c	0.131	0.282	0.182
			P_d	0.268	0.576	0.371
			P_e	0.465	1.000	0.644
	Impact	0.3561	I_a	0.097	0.181	0.064
			I_b	0.131	0.244	0.087
			I_c	0.236	0.440	0.157
			I_d	0.536	1.000	0.356

Table 4. Alternatives' Crisp Priority Vectors.

		Impact on Costs							
		I_a		**I_b**		**I_c**		**I_d**	
Probability	P_a	r1	0.146	r2	0.168	r3	0.238	r4	0.438
	P_b	r5	0.171	r6	0.193	r7	0.263	r8	0.463
	P_c	r9	0.246	r10	0.269	r11	0.339	r12	0.538
	P_d	r13	0.436	r14	0.458	r15	0.528	r16	0.538
	P_e	r17	0.708	r18	0.731	r19	0.801	r20	1.000

Based on the results from our FAHP model implementation, r20 is identified as posing the highest potential risk, demanding attention from both contracting authorities and contractors. They may opt to deploy assessment, corrective, and managerial tools specifically targeting risks ranked highest in our model. Given the frequent extensions of timelines and budget overruns in public construction projects, it is crucial for involved stakeholders to develop effective risk assessment and mitigation tools. These tools should identify the most critical project risks. Our model addresses this requirement by offering a clear and practical risk ranking, enhancing the interpretability and application of risk matrices. To test our ranking model, we applied this approach to a case study involving a recently completed section of an Italian State Road.

Case Study Application

The case study is situated in the Province of Treviso, within the Municipality of Vittorio Veneto in the Venetian Prealps, and is referred to as "State Road No. 51 of Alemagna Vittorio Veneto Variant" (SSv-51). Initiated in 1987 by the National Autonomous Roads Company (Azienda Nazionale Autonoma delle Strade, ANAS S.p.A.), a public Italian national joint-stock company responsible for managing state infrastructure, roads, and highways, this project has experienced numerous modifications over the years. These changes were prompted by non-compliance with urban planning regulations, resulting in the project being split into two subsequent road sections. In 2012, only one of the two variants received final approval while the other was discontinued. The approved variant underwent multiple revisions due to existing environmental plans and regional restrictions. The final design was completed and approved in 2017. Further details about the case study and the infrastructure project can be found in the works of Gallo and Canesi [29].

The current study analyzes the risks identified and classified in this infrastructure project, using them as alternatives in our FAHP Model. In Appendix A (Table A2), we include the risk analysis from a previous study that examined this specific infrastructure project's risks [29]. The goal of Canesi and Gallo's study was to develop a tool for assessing and managing risks in construction projects by identifying, analyzing, and evaluating uncertainty factors to minimize their probability and impact, thereby maximizing the project's chances of successful completion. Their risk analysis aimed to pinpoint vulnerable risks linked to potential unforeseen events and to devise strategies for mitigating their impact, recognizing the impossibility of completely eliminating these risks. The study utilized a risk list previously proposed by ANAC, which categorized risks into four main groups: Construction Risks (RCs), Performance Risks (RPs), Demand Risks (RDs), and Other Risks (ROs). Each category included various specific risks such as Construction Risk, Design Risk, Administrative Risk, Eminent Domain Risk, Performance Risk, and Risk of Interference, among others. For a detailed list and descriptions of each risk, refer to Table A2. After identifying strategies for risk elimination or mitigation, a risk matrix was developed to catalog and evaluate each risk based on its probability of occurrence and its expected impact on the project, as detailed in Table A2.

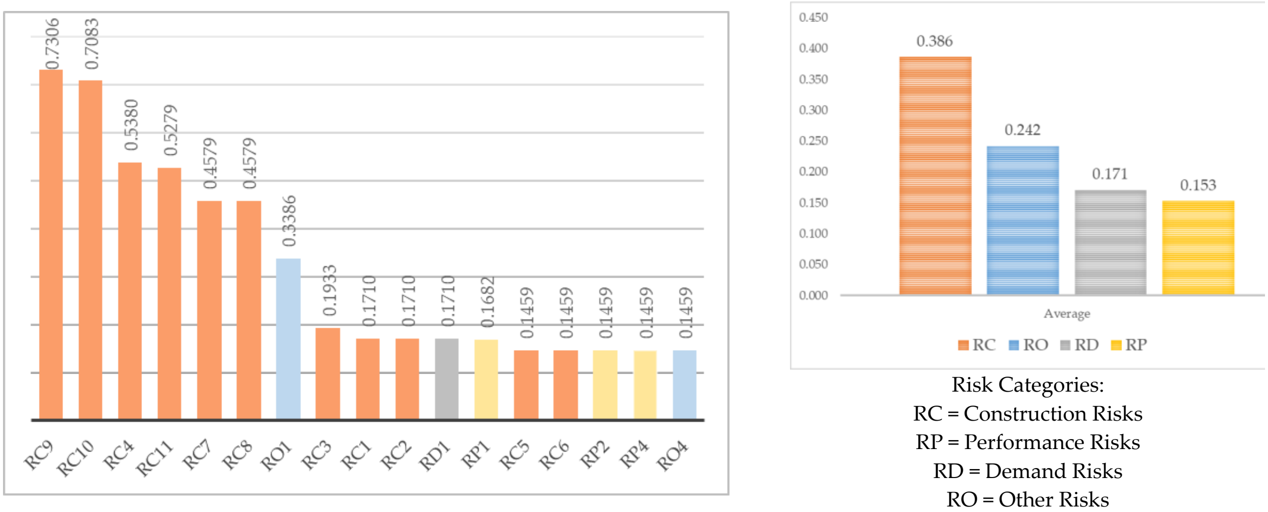
Building on the risk analysis combining the probability of occurrence and impact on costs, as proposed in the previous study, we aim to apply our FAHP model's results to each risk, as classified in Table A2. In Table 5, we assign each risk, based on the estimated ratings, its Risk Matrix Code and, subsequently, the Crisp Priority Value previously calculated in Table 4.

Table 5. Infrastructure project's risk Priority Values.

Risk Code	Probability of Risk Occurrence	Impact: Costs Overrun	Risk Matrix Code	Crisp Priority Value
RC1	P_b	I_a	r5	0.1710
RC2	P_b	I_a	r5	0.1710
RC3	P_b	I_b	r6	0.1933
RC4	P_c	I_c	r12	0.5380
RC5	P_a	I_a	r1	0.1459
RC6	P_a	I_a	r1	0.1459
RC7	P_d	I_b	r14	0.4579
RC8	P_d	I_b	r14	0.4579
RC9	P_e	I_b	r18	0.7306
RC10	P_e	I_a	r17	0.7083
RC11	P_d	I_c	r15	0.5279
RP1	P_a	I_b	r2	0.1682
RP2	P_a	I_a	r1	0.1459
RP4	P_a	I_a	r1	0.1459
RD1	P_b	I_a	r5	0.1710
RO1	P_c	I_c	r11	0.3386
RO4	P_a	I_a	r1	0.1459

According to the Priority Values, we ranked each risk component, as shown in Figure 4a, from highest to lowest. The higher values correspond to risks with a greater probability of occurrence and a more significant impact on associated costs. Based on this ranking, the five most critical risks to address first and with greater attention are (i) Eminent domain risk—RC9; (ii) Environmental and/or archaeological risk—RC10; (iii) Risk of inaccurate assessment of construction costs and project timelines—RC4; (iv) Risk of interference (RC11); and (v) Commissioning risk (RC7) and Administrative risk (RC8) ranked in the same place. The weighted average vectors for each of the four risk categories (RC in orange, RP in blue, RD in yellow, and RO in green), as illustrated in Figure 4b, show that the

Construction Risk (RC) category has the highest crisp value, with an average priority vector of 0.386. The Demand Risk category ranks second with a value of 0.242.



Risk Categories:
RC = Construction Risks
RP = Performance Risks
RD = Demand Risks
RO = Other Risks

(**a**) (**b**)

Figure 4. (**a**) Alternative risk ranking; (**b**) risk categories' average Crisp Value.

These results confirm the need to prioritize attention to risks associated with the construction phase of the project (RC), which include costs related to delays, non-compliance with project standards, cost increases, technical issues, and the potential failure to complete the project. In second place, risks related to the Demand Risk (RD) category are placed, which involves varying volumes of service demand that the concessionaire must meet. This includes the risk of a lack of users and, consequently, future cash flow shortfalls. These findings aid both the contracting authority and the contractor in managing risks throughout all phases of the project. This support is essential for preventing cost escalations, which are one of the main causes of failure in significant projects. By identifying the most critical risks, it becomes possible to calculate the potential cost escalation of each risk associated with different cost categories. This is achieved through levels of increase weighted according to the probability of occurrence, defining the Estimated Risk Value, as performed by Gallo and Canesi [29].

5. Conclusions

The construction industry faces persistent challenges in productivity and efficiency, largely due to its dynamic and project-based nature, which fosters high uncertainty and risk. Effective risk management is crucial to mitigate these challenges, starting with accurate risk identification, assessment, and management strategies. Traditional methods often rely on expert judgment, but these can be limited by the inherent uncertainty and vagueness in early project stages. To address inherent vagueness, this study proposed a Fuzzy Analytic Hierarchy Process (FAHP) model tailored to rank risks influencing construction cost escalation. By integrating fuzzy logic with AHP, we addressed the complexities of risk evaluation, accommodating imprecise information and subjective judgments inherent in real-world decision-making.

Our application of the FAHP model to a case study on the SSv-51 infrastructure project exemplifies its effectiveness in prioritizing risks. Through structured hierarchical analysis and fuzzy pairwise comparisons, we identified and ranked risks based on their probability of occurrence and impact on cost escalation. This approach not only enhances decision-making by providing clear and interpretable risk rankings but also supports stakeholders in allocating resources more effectively to mitigate high-priority risks.

The findings underscore the importance of integrating advanced decision support tools like FAHP in construction project management. By enhancing risk visibility and prioritization, stakeholders can proactively manage uncertainties that often lead to project delays and budget overruns. The identified risks, such as eminent domain issues and environmental risks, highlight critical areas for intervention to safeguard project success.

Our study is focused on a specific infrastructure project, which may limit the generalizability of the findings to other types of construction projects. However, moving forward, the FAHP model can be further refined and applied in broader contexts within the construction industry, accommodating diverse risk landscapes and enhancing overall project resilience. In the future, this approach could also be applied to different phases of construction. It could be used as a dynamic tool for ongoing cost management during the construction process and as an ex-post control instrument. This would enhance its utility as a comprehensive risk-management tool in diverse construction contexts. Furthermore, future research efforts should focus on refining fuzzy logic applications, improving consistency-analysis methods, and validating results across different project types and scales. In conclusion, our study contributes to advancing the field of construction risk management by providing a robust framework for assessing and prioritizing risks. By leveraging fuzzy logic within the FAHP model, we offer a practical toolset for enhancing decision-making and mitigating cost-escalation risks in complex construction projects.

Author Contributions: Conceptualization, R.C. and C.D.; methodology, R.C.; software, R.C.; formal analysis, R.C.; data curation, R.C.; writing—original draft preparation, R.C. and C.D. (Introduction); writing—review and editing, R.C. and C.D. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by NOP on Research and Innovation (PON Ricerca e Innovazione) 2014–2020, Asse IV–Action IV.4 and Action IV.6 “Research Contracts on Green Themes” (Ministry of University and Research MUR—DM 1062/2021), Towards green transition: new indicators for the assessment of territorial projects development (TGTIndex), Cod. 19-G-14046-1. The views and opinions expressed are solely those of the authors.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

Table A1. Alternatives' priority vector.

Criteria	Alternatives Rating	r1	r2	r3	r4	r5	r6	r7	r8	r9	r10	r11	r12	r13	r14	r15	r16	r17	r18	r19	r20
Probability	P_a	0.081	0.081	0.081	0.081	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	P_b	0.000	0.000	0.000	0.000	0.107	0.107	0.107	0.107	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	P_c	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.182	0.182	0.182	0.182	0.000	0.000	0.000	0.182	0.000	0.000	0.000	0.000
	P_d	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.371	0.371	0.371	0.000	0.000	0.000	0.000	0.000
	P_e	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.644	0.644	0.644	0.644
Impact	I_a	0.064	0.000	0.000	0.000	0.064	0.000	0.000	0.000	0.064	0.000	0.000	0.000	0.064	0.000	0.000	0.000	0.064	0.000	0.000	0.000
	I_b	0.000	0.087	0.000	0.000	0.000	0.087	0.000	0.000	0.000	0.087	0.000	0.000	0.000	0.087	0.000	0.000	0.000	0.087	0.000	0.000
	I_c	0.000	0.000	0.157	0.000	0.000	0.000	0.157	0.000	0.000	0.000	0.157	0.000	0.000	0.000	0.157	0.000	0.000	0.000	0.157	0.000
	I_d	0.000	0.000	0.000	0.356	0.000	0.000	0.000	0.356	0.000	0.000	0.000	0.356	0.000	0.000	0.000	0.356	0.000	0.000	0.000	0.356
Crisp Priority Value		0.146	0.168	0.238	0.438	0.171	0.193	0.263	0.463	0.246	0.269	0.339	0.538	0.436	0.458	0.528	0.538	0.708	0.731	0.801	1.000

Table A2. Risk matrix applied to the analyzed project, including probability of risk occurrence and estimated impact on costs. Source: Gallo and Canesi, 2023 [29].

Risk Category	Risk Name	Risk Code	Description	Interference with the Project	Probability of Risk Occurrence *	Impact: Costs Overrun **
Construction Risks	Planning/Design Risk	RC1	The risk associated with potential changes and adjustments to the executive project due to mistakes or oversights, which may lead to substantial delays and escalated costs.	The current executive project was drawn up on the basis of the definitive one, which in turn is the result of a long process of design and modifications in compliance with regulations and suggestions from the Superintendency for Architectural and Landscape Heritage. Therefore, the project was revised several times in order to minimize possible design errors.	P_b	I_a
	Discrepancy Risk	RC2	The risk stemming from the possibility that construction work deviates from the executive project due to non-compliance with design standards and on-site construction errors.	The risk of discrepancy is mitigated by the numerous investigations, inspections and core samplings carried out on site.	P_b	I_a

Table A2. *Cont.*

Risk Category	Risk Name	Risk Code	Description	Interference with the Project	Probability of Risk Occurrence *	Impact: Costs Overrun **
Construction Risks	Risk of increase in production costs	RC3	Risk due to the possibility of an increase in the costs of production factors or the need to replace them with respect to those listed in the approved bill of quantities.	This risk is very sensitive to the socio-economic factors in which the project is being executed. Construction is taking place during the pandemic period which has caused not only an increase in prices but also a delay in the delivery of materials.	P_b	I_b
	Risk of inaccurate assessment of construction costs and project timelines	RC4	Risk associated with an incorrect ex-ante assessment of the project costs and time-schedule.	This risk is very high in large infrastructure projects where ex-ante estimates are often disregarded by unexpected events and situations that occur on site, such as unforeseen circumstances that increase the estimated costs. The subject has a very detailed time schedule' project and a exhaustive bill of quantities but despite this, being a large work, it is subject to this specific risk.	P_c	I_c
	The risk of suppliers and subcontractors failing to meet their contractual obligations	RC5	The risk related to the likelihood that replacing non-compliant suppliers or subcontractors will lead to increased costs and extended project timelines.	The contract in question is an integrated agreement, where the winning company is responsible for both drafting the executive project and executing the construction work, with the goal of reducing the risk of non-compliance.	P_a	I_a

Table A2. *Cont.*

Risk Category	Risk Name	Risk Code	Description	Interference with the Project	Probability of Risk Occurrence *	Impact: Costs Overrun **
Construction Risks	Risk of unreliability and inadequacy of the used technology	RC6	Risk arising from technological advancements in both the construction field and ex-ante predictive investigations, which can render the technology used obsolete. This risk is heightened in highly complex projects that require many years for both design and implementation.	The project, although an infrastructure project, does not appear to be a highly complex work and has also already undergone several changes over the years that have included more advanced technological solutions.	P_a	I_a
	Commissioning risk	RC7	The risk related to the possibility that the project may not gain approval from the relevant public stakeholders, leading to delays and the potential for disputes and legal challenges.	The project, which impacts the landscape and alters the local road system, has been the subject of numerous investigations and protests by citizens due to its potential environmental impact and the required eminent domain numerous actions.	P_d	I_b
	Administrative risk	RC8	The risk linked to the possibility that public administrations may not issue authorizations, permits, and licenses within the anticipated timeframe, resulting in delays.	The administrative procedures have not yet been fully completed and therefore this risk is not completely eliminated.	P_d	I_b
	Eminent domain risk	RC9	The risk involves the likelihood of delays arising from condemnation procedures and the potential for increased compensation due to assessment underestimation.	This risk is very significant in this project given the numerous changes to the route and the numerous eminent domain procedures activated.	P_e	I_b

Table A2. *Cont.*

Risk Category	Risk Name	Risk Code	Description	Interference with the Project	Probability of Risk Occurrence *	Impact: Costs Overrun **
Construction Risks	Environmental and/or archaeological risk	RC10	The risk arises from inaccurate evaluations of ground conditions and soil composition, as well as the discovery of artifacts during excavation, which can lead to delays and higher costs for remediation or archaeological preservation.	The project is situated near the ecclesiastical district of St. Andrew, an area notable for archaeological discoveries dating to the 6th century.	P_e	I_a
	Risk of interference	RC11	The risk related to the uncertainty regarding the presence or absence of above-ground and below-ground utilities (e.g., water, gas, electricity, cables, fiber optics, etc.).	The project involves a large area of intervention where often the public plans and maps are not always updated in indicating the exact location of the services. It is therefore possible, during the works, to damage public pipes and cables as well as private connections.	P_d	I_c
Performance Risks	Risk of extraordinary maintenance	RP1	The risk associated with the potential for unforeseen extraordinary maintenance costs arising from design or construction defects or inadequacies, which could lead to the unavailability of the infrastructure.	The infrastructure maintenance plan has already been drawn up, with the aim of planning and scheduling future maintenance activities.	P_a	I_b
	Performance risk	RP2	The risk related to the possibility that the project and the services provided fail to meet the estimated requirements, leading to reduced expected income and revenue.	The project was drawn up by consulting the predictive traffic volumes, estimated from a 2004 database with a trend towards 2010. However, these traffic volumes are expected to increase, supporting the need for this project.	P_a	I_a
	Risk of technical obsolescence	RP4	Risk due to the rapid obsolescence of the chosen technologies that causes increases in future management and maintenance costs of the project.	This project is the result of continuous study and adaptation over the years and the technologies used are consolidated but innovative.	P_a	I_a

Table A2. *Cont.*

Risk Category	Risk Name	Risk Code	Description	Interference with the Project	Probability of Risk Occurrence *	Impact: Costs Overrun **
Demand Risks	Risk of contraction in market demand	RD1	Risk due to a potential contraction in market demand. This decrease could impact expected revenues, rendering the project economically inefficient.	This project has included extensive research on vehicular traffic with the goal of removing cars from the historic center to preserve its unique characteristics and significantly benefit the area. Additionally, an increase in traffic is anticipated, and it is not expected to pose risks related to a decline in demand.	P_b	I_a
Other Risks	Planning-regulatory risk	RO1	There is a risk related to potential alterations in regulations and unexpected policy changes, which could lead to higher compliance costs. Such risks might ultimately jeopardize the success of the assignment process.	The project has undergone many adaptation changes due to the succession of administrations and protests, a sudden change of administrative and governmental direction is not expected but on the other hand it cannot be excluded either.	P_c	I_c
	Residual value risk	RO4	Risk associated with the probability that at the end of the concession contractual relationship, the residual value of the asset is much lower than the initial estimates.	The estimates for the anticipated increase in traffic volume over the coming years indicate that the asset will generate a strong income stream and maintain a residual value at least equal to expectations. This is further supported by the comprehensive estimate of management costs.	P_a	I_a

* Minimum-P_a, Extemely Low-P_b, Low-P_c, Medium-P_d, High-P_e; ** Light -I_a, Mediocre-I_b, Severe-I_c, Critical-I_d.

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