Fuzzy algorithms applied to the comparative evaluation of crossroad designs

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Abstract:

Introduction/purpose: Urban traffic crossroads represent highly complex nodes within transportation networks due to the convergence of multiple, often conflicting, traffic streams. Managing these competing flows poses significant challenges, leading to issues such as fluctuating delays and backflow, particularly at supersaturated intersections. Given that these crossroads frequently act as bottlenecks, accurate short-term traffic flow predictions are crucial for effective planning and congestion mitigation. This study aims to propose a robust, multi-criteria evaluation framework for *crossroad design to support optimized urban planning and traffic management.*

Methods: To address the inherent complexities and uncertainties associated with evaluating such designs, this research employs the Fuzzy Analytic Hierarchy Process (FAHP). This method is particularly suited for contexts in which expert judgments, often involving qualitative criteria such as landscape integration and local economic impact, lack absolute precision. Our approach integrates fuzzy logic to manage the subjective and imprecise nature of these evaluations, alongside quantitative factors such as cost and traffic saturation. Based on an extensive literature review and established disciplinary standards in traffic engineering and urban planning, we developed a comprehensive grid of 32 criteria and sub-criteria. These criteria cover key aspects such as road safety, service level, and traffic flow. Experts then assign weights to these criteria, which are processed through FAHP to produce a global performance indicator. This indicator allows the ranking and comparison of different alternative designs.

Results: The application of this FAHP-based framework yields a global performance indicator that facilitates the objective ranking of alternative crossroad designs. The methodology provides a structured approach to balance multiple, often conflicting, criteria in complex decision environments. The practical relevance of this method is demonstrated through a case study of the Chettia junction, where it successfully identifies the optimal configuration among several proposed alternatives. This underscores FAHP's versatility in evaluating performance within intricate urban systems.

Conclusion: This study successfully situates FAHP within a broader Multi-Criteria Decision Analysis (MCDA) framework, offering an original application to crossroad design. By integrating fuzzy logic, it effectively manages the uncertainty associated with both qualitative and quantitative evaluation criteria, proving particularly valuable when precise expert judgments are diffucult for experts to provide. The proposed framework provides a robust and multidimensional evaluation tool for urban planners and traffic engineers, enabling more informed and optimized infrastructure decisions for complex urban intersections.

Key words: crossroad, fuzzy analytic hierarchy process (FAHP), design alternatives, criteria, level of service, comprehensive performance indicator (CPI).

Introduction

Urban traffic crossroads are among the most complex points in transportation networks due to the convergence of multiple conflicting traffic streams. This complexity arises from managing these competing flows, as shown in extensions of Tanner’s work on unsignalized intersections, where delays in minor streams depend on gaps in major flows (Cowan, 1987). At supersaturated intersections, backflow and fluctuating delays further underscore these challenges (Liu & Wu, 2009). Given that crossroads often act as bottlenecks, short-term traffic flow predictions are essential for effective planning and congestion mitigation (Qu et al., 2020). Models that account for multimodal demand and traffic priority at unsignalized intersections offer structured approaches for delay estimation and flow management (Guler & Menendez, 2016).

Consequently, the growing complexity of traffic problems has driven the shift from cost-benefit analysis (CBA) to Multi-Criteria Analysis (MCA), also known as Multiple-Criteria Decision-Making (MCDM). MCA evaluates alternatives across competing objectives, offering a structured, flexible framework increasingly adopted in transport planning (Dean, 2020).

Furthermore, integrating CBA and MCA combines their strengths, enhancing project prioritization and policy alignment (Gühnemann, Laird & Pearman, 2012; Henke, Cartenì & Di Francesco, 2020). Participatory MCA, involving stakeholders in decision-making, captures diverse perspectives but presents challenges in participant selection and criteria definition (Dean, Hickman & Chen, 2018; Hickman & Dean, 2017). To address these complexities, techniques such as the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) structure evaluations based on multiple criteria and uncertainty. They improve objectivity in transport planning by integrating technical, environmental, social, and economic factors (Bandyopadhyay, 2021; Sari & Şen, 2021; Otković et al., 2021; Singh, Singh & Singh, 2024). Indeed, numerous studies confirm the value of MCDM in infrastructure planning. AHP has been used to compare road designs (Barić, Pilko & Županović, 2016), support strategic planning (Barić & Starčević, 2015), and prioritize scenarios in cities such as Baghdad (Abdullah & Asmael, 2023). Hybrid approaches combining AHP with CBA strengthen investment decisions (Barić, Pilko & Dragčević, 2007). Fuzzy AHP (FAHP) further enhances transparency in uncertain contexts such as supplier selection (Ha, Fugate & Kazemi, 2015).Building on this foundation, fuzzy logic, introduced by Zadeh in 1965, enables experts to manage imprecision and subjectivity. FAHP, by integrating fuzzy sets into AHP, is widely applied in energy site selection, sustainable infrastructure, and resource management (Chan, Sun & Chung, 2019; Liu, Eckert & Earl, 2020; Ren et al., 2019). It effectively balances multiple, often conflicting, criteria in complex decision environments. Reflecting its growing importance, since 2008, MCDM research has expanded significantly.

Hybrid models such as FAHP-FTOPSIS demonstrate FAHP's versatility in evaluating performance in complex systems (Chamoli, 2015).

In this context, this study situates FAHP within the broader Multi-Criteria Decision Analysis (MCDA) framework. It applies fuzzy logic to address the uncertainty inherent in evaluating both qualitative criteria such as ecological and local economic impact and quantitative factors such as cost and traffic saturation. FAHP proves particularly suited to contexts where expert judgments lack precision. Specifically, based on the literature and disciplinary standards in traffic engineering and urban planning, this study proposes a grid of 32 criteria and sub-criteria. It offers an original application of FAHP to crossroad design, supporting a multidimensional evaluation framework. Experts assign weights to criteria related to road safety, service level, and traffic flow, producing a global performance indicator to rank the four alternative designs.

To demonstrate its practical application, the case study of Chettia junction illustrates the method's for selecting the optimal configuration among proposed alternatives. Ultimately, the article comprises six sections: an introduction and literature review; the study area and the intersection; explanation of the FAHP methodology; a comparative analysis of alternatives; and conclusions with research perspectives.

Fundamental information

Study area

This study focuses on an unsignalized intersection at Chettia on National Route 19 (NR 19) in Chlef province, Algeria. Because of this problematic intersection, traffic frequently backs up on this vital road, which serves the port of Tenes and connects to the east-west freeway. Due to the discomfort and danger it causes, local authorities are considering ways to address this issue. Consequently, they proposed four development plans to enhance the efficiency and safety (Figure 1).

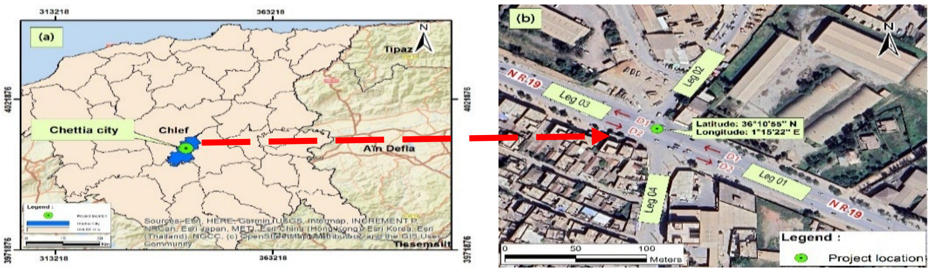

Figure 1 – Global location of the study area, (a) the Chlef province; (b) satellite image of the crossroad in the city of Chettia. Source: authors

The current state and geometric configuration of the crossroad

As shown in Figure 1b, the crossroad under study is located on flat terrain and consists of four distinct legs, each with specific characteristics. The first leg, part of NR19, is a major road in the Chlef province, featuring two lanes in each direction, a 7-meter carriageway on each side, and a 1-meter central reservation. The second leg is a bidirectional 7-meter-wide collector road serving the hospital and post office in Chettia, carrying fairly heavy traffic. The third leg, also on the NR19, leads to Chettia's north exit and Tenes port, with dimensions identical to the first. The fourth leg is a 7-meter-wide bidirectional collector road toward the southern extension of Chettia and the East-West motorway. This crossroad plays an essential role in traffic flow and access to services in the region.

Traffic flow and road safety

The traffic at this crossroad is heterogeneous, consisting mainly of light vehicles but also heavy goods vehicles, motorized two-wheelers, and bicycles. Figure 2 illustrates the crossroad's operational problems, which result in traffic jams that affect road users' comfort and safety.

Figure 2 – Photographs illustrating the operational problems at the studied crossroad. Source: authors

The Technical Studies Company of Sétif reports that traffic data collected at the main intersection in Chettia show significant differences in how vehicles move across the four approaches. The traffic study conducted at the Chettia crossroads on NR19 indicates a daily average volume ranging from 40,000 to 50,000 vehicles. Approach 1 has the highest traffic, with 24,865 vehicles going to the port of Ténès and 24,738 going to the city centre of Chlef every day. Approach 3 also has a lot of traffic, with 22,463 vehicles going to Chlef and 22,091 vehicles going to Ténès daily. Approach 2, which goes to the hospital, carries 14,424 vehicles daily. Approach 4, which connects to the East-West Highway, on the other hand, has the lowest traffic, with only 2,962 vehicles per day.

These numbers show how important the intersection is for traffic between Chlef's urban centre and the port of Ténès. They also confirm that it is a key node in the regional transport network.

Figure 3 illustrates the distribution of vehicles at the crossroad by transport mode. Light vehicles (LV) account for approximately 65%, utility vehicles (CV) about 18%, and heavy vehicles 12%. Most traffic originates from Leg A with 2189 pcu/hr (47% of total), followed by Leg C with 1758 pcu/hr (37%), Leg B with 632 pcu/hr (13%), and Leg D with 126 pcu/hr (3%).

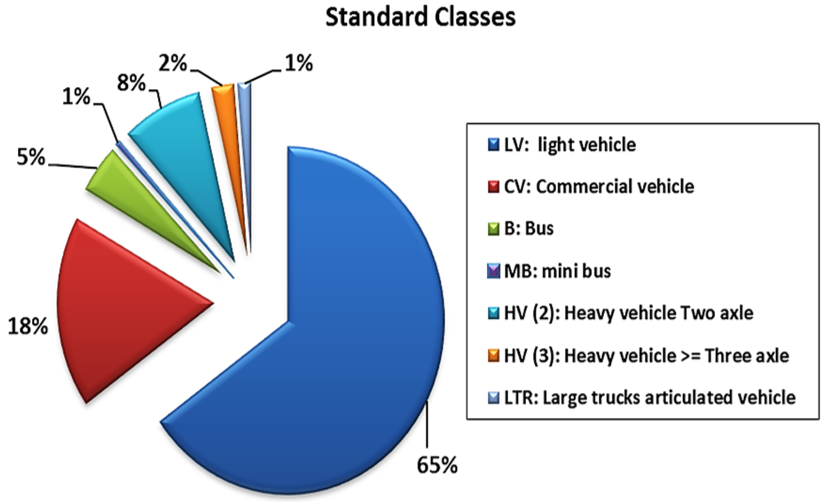

Figure 3 – Standard classes. Source: Technical Studies Company of Sétif

Overview of alternatives

Four design solutions for reconstruction were proposed by the leaders (Department of Public Works of Chlef). We aim to develop a fuzzy algorithm-based technique to control uncertainty and prioritize various criteria for selecting the optimal alternative. The method remains flexible, allowing modification of weights if designs change. Its adaptability and the generalization of criteria and sub-criteria are advantages for responding to design changes.

Figure 4 – Suggested alternatives for the reconstruction of Chettia Crossroad: (a) alternative 1 (priority-controlled intersection), (b) alternative 2 (roundabout), (c) alternative 3 (under pass - roundabout), (d) alternative 4 (signalised intersection). Source: authors

Alternative 1: Current state (priority-controlled intersection)

Alternative 1 (Scenario 1) involves preserving the current design while improving the visibility and understanding of horizontal and vertical signage. Horizontally, it includes redefining road markings such as stop lines, pedestrian crossings, and directional arrows. Vertically, it is advisable to install highly visible traffic signs at optimal heights with LED lighting. This would aid decision-making for drivers and pedestrians, enhancing safety and promoting smooth traffic flow (Figure 4a).

Alternative 2: Roundabout

This entails creating a circular crossroad with four arms, each with a 15 m turning radius. The circulatory carriageway has two 3.5 m lanes plus a 1.5 m overrun strip. NR19 consists of two two-lane roads (7 m each) with a 2 m central reservation. The entering radius is 12 m and the exit radius is 20 m. The two other arms have two 3.5 m lanes in both directions, a 4.5 m entering lane, and a 5.5 m departure lane. A 4 m-wide slip lane with a 23.5 m inner radius is proposed to eliminate overlap and improve safety and flow. Figure 4b shows a proposal for two 33 m-long, 3.5 m-wide bus stops on the main road in each direction.

Alternative 3: Underpass – roundabout

The third alternative proposes an underpass-roundabout design, with a four-legged roundabout at the upper level and an underpass (covered trench) at the lower level (-1) on NR19 to facilitate linear traffic flow. The roundabout has a 20 m turning radius and two 4 m-wide lanes. The underpass includes two 7 m-wide lanes in each direction with a 1.5% gradient and 1 m sidewalks on both sides; the clearance height is 5.25 m. The open section (Figure 4c) also features two 7 m lanes per direction, a 2 m central median, a 6% longitudinal slope, and 1 m sidewalks. The design aims to enhance safety, improve service, and increase intersection capacity.

Alternative 4: Signalized intersection

The rehabilitation plan includes synchronized traffic signal cycles (red, yellow, green) for three 3.5 m-wide lanes, with a 2 m central median on the circulatory route to manage peak traffic. Dedicated signal phases for pedestrians and cyclists will ensure safe crossing and reduce conflicts with vehicles. LED lighting and additional signage will enhance night visibility, indicate phase changes, improve intersection management, reduce accidents, and enhance traffic flow (Figure 4d).

Integration of fuzzy logic in multi-criteria decision-making methods

Advantages and limitations

The integration of fuzzy logic into established multi-criteria decision-making methods such as the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) represents a significant methodological advancement in managing uncertainty and imprecision inherent in expert judgments (Pilevar et al., 2020; Yucesan & Gul, 2020). This hybridization substantially enhances the reliability and robustness of alternative rankings while effectively mitigating the risk of subjective errors that commonly plague conventional crisp approaches (Bouamrane et al., 2020). The fuzzy paradigm provides unprecedented methodological flexibility and enables the seamless incorporation of qualitative criteria that are traditionally challenging to quantify precisely, constituting a notable competitive advantage over conventional deterministic methods (Pilevar et al., 2020; Yucesan & Gul, 2020).

Fuzzy set theory has emerged as a powerful framework for addressing vagueness and epistemic uncertainty across diverse decision-making contexts, from risk assessment to strategic planning (Yucesan & Gul, 2020; Lyu et al., 2019). The Fuzzy Analytical Hierarchy Process (FAHP), in particular, has proven to be an exceptionally effective methodology for comprehensive risk assessment scenarios where expert knowledge is systematically captured through structured questionnaires and linguistic evaluations (Lyu et al., 2019). This approach significantly enhances assessment precision by employing flexible linguistic scales through sophisticated fuzzy membership functions and intuitive linguistic variables that better capture the nuanced nature of human judgment (Sayyaadi et al., 2021).

However, the literature also acknowledges several inherent limitations and implementation challenges associated with fuzzy approaches. The increased computational complexity represents a significant barrier, requiring specialized algorithms and extended processing times compared to traditional methods (Garg et al., 2020). Furthermore, the critical dependence on expert judgment for model calibration and the strong need for reliable, contextually appropriate data constitute substantial methodological challenges that can compromise result validity (Lyu et al., 2019; Sayyaadi et al., 2021). The determination of appropriate fuzzy numbers and reliable parameter estimations can prove particularly challenging in FAHP implementations, especially in data-scarce environments (Lyu et al., 2019). Ultimately, the effectiveness of fuzzy approaches remains highly contingent on the quality of the calibration process and the appropriateness of the selected membership functions for the specific context (Sayyaadi et al., 2021). While FAHP demonstrates clear potential for improving decision precision through flexible scaling mechanisms, the acquisition of reliable empirical data and adequate resources for location-specific implementations continues to present significant practical challenges (Sayyaadi et al., 2021).

FAHP-based assessment of intersection efficiency

The objective of this work is to develop a computerized modeling system based on the FAHP approach to assess and determine the optimal crossroad configuration. The methodology, illustrated in Fig. 5, follows five essential stages. The first stage identifies key factors that influence the intersection's operational effectiveness. The second stage establishes a hierarchical framework for the model. In the third stage, the FAHP technique evaluates the relative importance of identified elements and sub-elements. The fourth stage calculates the Comprehensive Performance Indicator (CPI). Finally, the CPI categorizes the intersection's level of operational efficiency.

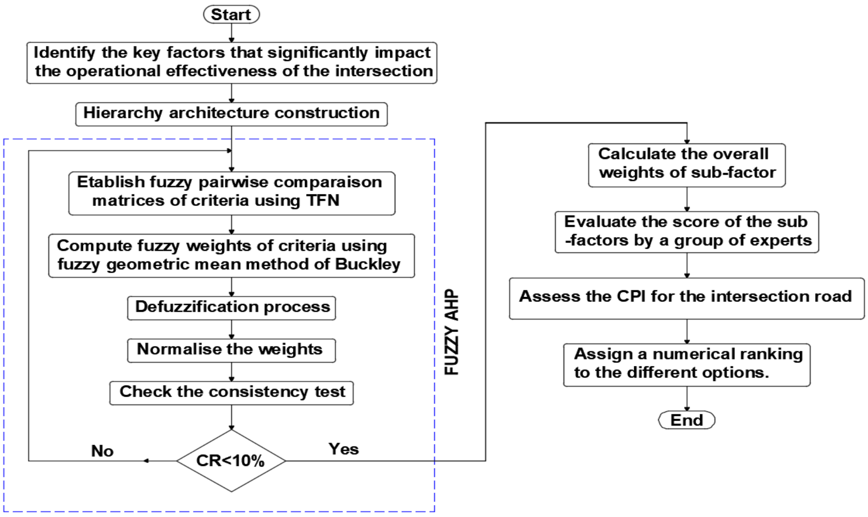

Figure 5 – A flowchart depicting the process of assessing the crossroad. Source: authors

Identifying the critical elements and establishing a hierarchical structure to select the optimal crossroad design

The first step of the model's calculation technique involves identifying crucial attributes that directly influence the performance of the optimal junction configuration (Figure 5). A rigorous elimination process removed less significant elements that did not contribute to operational efficiency. This selection draws from specialized literature and input from traffic engineering experts. The hierarchical structure, shown in Fig. 6, includes thirty-two criteria and sub-criteria.

The fuzzy analytic hierarchy process (FAHP) approach selects the optimal design among four alternatives using 32 economic, technical, and service-level criteria. Criterion C3 (level of service) divides into C3.1 (safety-related) and C3.2 (traffic-related), which includes C3.2.1 (traffic homogeneity), C3.2.2 (theoretical capacity), C3.2.3 (speed limit), and C3.2.4 (average waiting time).

The study incorporates human factors through C2.1 (mobility of pedestrians and cyclists), which evaluates the pedestrian experience based on comfort and safety, from absence of facilities to well-signposted, secure crossings. This criterion integrates vulnerable users' perception, often neglected in technical approaches.

Criteria linked to level of service (e.g., C3.2.1, C3.2.2) reflect driving conditions, fluidity, traffic light wait times, and congestion risks, all influencing pedestrian safety. Vehicle-pedestrian interaction is addressed through C3.1.3 (pedestrian and cyclist safety), C4.1 (visibility), and C4.2 (readability), assessing visual and cognitive clarity in the urban space. These criteria highlight the need for understandable, safe designs: poor visibility increases accident risk, while signalized crossroads enhance structure and visibility. Roundabouts can provide dynamic visibility when the central island is properly designed.

The FAHP model criteria quantify design impacts on human behavior and account for perceptual, safety, and operational urban dimensions, strengthening evaluation relevance and robustness. A group of seven experts evaluated each alternative, assigning scores from 0 to 10 per criterion based on their influence on overall performance. This impartial evaluation method identifies the solution best aligned with project requirements. The hierarchical structure plays a key role in ensuring th operational efficiency of the proposed junction.

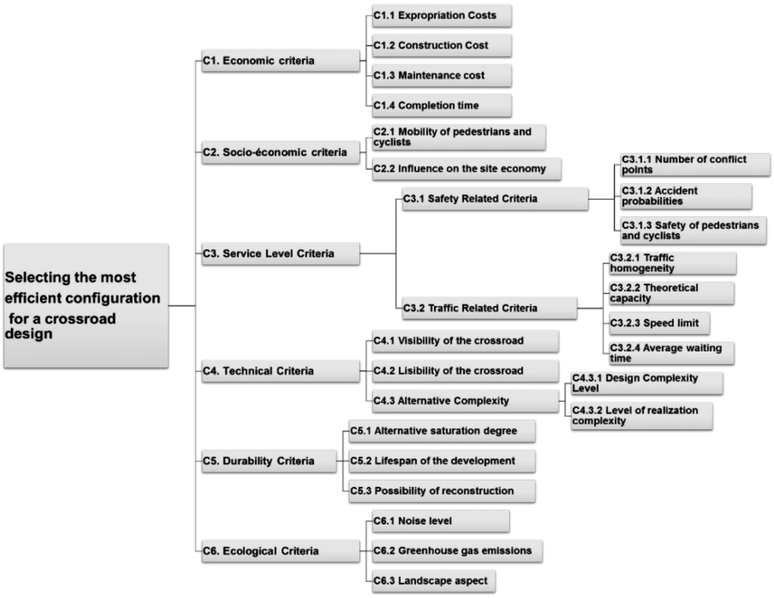

Figure 6 – The hierarchical structure of the adopted assessment criteria. Source: authors

Weight calculation using the FAHP method

Choice of membership functions and methodological implications

The choice between triangular, trapezoidal, and Gaussian membership functions constitutes a fundamental methodological decision whose impact on result quality is now well documented in the scientific literature. Several studies emphasize the crucial importance of this selection (Ameljanczyk, 2021), particularly through recent sensitivity analyses that demonstrate how the shape of the selected function can significantly modify the final ranking of alternatives, especially when differences between options are slight (Shukla & Muhuri, 2024; Faizi et al., 2020). Triangular functions, characterized by their conceptual simplicity and ease of interpretation, prove particularly suitable for situations where methodological transparency constitutes an essential prerequisite for stakeholder acceptance (Khokhar & Peng, 2022; Raval & Tailor, 2020). In contrast, trapezoidal functions offer better consideration of tolerance zones by enabling the modeling of maximum membership plateaus, while Gaussian functions prove particularly appropriate for representing naturally distributed data following a normal distribution, although they require more complex calibration and increased technical expertise. This selection invariably involves a delicate trade-off between methodological simplicity (promoting appropriation by decision-makers and operational robustness) and representational precision (enabling more faithful modeling of the uncertainty and variability inherent in the studied phenomena), necessitating a contextualized analysis of the specific requirements of the considered decision problem.

The TFNs, or triangular fuzzy numbers:

To solve the inherent imprecision and ambivalence in our study, we have opted to utilize the triangular fuzzy number (TFN) within the context of the FAHP approach. Many researchers prefer using TFN since they are easy to implement computationally. A triangular fuzzy number (TFN) is defined by a set of three numbers (l, m, u), where 'l' represents the lower bound, 'm' represents the middle value, and 'u' represents the upper bound of the TFN. Fig. 7 illustrates the visual representation of a TFN's membership function. This methodology enables the accurate representation of imprecise or ambiguous data, thereby providing increased adaptability in the analysis of intricate variables in our research. Utilizing TFNs in the FAHP procedure allows us to effectively collect and measure subtle intricacies and deviations that may go unnoticed in a traditional study.

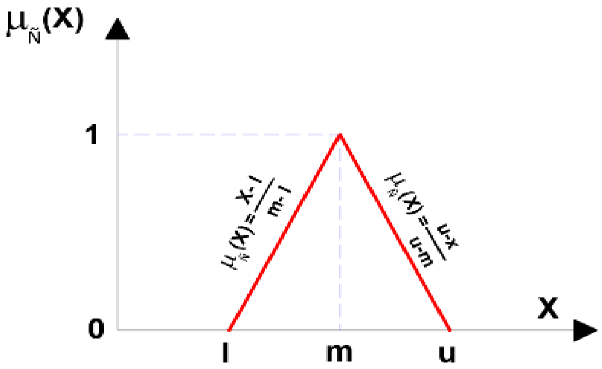

Figure 7 – Graphical illustration of TFNs. Source: Lallam & Mammeri, 2023

The conventional comparative scale

The selection of an appropriate triangular fuzzy number (TFN) requires a meticulous evaluation. This process necessitates a concurrent assessment of two critical parameters, the relative importance of which varies according to the specific objectives of the study. Figure 8 provides a detailed graphical representation of this complex decision-making process. Experts must exercise considerable judgment to balance these two criteria, each of which significantly impacts the suitability of the chosen TFN. This two-dimensional approach ensures that the selected TFN optimally meets the unique requirements of our research project.

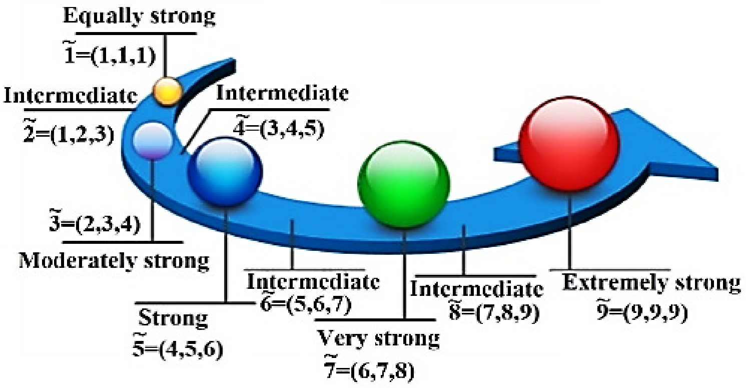

Figure 8 – Evaluation scale for criteria in terms of TFNs. Source: Lallam, Mammeri & Djebli, 2021

Fuzzy geometric mean method (FGMM)

Figure 9 presents a flowchart illustrating the fuzzy analytic hierarchy process (FAHP). The method starts by constructing pairwise comparison matrices using triangular fuzzy numbers to express uncertain judgments. These fuzzy values are then converted into crisp numbers to ease the computation. A consistency check follows to ensure the reliability of comparisons. The process continues with the calculation of fuzzy geometric means and weights, which are then defuzzified and normalized. The FAHP method provides a structured framework for handling uncertainty and ranking alternatives across multiple criteria. Table 1 complements the flowchart.

Table 1 – Random coherence index (RI). Source: Lallam, Mammeri & Djebli (2021, pp.1933–1946)

n	3	4	5	6	7	8	9	10
RI	0.525	0.882	1.109	1.248	1.342	1.406	1.450	1.485

This paper applies the proposed methodology to determine the weights of the primary criteria using the FAHP at level one of the hierarchical structure. This application demonstrates the approach’s feasibility and applicability.

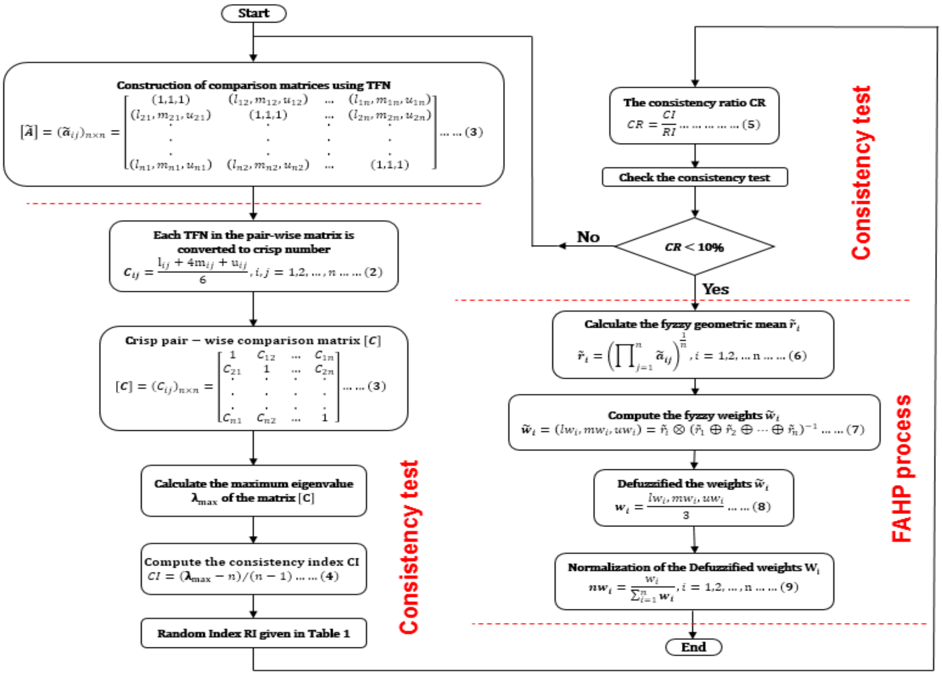

Figure 9 – A flowchart of the process of calculating weight using the fuzzy geometric mean method. Source: authors

Assessment of expert rating (ER)

In this section of the study, the relative weights of each element are determined using the FAHP method. Afterwards, experts award an intersectional functioning index (ER) to each element, ranging from 0 to 10. This index represents the comparative significance of each component in assessing the efficient operation of a crossroad. Table 2 displays the relationship between 'ER' and its equivalent scale.

Table 2 – Status of grading. Source: Lallam, Djebli & Mammeri, 2023

ER	State condition of scaling
[0,2]	super high
]2,4]	high
]4,6]	moderate
]6,8]	low- grade
]8,10]	grade noticed

The collective expert assessment (CEA) is derived using the following equation:

$$CEA_i = \frac{\sum_{j=1}^{m} ER_j}{m} \tag{1}$$

The number *m* represents the total number of specialists involved in the evaluation process. To conclude, the Comprehensive Performance Indicator (CPI), which represents the overall operational effectiveness of the intersection under scrutiny, is mathematically expressed as

$$CPI = \sum_{i=1}^{k} W_i \times CEA_i \tag{2}$$

In this formula, *i* ranges from 1 to *k*, where *k* denotes the number of the sub-factors chosen for analysis.

Comparative assessment

The evaluation process is based on the pairwise comparison method. It offers the possibility to analyze the criteria, sub-criteria, and their descriptions in depth. During these comparisons, the criteria are evaluated based on their relative weight with respect to each other. Experts are encouraged to evaluate the criteria and sub-criteria two by two, detailing their importance, definition, and justification, as presented in the case of the criterion Completion Time (C1.4) in Table 3. Experts can consult this information to better understand the evaluation process.

Table 3 – Intensity of the importance of the completion time criteria C1.4 (adapted to Saaty's scale). Source: authors

Criteria Score	Description	Interpretation
[0,2]	Very long	The completion time is very long (>6 months).
[2,4]	Long	The completion time is long (4 to 6 months).
[4,6]	Medium	The completion time is Medium (2 to 4
[6,8]	Short	The completion time is short (1 to 2 months).
[8,10]	Very short	The completion time is very short (<1 month).

Analysis of the results

The algorithm's numerical calculations, illustrated in Figure 5, were executed in Excel to enhance simplicity. Table 4 includes all the comparisons made between the different criteria. The evaluation of the judgment matrices' consistency, indicated by the CRs, demonstrates a high level of coherence, with all CRs below the 10% threshold.

Table 4 – Pairwise comparison matrices and their consistency tests. Source: authors

Factors	C1	C2	C3	C4	C5	C6	Consistency test
C1	$\tilde{1}$	$\tilde{4}$	$\tilde{2}$	$\tilde{2}$	$\tilde{4}$	$\tilde{5}$	λmax=6.077, CI=0.015, RI=1.240, CR=1.24%< 10%
C2	$\tilde{4}^{-1}$	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{1}$	
C3	$\tilde{2}^{-1}$	$\tilde{2}$	$\tilde{1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$	
C4	$\tilde{2}^{-1}$	$\tilde{2}$	$\tilde{1}$	$\tilde{1}$	$\tilde{2}$	$\tilde{3}$	
C5	$\tilde{4}^{-1}$	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{2}$	
C6	$\tilde{5}^{-1}$	$\tilde{1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{2}^{-1}$	$\tilde{1}$	
	C1.1	C1.2	C1.3	C1.4			Consistency test
C1.1	$\tilde{1}$	$\tilde{4}^{-1}$	$\tilde{2}$	$\tilde{2}$			λmax=4.165, CI=0.055, RI=0.900, CR=6.12%< 10%
C1.2	$\tilde{4}$	$\tilde{1}$	$\tilde{6}$	$\tilde{3}$			
C1.3	$\tilde{2}^{-1}$	$\tilde{6}^{-1}$	$\tilde{1}$	$\tilde{3}^{-1}$			
C1.4	$\tilde{2}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}$	$\tilde{1}$			
	C2.1	C2.2					Consistency test
C2.1	$\tilde{1}$	$\tilde{2}$					CR not verified for comparison between two criteria
C2.2	$\tilde{2}^{-1}$	$\tilde{1}$					
	C3.1	C3.2					Consistency test
C3.1	$\tilde{1}$	$\tilde{2}^{-1}$					CR not verified for comparison between two criteria
C3.2	$\tilde{2}$	$\tilde{1}$					
	C3.1.1	C3.1.2	C3.1.3				Consistency test
C3.1.1	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$				λmax=3.042, CI=0.021, RI=0.580, CR=3.64%< 10%
C3.1.2	$\tilde{2}$	$\tilde{1}$	$\tilde{2}^{-1}$				
C3.1.3	$\tilde{2}$	$\tilde{2}$	$\tilde{1}$				
	C3.2.1	C3.2.2	C3.2.3	C3.2.4			Consistency test
C3.2.1	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{1}$			λmax=4.054, CI=0.018, RI=0.900, CR=2.01%< 10%
C3.2.2	$\tilde{2}$	$\tilde{1}$	$\tilde{2}$	$\tilde{1}$			
C3.2.3	$\tilde{1}$	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{1}$			
C3.2.4	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$			

Factors	C1	C2	C3	C4	C5	C6	Consistency test
	C4.1	C4.2					Consistency test
C4.1	$\tilde{1}$	$\tilde{2}$					CR not verified for comparison between two criteria
C4.2	$\tilde{2}^{-1}$	$\tilde{1}$					
	C4.1	C4.2	C4.3				Consistency test
C4.1	$\tilde{1}$	$\tilde{1}$	$\tilde{3}^{-1}$				λmax=3.000, CI=0.000, RI=0.580, CR=0.00%< 10%
C4.2	$\tilde{1}$	$\tilde{1}$	$\tilde{3}^{-1}$				
C4.3	$\tilde{3}$	$\tilde{3}$	$\tilde{1}$				
	C4.3.1	C4.3.2					Consistency test
C4.3.1	$\tilde{1}$	$\tilde{2}$					CR not verified for comparison between two criteria
C4.3.2	$\tilde{2}^{-1}$	$\tilde{1}$					
	C5.1	C5.2	C5.3				
C5.1	$\tilde{1}$	$\tilde{2}$	$\tilde{2}$				λmax=3.061, CI=0.030, RI=0.580, CR=5.23%< 10%
C5.2	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{2}$				
C5.3	$\tilde{2}^{-1}$	$\tilde{2}^{-1}$	$\tilde{1}$				
	C6.1	C6.2	C6.3				
C6.1	$\tilde{1}$	$\tilde{1}$	$\tilde{2}$				λmax=3.056, CI=0.028, RI=0.580, CR=4.79%< 10%
C6.2	$\tilde{1}$	$\tilde{1}$	$\tilde{1}$				
C6.3	$\tilde{2}^{-1}$	$\tilde{1}$	$\tilde{1}$				

Figure 10 presents a sunburst chart illustrating the local weights acquired following consistency tests.

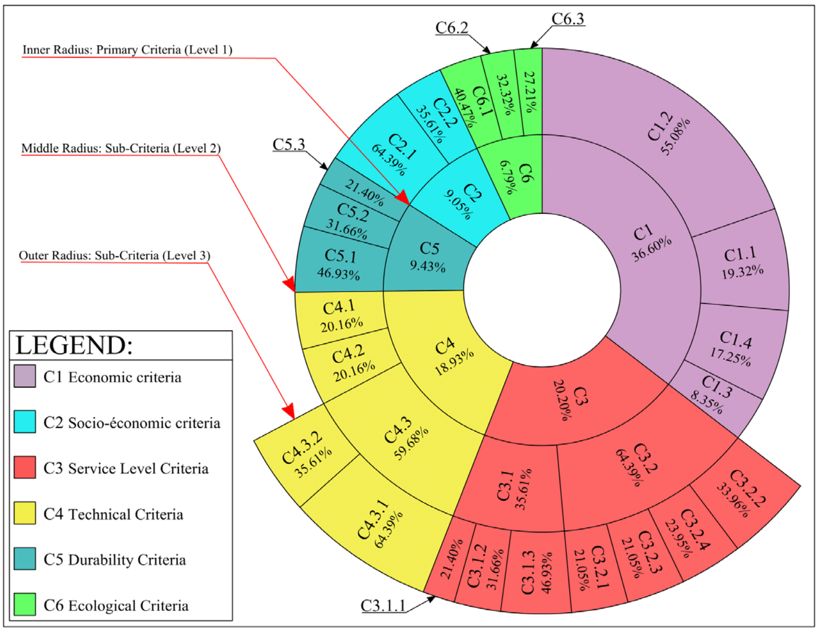

Figure 10 – Sunburst chart for local weightings. Source: authors

The hierarchical sunburst chart offers an effective visualization of hierarchical data. It consists of a central circle surrounded by concentric rings, each representing a different level. Segment sizes are proportional to their values, allowing a clear distribution display and facilitating detection of the relationships between categories. This layered structure also supports interactive exploration.

At level 1 of Figure 10, economic criteria dominate with a weight of 35.60%, followed by level of service (20.20%) and technical factors (18.93%). Sustainability and socio-economic elements weigh 9.43% and 9.05%, respectively, while environmental criteria hold the lowest weight at 6.79%. These weightings reflect a prioritization of economic, technical, and service-related factors.

The hierarchical model calculates the global weights of sub-criteria by multiplying local weights of their parent criteria at lower levels (Lallam, Djebli & Mammeri, 2023, pp.1–20; Bandyopadhyay, 2021).

Categorization of the optimal design from the four different alternatives

The approach adopted in this article, known for managing uncertainty through fuzzy numbers, relies heavily on the quality and representativeness of expert evaluations. To ensure methodological robustness and practical applicability, a rigorous expert selection process was implemented, emphasizing a balance between academic and professional profiles.

In the first phase, the theoretical foundations of the criteria grid were established through academic research and comparison with similar studies, identifying converging trends and ensuring scientific and geographical relevance. This led to a structured initial set of criteria classified by intervention area, serving as the basis for expert selection.

In the second phase, seven experts from diverse professional backgrounds were selected, including a transportation economist, two design engineers, a traffic engineer, two project managers, and a business engineer, each with over ten years of experience. This balanced panel ensured reliable and consistent evaluations.

A synthesis of 32 criteria and sub-criteria was then consolidated as a structured foundation for FAHP analysis. This method streamlines the comparison of alternatives. Unlike traditional AHP, it avoids recalculating judgment matrices for each alternative. Once criteria scores are assigned (Table 4), calculating the Comprehensive Performance Indicator (CPI) and ranking alternatives becomes straightforward. This simplifies the numerical implementation of the methodology.

The study applies the FAHP method to a real case involving a crossroad in Chettia, Chlef province, Algeria. The method offers a structured framework to synthesize expert opinions and establish a clear hierarchy of alternatives, providing practical value while maintaining scientific rigor.

A panel of seven specialists evaluated the four project alternatives. Each expert assigned a score from 0 to 10 to each criterion per variant, based on its impact on overall performance. This ensured impartial assessment and selection of the most suitable solution. Table 5 presents the complete evaluation results.

Table 5 – Full results of the evaluation by experts. Source: authors

N°	Factors	W_i	CEA$_i$			
			Alternative1	Alternative2	Alternative3	Alternative4
1	C1.1	0,069	9,214	6,714	2,429	8,500
2	C1.2	0,196	9,250	7,214	3,071	6,429
3	C1.3	0,030	8,250	7,714	4,536	5,000
4	C1.4	0,061	9,214	7,286	2,643	6,786
5	C2.1	0,058	1,571	4,143	7,571	8,786
6	C2.2	0,032	5,000	5,000	3,000	5,000
7	C3.1.1	0,015	1,000	7,000	10,000	9,000
8	C3.1.2	0,023	1,286	4,714	7,571	7,000
9	C3.1.3	0,034	1,000	4,857	8,286	8,357
10	C3.2.1	0,027	1,000	3,429	8,714	2,714
11	C3.2.2	0,044	1,000	5,143	9,214	6,857
12	C3.2.3	0,027	1,286	5,714	9,214	4,000
13	C3.2.4	0,031	1,000	6,429	9,000	3,429
14	C4.1	0,038	2,714	6,143	9,000	7,857
15	C4.2	0,038	3,857	7,643	7,714	7,929
16	C4.3.1	0,040	9,000	7,286	2,857	7,571
17	C4.3.2	0,073	9,000	7,143	3,000	7,429
18	C5.1	0,044	1,000	3,000	9,071	5,000
19	C5.2	0,030	2,286	4,500	8,714	2,571
20	C5.3	0,020	9,071	7,000	2,000	7,714
21	C6.1	0,027	1,571	5,000	8,286	2,714
22	C6.2	0,022	1,286	4,714	8,857	2,143
23	C6.3	0,018	1,071	6,571	8,643	3,571
$CPI = \sum_{i=1}^{23} W_i \times CEA_i$			5.382	6.122	5.643	6.346
Rank			4	2	3	1

According to the comprehensive performance indicator (CPI), Table 5 shows how the four choices performed in comparison. Alternative 4 ranks first with a CPI of 6.346, followed by Alternative 2 (6.12), Alternative 3 (5.643), and Alternative 1 (5.382). A CPI of 6.346 positions Alternative 4 as the most effective solution, reflecting a balance between economic criteria, service level, technical aspects, sustainability, and environmental factors.

For expropriation costs (C1.1), Alternative 4 scores 8.500, indicating a moderate land footprint and minimal implementation constraints. Alternative 1 scores higher (9.214), but its overall weaknesses outweigh this advantage. In construction cost (C1.2), Alternative 1 scores highest (9.25), offering the lowest expense, yet it has the shortest lifespan (C5.2 = 2.286). Alternative 4, with a C1.2 score of 6.429, presents an "appropriate" cost (200–400 MDA).

On pedestrian and cyclist safety (C3.1.3), Alternative 4 scores 8.357, classified as "optimal," predicting lower accident risks. It also ranks highest in conflict point reduction (C3.1.1 = 9.000), reflecting an effective geometric design. In terms of mobility (C2.1), it scores 8.786, described as "pleasant," improving accessibility.

Operationally, Alternative 3 achieves the highest theoretical capacity (C3.2.2 = 9.214), manages congestion and traffic imbalance effectively (C3.2.1 = 8.714), offers minimal waiting time (C3.2.4 = 7.429), and maintains a smooth flow (C5.1 = 9.071). However, it has low scores in expropriation (C1.1 = 2.429), construction cost (C1.2 = 3.071), and requires a longer completion time.

Alternative 3 shows strong environmental performance with high scores for emissions (C6.2 = 8.857) and noise (C6.1 = 8.286), but its complexity of implementation (C4.3.2 = 3.0) limits its feasibility in constrained areas. In contrast, Alternative 4 offers low complexity (7.429), easier implementation, and maintains strong service-level performance.

Conclusion

This study presents an application of the Fuzzy Analytic Hierarchy Process (FAHP) for optimizing urban crossroad design, addressing a critical challenge in contemporary traffic engineering. Our comprehensive evaluation framework, incorporating 32 criteria across six dimensions, demonstrates the method's effectiveness in managing the inherent uncertainty and complexity of multi-criteria decision-making in urban infrastructure planning.

The primary contribution of this research lies in developing a holistic evaluation framework that significantly extends beyond traditional approaches. Our hierarchical model revealed that economic criteria dominate decision-making (35.60%), followed by level of service (20.20%) and technical considerations (18.93%), while sustainability (9.43%), socio-economic factors (9.05%), and environmental criteria (6.79%) play complementary roles. The application to the Chettia crossroad case study validated the framework's practical utility, with Alternative 4 emerging as the optimal solution through its integration of synchronized traffic light cycles and dedicated phases for vulnerable road users.

The methodological innovation resides in the streamlined implementation of FAHP, which eliminates the computational burden of recalculating judgment matrices for each alternative—a significant limitation of traditional AHP approaches. The Comprehensive Performance Indicator (CPI) introduced here enables straightforward ranking through simple score sorting, enhancing the method's scalability and practical applicability. This computational efficiency, combined with the flexibility to incorporate qualitative criteria through fuzzy membership functions and linguistic variables, represents a substantial advancement over conventional deterministic methods.

The framework's societal implications extend beyond technical optimization. By prioritizing safety through dedicated pedestrian and cyclist infrastructure while maintaining economic viability, the approach directly addresses the Sustainable Development Goals related to sustainable cities and communities. The potential reduction in road accidents and improvement in quality of life demonstrate the method's alignment with contemporary urban planning priorities.

While the FAHP approach successfully manages uncertainty, several limitations warrant consideration. The method's effectiveness remains contingent upon expert judgment quality and appropriate membership function calibration. The increased computational complexity compared to deterministic methods, though mitigated by our streamlined approach, may still present challenges for practitioners lacking specialized expertise. Additionally, data acquisition for location-specific parameters continues to pose practical constraints.

Future research should focus on three critical areas. First, applying the framework to diverse intersection typologies across different urban contexts will test its generalizability and robustness. Second, integrating FAHP with real-time traffic simulation tools could enhance predictive accuracy and enable dynamic optimization. Finally, developing automated calibration procedures using machine learning techniques could reduce dependency on expert judgment while maintaining decision quality.

This research establishes a reproducible, adaptable framework for urban crossroad design that balances technical rigor with practical applicability. The proposed 32-criteria evaluation grid, coupled with the flexible weighting system, provides urban planners and traffic engineers with a robust decision-support tool capable of addressing the multifaceted challenges of modern urban mobility. As cities worldwide grapple with increasing traffic complexity and sustainability imperatives, this FAHP-based approach offers a structured pathway toward evidence-based infrastructure decisions that optimize safety, efficiency, and societal benefit.

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Primena fazi algoritama u komparativnoj evaluaciji projektovanja raskrsnica

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OBLAST: građevinarstvo, saobraćajno inženjerstvo
KATEGORIJA (TIP) ČLANKA: originalni naučni rad

Sažetak:

Uvod/cilj: Urbane saobraćajne raskrsnice su izuzetno složeni čvorovi u transportnim mrežama zbog ukrštanja više, često međusobno konfliktnih, saobraćajnih tokova. Upravljanje takvim tokovima predstavlja značajan izazov, što dovodi do problema poput promenljivih vremena zadržavanja i vraćanja saobraćaja, naročito kod preopterećenih raskrsnica. Budući da ovakve raskrsnice često deluju kao uska grla, tačne kratkoročne prognoze saobraćajnih tokova su ključne za efikasno planiranje i ublažavanje zagušenja. Cilj ove studije je da predloži robustan okvir za višekriterijumsku evaluaciju projektovanja raskrsnica kako bi se podržalo optimizovano urbano planiranje i upravljanje saobraćajem.

Metode: Da bi se odgovorilo na inherentne složenosti i neizvesnosti u vezi sa evaluacijom ovakvih rešenja, u ovom istraživanju se primenjuje fazi analitički hijerarhijski proces (FAHP). Ova metoda je posebno pogodna za kontekste u kojima se stručne evaluacije, koje često uključuju kvalitativne kriterijume poput uklapanja u pejzaž ili uticaja na lokalnu ekonomiju, ne mogu izraziti sa apsolutnom preciznošću. Naš pristup integriše fazi logiku radi upravljanja subjektivnošću i neodređenošću u evaluacijama, kao i *kvantitativnim faktorima poput troškova i zasićenosti saobraćaja. Na osnovu opsežnog pregleda literature i utvrđenih standarda u oblasti saobraćajnog inženjeringa i urbanog planiranja, razvijena je sveobuhvatna mreža od 32 kriterijuma i potkriterijuma koji obuhvataju ključne aspekte kao što su bezbednost saobraćaja, nivo usluge i protok saobraćaja. Eksperti dodeljuju težinske vrednosti ovim kriterijumima, a one se zatim obrađuju pomoću FAHP metode kako bi se dobio globalni pokazatelj performansi. Ovaj pokazatelj omogućava rangiranje i poređenje različitih projektnih rešenja.*

Rezultati: Primena FAHP okvira dovodi do izračunavanja globalnog pokazatelja performansi koji omogućava objektivno rangiranje alternativnih rešenja za raskrsnice. Metodologija pruža strukturiran pristup za balansiranje više, često konfliktnih, kriterijuma u složenim okruženjima odlučivanja. Praktična primenljivost metode prikazana je kroz studiju slučaja raskrsnice Šetija, u kojoj je uspešno identifikovana optimalna konfiguracija od više predloženih varijanti. Ovo potvrđuje svestranost FAHP metode u evaluaciji performansi unutar složenih urbanih sistema.

Zaključak: Ova studija uspešno pozicionira FAHP unutar šireg okvira višekriterijumske analize odlučivanja (MCDA) i nudi originalnu primenu u oblasti projektovanja raskrsnica. Integracijom fazi logike, metodologija efikasno upravlja neizvesnošću u vezi sa kvalitativnim i kvantitativnim kriterijumima evaluacije, što je posebno korisno kada je teško doći do preciznih stručnih procena. Predloženi okvir predstavlja robustan i višedimenzionalan alat za urbaniste i saobraćajne inženjere, i omogućava informisanje i optimizovanje odluke o infrastrukturi u složenim urbanim raskrsnicama.

Ključne reči: raskrsnica, fazi analitički hijerarhijski proces (FAHP), alternativna projektna rešenja, kriterijumi, nivo usluge, složeni pokazatelj performansi (CPI).

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