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Evaluating Sustainable Urban Development Strategies through Spherical CRITIC-WASPAS Analysis

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Abstract: This investigation delves into the critical challenges of urban development and management, employing a comprehensive evaluation of four strategic alternatives: transit-oriented development, green infrastructure investment, smart city technologies, and community-based development. These alternatives are rigorously assessed against a set of eight meticulously chosen criteria. Distinct from conventional analyses, the study adopts the sophisticated Criteria Importance Through Inter-criteria Correlation (CRITIC)-Weighted Aggregated Sum Product Assessment (WASPAS) methodology, utilizing spherical fuzzy sets (SFS). This approach mitigates uncertainties inherent in decision-making processes, thereby refining the accuracy of the evaluation. The CRITIC-WASPAS method, with its innovative application in this context, augments the precision of the assessments, yielding a detailed appraisal of each alternative's merits and limitations. Through assigning weighted criteria and systematically ranking these alternatives, the study furnishes pivotal insights for urban planners and policymakers. This contribution is instrumental in guiding decisions that promote resilience, equity, and environmental sustainability in urban environments. The novel integration of the CRITIC-WASPAS method in this domain not only propels the field forward but also lays a robust foundation for informed and effective decision-making. The outcomes of this research are poised to significantly impact the discourse on sustainable urban development, offering a data-driven framework that is essential for sculpting the future of cities amidst evolving urban challenges.

Keywords: Transit-oriented development; Green infrastructure investment; Smart city technologies; Criteria Importance Through Inter-criteria Correlation (CRITIC); Weighted Aggregated Sum Product Assessment (WASPAS); Spherical fuzzy sets (SFS); Multi-criteria decision-making

1 Introduction

In the midst of rapid urbanization and the relentless pace of societal evolution, cities worldwide find themselves confronted with an unprecedented challenge—achieving sustainable development [1]. The pursuit of sustainable urban development has become a shared aspiration globally [2], prompting a reevaluation of city-related dynamics and sparking diverse lines of contemplation. Central to this conceptual exploration are three fundamental pillars: environment, society, and economy. Cities, under the weight of intricate pressures and expectations, necessitate a reconceptualization and restructuring of the intricate interplay between residents, ecology, economy, society, and politics. Addressing the evolving landscape of urban sustainable development calls for a heightened reliance on the unique characteristics and opportunities that urban life affords [3].

Beyond merely meeting quantifiable physical standards such as air quality indices, green space ratios, population densities, and resource utilization, a thriving and evolving city must foster interpersonal exchanges and life interactions to elevate its overall quality [4]. Agenda 21 (1992), serving as the blueprint for 21st-century sustainable development, intertwines the environment within the societal and economic framework, grounded in the perspective of human living needs. It underscores that a healthy life forms the bedrock of sustainable development, viewing it as the culmination of environmental and socioeconomic advancements. In alignment with this perspective, the World Health Organization (WHO) introduced the Healthy City (HC) project in 1997, aiming to actualize urban sustainable development [5]. Subsequent initiatives, such as Eco-City [6, 7], Green City [8, 9], Resilient City [10, 11], Smart City [12, 13], Inclusive City [14, 15], and Livable City [16, 17], mirror a global movement towards sustainability in urban development [18].

The multidimensional nature of urban system sustainability encompasses various facets, including environmental conservation, resource utilization, land use, economic development, resource management, social well-being, living space, climate change, energy efficiency, and waste reduction [19]. The inherent complexity of the urban system demands a practical approach, translating these multidimensional characteristics and concepts into actionable models for tangible development. This necessitates addressing two structural challenges: firstly, the elucidation of the core nature of urban sustainability, and secondly, the quest for an objective and effective evaluation method. In navigating these intricacies, cities and researchers alike are poised to contribute to the global discourse on sustainable urban development, marking it as a pivotal and urgent issue on the global stage.

In the dynamic landscape of urban development, the collective pursuit of creating cities that embody the ideals of health, sustainability, resilience, intelligence, inclusivity, and livability finds its cornerstone in the subjective experience of residents—commonly referred to as the quality of life (QOL). This multifaceted concept intricately weaves together the threads of societal, economic, and environmental dimensions, shaping the very fabric of urban existence. In the wake of formidable global environmental challenges, the imperative for sustainable urban development becomes increasingly evident, with QOL emerging as the quintessential barometer of progress. Against this backdrop, the "Life-City" (LC) project takes center stage, offering a visionary framework that transcends conventional notions of urban development. Defined as a city not merely meeting basic living standards but continually propelling forward the realms of QOL, environmental well-being, and competitiveness, LC encapsulates a paradigm shift in our approach to urban planning. It envisions cities as vibrant ecosystems where the pulse of life resonates in harmony with the broader goals of sustainability. The LC project becomes a catalyst for perpetual advancement, fostering an environment where residents experience not just a habitat but a dynamic and thriving urban landscape. Recognizing that the core of sustainable urban development lies in elevating the human experience, the LC initiative endeavors to create cities that are not just resilient to environmental challenges but actively contribute to the flourishing well-being of their inhabitants. In essence, it aspires to be a dynamic force, a living entity that evolves in tandem with the evolving needs and aspirations of its residents, fostering a harmonious relationship between human prosperity, ecological health, and economic vitality. In this transformative vision, the Life-City project stands as a testament to the belief that the future of urban living is not only sustainable but also profoundly enriching for the lives it encompasses.

1.1 Literature Review

Zadeh's foundational work on "fuzzy sets" (FS) [20] has played a transformational role in altering the environment of decision-making under uncertainty. His mathematical framework is a powerful tool for articulating and handling imprecise and ambiguous information, making it a valuable resource for navigating the complexities of decision-making processes. In the world of decision-making, where uncertainties abound, Zadeh's FS provides a flexible and intuitive approach to modeling and dealing with imprecision. Building on this foundation, Atanassov's "intuitionistic fuzzy sets" (IFS) [21] reflects a further step, integrating evaluations of both membership and non-membership features. This extension improves the adaptability of fuzzy sets in dealing with the complexities inherent in decision-making contexts. The integration of non-membership elements in IFS is especially significant in decision-making contexts where the lack of quality is as important as its existence. Cuong's essential contribution involves the development of "picture fuzzy sets" (PFS) [22, 23], introducing a visual aspect into the decision-making process. This advancement allows for a more natural representation of human perspectives in decision-making, bringing realism to the models. Cuong and Hai's further advances, documented in the study [24, 25], present crucial operators and features that enhance the theoretical underpinning of PFSs, providing DMs with more sophisticated tools. Some new ideas were put forward by Li et al. and Ashraf et al. [26]. These included generalized simplified neutrosophic Einstein AOs and a unique distance metric for fuzzy collections of cubic PFSs [27, 28]. Ashraf et al. [29] established the concept of SFS as an extension of image fuzzy sets and Pythagorean fuzzy sets. SFS improves the accuracy and usefulness of fuzzy set models by changing the way membership degrees are defined. In PFSs, they are usually written as $0 \leq P(x) + I(x) + N(x) \leq 1$. However, SFS defines them as $0 \leq P^2(x) + I^2(x) + N^2(x) \leq 1$. The authors make a foundational contribution by exploring the core operations governing SFSs and extending operational laws to aggregation operators. Novel aggregation operators, including weighted averaging and weighted geometric aggregation operators, are described, showcasing their potential applications in various decision-making settings.

The development of a multi-attribute decision-making approach, which provides a strong framework for decision-making in scenarios involving several attributes, exemplifies the practical value of these principles. Thus, it makes a substantial contribution to the literature by providing a comprehensive analysis of spherical fuzzy sets, their operational features, and their use in decision-making situations, laying the framework for future research and applications in the broader field of fuzzy set theory. Significant contributions have been made to the literature on spherical fuzzy sets, with papers examining their applications and methodology. Based on this, Kahraman and Gündodu [30] expanded on the concept of decision-making with spherical fuzzy sets, adding to a broader understanding of their practical uses. Mahmood et al. [31] used spherical fuzzy sets to tackle decision-making and medical diagnosis challenges, demonstrating their utility in a variety of fields. Ullah et al. [32] investigated similarity measures for T-spherical fuzzy sets and provided insights into pattern recognition applications. Furthermore, Gündodu and Kahraman [33] introduced a novel spherical fuzzy analytic hierarchy approach with a specific focus on its use in renewable energy situations, adding to the body of knowledge on spherical fuzzy sets. This research, taken together, contributes to a thorough understanding of the theoretical foundations, techniques, and practical applications of spherical fuzzy sets in a variety of disciplines.

Diakoulaki et al.'s CRITIC procedure, introduced in 1995 [34], is a strong solution to the difficult task of assigning weights to various criteria in the context of multi-criteria decision making (MCDM). This technique, which is based on comparative ratio analysis, provides a reliable solution by using pairwise comparisons to determine the relative importance of each criterion. The literature review includes a wide range of studies that use the CRITIC technique on a variety of topics. Kaur et al. [35] present a CRITIC-TOPSIS MCDM technique for selecting aeroplanes in a neutrosophic environment. Sleem et al. [36] use a neutrosophic CRITIC MCDM approach to extend the application to the virtual reality metaverse. Mishra et al. [37] suggest a unique technique for multicriteria decision-making using Fermatean fuzzy numbers in the CRITIC method. Cui et al. [38] use Monte Carlo simulation to improve decision-making stability in a hybrid MCDM model. Das [39] employs an MCDM technique to analyze surface water quality in the Mahanadi River Basin. Jusufbai [40] provides a brief overview of MCDM strategies for handling logistics equipment selection. Ertemel et al. [41] use Pythagorean Fuzzy CRITIC-TOPSIS to examine the long-term viability of smartphone addiction. Ranjan et al. [42] use the CRITIC-MARCOS material selection model for sintered pulley manufacture. Mukhametzyanov [43] investigates the differences between the entropy, CRITIC, and SD approaches for establishing criteria weights. Peng et al. [44] use Pythagorean fuzzy MCDM with CoCoSo and CRITIC to evaluate the 5G industry. Zafar et al. [45] use the entropy-CRITIC weight approach and MCDM methodologies to create an effective blockchain evaluation system. In an e-commerce recommendation system, Bczkiewicz et al. [46] investigate the methodical features of MCDM. Hassan et al. [47] use CRITIC-TOPSIS MCDM to determine the best location for a solar PV farm. Kumar and Singh [48] provide an integrated MCDM method for multi-objective optimization of powder-mixed green EDM parameters. Saxena et al. [49] present a novel CRITIC-TOPSIS approach for determining the best software reliability growth model. Vadivel et al. [50] use the CRITIC technique to find sustainable green suppliers. In Table 1, some work related to decision-making is given.

Zavadskas and Turskis' WASPAS method is an important approach in MCDM. This method provides a framework for assessing and ranking alternatives based on a variety of criteria. The contributions of Zavadskas and Turskis to the development of the WASPAS method have had a significant impact on decision science, providing a systematic and weighted methodology for DMs to examine complex scenarios and make educated choices. Researchers and practitioners have investigated and applied the WASPAS technique in a variety of disciplines, demonstrating its adaptability and usefulness in addressing real-world decision problems.

Table 1. Some work related to decision-making

Author & Year	Technique	Application
Zavadskas et al. [51] (2012)	WASPAS	Optimization in Elektronika ir elektrotechnika.
Zavadskas et al. [52] (2013)	WASPAS and MULTIMOORA	Verification of robustness when assessing alternative solutions.
Bid & Siddique [53] (2019)	TOPSIS and WASPAS	Human risk assessment of Panchet dam in India.
Baykasoğlu & Gölcük [54] (2020)	WASPAS	Revisiting ranking accuracy within the WASPAS method.
Keshavarz-Ghorabaee et al. [55] (2020)	Fermatean fuzzy sets and WASPAS	Green construction supplier evaluation.
Badalpur & Nurbakhsh [56] (2021)	WASPAS	Risk qualitative analysis of a road construction project in Iran.
Senapati et al. [57] (2021)	Picture fuzzy WASPAS	Application in multi-criteria decision-making.
Rudnik et al. [58] (2021)	WASPAS	Multi-criteria decision-making.
Sokolović et al. [59] (2021)	TOPSIS and WASPAS	Selection of process for aluminum separation from waste cables.

Author & Year	Technique	Application
Bagal et al. [60] (2021)	Hybrid Taguchi-CocoSo-EDAS-WASPAS	Optimization of characteristics in resistance spot welding for dissimilar materials.
Simić et al. [61] (2021)	Picture fuzzy WASPAS	Selection of last-mile delivery mode in Belgrade.
Eghbali-Zarch et al. [62] (2022)	Fuzzy IDOCRIW and WASPAS	Prioritizing effective strategies for construction and demolition waste management.
Vaid et al. [63] (2022)	VIKOR-WASPAS-Entropy methods	Application in silent Genset decision-making.
Seker & Aydin [64] (2022)	Integrated MCDM approach with WASPAS	Assessment of hydrogen production methods under uncertainty.
Nguyen et al. [65](2022)	Spherical Fuzzy WASPAS	Objective weighting for international payment method selection.
Alrasheedi et al. [66] (2022)	Pythagorean fuzzy entropy-SWARA-WASPAS	Evaluation of sustainable suppliers in manufacturing companies.
Senapati & Chen [67] (2022)	Picture fuzzy WASPAS	Application in multi-criteria decision-making.
Masoomi et al. [68] (2022)	Fuzzy BWM-WASPAS-COPRAS	Strategic supplier selection for renewable energy supply chain.
Alptekin Ulutaş et al. [69](2021)	MULTIMOOSRAL	Development of an integrated MCDM approach for supplier selection.
Bathrinath et al. [70] (2022)	Fuzzy AHP-WASPAS	Analysis of factors affecting sustainable performance in construction sites.
Al-Barakati et al. [71] (2022)	Extended interval-valued Pythagorean fuzzy WASPAS	Evaluation of renewable energy sources.
Sıcakyüz [72] (2023)	Fuzzy LMAW and Fermatean fuzzy WASPAS	Analyzing healthcare and wellness products' quality in online customer reviews.
Dede & Zorlu [73] (2023)	Entropy-based WASPAS	Geoheritage assessment on Karçal Mountains (Turkey).
Solanki et al. [74] (2023)	WASPAS and TOPSIS	Evaluation of factors for IoT and cloud computing in the construction industry.
Handayani et al. [75] (2023)	WASPAS	Multi-criteria decision making for online English course selection.

1.2 Motivation and Contribution

The motivation behind this research stems from the imperative to address the intricate challenges of urbanization with innovative and data-driven solutions. Rapid urban growth necessitates a nuanced evaluation of sustainable alternatives, considering their impact on urban density, environmental sustainability, and community engagement. The CRITIC WASPAS method on spherical fuzzy sets serves as a motivated choice, recognizing the inherent uncertainties in decision-making processes. By employing this advanced methodology, our research seeks to motivate urban planners and policymakers to make informed decisions that transcend conventional approaches. Ultimately, the motivation is to contribute to shaping the future of urban landscapes, fostering sustainable development that aligns with the evolving dynamics of contemporary cities.

This research makes a significant contribution to the field of urban development and management by introducing a comprehensive evaluation framework for sustainable alternatives. The integration of the CRITIC WASPAS method on spherical fuzzy sets represents a novel approach, enhancing the precision and robustness of decision-making in urban planning. By systematically assessing transit-oriented development, green infrastructure investment, smart city technologies, and community-based development against a diverse set of eight criteria, our study provides nuanced insights that go beyond traditional evaluations. This contribution aims to enrich the understanding of urban development strategies and guide future initiatives toward more resilient, equitable, and environmentally conscious outcomes.

1.3 Structure of the Paper

The study is organized systematically, beginning with an in-depth exploration of the fundamental notions and operations of SFSs in Section 2. This section methodically lays the framework by elucidating essential principles, mathematical formulas, and critical aspects of SFSs. Building on this basis, Section 3 provides the suggested CRITIC-WASPAS methodology, which skillfully combines the CRITIC method for determining criteria weights with the WASPAS method for aggregation. Methodological complexities, such as intercriteria correlations and total aggregation, are thoroughly discussed. In Section 4, the practical applicability of CRITIC-WASPAS is demonstrated by applying it to a real-world scenario in WMS software selection. Section 5 digs deeply into the implications of the findings before finishing with a concise overview emphasizing the methodology's critical role in constructing decision-making frameworks. The clarity, coherence, and methodological rigor of the research all contribute to its importance in developing decision-making procedures, particularly in the field of WMS software selection.

2 Preliminaries

Definition2.1 [20] Consider the universal set $\mathfrak{Z}$. Let $\mathbb{E}$ denote a fuzzy set in $\mathfrak{Z}$, defined as

$$\mathbb{E} = \{(x, \eta\mathfrak{c} : x \in \mathfrak{Z}\},$$

where, $\eta\mathfrak{c}$ represents the degree of membership (DoM) of the element $\mathfrak{c}$ in the universal set $\mathfrak{Z}$.

Definition2.2 [22, 23] A PFS denoted as $\mathbb{E}$, defined on a universe $\mathfrak{Z}$, takes the form

$$A = \{\langle \mathfrak{c}, \eta\mathfrak{c}, \varrho\mathfrak{c}, \theta\mathfrak{c} \mid \mathfrak{c} \in \mathfrak{Z}\rangle\}$$

where, $\eta\mathfrak{c} \in [0, 1]$ represents the degree of positive membership (PMD) of $\mathfrak{Z}$ in $\mathbb{E}$, $\varrho\mathfrak{c} \in [0, 1]$ represents the degree of neutral membership (NuMD) of $\mathfrak{Z}$ in $\mathbb{E}$, and $\theta\mathfrak{c} \in [0, 1]$ represents the degree of negative membership of $\mathfrak{Z}$ in $\mathbb{E}$, subject to the condition $0 \leq \eta\mathfrak{c} + \varrho\mathfrak{c} + \theta\mathfrak{c} \leq 1$ for all $x \in \mathfrak{Z}$.

Definition2.3 [29] A "spherical fuzzy set" (SFS) in Θ is defined as

$$\chi = \{\langle \breve{\Upsilon}, \mu_\chi(\breve{\Upsilon}), \nu_\chi(\breve{\Upsilon}), \tau_\chi(\breve{\Upsilon}) | \breve{\Upsilon} \in \Theta\rangle\} \tag{1}$$

where, $\mu_\chi(\breve{\Upsilon}), \nu_\chi(\breve{\Upsilon}), \tau_\chi(\breve{\Upsilon}) \in [0, 1]$, such that $0 \leq \mu_\chi^2(\breve{\Upsilon}) + \nu_\chi^2(\breve{\Upsilon}) + \tau_\chi^2(\breve{\Upsilon}) \leq 1$ for all $\breve{\Upsilon} \in \Theta$. $\mu_\chi(\breve{\Upsilon}), \nu_\chi(\breve{\Upsilon}), \tau_\chi(\breve{\Upsilon})$ denote PMD, N_uMD and N_gMD respectively for some $\breve{\Upsilon} \in \Theta$.

We denote this pair as $\breve{\Upsilon} = (\mu_{\breve{\Upsilon}}, \nu_{\breve{\Upsilon}}, \tau_{\breve{\Upsilon}})$, throughout this article, and called as SFN with the conditions $\mu_{\breve{\Upsilon}}, \nu_{\breve{\Upsilon}}, \tau_{\breve{\Upsilon}} \in [0, 1]$ and $\mu_{\breve{\Upsilon}}^2 + \nu_{\breve{\Upsilon}}^2 + \tau_{\breve{\Upsilon}}^2 \leq 1$.

Definition2.4 [29] It is vital to rank the SFNs when applying them to real problems. For this, "score function" (SF) corresponding to SFN $\breve{\Upsilon} = (\mu_{\breve{\Upsilon}}, \nu_{\breve{\Upsilon}}, \tau_{\breve{\Upsilon}})$ be defined as

$$S(\breve{\Upsilon}) = \frac{2 + \mu_{\breve{\Upsilon}} - \nu_{\breve{\Upsilon}} - \tau_{\breve{\Upsilon}}}{3} \tag{2}$$

However, the abovementioned function seems unable to classify the SFNs in several circumstances, then it is impossible to know which one is bigger. For this, an accuracy function H of $\breve{\Upsilon}$ is defined as

$$H(\breve{\Upsilon}) = \mu_{\breve{\Upsilon}} - \tau_{\breve{\Upsilon}} \tag{3}$$

Now we will presented some operational rules to aggregate the SFNs.

Definition2.5 [29] Let $\breve{\Upsilon}_1 = \langle \mu_1, \nu_1, \tau_1\rangle$ and $\breve{\Upsilon}_2 = \langle \mu_2, \nu_2, \tau_2\rangle$ be two SFNs, then

$$\breve{\Upsilon}_1^c = \left\langle \tau_1, \nu_1, \mu_1 \right\rangle \tag{4}$$

$$\breve{\Upsilon}_1 \vee \breve{\Upsilon}_2 = \left\langle max\{\mu_1, \mu_2\}, min\{\nu_1, \nu_2\}, min\{\tau_1, \tau_2\} \right\rangle \tag{5}$$

$$\breve{\Upsilon}_1 \wedge \breve{\Upsilon}_2 = \left\langle min\{\mu_1, \mu_2\}, max\{\nu_1, \nu_2\}, max\{\tau_1, \tau_2\} \right\rangle \tag{6}$$

$$\breve{\Upsilon}_1 \oplus \breve{\Upsilon}_2 = \left\langle \sqrt{\mu_1^2 + \mu_2^2 - \mu_1^2\mu_2^2}, \nu_1\nu_2, \tau_1\tau_2 \right\rangle \tag{7}$$

$$\breve{\Upsilon}_1 \otimes \breve{\Upsilon}_2 = \left\langle \mu_1\mu_2, \sqrt{\nu_1^2 + \nu_2^2 - \nu_1^2\nu_2^2}, \sqrt{\tau_1^2 + \tau_2^2 - \tau_1^2\tau_2^2} \right\rangle \tag{8}$$

$$\sigma\breve{\Upsilon}_1 = \left\langle \sqrt{1 - (1 - \mu_1^2)^\sigma}, \nu_1^\sigma, \tau_1^\sigma \right\rangle \tag{9}$$

$$\breve{\Upsilon}_1^\sigma = \left\langle \mu_1^\sigma, \sqrt{1 - (1 - \nu_1^2)^\sigma}, \sqrt{1 - (1 - \tau_1^2)^\sigma} \right\rangle \tag{10}$$

3 Algorithm

Step 1: Presenting the SFNs dataset, where each alternative ($\mathtt{Al_k}$ with $k = 1, 2, ..., r$) is evaluated across a range of criteria ($\mathtt{Cr_k}$ with $k = 1, 2, ..., s$). DMs input decision matrices, symbolized by $\mathtt{Cr} = \left[\mathtt{Cr_{ij}}\right]_{s\times r}$.

$$\begin{array}{c} \\ \mathtt{Al_1} \\ \mathtt{Al_2} \\ \vdots \\ \mathtt{Al_n} \end{array} \begin{array}{c} \begin{array}{cccc} \mathtt{Cr_1} & \mathtt{Cr_2} & & \mathtt{Cr_q} \end{array} \\ \begin{bmatrix} (\mathtt{AT}_{11}, \mathtt{AT}_{11}, \mathtt{AT}_{11}) & (\mathtt{AT}_{12}, \mathtt{AT}_{12}, \mathtt{AT}_{12},) & \dots & (\mathtt{AT}_{1m}, \mathtt{AT}_{1m}, \mathtt{AT}_{1q}) \\ (\mathtt{AT}_{21}, \mathtt{AT}_{21}, \mathtt{AT}_{21}) & (\mathtt{AT}_{22}, \mathtt{AT}_{22}, \mathtt{AT}_{22}) & \dots & (\mathtt{AT}_{2q}, \mathtt{AT}_{2q}, \mathtt{AT}_{2q}) \\ \vdots & \vdots & \ddots & \vdots \\ (\mathtt{AT}_{p1}, \mathtt{AT}_{p1}, \mathtt{AT}_{p1},) & (\mathtt{AT}_{p2}, \mathtt{AT}_{p2}, \mathtt{AT}_{p2}) & \dots & (\mathtt{AT}_{pq}, \mathtt{AT}_{pq}, \mathtt{AT}_{pq}) \end{bmatrix} \end{array}$$

In the context of the SFNs dataset, $\mathtt{Cr_{ij}}$ is defined as $(\mathtt{AT}ij, \mathtt{AT}ij, \mathtt{AT}_{ij})$, where (i=1,2,...,r) and (j=1,2,...,s) represent T-SFN information capturing details about alternatives with respect to DM criteria. Each alternative is characterized by eight linguistic terms, as outlined in Table 2. Moreover, expertise-related linguistic expressions, detailed in Table 3, complement these terms. This diverse array of linguistic expressions enhances the comprehensive representation of the information evaluation process.

Step 2: Compute the DM's weights using the scoring function specified in Eq. (2). Subsequently, incorporate the obtained scores into the designated Eq. (11).

$$\mathfrak{Sco}_{ij} = \frac{\sum_i^3 (\frac{2+\mu_{\breve{\Upsilon}} - \nu_{\breve{\Upsilon}} - \tau_{\breve{\Upsilon}}}{3})}{\sum_j^3 (\sum_i^3 (\frac{2+\mu_{\breve{\Upsilon}} - \nu_{\breve{\Upsilon}} - \tau_{\breve{\Upsilon}}}{3}))} \tag{11}$$

Table 2. Linguistic terms for evaluation in the case study

Evaluation Term	Description	Membership Values (SFSs)
Extremely high (EH)	Represents the highest level of the evaluated criterion.	$(0.95, 0.02, 0.03)$
Very high (VH)	Significantly above average performance with minimal room for improvement.	$(0.90, 0.10, 0.10)$
High (H)	Performance is notable and exceeds expectations.	$(0.80, 0.15, 0.20)$
Moderately high (MH)	Above average performance with room for improvement.	$(0.70, 0.25, 0.30)$
Fair (F)	Meets basic requirements without significant advantages or disadvantages.	$(0.65, 0.30, 0.40)$
Moderately low (ML)	Below average performance with room for improvement.	$(0.60, 0.40, 0.50)$
Low (L)	Performance is below expectations with significant room for improvement.	$(0.50, 0.45, 0.55)$
Very low (VL)	Poor performance with minimal positive attributes.	$(0.40, 0.50, 0.60)$
Extremely low (EL)	Represents the lowest level of the evaluated criterion.	$(0.30, 0.55, 0.65)$

Step 3: Generate the aggregated decision matrix $M = [M_{ij}]_{q\times p}$ by applying the formula defined in Eq. (12).

$$\text{T-SFWG}(S_1, S_2, \dots, S_s) = \left(\prod_{j=1}^{s} (\eta_j + \varrho_j)^{\omega_j} - \prod_{j=1}^{s} \varrho_j^{\omega_j}, \prod_{j=1}^{s} \varrho_j^{\omega_j}, \sqrt[n]{1 - \prod_{j=1}^{s} (1 - \theta_j^s)^{\omega_j}} \right) \tag{12}$$

Table 3. Decision makers and roles in urban development with linguistic terms

Decision Maker	Role	Key Decisions/Responsibilities
Urban Planner	Planning Lead	Overall coordination and strategic planning for urban development alternatives.
$(\mathbb{EH})$	$(\mathbb{F})$	$(\mathbb{H})$
Environmental Analyst	Sustainability Expert	Assess and analyze the environmental impact of each alternative.
$(\mathbb{F})$	$(\mathbb{H})$	$(\mathbb{ML})$
Community Liaison Officer	Community Engagement Specialist	Facilitate community involvement in decision-making processes.
$(\mathbb{ML})$	$(\mathbb{H})$	$(\mathbb{VL})$

Step 4: CRITIC Method

When dealing with Multiple Criteria Decision Making (MCDM), the CRITIC technique evaluates the relative value of criteria. The following stages will clarify the calculation procedure.

Step 4.1: Calculate the score for the aggregated decision matrix by utilizing the provided Eq. (13).

$$\mathfrak{Sco}_{ij} = \eta_F^t - \varrho_F^t \tag{13}$$

Step 4.2: Transform the matrix $\mathfrak{Sco}$ into a standard SFNs matrix using the conversion formula given in Eq. (14).

$$\widetilde{\mathfrak{Sco}}_{ij} = \begin{cases} \frac{\mathfrak{Sco}_{ij} - \mathfrak{Sco}_j^-}{\mathfrak{Sco}_j^+ - \mathfrak{Sco}_j^-}, & j \in \mathfrak{Cr}_b \\ \frac{\mathfrak{Sco}_j^+ - \mathfrak{Sco}_{ij}}{\mathfrak{Sco}_j^+ - \mathfrak{Sco}_j^-}, & j \in \mathfrak{Cr}_c \end{cases} \tag{14}$$

Here, $\mathfrak{Sco}_j^+ = \max i\mathfrak{Sco}ij$ and $\mathfrak{Sco}j^- = \min_i \mathfrak{Sco}ij$. Additionally, $\mathfrak{Cr}_b$ and $\mathfrak{Cr}_c$ denote the benefit-type and cost-type criteria, respectively.

Step 4.3: Estimate criteria standard deviations using Eq. (15).

$$F_j = \sqrt{\frac{\sum_{i=1}^{n} \left(\mathfrak{Sco}_{ij} - \bar{\mathfrak{Sco}}_j\right)^2}{n}}. \tag{15}$$

where, $\bar{\mathfrak{Sco}}_j = \sum_{i=1}^{n} \widetilde{\mathfrak{Sco}}_{ij}/n$.

Step 4.4: Compute the correlation coefficient for the criterion using Eq. (16).

$$k_{jt} = \frac{\sum_{i=1}^{n} \left(\mathfrak{Sco}_{ij} - \bar{\mathfrak{Sco}}_j\right)\left(\mathfrak{Sco}_{ij} - \bar{\mathfrak{Sco}}_t\right)}{\sqrt{\sum_{i=1}^{n} \left(\mathfrak{Sco}_{ij} - \bar{\mathfrak{Sco}}_j\right)^2 \left(\mathfrak{Sco}_{ij} - \bar{Sc}_t\right)^2}} \tag{16}$$

Step 4.5: Evaluate the information for each criterion utilizing Eq. (17).

$$\mathfrak{cr}_\mathfrak{j} = \beth \sum_{t=1}^{m} (1 - k_{jt}) \tag{17}$$

As the value of $\mathfrak{cr}_\mathfrak{j}$ rises, a particular criterion incorporates more information than others, leading to an increased weight assigned to that criterion compared to other factors.

Step 4.6: Calculate the objective weight for each criterion using Eq. (18).

$$\omega_\mathfrak{j} = \frac{\mathfrak{cr}_\mathfrak{j}}{\sum_{j=1}^{p} \mathfrak{cr}_\mathfrak{j}} \tag{18}$$

Step 5: Normalize the cost criteria and benefit criteria using Eq. (19).

$$\mathfrak{WS}_{ij} = \begin{cases} \frac{\mathfrak{S}ij}{\max\limits_{i} \mathfrak{S}ij}, & j \in \mathfrak{Cr}_b \\ \frac{\max\limits_{i} \mathfrak{S}ij}{\mathfrak{S}ij}, & j \in \mathfrak{Cr}_c \end{cases} \tag{19}$$

Step 6: Employ Eq. (20) to determine the additive relative importance in the weighted normalized data for each alternative.

$$Q^1{}_i = \sum_{j=1}^{n} \mathfrak{WS}_{ij} \cdot \omega_j \tag{20}$$

$Q^1{}_i$ signifies the additive relative importance of each alternative.

Step 7: Use Eq. (21) to compute the multiplicative relative importance of the weighted normalized data for each alternative.

$$Q^2{}_i = \prod_{j=1}^{n} \mathfrak{WS}_{ij}^{\omega_j} \tag{21}$$

Step 8: Introduce the joint generalized criterion (Q), designed to generalize and integrate additive and multiplicative methods, as defined by Eq. (22).

$$Q_i = \frac{1}{2}\left(\sum_{j=1}^{n} \mathfrak{WS}_{ij} \cdot \omega_j + \prod_{j=1}^{n} \mathfrak{WS}_{ij}^{\omega_j}\right) \tag{22}$$

Additionally, Eq. (23) has been introduced to improve ranking accuracy.

$$Q_i = \lambda \sum_{j=1}^{n} \mathfrak{WS}_{ij} \cdot \omega_j + (1-\lambda) \prod_{j=1}^{n} \mathfrak{WS}_{ij}^{\omega_j} \tag{23}$$

A flowchart is utilized to visually depict the method, presenting its step-by-step logic and decision-making process is given in Figure 1.

4 Case Study

Urbanization has emerged as one of the defining trends of the 21st century, transforming the global landscape and presenting unprecedented challenges and opportunities for sustainable development. As cities continue to swell with population growth and economic activities, the traditional models of urban development have faced increasing scrutiny. This case study delves into the intricate background of this urban dilemma, motivated by the imperative to explore alternative strategies that can harmonize economic progress, environmental stewardship, and social inclusivity. The rapid pace of urban growth, driven by factors such as migration, industrialization, and globalization, has led to sprawling metropolises grappling with congestion, inadequate infrastructure, and environmental degradation. The backdrop of this case study is rooted in the recognition that the conventional urban development paradigm must evolve to address these challenges effectively. The imperative is not only to accommodate the expanding urban population but to do so in a manner that ensures resilience, equity, and sustainability. Against this backdrop, four distinct alternatives come to the forefront: transit-oriented development (TOD), green infrastructure investment, smart city technologies, and community-based development. Each alternative represents a unique approach to reshaping the urban landscape and navigating the complexities of modern urbanization. The case study unfolds within the context of these alternatives, seeking to understand their potential contributions and drawbacks against a backdrop of well-defined evaluation criteria.

4.1 Definition of Alternatives

Transit-Oriented Development (TOD) $(\mathfrak{Al}_1)$**:**

At the heart of urban mobility challenges lies Transit-Oriented Development, an alternative that reimagines urban spaces around efficient and accessible transit hubs. TOD emphasizes high-density, mixed-use communities that encourage residents to rely on public transportation, reducing their dependence on private vehicles. The criteria for evaluating TOD extend beyond its impact on urban density to include considerations of transit connectivity, environmental implications, infrastructure capacity, community engagement, economic viability, technological integration, equity, inclusivity, and resilience.

Green Infrastructure Investment $(\mathfrak{Al}_2)$**:**

Green Infrastructure Investment takes a holistic approach to urban development by dedicating resources to enhance and maintain environmentally friendly features within urban areas. This alternative prioritizes the development of green spaces, parks, and sustainable landscaping to improve air and water quality, promote biodiversity, and enhance the overall well-being of urban residents. The evaluation criteria encompass considerations of urban density, environmental impact, infrastructure capacity, community engagement, economic viability, technological integration, equity, inclusivity, and resilience.

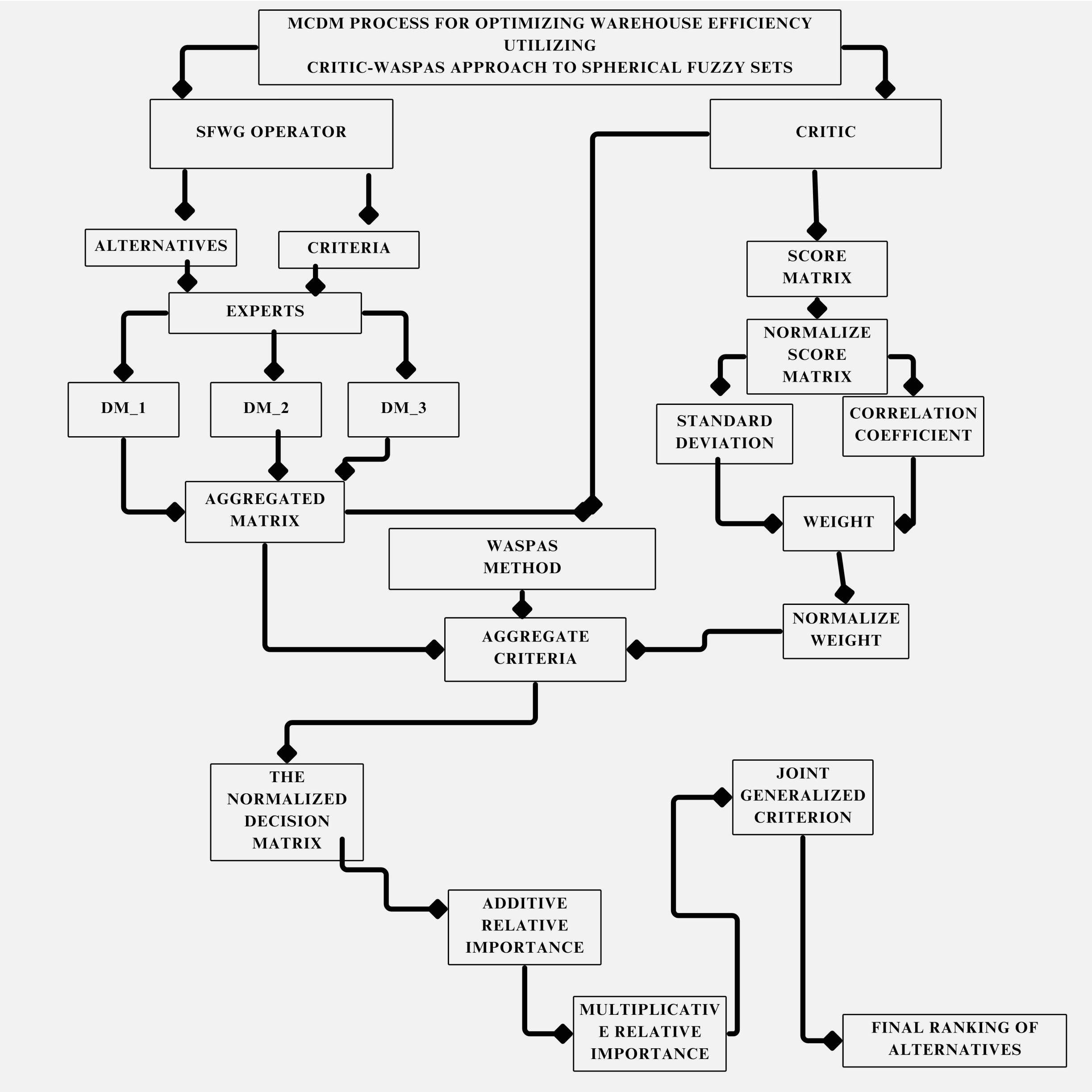

Figure 1. The algorithm's operational procedure

Smart City Technologies $(\mathfrak{A}\mathfrak{l}_3)$**:**

In the age of digital transformation, Smart City Technologies offer a technologically advanced alternative to urban development. This approach integrates cutting-edge technologies to optimize urban management, enhance sustainability, and improve residents' quality of life. From intelligent traffic management to data-driven decision-making, the criteria for evaluating Smart City Technologies span urban density, environmental impact, infrastructure capacity, community engagement, economic viability, technological integration, equity, inclusivity, and resilience.

Community-Based Development $(\mathfrak{A}\mathfrak{l}_4)$**:**

Recognizing the importance of local empowerment, Community-Based Development emerges as an alternative that empowers communities to actively participate in the decision-making and implementation processes of urban development projects. This bottom-up approach emphasizes community-driven initiatives, ensuring that the unique needs, cultural values, and social dynamics of residents shape the urban landscape. The criteria for evaluating Community-Based Development extend from urban density considerations to environmental impact, infrastructure capacity, community engagement, economic viability, technological integration, equity, inclusivity, and resilience.

The selection of these four alternatives was strategically made to facilitate the determination of the most suitable software for urban development and management. Expert assessments were specifically gathered based on the performance and features of these alternatives, providing a comprehensive evaluation for informed decision-making in urban development and management.

4.2 Definition of Criteria

Urban Density ($\mathfrak{Cr}_1$):

Urban Density serves as a foundational criterion, measuring the potential increase in population concentration and the reduction in urban sprawl achieved by each alternative. It involves evaluating how well the alternative contributes to creating compact, well-connected urban spaces while minimizing spatial expansion.

Environmental Impact($\mathfrak{Cr}_2$):

Environmental Impact is a critical consideration, focusing on the environmental benefits associated with each alternative. Factors such as reductions in carbon emissions, improvements in air and water quality, and the preservation of natural resources are carefully examined.

Infrastructure Capacity ($\mathfrak{Cr}_3$):

Infrastructure Capacity assesses the ability of existing and proposed infrastructure to support and accommodate each alternative. It involves evaluating transportation networks, utilities, and other essential services to ensure they can adequately support the chosen urban development strategy.

Community Engagement ($\mathfrak{Cr}_4$):

Community Engagement is a pivotal criterion that measures the level of involvement of local communities in the planning, decision-making, and execution processes of each alternative. Emphasizing inclusivity, this criterion evaluates the extent to which residents are empowered to contribute to the shaping of their urban environment.

Economic Viability ($\mathfrak{Cr}_5$):

Economic Viability is a multifaceted consideration that assesses the economic impact of each alternative. Factors such as job creation, changes in property values, and overall contributions to local economic growth are carefully examined.

Technological Integration ($\mathfrak{Cr}_6$):

Technological Integration is a contemporary criterion that evaluates the seamless incorporation of advanced technologies within each alternative. This involves assessing how smart solutions and innovations enhance urban management, infrastructure efficiency, and overall quality of life.

Equity and Inclusivity ($\mathfrak{Cr}_7$):

Equity and Inclusivity are paramount considerations, ensuring that each alternative fosters social equity and inclusivity. This criterion addresses potential disparities in access to resources, opportunities, and quality of life.

Resilience ($\mathfrak{Cr}_8$):

Resilience assesses the ability of each alternative to adapt and thrive in the face of future challenges. This criterion considers factors such as population growth, technological changes, and environmental shifts.

The procedure can be broken down into the following steps:

Step 1: Experts utilize the SFNs dataset, incorporating linguistic terms from Table 2 for each alternative $\mathfrak{Al}r$ (where $p = 1, 2, ..., r$), taking into account various criteria $\mathfrak{Cr}AT$, as detailed in Table 4.

Table 4. DM's evaluation table

DMs	Alternatives	$\mathfrak{Cr}_1$	$\mathfrak{Cr}_2$	$\mathfrak{Cr}_3$	$\mathfrak{Cr}_4$	$\mathfrak{Cr}_5$	$\mathfrak{Cr}_6$	$\mathfrak{Cr}_7$	$\mathfrak{Cr}_8$
DM_1	$\mathfrak{Al}_1$	$\mathbb{EH}$	$\mathbb{VH}$	$\mathbb{EL}$	$\mathbb{VL}$	$\mathbb{F}$	$\mathbb{MH}$	$\mathbb{ML}$	$\mathbb{MH}$
	$\mathfrak{Al}_2$	$\mathbb{L}$	$\mathbb{VH}$	$\mathbb{EL}$	$\mathbb{L}$	$\mathbb{MH}$	$\mathbb{F}$	$\mathbb{ML}$	$\mathbb{MH}$
	$\mathfrak{Al}_3$	$\mathbb{MH}$	$\mathbb{ML}$	$\mathbb{L}$	$\mathbb{H}$	$\mathbb{EH}$	$\mathbb{F}$	$\mathbb{H}$	$\mathbb{VL}$
	$\mathfrak{Al}_4$	$\mathbb{F}$	$\mathbb{VH}$	$\mathbb{ML}$	$\mathbb{F}$	$\mathbb{MH}$	$\mathbb{L}$	$\mathbb{H}$	$\mathbb{MH}$
DM_2	$\mathfrak{Al}_1$	$\mathbb{ML}$	$\mathbb{F}$	$\mathbb{MH}$	$\mathbb{EH}$	$\mathbb{L}$	$\mathbb{EL}$	$\mathbb{VH}$	$\mathbb{VL}$
	$\mathfrak{Al}_2$	$\mathbb{VH}$	$\mathbb{MH}$	$\mathbb{ML}$	$\mathbb{H}$	$\mathbb{L}$	$\mathbb{F}$	$\mathbb{EH}$	$\mathbb{EL}$
	$\mathfrak{Al}_3$	$\mathbb{H}$	$\mathbb{L}$	$\mathbb{VH}$	$\mathbb{MH}$	$\mathbb{ML}$	$\mathbb{VL}$	$\mathbb{F}$	$\mathbb{VL}$
	$\mathfrak{Al}_4$	$\mathbb{F}$	$\mathbb{MH}$	$\mathbb{EL}$	$\mathbb{L}$	$\mathbb{EH}$	$\mathbb{ML}$	$\mathbb{VH}$	$\mathbb{VL}$
DM_3	$\mathfrak{Al}_1$	$\mathbb{MH}$	$\mathbb{ML}$	$\mathbb{EL}$	$\mathbb{F}$	$\mathbb{VH}$	$\mathbb{EH}$	$\mathbb{L}$	$\mathbb{ML}$
	$\mathfrak{Al}_2$	$\mathbb{VH}$	$\mathbb{MH}$	$\mathbb{F}$	$\mathbb{ML}$	$\mathbb{L}$	$\mathbb{H}$	$\mathbb{ML}$	$\mathbb{VL}$
	$\mathfrak{Al}_3$	$\mathbb{H}$	$\mathbb{ML}$	$\mathbb{VL}$	$\mathbb{L}$	$\mathbb{VH}$	$\mathbb{F}$	$\mathbb{MH}$	$\mathbb{L}$
	$\mathfrak{Al}_4$	$\mathbb{F}$	$\mathbb{L}$	$\mathbb{VH}$	$\mathbb{MH}$	$\mathbb{H}$	$\mathbb{EH}$	$\mathbb{ML}$	$\mathbb{EL}$

Step 2: Determine the weights of decision makers (DMs) by applying the scoring function outlined in Eq. (11). Then, utilize the obtained scores in Eq. (2), and present the resulting values in Table 5.

Table 5. Decision makers and roles in urban development with linguistic terms

Decision Maker	Role	Key Decisions/Responsibilities	
Urban Planner	Planning Lead	Overall coordination and strategic planning for urban development alternatives.	
$(\mathbb{EH})$	$(\mathbb{F})$	$(\mathbb{EL})$	0.3371
Environmental Analyst	Sustainability Expert	Assess and analyze the environmental impact of each alternative.	
$(\mathbb{F})$	$(\mathbb{H})$	$(\mathbb{ML})$	0.3804
Community Liaison Officer	Community Engagement Specialist	Facilitate community involvement in decision-making processes.	
$(\mathbb{ML})$	$(\mathbb{H})$	$(\mathbb{VL})$	0.2825

Step 3: Calculate the aggregated decision matrix $M = [M_{ij}]_{q\times p}$ using Eq. (12), and display the results in Table 6.

Table 6. Aggregated decision matrix

$\mathfrak{Cr}_i$	$\mathfrak{Al}_1$	$\mathfrak{Al}_2$	$\mathfrak{Al}_3$	$\mathfrak{Al}_4$	$\mathfrak{Al}_5$
$\mathfrak{Cr}_1$	$\langle 0.500, 0.326, 0.391\rangle$	$\langle 0.900, 0.160, 0.119\rangle$	$\langle 0.600, 0.426, 0.525\rangle$	$\langle 0.650, 0.300, 0.300\rangle$	$\langle 0.750, 0.390, 0.481\rangle$
$\mathfrak{Cr}_2$	$\langle 0.750, 0.242, 0.234\rangle$	$\langle 0.500, 0.390, 0.477\rangle$	$\langle 0.751, 0.239, 0.190\rangle$	$\langle 0.802, 0.332, 0.406\rangle$	$\langle 0.900, 0.333, 0.407\rangle$
$\mathfrak{Cr}_3$	$\langle 0.601, 0.416, 0.516\rangle$	$\langle 0.651, 0.358, 0.438\rangle$	$\langle 0.410, 0.357, 0.427\rangle$	$\langle 0.900, 0.279, 0.338\rangle$	$\langle 0.650, 0.391, 0.468\rangle$
$\mathfrak{Cr}_4$	$\langle 0.650, 0.431, 0.517\rangle$	$\langle 0.740, 0.313, 0.383\rangle$	$\langle 0.801, 0.380, 0.469\rangle$	$\langle 0.500, 0.343, 0.401\rangle$	$\langle 0.600, 0.444, 0.534\rangle$
$\mathfrak{Cr}_5$	$\langle 0.901, 0.230, 0.226\rangle$	$\langle 0.801, 0.368, 0.4491\rangle$	$\langle 0.900, 0.180, 0.142\rangle$	$\langle 0.600, 0.0.405, 0.497\rangle$	$\langle 0.400, 0.465, 0.559\rangle$
$\mathfrak{Cr}_6$	$\langle 0.851, 0.375, 0.461\rangle$	$\langle 0.600, 0.330, 0.377\rangle$	$\langle 0.651, 0.401, 0.473\rangle$	$\langle 0.850, 0.206, 0.161\rangle$	$\langle 0.800, 0.230, 0.372\rangle$
$\mathfrak{Cr}_7$	$\langle 0.800, 0.219, 0.174\rangle$	$\langle 0.750, 0.234, 0.186\rangle$	$\langle 0.500, 0.395, 0.485\rangle$	$\langle 0.750, 0.340, 0.423\rangle$	$\langle 0.502, 0.323, 0.390\rangle$
$\mathfrak{Cr}_8$	$\langle 0.750, 0.433, 0.524\rangle$	$\langle 0.400, 0.451, 0.551\rangle$	$\langle 0.800, 0.446, 0.535\rangle$	$\langle 0.600, 0.457, 0.555\rangle$	$\langle 0.400, 0.468, 0.560\rangle$

Step 4.1: Compute the consolidated score of the decision matrix using Eq. (13).

$$\mathfrak{Sc}_{ij} = \begin{bmatrix} 0.718 & 0.687 & 0.621 & 0.693 & 0.859 & 0.918 & 0.666 & 0.675 \\ 0.860 & 0.722 & 0.677 & 0.681 & 0.661 & 0.774 & 0.684 & 0.639 \\ 0.775 & 0.676 & 0.659 & 0.670 & 0.861 & 0.690 & 0.721 & 0.645 \\ 0.701 & 0.670 & 0.850 & 0.713 & 0.776 & 0.921 & 0.689 & 0.631 \end{bmatrix}$$

Step 4.2: Transform the matrix $\bar{\mathfrak{Sc}}$ into a standard SFSs matrix using Eq. (14).

$$\bar{\mathfrak{Sc}}_{ij} = \begin{bmatrix} 0.896 & 0.673 & 1 & 0.476 & 0.990 & 0.985 & 0 & 1 \\ 0 & 0 & 0.756 & 0.742 & 0 & 0.361 & 0.333 & 0.164 \\ 0.532 & 0.890 & 0.833 & 1 & 1 & 0 & 1 & 0.301 \\ 1 & 1 & 0 & 0 & 0.572 & 1 & 0.416 & 0 \end{bmatrix}$$

Step 4.3: Calculate an estimate of the standard deviations for the criterion using the formula provided in Eq. (15).

$$\beth_j = \begin{bmatrix} 0.452 & 0.448 & 0.443 & 0.427 & 0.471 & 0.491 & 0.416 & 0.440 \end{bmatrix}$$

Step 4.4: Utilize Eq. (16) to calculate the correlation coefficient for the criteria.

$$r_{jt} = \begin{bmatrix} 1 & 0.857 & -0.386 & -0.670 & 0.683 & 0.688 & -0.201 & 0.280 \\ 0.857 & 1 & -0.410 & -0.367 & 0.768 & 0.241 & 0.332 & 0.004 \\ -0.386 & -0.410 & 1 & 0.765 & 0.263 & -0.399 & -0.086 & 0.729 \\ -0.670 & -0.367 & 0.765 & 1 & 0.084 & -0.896 & 0.520 & 0.154 \\ 0.683 & 0.768 & 0.263 & 0.084 & 1 & 0.063 & 0.200 & 0.567 \\ 0.688 & 0.241 & -0.399 & -0.896 & 0.063 & 1 & -0.798 & 0.284 \\ -0.201 & 0.332 & -0.086 & 0.520 & 0.201 & -0.798 & 1 & -0.518 \\ 0.280 & 0.004 & 0.729 & 0.154 & 0.567 & 0.284 & -0.518 & 1 \end{bmatrix}$$

Step 4.5: Evaluate the details for each criterion using Eq. (17).

$$\mathfrak{c}_{\mathfrak{j}} = \begin{bmatrix} 2.597 & 2.499 & 2.892 & 3.165 & 2.060 & 3.840 & 3.142 & 2.420 \end{bmatrix}$$

Step 4.6: Calculate the objective weight assigned to each criterion using Eq. (18).

$$\mathfrak{w}_{\mathfrak{j}} = \begin{bmatrix} 0.115 & 0.111 & 0.128 & 0.140 & 0.091 & 0.170 & 0.139 & 0.107 \end{bmatrix}$$

4.3 WASPAS

Step 5: Normalization of both cost and benefit criteria has been achieved using Eq. (19). The resulting values are presented in Table 7.

Table 7. Normalized decision matrix

Alternative	$\mathfrak{Cr}_1$	$\mathfrak{Cr}_2$	$\mathfrak{Cr}_3$	$\mathfrak{Cr}_4$	$\mathfrak{Cr}_5$	$\mathfrak{Cr}_6$	$\mathfrak{Cr}_7$	$\mathfrak{Cr}_8$
$\mathfrak{Al}_1$	0.782	0.748	0.676	0.755	0.936	1	0.725	0.735
$\mathfrak{Al}_2$	1	0.839	0.786	0.792	0.769	0.899	0.795	0.742
$\mathfrak{Al}_3$	0.901	0.785	0.765	0.778	1	0.801	0.837	0.748
$\mathfrak{Al}_4$	0.761	0.727	0.922	0.774	0.842	1	0.747	0.685

Table 8. Normalized decision matrix

Alternative	$\mathfrak{Cr}_1$	$\mathfrak{Cr}_2$	$\mathfrak{Cr}_3$	$\mathfrak{Cr}_4$	$\mathfrak{Cr}_5$	$\mathfrak{Cr}_6$	$\mathfrak{Cr}_7$	$\mathfrak{Cr}_8$
$\mathfrak{Al}_1$	0.0467	0.4009	0.1106	0.1714	1.0000	0.7397	0.5547	0.3766
$\mathfrak{Al}_2$	1.0000	0.0377	0.1866	0.3969	0.5435	0.1251	0.4008	-0.0142
$\mathfrak{Al}_3$	0.1080	0.4007	0.0076	0.5418	1.0000	0.1789	0.0367	0.5253
$\mathfrak{Al}_4$	0.1929	0.5496	1.0000	0.0450	0.1135	0.7529	0.3953	0.0983
$\mathfrak{Al}_5$	0.3892	1.0000	0.1822	0.1032	-0.0197	0.5546	0.0473	-0.0209

Step 6, 7 and 8: Eqs. (21)-(23) are applied to calculate the additive relative importance, multiplicative relative importance, and joint generalized criterion (Q) in the weighted normalized data for each alternative, respectively. The outcomes are presented in Table 8.

4.4 Sensitivity Analysis

The sensitivity analysis of decision outcomes in Table 9 reveals the consistent ranking of alternatives, namely $\mathfrak{Al}_1$ to $\mathfrak{Al}_4$, as the parameter λ fluctuates from 0.1 to 0.8, demonstrating the robustness and stability of the decision-making model. Notably, $\mathfrak{Al}2 \succ \mathfrak{Al}3 \succ \mathfrak{Al}4 \succ \mathfrak{Al}1$. The examination of various λ values on the joint generalized criterion unveils a trend: values tend towards additive relative importance as λ approaches 1 and shift towards multiplicative relative importance as it approaches zero. The graphical representation in Figure 2 illustrates the nuanced impact of different λ values on the decision-making process within the SFS framework, underscoring the model's adaptability. Overall, these findings emphasize the reliability and versatility of the decision-making model across a range of λ values.

Table 9. The influence of the parameter λ on the outcome of the decision

λ	$\mathfrak{Al}_1$	$\mathfrak{Al}_2$	$\mathfrak{Al}_3$	$\mathfrak{Al}_4$	**Ranking**
$\lambda = 0.1$	0.7926	0.8286	0.8177	0.8117	$\mathfrak{Al}_2 \succ \mathfrak{Al}_3 \succ \mathfrak{Al}_4 \succ \mathfrak{Al}_1$
$\lambda = 0.2$	0.7933	0.8289	0.8180	0.8123	$\mathfrak{Al}_2 \succ \mathfrak{Al}_3 \succ \mathfrak{Al}_4 \succ \mathfrak{Al}_1$
$\lambda = 0.3$	0.7940	0.8293	0.8183	0.8130	$\mathfrak{Al}_2 \succ \mathfrak{Al}_3 \succ \mathfrak{Al}_4 \succ \mathfrak{Al}_1$
$\lambda = 0.4$	0.7947	0.8296	0.8186	0.8137	$\mathfrak{Al}_2 \succ \mathfrak{Al}_3 \succ \mathfrak{Al}_4 \succ \mathfrak{Al}_1$
$\lambda = 0.5$	0.7955	0.8299	0.8189	0.8143	$\mathfrak{Al}_2 \succ \mathfrak{Al}_3 \succ \mathfrak{Al}_4 \succ \mathfrak{Al}_1$
$\lambda = 0.6$	0.7962	0.8303	0.8192	0.8150	$\mathfrak{Al}_2 \succ \mathfrak{Al}_3 \succ \mathfrak{Al}_4 \succ \mathfrak{Al}_1$
$\lambda = 0.7$	0.7969	0.8306	0.8195	0.8156	$\mathfrak{Al}_2 \succ \mathfrak{Al}_3 \succ \mathfrak{Al}_4 \succ \mathfrak{Al}_1$
$\lambda = 0.8$	0.7976	0.8310	0.8198	0.8163	$\mathfrak{Al}_2 \succ \mathfrak{Al}_3 \succ \mathfrak{Al}_4 \succ \mathfrak{Al}_1$

This ranking information provides decision-makers with an understanding of how the WMS software alternatives respond to changes in the importance assigned to decision criteria. It highlights the consistent and robust performance of $\mathfrak{Al}_2$ across different decision scenarios, offering valuable guidance for selecting the most suitable WMS software alternative based on specific decision-making priorities.

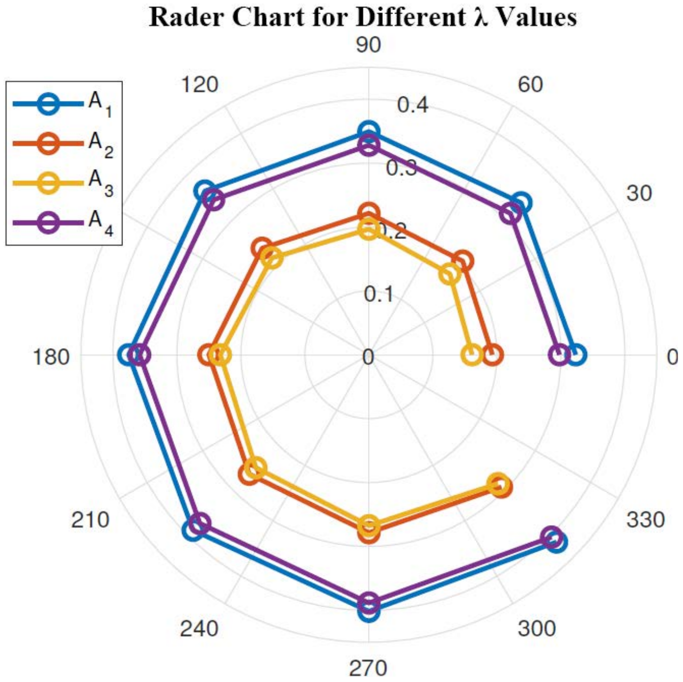

Figure 2. Visualizing variations with changing parameter (λ)

4.5 Comparative Analysis

In our extensive comparative research, we systematically examined the feasibility and effectiveness of decision-making procedures within SFNs. The meticulous scrutiny of each element, coupled with rigorous validation and robustness checks throughout the study, significantly enhances the reliability and consistency of our results. These methodological aspects not only contribute to the comprehensiveness of our research but also serve as the bedrock for our conclusive insights. The pivotal findings are succinctly presented in Table 10, offering a compelling overview of our investigation. The nuanced insights derived from our thorough analysis enable a comprehensive understanding of both the benefits and drawbacks associated with various decision-making procedures within SFNs. In essence, our research provides decision-makers with reliable insights, strategically guiding the integration of SFSs and enriching our collective comprehension of decision-making within the SFS framework.

Table 10. Comparison of newly proposed AOs with already existing AOs when $t = .5$

Authors	Methodology	Ranking of Alternatives	Optimal Alternative
Gündoğdu and Kahraman [76]	TOPSIS method	$\mathfrak{Al}_2 \succ \mathfrak{Al}_3 \succ \mathfrak{Al}_4 \succ \mathfrak{Al}_1$	$\mathfrak{Al}_2$
Ali [77]	CRITIC-MARCOS	$\mathfrak{Al}_2 \succ \mathfrak{Al}_3 \succ \mathfrak{Al}_1 \succ \mathfrak{Al}_4$	$\mathfrak{Al}_2$
Akdag and Menekse [78]	CRITIC-REGIME	$\mathfrak{Al}_2 \succ \mathfrak{Al}_4 \succ \mathfrak{Al}_3 \succ \mathfrak{Al}_1$	$\mathfrak{Al}_2$
Zhang et al. [79]	TODIM method	$\mathfrak{Al}_2 \succ \mathfrak{Al}_3 \succ \mathfrak{Al}_4 \succ \mathfrak{Al}_1$	$\mathfrak{Al}_2$
Anafi et al. [80]	TOP-DEMATEL	$\mathfrak{Al}_2 \succ \mathfrak{Al}_3 \succ \mathfrak{Al}_1 \succ \mathfrak{Al}_4$	$\mathfrak{Al}_2$
Proposed	CRITIC-WASPAS	$\mathfrak{Al}_2 \succ \mathfrak{Al}_3 \succ \mathfrak{Al}_4 \succ \mathfrak{Al}_1$	$\mathfrak{Al}_2$

In contrast to other methods, the CRITIC-WASPAS technique consistently outperforms in evaluating and ranking Warehouse Management System (WMS) choices. It surpasses established methods like TOPSIS, CRITIC-MARCOS, CRITIC-REGIME, TODIM, and TOP-DEMATEL in a thorough comparison across various methodologies. Notably, $\mathfrak{Al}_2$ emerges as the consistently top-rated alternative, underscoring CRITIC-WASPAS's effectiveness in guiding decision-making for WMS choices. This suggests its practicality and reliability, positioning it as a superior approach in this domain.

5 Conclusions

In summary, this study introduces the CRITIC-WASPAS model as a robust and effective decision-making solution within the SFS framework. The comprehensive sensitivity analysis, spanning from 0.1 to 0.8 for the parameter λ, consistently ranks $\mathfrak{Al}_2$ as the optimal choice, affirming the model's stability and competitiveness across diverse scenarios. The integration of the CRITIC approach with the WASPAS technique forms a synergistic alliance, providing decision-makers with not only reliable but also comprehensive insights into challenging multi-criteria decision scenarios. The real-world case study involving the incorporation of self-powered sensors into WMS serves as a compelling validation of the practical value of the CRITIC-WASPAS model. The consistent selection of $\mathfrak{A}_2$ as the optimal alternative across varied scenarios highlights the model's reliability and robustness in navigating the complexity of decision-making in dynamic, real-world environments.

Looking ahead, future research avenues could involve refining the CRITIC-WASPAS model to accommodate different choice contexts and conducting additional validations in diverse real-world scenarios. Exploring the model's scalability for larger decision landscapes, along with enhancements to address diverse decision-making complexities, could broaden its applicability. To conclude, CRITIC-WASPAS emerges as a dependable and versatile tool for addressing intricate decision situations within the SFS framework, making substantial contributions to the field, and laying the groundwork for future advancements in decision-making approaches.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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