Assessment of Airport Pavement Sustainability Using an Integrated Fuzzy ANP-TOPSIS Decision Model

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Abstract: Sustainable design is the future of heavy construction projects such as airports. However, these structures usually require constant maintenance, which can become a major financial burden. The maintenance and rehabilitation of pavement, especially at airports, is a costly process which includes labour, equipment, and material expenses. By transitioning to a system that uses more sustainable designs and building materials, it is possible to build better structures that will not suffer serious damage. This research aims at building a new assessment framework for sustainable air-port pavements to be later applied to the case study of Taif airport in Saudi Arabia. To assess the proposed international airport in terms of sustainability, four sustainable alternatives (A1, A2, A3, and A4) are proposed, along with nine criteria. These alternatives are studied and the TOPSIS method is used to select the best alternative. Additionally, weights are calculated using the Fuzzy Analytic Network Process (FANP). According to achieved results, the best alternative is A4 (pavement made with recycled materials). This eco-friendly solution is recommended to the local Saudi authority as the optimal material to be used in the construction of the new Taif airport by including sustainability factors into the design process, allowing for informed judgements. Enhances airport pavement design processes and decrease environmental impacts connected with airport operations in a variety of contexts and locations. However, it can be concluded that the key findings of this study could provide a robust framework for optimizing sustainability in airport pavement management, enhancing decision-making efficiency and promoting long-term environmental, economic, and operational benefits.

Keywords*:* Airport, Analysis multi-criteria, Sustainability development

تقييم استدامة رصف المطارات باستخدام نموذج القرار الضبابي المتكاملANP-TOPSIS

الملخص: التصميم المستدام هو مستقبل مشاريع البناء الثقيلة مثل المطارات. ومع ذلك، تتطلب هذه الهياكل عادة صيانة مستمرة، والتي يمكن أن تصبح عبئا ماليا كبيرا. إن صيانة وإعادة تأهيل الرصف، وخاصة في المطارات، هي عملية مكلفة تشمل العمالة والمعدات ونفقات المواد. من خلال الانتقال إلى نظام يستخدم تصاميم ومواد بناء أكثر استدامة، من الممكن بناء هياكل أفضل لن تعاني من أضرار جسيمة. يهدف هذا البحث إلى بناء إطار تقييم جديد لرصف المطارات المستدامة لتطبيقه لاحقًا على دراسة حالة مطار الطائف في المملكة العربية السعودية. لتقييم المطار الدولي المقترح من حيث الاستدامة، تم اقتراح أربعة بدائل مستدامة (A1، A2، A3، و A4)، إلى جانب تسعة معايير. تمت دراسة هذه البدائل واستخدام طريقة TOPSIS لاختيار البديل الأفضل. بالإضافة إلى ذلك، يتم حساب الأوزان باستخدام عملية الشبكة التحليلية الضبابية (FANP). وفقًا للنتائج المحققة، فإن أفضل بديل هو A4 (رصف مصنوع من مواد معاد تدويرها). يُوصى بهذا الحل الصديق للبيئة للسلطة المحلية السعودية باعتباره المادة المثلى التي يجب استخدامها في بناء مطار الطائف الجديد من خلال تضمين عوامل الاستدامة في عملية التصميم، مما يسمح بأحكام مستنيرة. يعزز عمليات تصميم رصف المطارات ويقلل من التأثيرات البيئية المرتبطة بعمليات المطار في مجموعة متنوعة من السياقات والمواقع. ومع ذلك، يمكن أن نستنتج أن النتائج الرئيسية لهذه الدراسة يمكن أن توفر إطارًا قويًا لتحسين الاستدامة في إدارة رصف المطارات، وتعزيز كفاءة اتخاذ القرار وتعزيز الفوائد البيئية والاقتصادية والتشغيلية طويلة الأجل.

1. Introduction

The concept of sustainability was first formulated in the Brundtland Report [1], where it was stated that the goal of sustainability is to “meet the needs of the present generation without compromising the ability of future generations to meet their own needs” [2]. The concept of sustainability is considered as a anticipated objective of development and environmental management [3]. Terminology which either directly cites or is related to sustainable development is becoming more and more common, with the number of sustainability-related terms increasing along with the rapid rise in aware-ness of the importance of sustainability [4]. According to many authors [5, 6], “sustainability” is coloured by context, that is, whether the notion of sustainability being ad-dressed concerns ecological sustainability, economic sustainability, social sustainability, or some other form [7]. The rapid expansion of the global society and economy has had a negative impact on sustainability, and the aviation industry, which is growing at an average annual rate of 5%, has contributed significantly to environmental issues while also promoting economic growth and addressing social employment challenges [8,9]. Airports play a crucial role in integrating air and ground traffic, and their sustainability is essential to meet the industry's growing objectives. To enhance airport sustainability, international initiatives have been implemented, such as the "Airports Sustainability Declaration" signed by over 20 airports in 2016 [10, 11]. However, technological innovation alone cannot address the issues posed by aviation as air travel continues to increase [12]. Effective management requires a thorough assessment of sustainability before any action can be taken [13]. The evaluation criteria and method-ologies used are critical in ensuring and enhancing airport sustainability through focused initiatives [14, 15]. Although numerous scholars have concentrated on operational aspects such as energy efficiency, water resource management, pavement materials, and the expansion of commercial facilities within airports, research specifically dedicated to the holistic assessment of airport sustainability remains relatively limited [16, 17]. Addressing this gap necessitates a comprehensive understanding of the interplay between theoretical frameworks and the practical challenges faced by airports in their current operational contexts. Such an approach is critical for ensuring effective evaluation and enhancement of sustainability practices [18, 19]. This study aims to highlight the importance of adopting environmentally sustainable pavement systems for the international airport located in Taif City, Saudi Arabia. By employing a combination of an indicator-based methodology and a comprehensive index, the research provides a dynamic assessment framework for Airport Pavement Sustainability (APS). The evaluation process explores APS alongside alternative sustainable solutions to identify strategies that minimize environmental impacts associated with intensive construction activities and prolonged industrial operations. This aligns with the broader vision of Saudi Arabian authorities to promote eco-friendly practices, thereby reducing ecological footprints and mitigating adverse effects on both the environment and public health.

To the best of our knowledge from previous literatures, the present study would be of the first of its kind to assess APS by employing a hybrid method that includes the Fuzzy Analytic Network Process (FANP) and the TOPSIS method. A variety of mathematical methodologies has been used in the suggested assessment model. First, fuzzy set theory (FST) has been utilized to cope with uncertainty in the judgements of decision makers (DMs). Second, aspects and indicator weights were calculated using the fuzzy analytic network method (FANP). Finally, the TOPSIS approach has been utilized to compute the total sustainability index and pick the optimal option. For clarity's sake, the novelty of this research lies in the development of a hybrid decision-making framework that uniquely integrates FANP and TOPSIS to assess airport pavement sustainability. This innovative combination allows for precise handling of complex interdependencies among sustainability criteria while addressing uncertainties in decision-making. By applying this framework to evaluate sustainable pavement alternatives for Taif airport, the study pioneers an advanced methodology that enhances decision-making efficiency and promotes eco-friendly solutions in airport construction projects.

2. Literature review

The construction of airport infrastructure is essential to the global transportation network, facilitating efficient travel and economic growth. Nonetheless, the environmental impact of airports is undeniable. Pavement systems are crucial for airport sustainability since they constitute a fundamental aspect of the infrastructure. Therefore, with the right methods to optimise airport pavement improvements are important. Thus, this literature review aims to introduce a summary of the state-of-the-art sustainability assessment methods applied on airports pavement. It is discussed case studies using different methods, critique and compare these approaches and reflect on trends or innovations made along the way, whilst identifying opportunities for future research efforts. Sustainability assessment procedures are structured frameworks or instruments used to assist decision-makers and policymakers in discerning acceptable and unacceptable acts to enhance societal sustainability [20]. Numerous sustainability evaluation approaches are used worldwide to evaluate airport projects, including Green Building Certification Systems (LEED and BREEAM), Life Cycle evaluation (LCA), and Multi-Criteria Decision Analysis (MCDA).

Numerous studies have developed various sustainability evaluation methodologies to evaluate airports broadly, as well as specific approaches for paving projects, each exhibiting differing levels of efficacy. For example, Fann and Rakas [21] proposed a structured methodology to evaluate the environmental sustainability of airport expansion projects. This framework is designed to be adaptable and integrates multiple criteria for assessing environmental impacts across the entire life cycle of airport projects, encompassing carbon emissions, resource utilization, and ecological consequences. The main objective of this research approach is to provide airport administrators and stakeholders with a structured framework for making sustainable decisions during the initial stages of project planning and design.

Although the framework is theoretically robust, its practical utility remains limited due to the absence of empirical validation. The lack of real-world applications or case studies makes it challenging to translate the framework into actionable strategies, potentially rendering it too abstract for direct implementation.

To evaluate the environmental implications of the construction of airport pavement, a Life Cycle Assessment (LCA) was conducted, focusing on metrics such as Total Primary Energy (TPE) consumption and greenhouse gas (GHG) emissions [22].

This analysis relied on secondary data sources, including the Ecoinvent database, to model construction processes and material production in compliance with ISO 14040 standards. To address uncertainties in the life-cycle inventory data, a probabilistic LCA tool was developed using the Monte Carlo simulation method. A case study on Runway 10R-28L at Chicago O'Hare International Airport revealed that material production processes, particularly those involving asphalt binder and Portland cement, were the primary contributors to environmental impacts. In contrast, construction activities contributed less than 2% of the total TPE and GHG emissions. The findings further demonstrated that incorporating recycled materials and warm-mix asphalt during the design phase significantly reduced environmental impacts, achieving a 30% decrease in both total primary energy use and greenhouse gas emissions compared to traditional designs. This outcome was verified through probabilistic analysis, highlighting the potential for sustainable practices in airport pavement construction to mitigate environmental harm. However, the scope of this study is limited to confine to the construction phase of airport pavements and does not extend to other critical life-cycle stages, such as maintenance, rehabilitation, operational use, or end-of-life processes. Consequently, the study underscores the need for further research to address these omitted phases, providing a more comprehensive understanding of sustainability in airport infrastructure development. Besides, it is assessed sustainability measures at Polish airports, including the use of solar panels and environmentally sustainable technology [23].

This article evaluates the advancement of Polish airports in implementing sustainable practices using a survey and case study methodology, highlighting the obstacles and possibilities related to the integration of environmentally friendly infrastructure amid increasing air traffic and environmental issues.

Focusing just on Polish airports restricts the application of the results to other locations, since various countries possess distinct regulatory frameworks, economic conditions, and environmental objectives.

It is also examined the sustainability performance of leading global airports on a capital basis framework based on environmental, social and economic dimensions [24]. Using Data Envelopment Analysis (DEA) to derive sustainability attributes (waste, energy, water and carbon) and favourable outcomes (passenger, revenue and employment), this study sought to perform two things: identify high-performing "frontier" airports from among the entire US airport network; and explore differences between them.

This benchmarking method seeks to establish performance improvement objectives and enhance transparency in sustainability reporting. Nevertheless, the system depends on continuous, high-caliber data to provide dependable benchmarking. However, airports globally vary in their degree of transparency and data availability, potentially affecting the reliability of the comparative findings. Similarly, it is reported that another study built a physical and operating requirement-based assessment framework to evaluate the environmental sustainability of airports [25]. This paper utilizes text mining methods to evaluate airport sustainable development reports as a preliminary step for recognizing priority environmental indicators. The final results generated an airport-specific environmental database (As a basic study, these metrics should be optimally evaluated by comparing against GBRTs; this last step is beyond the scope of the paper). Using GRI and other green certification database data, the report aims to identify shortcomings and align environmental categories within an aviation sustainability framework.

Certain airports disseminate environmental data; nonetheless, sustainability reporting is inconsistent and lacks commitment, especially in developing nations. A green grading system tailored for airports is introduced, which evaluates energy, water, emissions, and waste management [16]. The absence of consistent and comprehensive data in airport sustainability reports undermines the framework's reliability and applicability. This diversity, particularly in underdeveloped countries, complicates the establishment and implementation of environmental indicators for various airport operations.

In a recent study, established guidelines for the utilization of recycled materials in airport pavement design to enhance sustainability while meeting the stringent performance requirements of aircraft traffic [26]. The study does a comprehensive assessment of various recycled materials, such as industrial slag, recycled asphalt pavement (RAP) , and crumb rubber, and examines their applications in asphalt, concrete, and granular pavement layers [27]. Sustainability is assessed based on a triple bottom line framework that consists of financial, environmental and social dimensions using methods such as life cycle cost analysis and life cycle assessment (LCA). Recycled materials deliver significant environmental, (including reduced GHG emissions and lower vulnerability to supply chain disruptions because of decreased reliance on virgin materials), but their adoption is hampered by issues such as material inconsistency, difficulties in scaling up production and a natural risk aversion within industry [12]. The research emphasizes the need of performance testing, localized material sourcing, and modifications to procurement techniques and performance-based criteria to enhance acceptance. The primary weakness of this study is its dependence on a qualitative review of prior research instead of offering empirical validation or case studies to clearly evaluate the proposed principles for using recycled materials into airport pavements.

In summary, assessing sustainability in airport pavement projects helps to meet the environmental, social and economic objectives desired for long-term success. The present sustainability evaluation methods (such as green building certification systems, life cycle assessment (LCA) and multi-criteria decision analysis (MCDA)) have contributed in identifying necessary characteristics for assessing the airport pavements sustainability performance. However, these methods have shortcomings that must be addressed.

Future studies should address the shortcomings of current data collection methods based on a stakeholder analysis and a longer time horizon by including representatives of different interest groups as stakeholders in airport infrastructure projects, but also by providing more insight into expected technological developments, such that they can inspire innovations facilitating sustainable development.

3. Research methodology

The research methodology, as illustrated in Figure 1, commences with an extensive review of existing literature, which involves a systematic examination of prior studies to extract pertinent findings. This step aims to identify existing gaps in the body of knowledge that necessitate further investigation. Additionally, it explores the integration of fuzzy logic and the TOPSIS as analytical tools for promoting sustainability in airport pavement manufacturing, facilitating the selection of an initial set of Sustainability Indicators (SIs). The justification of selection these SIs was based on their comprehensive representation of key sustainability dimensions in airport pavement systems. Economic factors ensure cost-effectiveness and financial feasibility, while technical aspects address performance and durability.

Environmental indicators minimize ecological impacts, such as emissions and resource use, and social criteria consider safety, community acceptance, and job creation. These indicators collectively ensure a balanced and holistic evaluation of sustainability, tailored to the unique demands of airport pavement projects.

Following this preliminary stage, the methodology incorporates a structured questionnaire survey to refine and prioritize the key SIs. The process of identifying sustainability benchmarks for airport pavements involves a comprehensive evaluation of critical environmental, social, and economic dimensions. This systematic approach ensures that the selected indicators effectively address the multifaceted nature of sustainability in airport infrastructure, providing a robust foundation for the subsequent phases of the research. Reviewing pertinent research and speaking with professionals in the field helped determine the requirements This is succeeded by conducting interviews with experts to compute chosen SI's using fuzzy logic methodology. In this stage, membership functions such as trapezoidal or triangular ones was used to transform crisp values numbers with definite values into fuzzy values, which have uncertain or im-precise values.

Fuzzification makes it possible to handle these situations which uses a FANP to ascertain the relative relevance of each criterion. Using a matrix that allocates weights depending on relevance levels (e.g., equally important, fairly important, and highly important), the ANP technique compares criteria pairwise. Then, TOPSIS methodology has been used to calculate the distance between each alternative (e.g., various airport pavement materials or de-signs) and the ideal solution (i.e., the best alternative) based on sustainability criteria. Based on sustainability criteria, the options that are closest to the ideal solution, deeming the most sustainable.

A real-world case study was employed to demonstrate the validity of the developed model. The fifth phase was also incorporated the fuzzy TOPSIS technique into actual airport pavement design methods. This could be done in conjunction with stakeholders and industry experts to guarantee the methodology's applicability and practicality. This stage is also entailed at putting the technique to the test using case studies at certain airports to assess how well it works to improve the sustainability of airport pavement while maintaining functioning and safety.

This study presents findings from a case analysis conducted to assess the effectiveness of a newly developed fuzzy hybrid methodology for sustainability evaluations in infrastructure projects. The proposed assessment framework integrates multiple mathematical techniques to ensure comprehensive and reliable evaluations. The research framework begins by employing fuzzy set theory (FST) to address and reduce uncertainties associated with the subjective assessments provided by decision-makers (DMs). This approach ensures a more reliable interpretation of qualitative judgments by incorporating the inherent vagueness of human evaluations into the analysis. Following this, the FANP is implemented to establish the relative importance of various sustainability dimensions and their associated indicators. This method allows for a nuanced weighting process that reflects the interconnected nature of sustainability criteria. In the final step, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is utilized to calculate the comprehensive sustainability index, thereby enabling the identification of the best substitution. Each of these methodologies is discussed in detail in the subsequent sections to provide a clear understanding of their application and integration within the research framework.

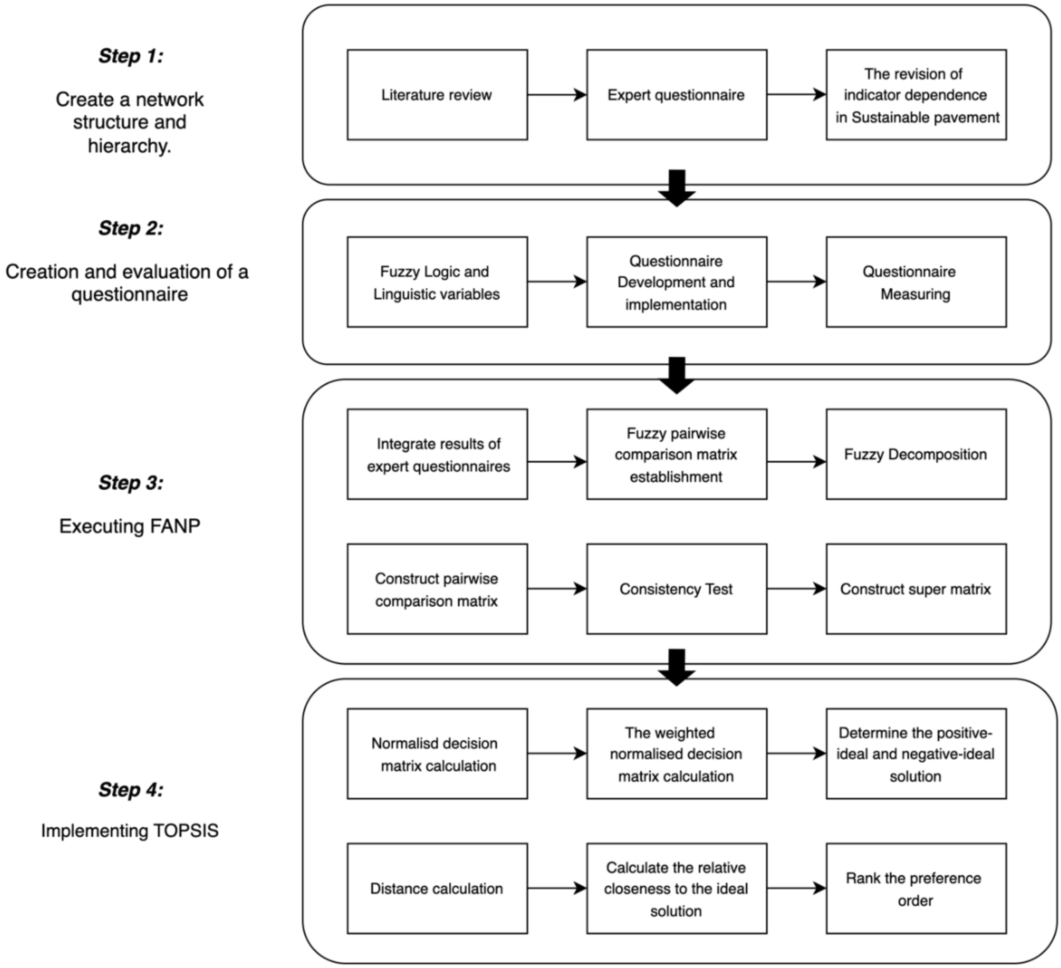

Fig. 1. The proposed Fuzzy-ANP–TOPSIS methodology for sustainable airport pavement performance

4. Materials and Methods

4.1. Fuzzy linguistic variables

As Zadeh [28] defines, a linguistic variable represents expressions in the form of words or sentences, derived from either natural or artificial languages, rather than numerical values. This concept proves particularly advantageous for describing complex phenomena that are not easily captured through conventional quantitative methods [29].

Consequently, linguistic variables are invaluable in contexts that require qualitative descriptors to convey information effectively [20, 31].

Within the realm of performance evaluation, the application of linguistic variables provides decision-makers with a flexible and intuitive mechanism to express their judgments [23]. For instance, when assigning ratings to performance criteria, decision-makers can employ linguistic scales tailored to the specific assessment context. A commonly utilized scale consists of five fundamental fuzzy subsets: Very Low (VL), Low (L), Moderate (M), High (H), and Very High (VH). This approach enhances clarity and adaptability in performance assessments.

4.2. Arithmetical operations based on support values

The mathematical foundation of arithmetic operations involving fuzzy numbers lies in the extension principle, which extends traditional arithmetic to accommodate the fuzzy domain. This principle operates by executing pointwise calculations on the discrete elements of fuzzy input numbers, ultimately deriving the membership functions of the resulting fuzzy outputs. Within the proposed framework, these arithmetic operations are implemented using the support values method, chosen for its computational efficiency and straightforward implementation. This approach ensures that the assessment model remains user-friendly and accessible for practical applications. In this framework, the arithmetic operations leverage the support values method to process two triangular fuzzy numbers (TFNs) as inputs, resulting in the computation of output TFNs. The detailed procedure for performing these operations is mathematically expressed through Equations 1 to 5, illustrating the application of this method in deriving fuzzy results. This structured approach enhances both the precision and usability of the proposed model in handling fuzzy data.

Addition of two TFNs:

$$\tilde{C} = \tilde{A} + \tilde{B} = (a_1,a_2,a_3) + (b_1,\mathrm{b}_2,\mathrm{b}_3) = (a_1 + b_1,a_2 + b_2,a_3 + b_3) \tag{1}$$

Subtraction of two TFNs:

$$\tilde{C} = \tilde{A}\text{-}\widetilde{\mathrm{B}} = (a_1,a_2,a_3)\text{- }(b_1,\mathrm{b}_2,\mathrm{b}_3) = (a_1 - b_1,a_2 - b_2,a_3 - b_3) \tag{2}$$

Multiplication of two TFNs:

$$\tilde{C} = \tilde{A} \times \tilde{B} = (a_1,a_2,a_3) \times (b_1,\mathrm{b}_2,\mathrm{b}_3) = (a_1 \times b_1,a_2 \times b_2,a_3 \times b_3) \tag{3}$$

Division of two TFNs:

$$\tilde{C} = \tilde{A}/\widetilde{\mathrm{B}} = (a_1, a_2,a_3)/(b_1,b_2,b_3) = \left(\frac{a_1}{b_1},\frac{a_2}{b_2},\frac{a_3}{b_3}\right), a_i > 0, b_i > 0, \forall i \in [1,3] \tag{4}$$

Average of two TFNs:

$$A_{average} = \left(\frac{1}{n}\sum_{i=1}^{n} a_1^{(i)}, \frac{1}{n}\sum_{i=1}^{n} a_M^{(i)}, \frac{1}{n}\sum_{i=1}^{n} a_2^{(i)}\right) \quad (5)$$

Where a, b and c are real numbers.

An algorithm using fuzzy numbers is called fuzzy logic. Fuzzy numbers were examined in light of this [24]. Initially, a number of academics [31-33] noted that in order to make fuzzy numbers more useful in real-world applications, their properties are typically stated mathematically. The triangular fuzzy number $A(a1, a2, a3)$, for instance, is represented by the following equation and is shown in Figure 2.

$$\mu_{\tilde{A}}(x) = \begin{cases} \frac{x-a_1}{a_2-a_1} & a_1 \leq x \leq a_2 \\ \frac{x-a_3}{a_2-a_3} & a_2 \leq x \leq a_3 \\ 0 & otherwise \end{cases} \quad (6)$$

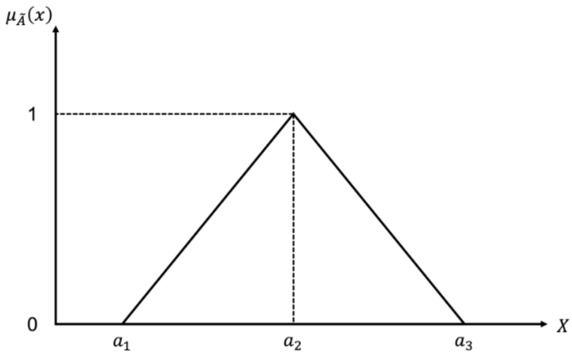

Fig. 2. Fuzzy triangular number

In the meantime, a large body of research [27] indicated that the crisp value is the most likely value for triangular fuzzy numbers. The following equation provides the triangular fuzzy numbers' crisp value:

$$A_a = [(a_2 - a_1)a - (a_3 - a_2)a + a_3] \quad (7)$$

4.3. Defuzzification

Expert opinion in fuzzy set theory is usually expressed as a linguistic variable value. It is numerically transformed so that it may be used for rating, weighing, or grading purposes. The process is known as defuzzification. Most people prefer to use the centroid approach, which is also called the centre of gravity method, since it is quick, easy, and accurate. Because of these features, the centroid method is used for defuzzification in the proposed model [32] by applying following equation.

$$X = \frac{\int \mu_e(x).xdx}{\int \mu_e(x)dx} \quad (8)$$

Where, e = defuzzification (crisp value) of TFN (x1, x2, x3)

4.4. Fuzzy Analytic Network Process (FANP)

The analytic hierarchy process (AHP), which was introduced by Saaty (1980) several decades ago, deals with principles of synthesis, pairwise comparisons, decomposition, and priority vector generation. Since its introduction, AHP has been the general default approach for handling feedback and dependence around decision-making strategies [31-33]. The primary benefit of AHP has been its ability to deal with multiple criteria, whether quantitative or qualitative [32, 34].

Saaty and Takizawa [35] introduced an extension of AHP called ANP, which is a system that includes feedback. While this study is mainly focused on developing a hybrid decision-making framework that distinctively combines FANP and TOPSIS methodologies to evaluate the sustainability of airport pavements. In general terms, ANP is useful in instances involving interactions of system elements within a network structure. Furthermore, unlike AHP, ANP does not have a rigid hierarchical structure, which means it can model and frame a decision problem by employing a “system with feedback” strategy. Specifically, ANP is able to capture feedback in addition to interdependent relationships at the component level. Numerous researchers [34, 35] have highlighted various advantages of employing the Analytic Network Process (ANP) over the Analytic Hierarchy Process (AHP). Unlike the linear structure of AHP, ANP utilizes a more flexible and non-linear network structure, allowing for a broader and more nuanced analysis. It facilitates the integration of both tangible and intangible criteria within the decision-making process, offering a realistic perspective on complex problems through the formation of clusters. Moreover, ANP accommodates intricate and interdependent relationships among elements [36-38]. Despite these strengths, ANP is not without limitations; one notable drawback is its inability to adequately address the inherent subjectivity in pairwise comparisons. The computation process for the Fuzzy Analytic Network Process (FANP), based on Chang’s [39] extent analysis method, involves four systematic steps, detailed as follows.

Consider an object let X={x_1, x_2,…, x_n}, G = {g_1, g_2,…, g_m}. In this method, each object is evaluated by conducting an extent analysis for every goal, gig_igi. Consequently, mmm extent analysis values are generated for each object, represented with specific notations.

$$M_{gi}^{1}, M_{gi}^{2}, \ldots, M_{gi}^{m}, i = 1,2, \ldots., n \quad (9)$$

where all $M_{gi}^{j}, j = 1,2, \ldots., m$ values are represented as triangular fuzzy numbers (TFNs). The steps involved in Chang's extent analysis method (1992, 1996) can be outlined as follows:

Step 1: The fuzzy synthetic extent value corresponding to the i-th object is defined as:

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} \quad (10)$$

To obtain $\sum_{j=1}^{m} M_{gi}^{j}$, make the fuzzy addition operation on m extent analysis values for a specific matrix, ensuring accuracy and consistency, such that

$$\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right) (11)$$

To obtain $\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j}\right]^{-1}$, perform the fuzzy addition operation of $M_{gi}^{j}, j = 1,2, \ldots., m$ values, such that

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right) \quad (12)$$

Then compute the inverse of the vector in Equation (12), such that

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{j=1}^{m} u_j}, \frac{1}{\sum_{j=1}^{m} m_j}, \frac{1}{\sum_{j=1}^{n} l_j}\right) \quad (13)$$

Step 2: The possibility degree of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined as:

$$V(M_2 \geq M_1) = sup\left[min\, \mu_{M_1}(x), \mu_{M_2}(x)\right] \quad (14)$$

and can be consistently stated as:

$$V(M_2 \geq M_1) = hgt(M_2 \cap M_1) = \begin{cases} 1, & if \ m_2 \geq m_1 \\ 0, & if \ l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & otherwise \end{cases} \tag{15}$$

Where d represents the ordinate of the highest intersection point D between $\mu(M_1)$ and $\mu(M_2)$.

To compare M_1 and M_2, it needs the values of both $V(M_2 \geq M_1)$ and $V(M_1 \geq M_2)$

Step 3: The degree of possibility for a convex fuzzy number M to be greater than k convex fuzzy numbers M_i ($i = 1, 2\ldots k$) can be well-defined by:

$$\begin{aligned} V(M \geq M_1, M_2, \ldots, M_k) &= V[(M \geq M_1) \text{ and } (M \geq M_2) \text{ and} \ldots (M \geq M_k)] \\ &= \min V(M \geq M_i), \quad i = 1, 2, \ldots, k \end{aligned} \tag{16}$$

Assume that

$$d'(A_i) = minV(S_i \geq S_k) \tag{17}$$

For $k = 1, 2, \ldots, n$; $k \neq i$. The weight vector is then given by:

$$W' = (d'(A_1), d'(A_2), \ldots \ldots, d'(A_n))^T \tag{18}$$

where A_i ($i = 1, 2, \ldots, n$) are n elements.

Step 4: Via normalization, the normalized weight vectors are:

$$W = (d(A_1), d(A_2), \ldots \ldots, d(A_n))^T \tag{19}$$

where W is a nonfuzzy number.

4.5. TOPSIS method

The method for formulating importance weights in evaluation criteria by applying the fuzzy ANP approach was given in preceding sections. In this section, TOPSIS is used for ranking alternatives. It should be noted that, when using criteria restricted by amount, every step in the fuzzy ANP for ranking alternatives would have to be followed. In the present work, in order to hold the pairwise comparisons from DMs below a certain amount, only fuzzy ANP has been applied for calculating relative weights in the evaluation criteria. TOPSIS is then used to obtain final ranking results. More details for these methods can be acquired by applying the following equations. TOPSIS comprises the following six sequential steps:

Step 1: The normalized decision matrix is computed by calculating the normalized value r_{ij} using the following formula:=

$$x_{ij}\sqrt{\sum_{i-1}^{m} x_{ij}^{2}}\ , \quad i = 1,2,\ldots,m \text{ and } j = 1,2,\ldots,n. \tag{20}$$

Step 2: Determine the weighted normalized decision matrix, where the weighted normalized value vij is calculated as:

$$v_{ij} = r_{ij} \times w_j\ , \quad i = 1,2,\ldots,m \text{ and } j = 1,2,\ldots,n. \tag{21}$$

where w_j is the weight of the j^{th} criterion or attribute and $\sum_{j=1}^{n} w_j = 1$.

Step 3: Find the ideal (A^*) and negative ideal (A^-) solutions:

$$A^* = \{(\max_i v_{ij} | j \in C_b), (\min_i v_{ij} | j \in C_c)\} = \{v_j^* | j = 1,2,\ldots,n\} \tag{22}$$

$$A^- = \{(\min_i v_{ij} | j \in C_b), (\max_i v_{ij} | j \in C_c)\} = \{v_j^- | j = 1,2,\ldots,n\} \tag{23}$$

Step 4: Calculate the separation measures using the m-dimensional Euclidean distance. The separation measures for each alternative from both the positive ideal solution and the negative ideal solution are as follows:

$$S_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2}\ , \qquad i = 1,2,\ldots,m \tag{24}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}\ , \qquad i = 1,2,\ldots,m \tag{25}$$

Step 5: Determine the relative closeness to the ideal solution. The relative closeness of alternative Ai to A∗ is defined as:

$$RC_i^* = \frac{S_i^-}{S_i^* + S_i^-}, \qquad i = 1,2,\ldots,m \tag{26}$$

Step 6: Rank the preference order.

4.6. Normalize quantitative indicators

To utilize the values of sustainability indicators, the quantitative indicators need to be normalized. The normalization is computed via the below equations [40]:

when indicator is larger:

$$r_{ij} = \frac{[x_{ij} - min\{x_{ij}\}]}{[max\{x_{ij}\} - min\{x_{ij}\}]} \tag{27}$$

when indicator is smaller:

$$r_{ij} = \frac{[min\{x_{ij}\} - x_{ij}]}{[max\{x_{ij}\} - min\{x_{ij}\}]} \tag{28}$$

where r_{ij} = normalized value of indicator.

4.7. Sustainability Assessment

In formulating alternatives, DMs (or assessors) should first and foremost com-prehend the main objectives of a project, while at the same time being cognizant of any expressed needs underlying the project’s proposal. Having a solid understanding of the project’s objectives and needs to ensure the compliance of any proposed alternatives with the project overall. For the case study, we present four alternatives, as shown in Table 1.

Table 1: Proposed project alternatives.

ıtive	ɔtion	atures
	ent with natural ruction Strategy 1)	mıg natural materials in sub-base layer, the pa esigned to have 20 years life.
	ent with natural ruction Strategy 2)	mıg natural materials in sub-base layer, the pa esigned to have 10 years life.
	ent with recycled ruction Strategy 1)	mıg recycled materials in sub-base layer, the pa ; designed to have 20 years life.
	ent with recycled ruction Strategy 2)	mıg recycled materials in sub-base layer, the pa esigned to have 10 years life.

In the proposed model integrating FANP and TOPSIS is designed to address complicated decision-making scenarios characterized by interdependencies across sustainability indicators and alternatives, while also facilitating the effective ranking of alternatives.

this sustainable model for selecting the optimal concrete is composed of three levels (1, 2 and 3). In level 1, the problem is defined, and the alternatives (Ai) and Indicators (Ci) are identified. In level 2, the pairwise matrix is established, and weights are calculated. In level 3, the alternatives are evaluated and the best one selected. In the pro-posed assessment model, there are eight steps that lead to calculating the overall sustainability performance

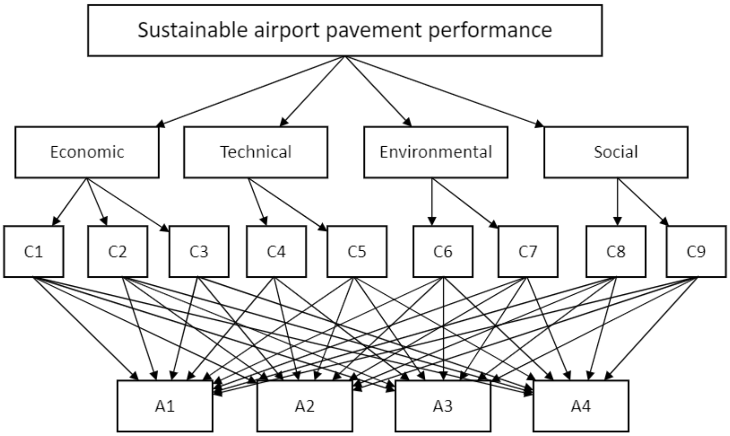

Fig. 3. The research's network structure and hierarchy.

5. Results & Discussions

Various methodologies have been developed for conducting sustainability assessments. From a decision-making standpoint, the indicator-based approach emerges as particularly advantageous due to its inherent transparency, temporal consistency, and practical applicability. This study aims to identify sustainability indicators (SIs) commonly employed within the industry by compiling a comprehensive list derived from an extensive review of existing literature, including academic publications and practitioner-oriented journals. The identified SIs are categorized into four primary dimensions of sustainability, each corresponding to specific indicators: (1) economic, (2) technical, (3) environmental, and (4) social. A detailed representation of these indicators is provided in Table 2.

Table 2. Sustainability Indicators used in the case study.

Aspect	Indicator	Measurement unit
Economic	Capital cost (C1)	Monetary unit (SAR)
	Benefits (C2)	Qualitatively
	Affordability (C3)	Qualitatively
Technical	Performance (C4)	Young's Modulus (Kgf/cm^2)
	Flexibility (C5)	Qualitatively
		Qualitatively
Environmental	Ecological Impacts (C7)	Qualitatively
	GHG (C6)	T CO_2 eq
Social	Community Engagement (C9)	Qualitatively
	Safety and Security (C8)	Qualitatively

The main aim of quantifying sustainability indicators (SI) rates for each alternative is quantifying any of the indicators that were selected during the assessment. Note that the quantitative and qualitative indicators must be subjected to different forms of calculations. For quantitative indicators, traditional engineering calculations can be applied, whereas for qualitative indicators, the fuzzy set approach is used for numerically quantifying indicator rates. The DMs utilize classic membership functions (MFs) for linguistic variables suggested in the assessment model. The fuzzy linguistic variables scale proposed in the assessment model are reported on Table 3.

Table 3. Linguistic scale for rating of project alternatives.

Linguistic set	Fuzzy number
Very well (VW)	(0.75,1.0,1.0)
Well (W)	(0.5,0.75,1.0)
Moderate (M)	(0.25,0.5,0.75)
Poor (P)	(0,0.25,0.5)
Very poor (VP)	(0,0,0.25)

Numerical rates for the qualitative indicators of each alternative are reported in Table 4.

Table 4. Quantitative values for the qualitative indicators of each alternative.

	A1	A2	A3	A4
Affordability (C3)	0.25	0.4	0.6	0.8
Flexibility (C5)	0.28	0.63	0.28	0.63
Ecological impacts (C7)	0.0	0.2	0.5	0.7
Personal safety/security (C8)	0.4	0.5	0.7	0.8
Community engagement (C9)	0.25	0.25	0.5	0.5

In order to employ the sustainability indicator values, the quantitative indicators need to be normalized. The normalization is calculated using the methods of Bardossy & Duckstein [40]. The quantitative indicators have been normalized accordingly. Table 5 presents the values of the sustainability indicators for each alternative.

Table 5. Normalized indicators values.

Indicator		Alternatives			
		A1	A2	A3	A4
Total Capital cost	C1	0.0	0.47	0.54	1.0
Affordability	C3	0.25	0.4	0.6	0.8
Benefits	C2	0.2	0.4	0.7	1.0
Performance	C4	1.0	1.0	0.0	0.0
Flexibility	C5	0.28	0.63	0.28	0.63
GHG	C6	0.0	0.89	0.11	1.0
Ecological Impacts	C7	0.0	0.2	0.5	0.7
Community engagement	C9	0.25	0.25	0.5	0.5
Safety and Security	C8	0.4	0.5	0.7	0.8

Also, fuzzy pair-wise comparison matrices are formed by the DMs using the scale given in Table 2. For instance, a comparison is made between the economic aspect (EA) and the technical aspect (TA) through the inquiry, “How significant is (EA) in relation to (TA)?” with the answer being “JE, MI”, as given by the two DMs. The linguistic scales are laced in the relevant cell against the TFNs (1, 1, 1) and (1, 3/2, 2), which are then aggregated. All fuzzy assessment matrices are generated using a consistent methodology. The subsequent step involves analyzing the pairwise comparison matrices through the application of Chang’s [39] extent analysis method. This process is employed to determine the local weights (LW) for the four key sustainability aspects. The calculation of these weights follows the same methodology used for deriving the local weights of individual indicators. Furthermore, advancing environmental sustainability within global aviation infrastructure can be significantly supported by incorporating recycled materials into construction and maintenance practices. As airport pavements can be considered a source of air pollution due to their production of greenhouse gases, odors, volatile organic compounds and dusts, airport DMs are interested in selecting the preferred pavement design and rehabilitation strategy that takes economic, environmental, and societal constraints into consideration, along with performance requirements. However, most of the activities belonging to airport transportation must take into account a large number of alternatives, which some-times hinders their management as a whole. Many mathematical methods and models have been used over the years to help authorities and communities model complex problems such as these. Of these, several can be used to evaluate the proposed solutions and alternatives.

The TOPSIS is a widely employed method for optimizing complex multi-criteria decision-making (MCDM) systems [40]. This approach is based on the concept that the best alternative should have the smallest distance from the positive ideal solution and the greatest distance from the negative ideal solution. In this analysis, the TOPSIS method is applied to determine the most optimal alternative from a set of choices. The process begins with determining the weights of the criteria, which are then used to scale the indicator values by multiplying them with their respective weights. This step ensures that each criterion is proportionally represented in the decision-making process. The alternatives (denoted as A1, A2, A3, and A4) are evaluated against multiple criteria functions (C1, C2, C3, C4, C5, C6, C7, C8, C9). The ranking of alternatives is then derived by assessing their relative proximity to the ideal solution, as depicted in Table 6 and Figure 4. Both the positive ideal solution and the negative ideal solution are defined within the analysis.

The negative ideal solution is calculated using the same methodology applied to the positive ideal, ensuring a consistent framework. The distances of each alternative from the ideal and negative solutions are computed using the specified mathematical formulations (Equations 11 and 12). These calculations facilitate a systematic ranking of alternatives, providing a robust mechanism for identifying the most sustainable option. This systematic approach ensures a robust comparison and ranking of alternatives.

$$A^* = \{(\max_i v_{ij} | j \in C_b), (\min_i v_{ij} | j \in C_c)\} = \{v_j^* | j = 1,2,\ldots,n\} \quad (29)$$

$$A^- = \{(\min_i v_{ij} | j \in C_b), (\max_i v_{ij} | j \in C_c)\} = \{v_j^- | j = 1,2,\ldots,n\} \quad (30)$$

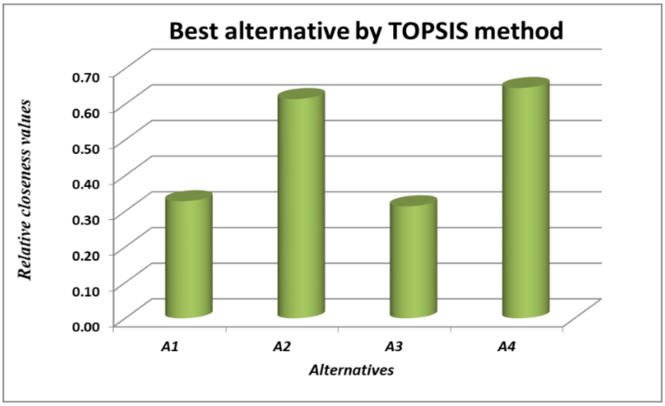

Fig. 4. TOPSIS method as tool to select the best alternatives.

Table 6. Relative closeness values.

Alternative	A1	A2	A3	A4
E+	0.51	0.27	0.45	0.28
E-	0.25	0.43	0.20	0.51
E-/(E- + E+)	0.33	0.61	0.31	0.65

The application of advanced decision-making frameworks has shown considerable potential in addressing the multifaceted challenges of sustainability within pavement and infrastructure management. It is demonstrated the practicality of combining fuzzy AHP with the VIKOR method to prioritize pavement maintenance, effectively balancing technical, economic, and operational factors [41]. Similarly, it is extended the decision-making paradigm by integrating IMF D-SWARA and Rough MARCOS to optimize the selection of road construction machinery, emphasizing sustainability and efficiency in resource-intensive operations [42]. While these models excel in structured decision support, their scalability across diverse contexts remains a critical challenge. In urban transportation, it is showcased the utility of multi-criteria decision-making to identify and address inefficiencies, presenting a replicable framework for sustainability assessments in metropolitan areas [43].

Adding to this, it is leveraged the TOPSIS method to compare road sustainability rating systems, offering insights into their adaptability in localized contexts such as Hungary, yet raising questions about their global applicability [44]. Also, it is provided a systematic review of decision-making techniques like ANP and TOPSIS in sustainable infrastructure, underscoring their versatility while also highlighting the need for further empirical validation in real-world scenarios [45]. It is also utilized the TOPSIS method to evaluate aggregates for road construction, providing a structured framework for selecting materials that balance performance, cost, and sustainability. This highlights the role of multi-criteria decision-making in enhancing infrastructure durability [46]. Similarly, it is employed GIS-integrated Spatial Multi-Criteria Analysis (MCA) to optimize airport and control tower site selection, demonstrating how geospatial data and analytical tools can address complex spatial planning challenges [47]. Together, these studies had revealed the promise, limitations and the transformative potential of combining systematic analysis with technological tools of integrating multi-criteria decision-making approaches in engineering and urban planning, emphasizing the importance of contextual adaptation and expanded validation to enhance their practical relevance and generalizability.

6. Conclusions and recommendations

In Saudi Arabia, the government and private sector are currently taking steps to reduce their climate change impact, with a major part of their strategies focusing on the concept of sustainability. According to the Saudi Vision 2030 plan, there is a concerted effort within both government and the private sector to reduce overall environmental impacts caused by industrialization. In the present paper, we investigated a range of suitable solutions for building the new airport at Taif, Saudi Arabia. Using different methods, we tested various sustainable solutions/alternatives, looking for the one that would best reduce the environmental impact caused by heavy construction and long-term industrial use.

Mathematical tools were applied to select the best alter-native. Using the selected model, our tests revealed that alternative (A4) was the most environmentally sustainable, followed closely by alternatives (A2) and (A3), ranked second and third, respectively. The results indicate that the alternatives fully or partially aligned with construction strategy 2 are ranked highest. This ranking is based on the most significant indicators, as determined by the FANP results, which received the highest ratings reflected in the overall sustainability index. Performance (C4), recognized as the second most influential indicator based on its global weight analysis, demonstrated the highest evaluation scores when compared across all alternatives. Notably, alternatives categorized under construction strategy 1 were ranked lower in performance compared to those associated with construction strategy 2.

Moreover, the key findings revealed that the third-ranked alternative (A3), which incorporates recycled materials, exhibits a greater overall sustainability compared to alternatives relying exclusively on natural materials. This outcome underscores the potential benefits of integrating recycled materials into construction practices to enhance sustainability. According to the results obtained, the pavement made with recycled mate-rials will be proposed as a sustainable solution. This eco-friendly solution should be tested under real conditions in Saudi Arabia. By using this method, airport pavements may become more sustainable by using less materials, using less energy, and leaving a smaller carbon imprint. Potential avenues for further study might involve conducting field testing and real-world applications to better validate the fuzzy logic model. Furthermore, investigating the incorporation of additional eco-friendly technology like smart sensors, renewable energy sources, and recycled materials might improve the efficiency and sustainability of airport pavements. Fuzzy logic models combined with artificial intelligence would be applied to make more effective decision maker. It is also a significant to apply various optimizations techniques like Particle swarm, Whale, Penguin emperor or Jaya etc., combined with Artificial intelligence would produce more than one solution with optimal values in each case as a reference for engineers and manufacturers.

Further, emerging technologies, such as smart pavements and artificial intelligence (AI), offer promising avenues to enhance sustainability assessments in the context of airport pavement management. Smart pavements, equipped with embedded sensors and data-gathering capabilities, can provide real-time information on structural performance, traffic loads, and environmental conditions, allowing for dynamic and precise evaluations. By leveraging these technologies, sustainability metrics can be updated continuously, fostering a proactive approach to maintenance and resource allocation. Similarly, AI can be integrated into decision models like the Fuzzy ANP-TOPSIS framework to enable predictive analytics, optimize resource usage, and simulate the environmental impacts of various scenarios. AI-powered algorithms can analyze large datasets from smart pavements, offering insights that refine sustainability metrics and provide actionable recommendations. Future studies incorporating these technologies could advance the field by offering comprehensive, data-driven solutions, ultimately contributing to the development of more resilient and environmentally sustainable airport pavements.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

No data was used for the research described in the article.

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