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Sustainable Prioritization of Public Asphalt Paved Road Maintenance

Kelvin Lungu Agabu[1], Chabota Kaliba[2] and Erastus Mishengo Mwanaumo[3]
[1]Lecturer, Department of Civil and Environmental Engineering, School of Engineering, University of Zambia, ZAMBIA
[2]Lecturer, Department of Civil and Environmental Engineering, School of Engineering, University of Zambia, ZAMBIA
[3]Lecturer, Department of Civil and Environmental Engineering, School of Engineering, University of Zambia, ZAMBIA

[1]Corresponding Author: lungukelvin91@gmail.com

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ABSTRACT

The development of transportation infrastructure is crucial for a country's progress as it enables access to social and economic amenities and acts as a vital link between production and consumption. This is particularly significant for landlocked nations like Zambia, which heavily rely on a wide network of public highways, including both paved and unsurfaced roads. Regardless of their quality and construction, all road surfaces degrade over time due to the combined effects of traffic load and environmental factors. If not properly managed, this can lead to costly repairs and rehabilitation efforts. Government organizations face a dilemma when deciding which public roads to prioritize for maintenance. This follows that the inherent hurdle is competing needs within limited finances for infrastructure development. However, the challenge of road maintenance prioritization can be addressed by adopting a multi-criteria approach. This study aims to address the issue of sustainability and provides insights into which public roads should be given priority for maintenance. The research proposes a comprehensive set of criteria focusing on sustainability and assigns relative importance to them, with emphasis on state of deterioration, emergency function, climate resilience, environment, strategic importance, social considerations, economic factors, and political importance. It suggests that road maintenance decision-making should prioritize sustainability, resilience, and societal well-being, challenging traditional assumptions.

Keywords— Decision-Criteria, Pavement, Prioritization, Road Maintenance, Sustainability

I. INTRODUCTION

It is evident that developing countries, including Zambia, grapple with the persistent challenge of rapid urban population growth and concurrent urban development [1], [2]. This urban development often comes at the expense of prioritizing road infrastructure improvement, which is critical for reducing motorist costs, including time, vehicle operating expenses, and accidents [3]. Furthermore, developing nations face additional hurdles, such as changes in policies and institutions, planning for rapid urbanization, refining land use and development processes, and securing funding sources [4]–[7]

A significant challenge in the context of infrastructure development and maintenance in these countries is their limited financial capacity, primarily evidenced by lower National Income/Revenue and Gross Domestic Product (GDP) compared to developed nations. To compensate, developing countries, like Zambia, heavily rely on donor funding and loans for their road infrastructure projects [6], [8], [9]. Given Zambia's landlocked status, road infrastructure plays a vital role in its economy [4], [10], [11]. Consequently, the Zambian government has initiated substantial projects, such as Link Zambia 8000 and Lusaka 400, with a focus on link and urban roads. In 2015, the National Road Fund Agency (NRFA) collaborated with local government agencies, Zambia's Road Development Agency (RDA), and other stakeholders to allocate ZMW 5.4 billion for road infrastructure development and transportation services, contributing to the completion of various mega-projects [12]–[14]. One notable project is the Lusaka Decongestion Project (LDP), launched in April 2018 for Lusaka, attracting a substantial investment of USD 289 billion for urban and link road development [12]–[14].

Globally, road authorities are confronted with the challenge of prioritizing roads for maintenance [15]. Given budget constraints, there is a pressing need for equitable road maintenance prioritization. This necessitates the development of robust maintenance strategies and a prioritization framework or model [15]–[17]. Such decision-making is a complex, multi-criteria problem, incorporating factors like road condition, traffic, safety, cost, and economic, social, and environmental considerations [18], [19]. Multi-criteria Decision Making (MCDM) models are commonly employed to address these challenges in maintenance project selection [18], [20], [21]

However, existing models, upon review, have limitations as they do not comprehensively address sustainability concerns, including emerging issues related to climate resilience. Consequently, there is a compelling

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need for a model that holistically addresses the prioritization of public asphalt roads for maintenance, incorporating sustainability concerns. This study characterises relevant decision-making criteria and their level of importance as a basis for theoretical and practical implications to decision-making support system and model development relevant to sustainable prioritization of asphalt paved road maintenance.

II. LITERATURE REVIEW

The distinction between asphalt and bitumen is a common point of confusion, often used interchangeably, though incorrectly. Bitumen serves as a petroleum-based binding agent for road surfacing or as a bituminous binder, whereas asphalt is a substance bonded with bitumen[22], [23]. Bitumen-sealed surfaces involve the application of bitumen followed by aggregate coating, sometimes performed twice to create a two-coat seal. Asphalt is produced by heating, drying, and blending gravel, bitumen, and sand, commonly used for surfaces like asphalt driveways. In this study, "bituminous pavements" refer to bitumen-bound asphalt pavements, not bitumen-sealed roads [22], [23].

Bituminous pavements, as opposed to concrete and interlocking paver roads, are the most commonly constructed public paved roads not only in Zambia but in many countries worldwide [12], [24], [25] Asphalt pavements are favoured for their durability and resilience, making them the material of choice for numerous national and link road projects. Despite their extended lifespan, the quality of asphalt pavements can be compromised by insufficient surface preparation, construction procedures, or prolonged exposure to environmental and traffic stress [26]. Compared to concrete pavements, asphalt pavements are cost-effective, simple to construct and maintain, and offer excellent riding quality [22], [23]. However, they face challenges, particularly when subpar materials or construction practices are employed [27].

It's important to note that asphalt pavements naturally deteriorate over time due to the degradation of their components, which is accelerated by environmental factors like rain, sunlight, and chemical exposure [26], [28]. This degradation can be exacerbated by construction defects or human errors, such as inadequate base compaction, poor asphalt compaction, drainage issues, or improper asphalt application [27]. Well-constructed asphalt pavements, with proper maintenance, can last up to 25 years [16], [22]. Therefore, regular maintenance is essential to mitigate the effects of water, sunlight, and chemicals on asphalt pavements [28].

Every pavement, regardless of its quality, will deteriorate over time due to the combined impact of traffic and environmental factors [28]. The rate of deterioration increases over time, with more distresses emerging as the pavement ages [26], [28], [29]. Maintenance and rehabilitation interventions are used to slow down this deterioration process and extend the pavement's life [30], [31].

Regular maintenance actions like crack sealing, patching, and surface treatments can address specific pavement deficiencies that contribute to overall deterioration [22], [32], [33] These treatments can immediately improve pavement condition and reduce the rate of deterioration by repairing minor flaws before they escalate [31]. However, there comes a point when routine maintenance cannot rectify larger defects, necessitating rehabilitation to address severe issues and significantly improve the pavement condition [29], [33].

The selection of maintenance projects for prioritization is critical for efficient resource allocation in road management [34]–[36]. Prioritization strategies influence project selection [35], [36],and they rely on sound engineering judgment and an understanding of local conditions [37], [38]. Priority analysis, a systematic process, ranks candidate sections for maintenance based on criteria like pavement condition, traffic volume, pavement function, and budget constraints [17], [18]. Several methods, ranging from simple engineering judgment to mathematical optimization, can be used for priority analysis.

Choosing which roads to prioritize for maintenance is a complex decision for both local and international road authorities [39], [40]. These decisions may range from purely economic considerations to multi-criteria decision-making problems, which factor in pavement deterioration, road safety, cost, economic, social, and environmental aspects [17], [18], [36].

Sustainability, particularly social and environmental concerns, increasingly play a role in pavement management [17], [18], [31], [41] Factors affecting road functionality include rider comfort, serviceability, road width, road markings, among others [19], [42], [43].

However, existing models often fall short of addressing sustainability concerns, socio-economic and environmental aspects, and emerging climate resilience issues [17] A holistic model is needed to effectively prioritize the sustainable maintenance of public asphalt paved roads. Consequently, it is crucial to establish relevant criteria and their respective importance in decision-making processes [31], [41] The primary aim of this study is to develop weighted decision-making criteria for sustainable road maintenance prioritization by employing a combined Analytic Hierarchy Process (AHP) and fuzzy logic approach.

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III. METHODOLOGY

In this research, an initial step involves a systematic review of pertinent literature to identify key decision criteria. The authors employ the PRISMA methodology to select papers from global electronic sources based on title and abstract reviews, resulting in a final selection of 15 papers for content analysis. These papers met two criteria: a) they pertained to Multi-Criteria Decision Making (MCDM) for prioritizing or selecting asphalt road maintenance, and b) they were scholarly articles published before 2010.

Subsequently, a content analysis is conducted on the chosen papers from the systematic review to identify relevant aspects related to sustainability and road maintenance prioritization. Open-ended interviews are then carried out to gain an in-depth understanding of sustainability-related aspects. The respondents, who are experts in various aspects of road infrastructure development, are sampled using purposive snowball sampling, with a total of 20 participants, including experts from Zambia's Road Development Agency (RDA) and those specialized in sustainability in road infrastructure development, road maintenance, and pavement management.

The authors employ an inductive approach during the qualitative analysis of the collected interview data, avoiding preconceived conclusions. Coding analysis is applied to discern important decision criteria, leading to the conceptualization of decision-criteria aspects. This conceptualization proceeds from higher-level criteria attributes to the establishment of associated sub-criteria, forming a secondary level of criteria attributes.

Following this characterization of criteria and sub-criteria, the authors create a pair-wise comparison interview where participants assess the relative importance of these attributes on a 9-point sliding scale. Ultimately, a Fuzzy-Analytic Hierarchy Process (fuzzy-AHP) analysis approach is utilized to derive crisp weight values for each decision-making attribute, culminating in the proposal of weighted decision-making parameters as the final analytical output. Taking a hybrid model integrating Fuzzy Logic and the Analytic Hierarchy Process (AHP) provides a strong solution to complicated decision-making, judgement making on relevant importance of criteria in this case. In adopting a fuzzy-AHP approach, this study takes advantage of the following:

i. Uncertainty Handling: Fuzzy Logic excels at managing imprecise data, making it appropriate for situations involving uncertain or ambiguous information.

ii. Structured Framework: AHP provides a hierarchical structured framework for decision analysis. It deconstructs large issues into smaller components, allowing for methodical examination.

iii. Subjectivity Balancing: The combination enables the integration of subjective judgements (AHP) with the capacity to represent uncertainty (Fuzzy Logic), establishing a balance between organized analysis and real-world complexity.

This research integrates the AHP methodology into its quantitative data collection and modelling processes, encompassing the following key components:

a) The first and second steps of the AHP method lay the foundation for gathering quantitative data in this study, involving:

- Identifying pertinent decision-making attributes (AHP Step 1).
- Determining their respective significance through pairwise comparative judgments employing a nine-point sliding scale (AHP Step 2).

b) The AHP methodology's third and fourth steps are employed for data modelling, building upon the information gathered in Steps 1 and 2. This modelling entails:

- Initially constructing comparative matrices (nxn) (AHP Step 3).
- Subsequently, establishing attribute weights, represented in matrices as local (derived from a single respondent) and global (aggregated from 20 respondents) priority vectors. These weights are calculated using a combination of geometric mean, normalization, and aggregated individual preference (AIP) mathematical modelling techniques (AHP Step 4).

A. Analytic Hierarchy Process (AHP) Method

Step 1

The primary objective when applying the Analytic Hierarchy Process (AHP) in Step 1 is to assess the relative significance of two specified attributes and address the question of, "Which attribute holds greater importance in comparison, and what is the degree of its dominance?" To accomplish this, the study necessitates the establishment of hierarchical levels to define these comparisons. This study's comparative structure encompasses three hierarchy levels:

a) **Level 1 (Goal):** Encompassing decision criteria relevant to the sustainable prioritization of road maintenance.

b) **Level 2:** Identifying criteria, denoted as Ci, where i ranges from 1 to n, representing the attributes under consideration.

c) **Level 3:** Defining secondary or sub-criteria, denoted as Si, where i ranges from 1 to n, further delineating the attributes at the n-th level.

B. Analytic Hierarchy Process (AHP) Method

Step 2

In Step 2 of the Analytic Hierarchy Process (AHP), the study incorporates a total of N=20 respondents,

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each providing their comparative judgments through pairwise comparisons employing a 9-point sliding scale. The adoption of a pairwise comparison sliding scale enables the study to elicit a diverse range of judgments and more precise ratings compared to conventional Likert scale responses, which typically offer a limited choice between two options, such as "disagree" to "strongly disagree" or rating on a scale of "1 to 5."

C. Analytic Hierarchy Process (AHP) Method

Step 3

The outcome of individual respondents' comparative judgments in this study culminates in the creation of comparative n x n matrices, denoted as A=(aij), in Step 3 of the Analytic Hierarchy Process (AHP). These matrices are derived from N=20 individual pairwise comparisons conducted at both Level 2 and Level 3, where i represents the i-th row and j represents the j-th column. Each entry aij signifies the weight of relative importance of attribute i in comparison to attribute j, with aii set at 1 for i and j values ranging from 1 to n.

The primary purpose of these matrices is to establish priority vectors that represent the assigned weights for each attribute. This includes the development of priority vectors based on the comparative n x n matrices for:

a) **Criteria** established within the Level 2 hierarchy in relation to the Goal hierarchy.

b) **Sub-criteria** established within the Level 3 hierarchy concerning Level 2 and the overarching Goal hierarchy.

D. Analytic Hierarchy Process (AHP) Method

Step 4

The authors develop firstly local priority vectors $\boldsymbol{W_{Lk} = [W_{Lb} \ldots W_{Lm}]^T}$ for each set of attributes **k=b… m** for **L-th individual respondent**, where these priority vectors represent weight of each **k-th** attribute for **L=1,2 … 20**.

Therefore, in this study from the collection of 20 expert individuals for collaborative judgement on **m** attributes, the priority vector $\boldsymbol{W_{Lk}}$ when normalized satisfies Equation 1.

$$\sum_{k=b}^{m} W_{Lk} = 1, for\ L = 1,2 \ldots 20\ for\ L-th\ respondent \quad (Equation\ 1)$$

Representing the priority vector by geometric mean $\boldsymbol{g_i}$ in proceeding equations, the individual priority vectors for each **L-th individual** from the **n x n comparison matrix A=(aij)** are calculated taking the following steps utilizing Equations 2 to 4:

(a) Step I: Calculate geometric means for each **i-th row** following Equation 2.

$$Individual\ geometric\ mean\ g_i\ for\ L-th\ individual = \sqrt[n]{\prod_{i,j=1}^{n} a_{ij}^{L}}\ , for\ i-th\ row\ and\ j-th\ column\ and\ L = 1,2 \ldots 20 \quad (Equation\ 2)$$

(a) Step II: Summation of the geometric means for **i=1, 2… n** following Equation 3.

$$\sum_{i=1}^{n} g_i^L\ , for\ i = 1,2 \ldots n\ and\ L = 1,2 \ldots .20 \quad (Equation\ 3)$$

(b) Step III: Normalization of the geometric means to determine the priority vector for the **L-th person** as stated in Equation 4, subject to the requirement that the summation of priority vector's must be equal to one.

$$Normalized\ priority\ vector\ for\ L-th\ individual = \left[g_i^L \Big/ \sum_{i=1}^{n} g_i^L \right] \quad for\ i = 1,2 \ldots n\ \ and\ L = 1,2 \ldots .20 \quad (Equation\ 4)$$

The authors proceed to develop global priority vectors, which encapsulate the collective judgments of the 20 participants involved in this study. In the realm of collaborative decision-making, there are two prevalent techniques for handling group judgments: Aggregating Individual Judgments (AIJ) and Aggregating Individual Priorities (AIP). In the former approach, the geometric mean of each individual judgment is employed to formulate a group judgment matrix, and the Analytic Hierarchy Process (AHP) is utilized to establish both local and global priorities. Initially, AIP estimates local priorities for each individual, and subsequently, group priorities are determined using the geometric mean, as described by Escobar and Moreno-Jiménez (2007) and Ossadnik et al. (2016).

This study uses the geometric mean approach to determine the priority vectors and the AIP to aggregate these individual judgments. Final priority global vector $\boldsymbol{W_k = [W_b \ldots W_m]^T}$ for each set of attributes **k=b... m** for **L=20 respondents** are analysed using the aggregating individual preferences (AIP) method by applying

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aggregated geometric mean on local priority vectors (geometric mean g_i^L for L-th individual and i-th row).

$$Aggregated\ geometric\ mean\ g_k\ for\ L\ experts = \sqrt[20]{\prod_{L=1}^{20} g_i^L}\ ,for\ i-th\ row\ and\ L = 1,2\ldots.20 \quad (Equation\ 5)$$

In the aggregation of these individual judgments, the authors employ Equation 5 to utilize the Aggregated Individual Preference (AIP) method, resulting in the derivation of the final priority vector denoted as $g_k = [g_b \ldots. g_m]^T$ with geometric means. In cases where the components of the final priority vector do not sum up to one, the authors conduct an additional normalization. These approaches were specifically selected because, unlike the utilization of Aggregated Individual Judgment (AIJ) through the geometric mean, the responses in this study originate from various organizations. Consequently, they do not suggest a synergistic aggregation of individual preferences. Furthermore, this methodology allows the authors to discern the variations in the assessments of each expert respondent by utilizing the AIP.

E. Fuzzy Logic

Additionally, this study integrates principles from fuzzy logic to develop both fuzzy local and global priority vectors. By infusing fuzzy logic into the Analytic Hierarchy Process (AHP) methodology, the model emulates the way human judgment handles digital values, specifically interval values such as 1, 3, 5, 7, and 9, by considering all possible gradations within these digital intervals.

The fuzzy values employed in this study encompass {(1,1,1), (2,3,4), (4,5,6), (6,7,8), (9,9,9)}, corresponding to the interval values {1,3,5,7,9} for all pair-wise comparisons. Similarly, for inverse digital values, the study utilizes fuzzy values {(1,1,1), (1/2,1/3,1/4), (1/4,1/5,1/6), (1/6,1/7,1/8), (1/9,1/9,1/9)}, which align with inverse interval values {1,1/3,1/5,1/7,1/9} for all pair-wise comparisons.

Moreover, considering the introduction of fuzzy logic, three normalized local priority vectors are associated with the importance weights for each respective 2nd and 3rd tier attribute for every individual respondent. In this context, the authors employ the center of area method to calculate a single crisp value representing the attribute's fuzzy weight. This is based on the central value located equidistantly between lower and upper values in the fuzzy weight range. These fuzzy weight crisp values are determined using Equation 6. Furthermore, if the summation of weights for each attribute does not equal 1, these weights undergo additional normalization.

$$Centre\ of\ area = \left[\frac{(l+m+u)}{3}\right]$$

$$where: normalized\ fuzzy\ weight\ values = (l,m,u)\ are\ defined\ as \begin{Bmatrix} l = lower\ crisp\ value \\ m = middle\ crisp\ value \\ u = upper\ crisp\ value \end{Bmatrix} \quad (Equation\ 6)$$

Fuzzification offers a solution to the limitations of a standalone AHP methodology, which struggles to effectively capture the subjectivity of human judgments when attempting to derive precise values from verbal assessments in pair-wise comparisons. By integrating the principles of fuzzy logic with AHP methodologies, this research initially presents AHP local and global priority vectors, followed by the application of fuzzy logic modelling to establish Fuzzy AHP local and global priority vectors.

F. Descriptive Statistical Analysis

In order to gain a deeper understanding of the comparative judgment datasets, the authors leverage descriptive statistical analysis, which includes the following techniques:

- Employing the mean as a measure of central tendency;
- Using standard deviation as a measure of data dispersion; and
- Applying Percentage Cumulative Frequency (PCF) as an indicator of data frequency.

IV. DATA ANALYSIS AND RESULTS

In the initial stages of this research, certain philosophical assumptions are made regarding the fundamental nature of reality concerning the identification of pertinent decision criteria for the sustainable prioritization of public asphalt roads for maintenance. This conceptual framework is depicted in Figure 1.

These attributes were predetermined after conducting a thorough review of relevant literature. This review involved a systematic content analysis of papers obtained from various global electronic sources. The selected papers met two specific criteria: (a) they were related to Multiple Criteria Decision Making (MCDM) in the context of prioritizing or selecting asphalt road maintenance, and (b) they were published prior to 2010. These identified attributes were subsequently incorporated into open-ended interviews aimed at acquiring a comprehensive comprehension of the decision criteria and sub-criteria pertinent to the sustainable prioritization of public asphalt roads in need of maintenance, focusing on the case of Zambia. In conducting open-ended interviews, and by way of coding analysis, the authors established

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what constitutes factually important decision-criteria with regards to this subject matter of sustainable road prioritization. These conceptualized attributes are presented in Figure 2.

Figure 1: Preconceived attributes

This research determined that certain initially conceived attributes are more appropriately categorized as sub-criteria. For example, the attribute of accessibility was redefined as a sub-criterion linked to the broader social category. Additionally, it was found that political aspects, including policy and decision-making, are shaped by the It is these attributes that were included in the pair-wise interviews translated to comparative judgement matrices representing relative importance of each attribute compared with another with respect to the associated higher-level hierarchy. The hierarchy levels characterized in this study are depicted in Figure 3.

An intriguing aspect of this study is that, while political importance may not hold substantial significance in the context of sustainability concerns related to prioritizing road maintenance, it remains a noteworthy consideration for decision-makers. Consequently, this research incorporated political importance as one of the assessed criteria and defined a specific value representing its level of importance. This value serves to counterbalance any rating assigned by a decision-maker when assessing the political importance of a road alternative within the model's input variables.

The authors create individual local priority vectors based on the judgments of each single respondent, and then they aggregate these to form global priority vectors, taking into account the assessments of all N=20 respondents. These priority vectors indicate the importance or weights assigned to each attribute concerning its higher-level hierarchy. They are determined using mathematical modeling techniques like the geometric mean, normalization, and aggregated individual preference (AIP).

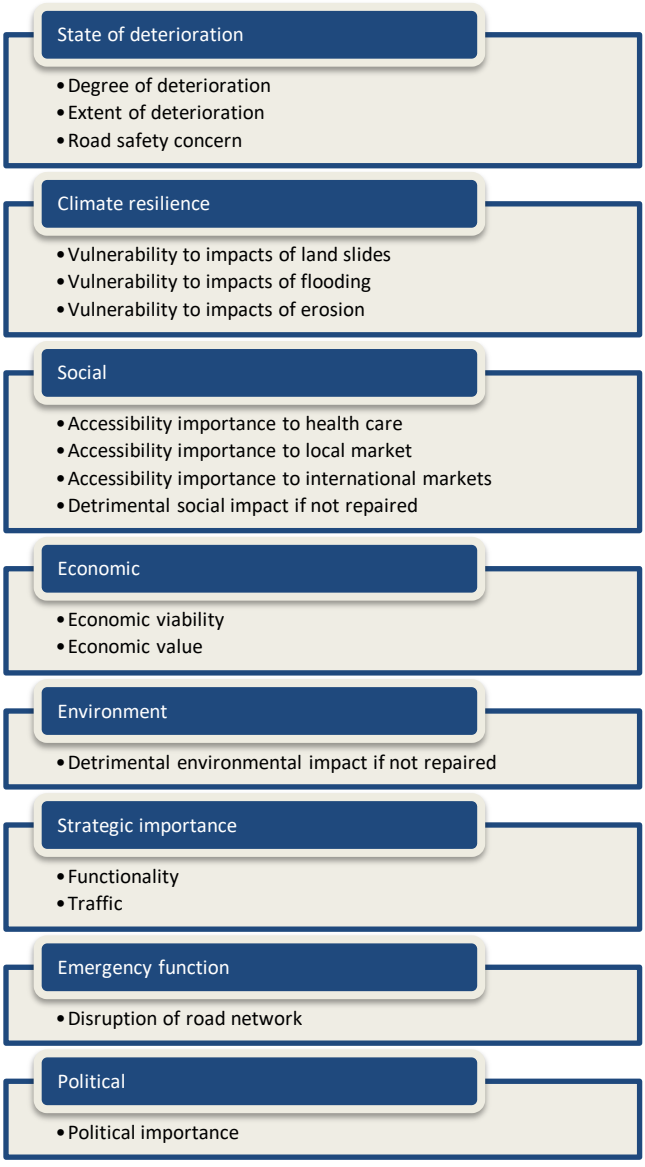

Figure 2: Conceptualized attributes

In this examination, these priority vectors are initially established through the Analytic Hierarchy Process (AHP). Subsequently, the authors apply fuzzy

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logic to the weightings within the comparative judgment matrix to derive crisp values for Fuzzy AHP.

In this study, each local priority vector in the i-th row was subjected to fuzzification, a method described in the previous chapter and implemented following the AHP Step 3 methodology. The data obtained from the 20 individual pair-wise comparisons for the established attributes were analyzed using mean, standard deviation, and variance as the primary indicators of data dispersion. Additionally, the coefficient of variance (CV) was employed to assess the exclusion of outlier datasets.

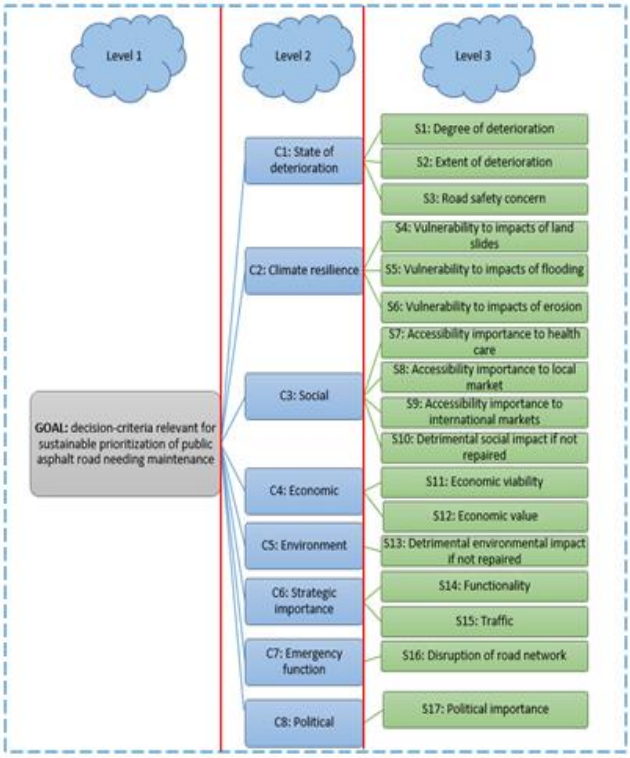

Figure 3: Hierarchy Framework for conceptualized attributes and their unique identifiers

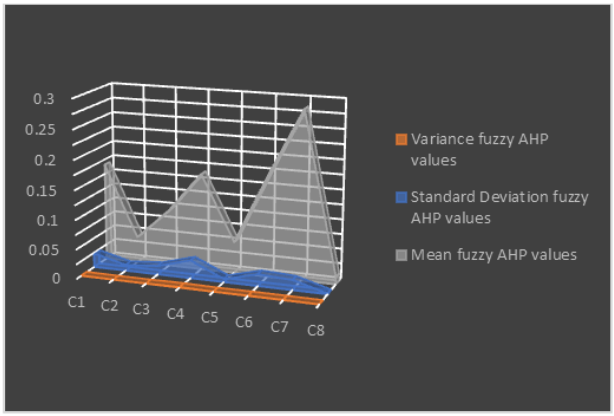

Figure 4: Measures of dispersion Level 2 Hierarchy

To clarify, these dispersion metrics were employed on the fuzzy AHP crisp values derived from the n x n matrices corresponding to each individual judgment obtained from the pair-wise comparison data. Figures 4 and 5 demonstrate that the Coefficient of Variation (CV), calculated as (standard deviation/mean) *100%, which is a function of variance, ranges from 7% to 22% for attributes C1 to C8 and from 0% to 28% for attributes S1 to S17.

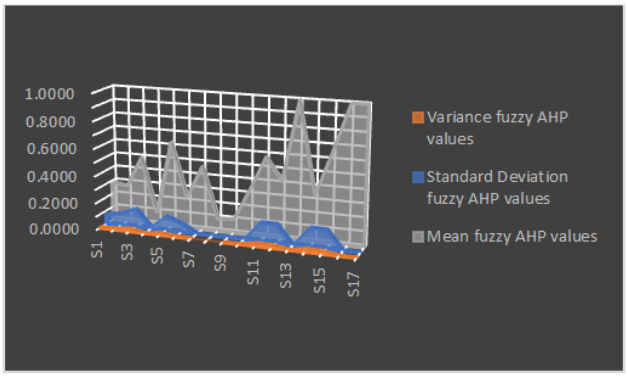

Figure 5: Measures of dispersion for Level 3 Hierarchy

The CV serves as an indicator of variability concerning the mean, with higher values indicating greater dispersion from the mean. According to the general rule for CV, any value exceeding 30% is deemed unacceptable. However, in this case, all the included data sets for fuzzy AHP values, after the removal of outlier data points, fell well within the acceptable range, as none of them exceeded 30%. This iterative process aimed to ensure that the final data sets for fuzzy AHP crisp values were within the acceptable range of less than 30% CV.

The mean and standard deviation were utilized to construct percentage cumulative curves, as depicted in Figures 6 through 11, which serve as visual representations of how responses are distributed based on these two dispersion measures. These curves provide priority crisp values that establish the order of importance, assigning weights indicative of the level of importance required when making objective decisions while scoring the rating for each sub-criterion associated with the main criteria, according to the qualitative descriptors outlined in this study. These ratings constitute the input variables for the model created within this research and are linked to each sub-criterion, which is subsequently presented based on respondent judgments concerning their relative importance in relation to the respective higher-level hierarchy clusters of attributes.

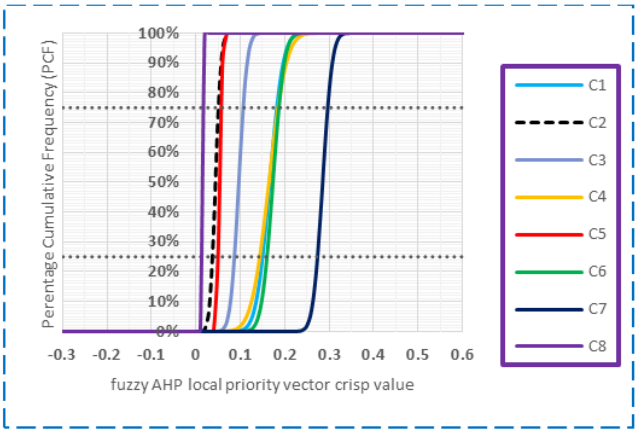

Figure 6: PCF curve for C1 to C8 criterion fuzzy AHP local priority crisp values

For instance, Figure 6 shows that more than 70% of respondents concur that the economic criterion (C4) holds the second-highest importance, following only the emergency function (C7) in terms of economic significance. Likewise, it is the consensus of more than 70% of respondents that strategic importance (C6) should be accorded a higher level of importance compared to the state of deterioration (C1), with the latter following closely in terms of priority.

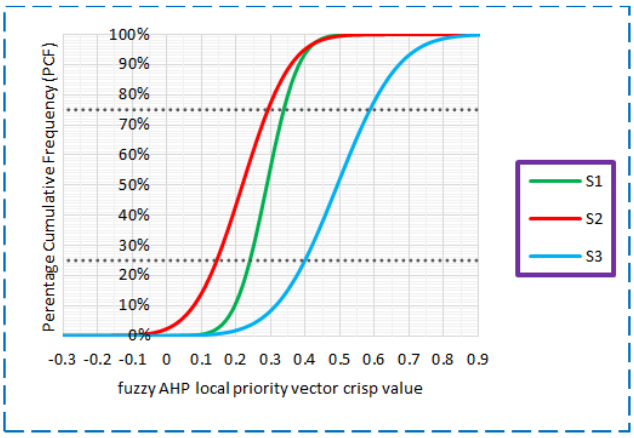

Figure 7: PCF curve for S1 to S3 sub-criterion fuzzy AHP local priority crisp values

This was clarified by illustrating that a road with an extremely high level of deterioration can only be considered for maintenance when evaluating the economic and strategic significance of the road. The strategic importance is, in turn, influenced by the functionality and traffic sub-criteria ratings for any road under assessment. Conversely, all respondents unanimously indicated the order of importance as follows: C3: social, C5: environment, C2: climate resilience, and finally C8: political importance attributes.

The findings from this study, as depicted in Figure 7, reveal that a unanimous 100% of respondents pointed out that S3: road safety is the most relatively significant decision-making attribute to be taken into account when assessing sub-criteria associated with the C1: state of deterioration criterion. This indicates that when determining which asphalt paved public road to maintain based on its state of deterioration, road safety carries greater importance than the level and extent of deterioration. Furthermore, up to 95% of respondents concurred that it is essential to consider S1: degree of deterioration before delving into discussions about S2: extent of deterioration.

Figure 8 illustrates unanimous agreement among respondents, with up to 100% of them concurring on the order of priority for sub-criteria within the C2: climate resilience criterion. Specifically, they rank S5: vulnerability to impacts of flooding as the most crucial, followed by S6: vulnerability to impacts of erosion, and finally S4: vulnerability to impacts of landslides.
Therefore, when making decisions that take climate resilience into account for a particular road in need of maintenance, vulnerability to impacts of flooding is considered the most significant aspect.

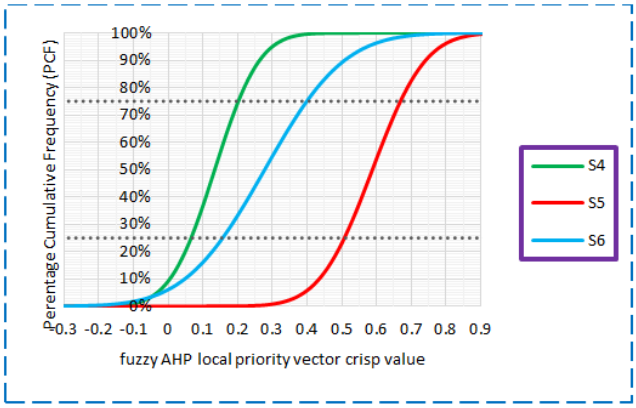

Figure 8: PCF curve for S4 to S6 sub-criterion fuzzy AHP local priority crisp values

As depicted in Figure 9, this study established that 100% of the respondents agree with the assertion that S7: accessibility to healthcare holds the utmost relative importance in the context of the C3: social criterion.

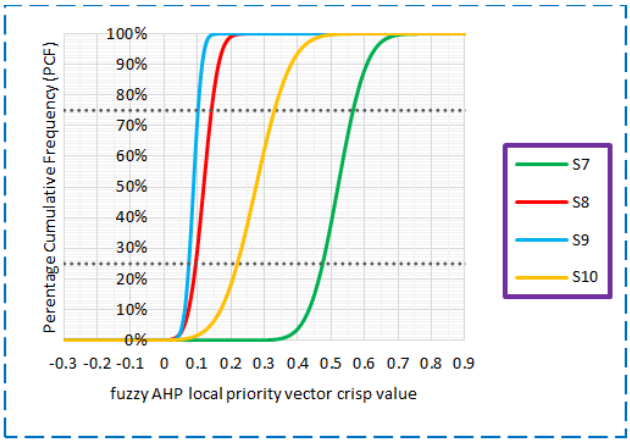

Figure 9: PCF curve for S7 to S10 sub-criterion fuzzy AHP local priority crisp values

Following this, the order of priority among the sub-criteria is as follows: S10: detrimental social impact if not repaired, S8: accessibility importance to local markets, and S9: accessibility importance to international markets.

Economic importance is characterised in this study by S11: economic viability and S12: economic value, with both closely equally important but economic viability holding more relative weight of importance to economic value of any given road needing repair.

Figure 10 illustrates these findings. Further, this study postulates that while economic value can cover an array of economic benefits that may directly or indirectly support development, a cost-benefit evaluation holds a greater weight of importance by firstly establishing the economic viability of repairing a particular road.

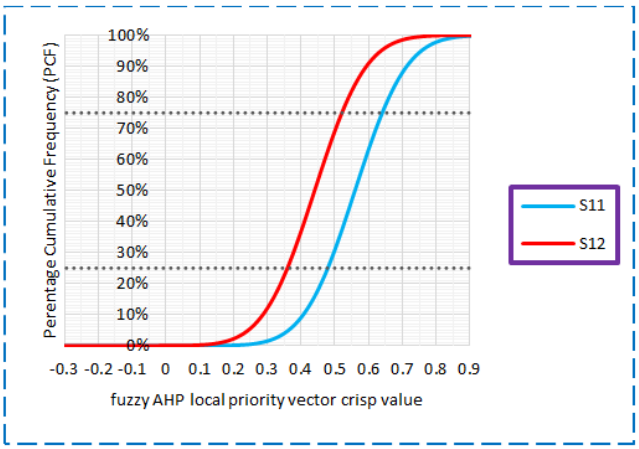

Figure 10: PCF curve for S11 and S12 sub-criterion fuzzy AHP local priority crisp values

This study defines C6: strategic importance by examining S14: functionality and S15: traffic. Of these, traffic holds greater importance when making decisions about road maintenance, specifically concerning the strategic significance of a road. Consequently, the study suggests that roads with higher traffic volumes are more deserving of maintenance attention before evaluating whether the functionality of a specific road classifies it as a trunk, collector, arterial, or local road, among others.

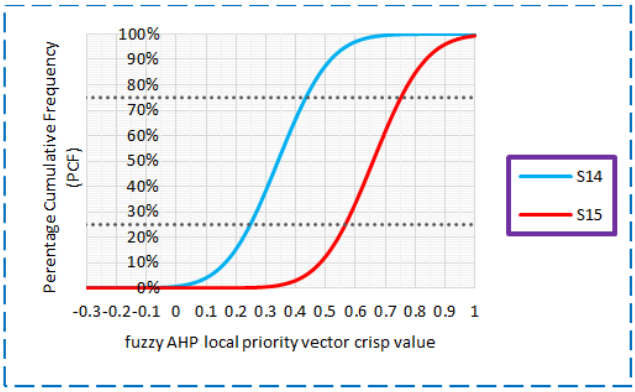

Figure 11: PCF curve for S14 and S15 sub-criterion fuzzy AHP local priority crisp values

Let's remember that for criteria C5: environment, C7: emergency function, and C8: political importance, there is only one corresponding sub-criterion, which are S13: detrimental effect to the environment, S16: disruption of road network, and S17: political importance, respectively. As a result, no comparative judgments were conducted for these sub-criteria, and they were assigned a priority vector crisp value of 1.

The authors determined fuzzy AHP global priority vectors (Figures 12 and 13) through the application of the aggregated individual preference (AIP) mathematical modelling approach using geometric mean and normalization techniques. This process aligns with the methodology based on creating normalized fuzzy local priority vectors based on fuzzy crisp value comparative matrices and then applying the geometric mean to derive the aggregated fuzzy AHP priority vectors.

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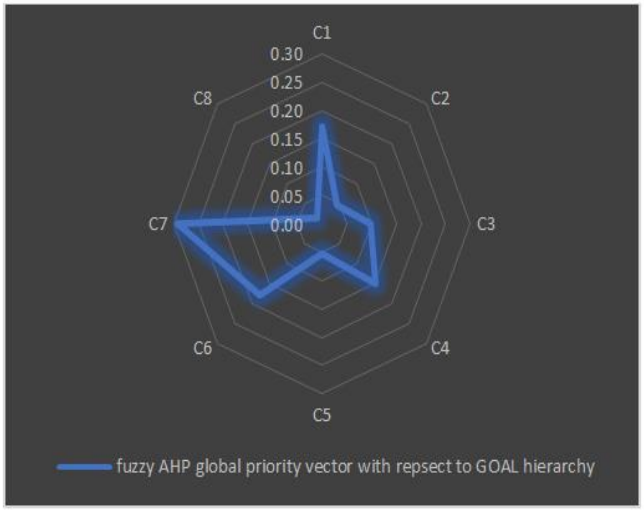

Figure 12: Fuzzy AHP global priority vector for criteria C1 to C8 with respect to goal hierarchy

In this study, the analysis initially focuses on the individual assessments for the established criteria C1 to C8 within the context of the top-level hierarchy, referred to as "decision-criteria relevant to sustainably prioritize road for maintenance." The priority vector matrix for C1 to C8 is illustrated in the radar chart established in this study represented by Figure 12.

The key question that arises is: What purpose do these crisp values serve? These priority values assign a weight of importance to each established attribute. These priority values act as coefficients in the model function, providing the 'true weight' for each attribute when combined with a decision-makers sub-criterion rating for an evaluated public asphalt paved road in need of repair. For instance, consider a criterion such as C8: political importance (coefficient=0.0131), which has only one sub-criterion, S17: political importance (coefficient=1). Its 'true weight' would be 0.0304 when given a 3/10 score for its sub-criterion. This demonstrates that the 'true weight' of a criterion is calculated as the sum of its associated sub-criterion 'true weights' multiplied by its model coefficient. It's important to note that each sub-criterion's 'true weight' depends on a decision-maker's score multiplied by its model coefficient.

The priority vectors established for each criterion reveal that discussions about the economic importance of a road, represented by C4, must first consider the strategic importance (C6) and the state of deterioration (C1) of the road. This supports the models proposed by other researchers, including Ahmed et al. in 2017, Bhuva et al. in 2019, and Mengistu et al. in 2020, who similarly emphasized that the state of deterioration holds a significant position as a decision-making criterion.

Additionally, this study determines that the emergency function (C7) holds the utmost priority and importance. This implies that when a road network requires maintenance, the failure to address this promptly could disrupt the entire network, taking precedence over all other criteria.

Furthermore, the study highlights the social importance (C3) in maintaining any road, which ranks ahead of the economic criterion (C4) in terms of relative importance. Even though decision-makers might consider political importance as influential in their decisions, its weight of importance, as indicated in this study (with a low value of 0.0131), suggests that any rating given by a decision-maker regarding the political importance of a road will have the least impact on the final model score used for ranking road alternatives in need of maintenance.

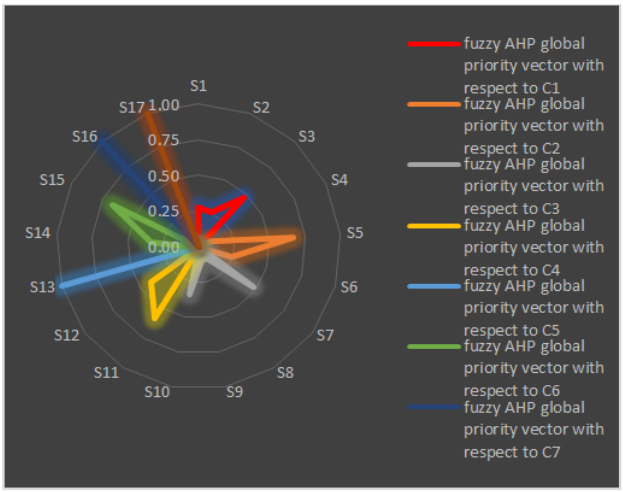

Figure 13: Fuzzy AHP global priority vector for criteria S1 to S17 with respect to their associated criterion

This study also developed fuzzy AHP global priority vectors for the 17 sub-criteria established in this study, with respect to their associated criterion. These findings are illustrated in the radar chart presented in Figure 13. These Level 3 hierarchy findings are further expounded in clusters with respect to each of their higher-Level hierarchy.

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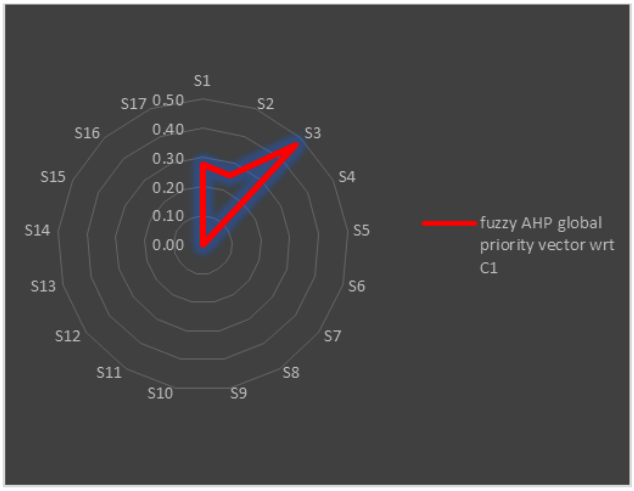

Figure 14: Fuzzy AHP global priority vector for criteria S1 to S3 with respect to C1

The results in Figure 14 present the priority vector for sub-criteria S1 to S3, with respect to C1. These findings indicate that road safety concern takes a higher priority compared to the other attributes with respect to the criterion state of deterioration. Further, the degree and extent of deterioration are almost equally important with the degree of deterioration taking precedence.

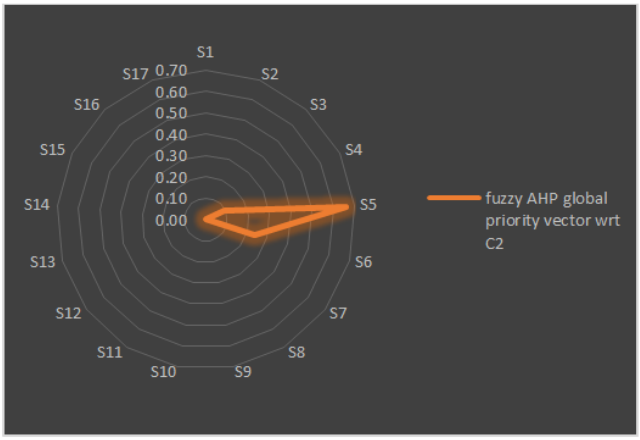

Figure 15: Fuzzy AHP global priority vector for criteria S4 to S6 with respect to C2

In an attempt to include climate change aspects in prioritization of which road to repair, this study explored the relative importance of vulnerability to impacts of landslides, flooding and erosion (Figure 15). Vulnerability to the impacts of flooding was determined as the most important factor with the other sub-criteria to a lesser extent. This postulation is drawn from findings presented in the radar chart captured in Figure 15.

However, this study also presents an argument that for country's more susceptible to landslides would hold a higher value for flooding and thus a switch to an order of priority were vulnerability to impacts of landslides takes precedence.

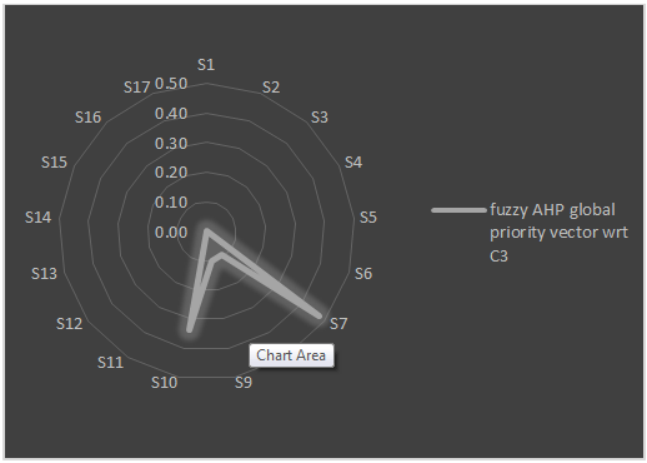

Figure 16: Fuzzy AHP global priority vector for criteria S7 to S10 with respect to C3

Accessibility to health care is established to have the highest order of priority with respect to social aspects when considering which road to repair, as presented in Figure 16.

The detrimental social impact if a road is not repaired is also a much important aspect compared to the other sub-criteria and this can be explained by the strong linkages from socio-economic and socio-environmental rolling effects due to social disbenefits incurred if the road is not repaired.

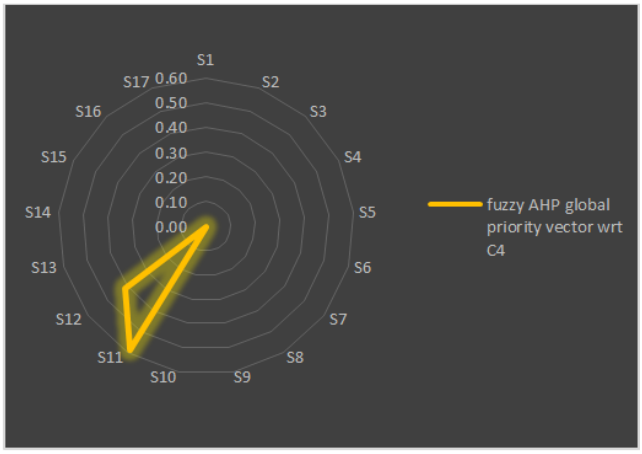

Figure 17: Fuzzy AHP global priority vector for criteria S11 to S12 with respect to C4

This study establishes that the economic value a road adds and economic viability in repairing the road are almost equally important based on economic importance as

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a decision-criteria in prioritizing which road to maintain (Figure 17).

This study contends that while economic value can cover a variety of economic benefits that may directly or indirectly support development, a cost-benefit analysis holds a greater weight of importance by first establishing the economic viability of repairing a particular road.

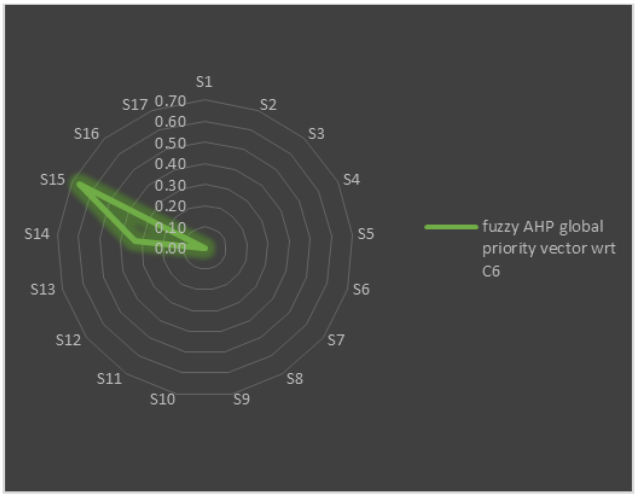

Figure 18: Fuzzy AHP global priority vector for criteria S14 to S15 with respect to C6

Results indicate that the maintenance of a road is more justifiable by the traffic volume it carries (Figure 18) which is almost twice as important as the functionality of the road. This order of priority follows the reasoning made in this study that a road can only be considered functional following the traffic volume it carries.

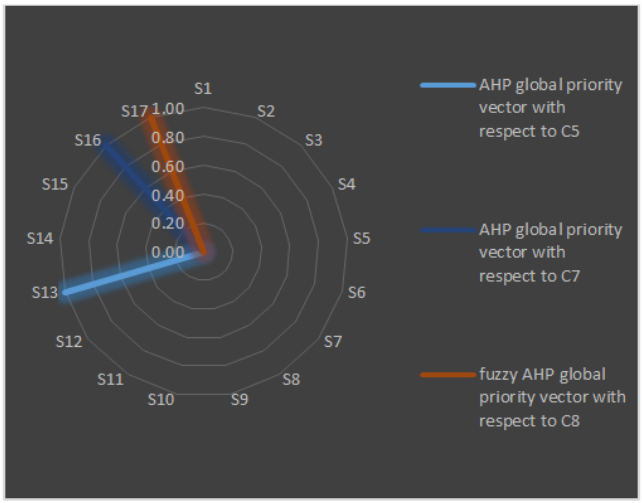

Figure 19: Fuzzy AHP global priority vector for criteria S13, S16 and S17

Priority vector matrix for S13 with respect to the criterion environment (C5), S16 with respect to the criterion emergency function (C7), and S17 with respect to the criterion political importance (C8) are all equal to [1], following that they are the only sub-criterion to make a judgement from with respect to their higher-level criterion, as earlier alluded. This is why they are represented by a line in the radar chart captured in Figure 19.

V. DISCUSSION

The authors delve into these criteria and their respective significance, drawing upon the insights of numerous scholars within the field. First and foremost, this study underscores the necessity of considering multiple criteria when evaluating road maintenance priorities. It asserts that economic importance (C4) cannot be examined in isolation; instead, it is intricately connected to the road's strategic importance (C6) and its current state of deterioration (C1). This observation aligns with previous research by Ahmed et al. (2017), Bhuva et al. (2019), and Mengistu et al. (2020), who have also advocated for the prioritization of the state of deterioration as a fundamental decision-making criterion.

Furthermore, this research pinpoints the emergency function (C7) as the highest-priority criterion, surpassing all others. This highlights the critical nature of addressing emergency concerns promptly, as an unmaintained road network could disrupt the entire system.

Within the realm of social importance, the study emphasizes the substantial weight carried by the social aspect of road maintenance, particularly in terms of healthcare accessibility, accounting for nearly 50% of the priority importance when determining which roads to repair. Suthanaya (2017) previously acknowledged the significance of social aspects in road maintenance, and our findings extend this understanding by emphasizing the role of healthcare accessibility as a key driver.

Moreover, this research underscores the importance of road safety concerns, which take precedence over other attributes when assessing the state of deterioration criterion. This corroborates the findings of Pamuković et al. (2021) and Abu Dabous et al. (2020). Importantly, our study reveals that road safety concerns are frequently overlooked in the models proposed by other scholars for prioritizing road maintenance, as indicated by our literature review.

Additionally, a substantial body of scholarly work, including Moazami et al. (2011), Parekh and Shah (2016), Utama et al. (2016), Suthanaya (2017), Sayadinia and Beheshtinia (2020), Pamuković et al. (2021), and Spits Warnars et al. (2021), has stressed the significance of taking traffic considerations into account when

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determining which roads to repair. Our research aligns with these findings and underscores the importance of traffic in assessing the strategic aspect of road maintenance.

Finally, our study highlights the often-neglected criterion of vulnerability to flooding, particularly in the context of climate change. We find that vulnerability to flooding emerges as the most crucial factor, whereas other sub-criteria related to climate change are given less weight. This finding contrasts with the prevailing trend in the literature, where climate change considerations are frequently omitted when prioritizing road maintenance.

In summary, our research contributes to the existing body of knowledge by emphasizing the interconnections between various criteria in road maintenance prioritization, highlighting the importance of emergency functions, healthcare accessibility, road safety, traffic, and vulnerability to flooding. Our findings challenge the conventional practices in the field and call for a more comprehensive and holistic approach to road maintenance prioritization, taking into account all relevant criteria to ensure the efficient allocation of resources and the resilience of road networks in the face of changing conditions.

V. CONCLUSION

This study endeavors to tackle the matter of sustainability and offers guidance on which public roads should be prioritized for maintenance. The research introduces an extensive array of criteria centered around sustainability and allocates varying degrees of importance to these criteria. Notably, it underscores the significance of factors such as the road's current state of deterioration, its capacity to address emergency situations, climate resilience, environmental concerns, strategic importance, social aspects, economic factors, and political significance. This approach suggests a departure from conventional assumptions by advocating for a road maintenance decision-making process that places sustainability, resilience, and the welfare of society at the forefront.

The findings of this study hold significant relevance for policymakers. The authors suggests that there is a pressing requirement for purposeful policy formulation that can be informed by the results of this research. These policies should aim to reduce the influence of subjectivity and instead prioritize objective decision-making that takes into account sustainability concerns in a comprehensive manner.

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