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A MULTI-CRITERIA DECISION FRAMEWORK FOR ROAD INFRASTRUCTURE MAINTENANCE PRIORITIZATION IN MUNICIPAL MANAGEMENT: A CASE STUDY OF THE ASEER REGION, SAUDI ARABIA

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Abstract
Road-maintenance prioritization in large municipal networks is often constrained by limited funding, ageing infrastructure, and the absence of transparent decision-making systems, resulting in inefficient allocation of resources. This study aimed to develop a transparent multi-criteria decision-analysis framework for prioritizing road-maintenance investment in the Aseer Region of Saudi Arabia. Specifically, the study examined the structural composition of the municipal road network, evaluated the limitations of a baseline prioritization model, and demonstrated the effectiveness of a four-criterion framework grounded in the Analytic Hierarchy Process (AHP) and weighted linear combination (WLC).

The study adopted a GIS-based multi-criteria evaluation methodology using official inventory data from the Aseer Municipality geospatial platform. The population comprised 41,744 road segments covering 20,851 km, all of which were analysed. Data were standardized, weighted through pairwise comparison, and aggregated into composite priority scores, while sensitivity analysis was conducted to assess the effects of alternative weight sets.

Findings revealed a significant mismatch between road count and maintenance value, with local roads constituting 77% of segments but accounting for only 46.4% of maintenance value, whereas regional and arterial roads concentrated disproportionately high per-asset criticality. The baseline model demonstrated weak discriminatory power, placing about 91% of segments within the two lowest priority bands. However, the proposed framework successfully re-ordered priorities by emphasizing strategic and economic consequences rather than network ubiquity.

The study concluded that the framework provides a transparent, auditable, and policy-aligned approach to municipal road-maintenance prioritization. It recommended the integration of geocoded condition data, formal expert weight elicitation, and machine-learning condition prediction to support continuous segment-level deployment.

Keywords: Multi-criteria decision analysis; road asset management; maintenance prioritization; municipal governance; Saudi Vision 2030; pavement condition index.

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I. INTRODUCTION

Road networks are among the most capital-intensive assets that municipal governments own and operate, and the decisions that determine where limited maintenance funds are spent have direct consequences for public safety, economic activity, and citizens' daily mobility. As networks expand and age, the volume of candidate maintenance interventions routinely exceeds available budgets by a wide margin, forcing administrators to rank competing road segments under conflicting objectives. The problem is fundamentally one of prioritization: which roads should be treated first, and on what defensible basis. In the absence of a structured method, such decisions are frequently made reactively or through informal judgement, which neither guarantees the efficient use of public funds nor withstands the scrutiny that accountable governance demands (Abu Dabous, Zeiada, Zayed, & Al-Ruzouq, 2020).

Multi-criteria decision analysis (MCDA) has emerged as the dominant response to this class of problem because it allows several quantitative and qualitative considerations to be combined into a single, traceable evaluation. Methods derived from the Analytic Hierarchy Process (AHP) and weighted linear combination (WLC) translate competing objectives into transparent weights and scores, enabling a network of alternatives to be ranked according to explicitly stated preferences (Saaty, 1980; Malczewski, 1999). Yet much of the published work concentrates on the engineering question of which treatment to select for an already-identified section, rather than on the prior managerial question of how an entire municipal network should be triaged when most segments are ostensibly eligible for attention.

This study addresses that managerial gap in a specific and policy-relevant setting. The Kingdom of Saudi Arabia has, under Vision 2030, placed the modernization of urban infrastructure and the quality of municipal services at the centre of its development agenda (Kingdom of Saudi Arabia, 2016). In support of this agenda, the Aseer Municipality compiled a comprehensive digital inventory of its road network on the national municipal geospatial platform, recording 41,744 road segments together with condition, dimensional, and functional attributes, and an estimated total maintenance value of approximately SAR 10.99 billion. This dataset offers a rare opportunity to examine, at full network scale, how prioritization logic shapes the distribution of maintenance attention.

The contribution of the paper is threefold. First, it documents the structural composition of a large real-world municipal network and shows why a naïve, volume-driven prioritization underperforms. Second, it develops a transparent, four-criterion decision framework grounded in established MCDA theory and applies it to the Aseer data, demonstrating how explicit weighting re-orders priorities in policy-meaningful ways. Third, it sets out a computational extension, drawing on machine-learning condition prediction, that would allow the framework to be deployed and updated at the individual-road level. The remainder of the paper reviews the relevant literature, describes the study context and data, presents the methodology and results, and discusses the managerial and policy implications.

II. LITERATURE REVIEW

2.1 Multi-criteria decision analysis in infrastructure prioritization

The theoretical foundation of modern prioritization practice rests on the work of Saaty (1977, 1980), whose Analytic Hierarchy Process decomposes a complex decision into a hierarchy of criteria and derives priority weights from pairwise comparisons, while quantifying the internal coherence of those judgements through a consistency ratio. A consistency ratio at or below 0.10 is conventionally taken to indicate acceptable judgement quality (Saaty, 1980). Parallel developments in multi-attribute decision making produced complementary aggregation techniques, including the distance-based methods systematized by Hwang and Yoon (1981), which broadened the analyst's toolkit for combining heterogeneous criteria.

Within the pavement and road-management domain, MCDA has been applied extensively to balance technical, economic, social, and environmental objectives. Bryce, Flintsch, and Hall (2014) demonstrated how environmental impacts could be embedded alongside cost considerations in sustainable infrastructure management, while Torres-Machi, Nasir, Achebe, Saari, and Tighe (2019) used multi-criteria techniques to formally evaluate the sustainability of pavement engineering alternatives, observing that environmental performance is seldom used in practice to select maintenance actions. Abu Dabous et al. (2020) advanced a sustainability-informed framework combining AHP with multi-attribute utility theory to rank and prioritize pavement sections under criteria spanning comfort, safety, environment, and agency and user cost. A consistent theme across this body of work is that single-indicator approaches, although computationally convenient, fail to capture the multifaceted nature of maintenance priority.

2.2 Pavement condition assessment and asset management

Condition measurement is the empirical backbone of any prioritization scheme. The Pavement Condition Index (PCI), standardized in ASTM D6433, expresses surface condition on a 0–100 scale derived from a structured visual survey of distress type, severity, and extent, and is widely adopted by municipalities for budgeting, rehabilitation timing, and network-level capital planning (ASTM International, 2020). Because the PCI is standardized, it provides a common language across jurisdictions and links surface distress directly to repair priorities. However, condition alone is an incomplete basis for prioritization: a low-condition residential lane and a low-condition strategic arterial carry very different consequences if left untreated, a distinction that condition-only triage cannot make.

2.3 Spatial multi-criteria evaluation in a GIS environment

Because road networks are inherently spatial, prioritization is naturally framed as a geographic problem. Malczewski (1999, 2000) established weighted linear combination as the most widely used GIS-based aggregation method, in which standardized criterion layers are combined through normalized weights to produce a dimensionless suitability or priority surface. Subsequent refinements recognized that decision-maker preferences are rarely uniform across space; the local weighted linear combination of Malczewski (2011) allows criterion weights to vary with geographic context, a property of direct relevance to a region as topographically and economically heterogeneous as Aseer. The integration of MCDA with GIS thus enables not only the ranking of alternatives but also the explicit consideration of where interventions are located.

2.4 The Saudi municipal context and the research gap

Saudi Arabia maintains an extensive network of highways and municipal roads whose upkeep is challenged by climate, traffic growth, and rapid urbanization, and Vision 2030 has prioritized data-driven, service-oriented infrastructure management as a national objective (Kingdom of Saudi Arabia, 2016). Sustainable project-management practices have been argued to materially affect the resilience and environmental performance of urban infrastructure programmes (Maqbool & Jowett, 2022). Despite this policy momentum, documented, full-scale applications of multi-criteria maintenance prioritization to a Saudi municipal network remain scarce in the peer-reviewed literature. The present study addresses this gap by applying an explicit MCDA framework to an official, network-wide dataset, and by treating the prioritization problem as a question of municipal management rather than purely of pavement engineering.

III. STUDY CONTEXT AND DATA

3.1 The Aseer Region

The Aseer Region occupies the mountainous south-west of Saudi Arabia, covering approximately 76,693 square kilometres and comprising seventeen governorates. Its population reached 2,024,285 in the 2022 national census, with the regional capital, Abha, accounting for 422,243 residents, or roughly one-fifth of the regional total (General Authority for Statistics, 2023). The region combines dense urban centres, dispersed mountain settlements, and a nationally significant tourism and heritage economy, a combination that produces highly uneven demand on the road network and makes spatially differentiated prioritization particularly valuable.

3.2 Data source and descriptive characteristics

The analysis draws on the road inventory compiled by the Aseer Municipality on the national municipal geospatial platform. The dataset records 41,744 road segments with a combined length of 20,851 kilometres, an average segment length of 495 metres, and an average width of 10 metres, covering a total surface area of 256 million square metres. The network's average PCI is 58, which sits at the boundary between the fair and satisfactory condition categories defined in ASTM D6433, indicating a network in aggregate need of programmed preventive and rehabilitative attention. The total estimated maintenance value is SAR 10.99 billion at an average unit rate of SAR 43 per square metre. Roads of fifteen metres width or greater number 7,516 and account for SAR 5.86 billion of that value, while 64.22% of segments fall within the excellent, good, or medium condition bands and 34.39% carry high or medium tourism-heritage significance. Table 1 summarizes the principal network indicators.

Network indicator	Value
Total road segments surveyed	41,744
Total network length	20,851 km
Total surface area	256 million m²
Average segment length	495 m
Average segment width	10 m
Average Pavement Condition Index (PCI)	58 (fair–satisfactory)
Average maintenance unit rate	SAR 43 / m²
Total estimated maintenance value	SAR 10.99 billion
Segments ≥ 15 m width (value)	7,516 (SAR 5.86 billion)
Segments in excellent/good/medium condition	64.22%
Segments of high/medium tourism-heritage value	34.39%
Average commercial licences per segment	2.03

Table 1. Descriptive characteristics of the Aseer municipal road network (source: Aseer Municipality inventory, national municipal geospatial platform).

IV. METHODOLOGY

4.1 Framework overview

The proposed framework follows the standard sequence of GIS-based multi-criteria evaluation: definition of the decision goal, selection of evaluation criteria, standardization of criterion values onto a common scale, derivation of criterion weights, and aggregation into a composite priority score (Malczewski, 1999, 2000). The decision goal is to assign each road segment a maintenance-priority score that reflects not only its physical condition but also the consequences of deferring its treatment. Aggregation uses the weighted linear combination, in which the composite score S for an alternative is the sum across criteria of the normalized criterion value multiplied by its weight:

$S = \Sigma (w_j \times r_j), \quad \text{with } \Sigma w_j = 1 \text{ and } 0 \leq r_j \leq 1,$

where w_j is the normalized weight of criterion j and r_j is the standardized score of the alternative on that criterion. Standardization uses linear maximum-score normalization, $r_j = x_j / x_j(\max)$, so that all criteria contribute on a comparable 0–1 scale regardless of their original units.

4.2 Criteria selection

Four criteria were selected to represent the dimensions along which the consequence of deferred maintenance varies. Functional-strategic hierarchy captures a road's position in the network and therefore the breadth of connectivity that would be impaired by its deterioration. Demand exposure captures the volume of users and activity served, proxied where segment-level traffic is unavailable by the density of segments and associated land use. Economic criticality captures the asset value at risk and the commercial activity dependent on the road, for which the inventory records an average of 2.03 commercial licences per segment. Pavement condition deficit captures maintenance need, expressed as the shortfall of the PCI below an acceptable threshold. The criteria, their operational definition, and their data source are summarized in Table 2.

Criterion	Operational definition	Data source
Functional-strategic hierarchy	Road class as an ordinal indicator of network-level connectivity (regional > arterial > main street > local).	Inventory classification
Demand exposure	Volume of users and activity served; proxied by network share and land-use density where segment traffic is unavailable.	Inventory; land-use layers
Economic criticality	Asset value at risk and dependent commercial activity (commercial licences per segment).	Inventory; maintenance valuation
Pavement condition deficit	Shortfall of segment PCI below an acceptable threshold (ASTM D6433).	Condition survey (PCI)

Table 2. Decision criteria, operational definitions, and data sources.

4.3 Weight derivation

Criterion weights are derived through pairwise comparison in the manner of the Analytic Hierarchy Process, with the resulting comparison matrix tested for coherence using Saaty's consistency ratio and accepted only where the ratio does not exceed 0.10 (Saaty, 1977, 1980). This procedure makes the relative importance assigned to each criterion explicit and auditable, in contrast to the implicit trade-offs embedded in informal decision making. Because the appropriate weighting is itself a policy choice rather than a fixed technical constant, the framework treats weights as adjustable parameters and is accompanied by a sensitivity analysis (Section 5.5) that examines how the ranking responds to alternative weight sets.

4.4 Baseline model and discrimination diagnostic

To establish a point of comparison, a baseline prioritization was first implemented using the two criteria most readily available across the full network: a population-demand component weighted at 0.40 and an economic-impact component weighted at 0.60. Segments were scored, banded into five priority levels, and the resulting distribution examined. The degree to which a prioritization scheme separates the network into usefully distinct priority tiers, rather than collapsing most segments into a single band, is termed here its discriminatory power, and serves as the principal diagnostic for evaluating the baseline against the enhanced framework.

V. RESULTS

5.1 Network composition and the count–value mismatch

Classifying the network by functional class reveals a marked structural asymmetry. Local roads dominate by sheer number, comprising 32,154 segments, or 77.0% of the network, yet account for only 46.4% of total maintenance value. Conversely, regional and arterial roads together represent fewer than 2% of segments but concentrate a disproportionate share of value relative to their count. Table 3 reports the full breakdown, and Figure 1 visualizes the mismatch between the share of road count and the share of maintenance value across functional classes.

Functional class	Segments	Count share	Maint. value (SAR bn)	Value share
Local	32,154	77.0%	5.10	46.4%
Other	6,575	15.8%	2.05	18.7%
Main streets	2,281	5.5%	1.83	16.7%
Arterial (main roads)	694	1.7%	1.44	13.1%
Regional	40	0.1%	0.57	5.2%
Total	**41,744**	**100%**	**10.99**	**100%**

Table 3. Network composition by functional class (source: Aseer Municipality inventory).

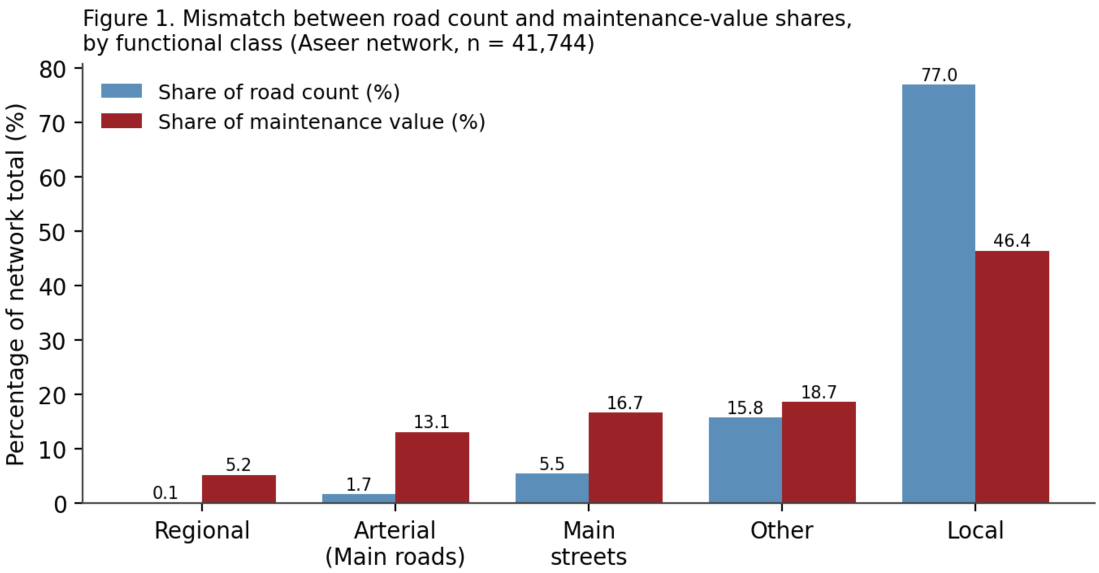

Figure 1. Mismatch between the share of road count and the share of maintenance value by functional class.

5.2 Concentration of per-asset criticality

Expressing maintenance value on a per-segment basis exposes the consequence of this asymmetry. The average regional road carries an estimated maintenance value of approximately SAR 14.25 million, against roughly SAR 2.07 million for an arterial road and only SAR 0.16 million for a local road, a difference of close to two orders of magnitude. Figure 2 plots per-asset maintenance value on a logarithmic scale and makes the concentration of criticality in the low-count, high-order classes visually unambiguous. The managerial implication is direct: a prioritization rule driven primarily by segment count or by raw network coverage will systematically channel attention toward the most numerous class while understating the strategic and financial exposure embedded in the small number of high-order roads.

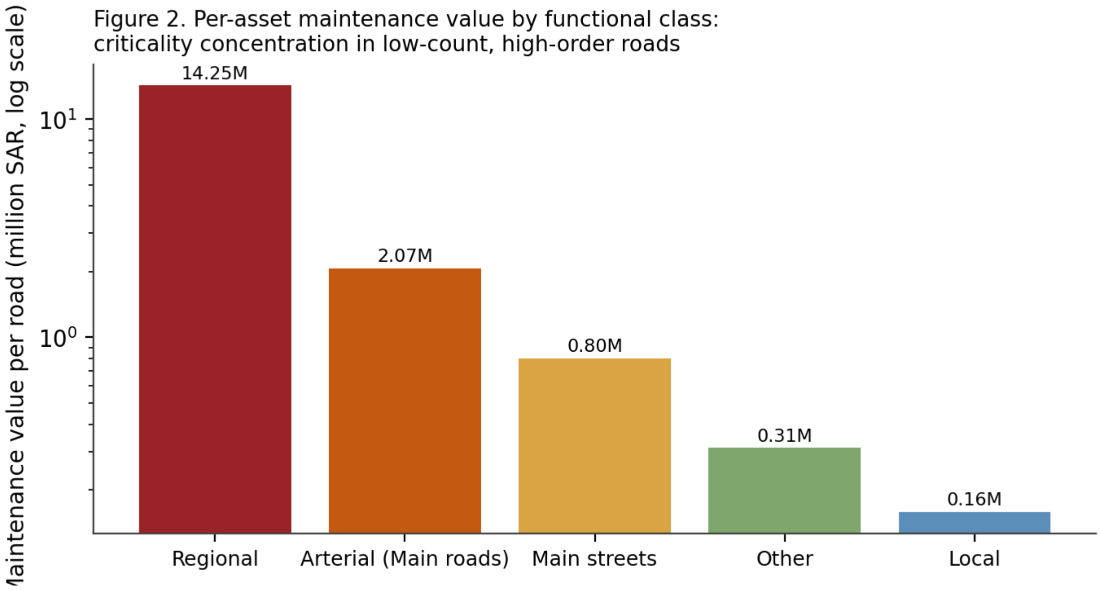

Figure 2. Per-asset maintenance value by functional class (logarithmic scale), illustrating the concentration of criticality in low-count, high-order roads.

5.3 Discrimination failure of the baseline model

When the baseline two-criterion model (population 0.40, economic 0.60) was applied across the network and the resulting scores banded into five priority levels, approximately 91% of segments fell into the two lowest priority bands. The model therefore failed to separate the network into operationally useful tiers: with nine in ten segments sharing essentially indistinct priority, the ranking offered little practical guidance for sequencing interventions. Spatially, the high-priority segments that the model did identify were heavily concentrated, with the Abha sector alone accounting for roughly 58% of them, reflecting the demand weighting's sensitivity to the region's largest urban concentration. This clustering is consistent with the count–value mismatch documented above: because local roads dominate the network and the demand component rewards ubiquity, the baseline rule reproduces the network's existing composition rather than re-ordering it according to consequence.

5.4 Illustrative application of the multi-criteria framework

To demonstrate how explicit, consequence-oriented weighting alters the ranking, the four-criterion framework was applied at the level of the functional classes, for which complete and verified aggregate attributes are available. Functional-strategic hierarchy was represented by an expert ordinal score (regional 1.00, arterial 0.85, main street 0.65, other 0.45, local 0.30); economic criticality by maximum-normalized per-asset maintenance value; and demand exposure by maximum-normalized network-count share. Under an illustrative weight set emphasizing consequence (hierarchy 0.40, economic criticality 0.40, demand exposure 0.20), the composite scores re-order the classes as shown in Table 4. The class-level scores are derived from the verified aggregate figures to illustrate the method transparently; operational deployment computes the same composite at the individual-segment level once geocoded condition and demand layers are joined.

Functional class	Hierarchy	Economic (norm.)	Exposure (norm.)	Composite S
Regional	1.00	1.000	0.001	**0.800**
Arterial (main roads)	0.85	0.146	0.022	**0.403**
Local	0.30	0.011	1.000	**0.324**
Main streets	0.65	0.056	0.071	**0.297**
Other	0.45	0.022	0.204	**0.230**

Table 4. Illustrative class-level composite priority scores under a consequence-oriented weight set (hierarchy 0.40, economic criticality 0.40, demand exposure 0.20).

Under this weighting the regional class ranks first by a wide margin, followed by the arterial class, with local roads displaced to third despite their numerical dominance. The framework thus corrects the baseline model's tendency to bury strategically critical, high-value-per-asset roads beneath the volume of low-consequence segments, while retaining demand exposure as a meaningful, non-trivial contributor rather than discarding it.

5.5 Weight sensitivity

Because the weighting reflects a policy judgement, the ranking's sensitivity to that judgement is material. Re-running the composite with a demand-dominant weight set (hierarchy 0.20, economic criticality 0.20, demand exposure 0.60) reverses much of the re-ordering: the local class returns to first place with a composite of approximately 0.66, while the regional class falls to second (0.40) and the arterial and main-street classes cluster closely behind. This contrast quantifies precisely why the demand-heavy baseline concentrated priority in the most numerous class, and underlines the framework's central managerial virtue. Rather than concealing the trade-off between serving the greatest number of users and protecting the most strategically and financially critical assets, the framework renders that trade-off explicit and adjustable, allowing decision makers to set weights deliberately and to document the basis on which public funds are allocated.

VI. DISCUSSION

6.1 Interpretation

The results carry a clear message for the management of large municipal road networks. The structure of the Aseer network, in which a small number of high-order roads concentrate the majority of per-asset value while a large number of local roads dominate by count, is not unique to Aseer; it is characteristic of municipal networks generally. Any prioritization rule that responds chiefly to ubiquity or to coverage will therefore tend to reproduce the network's composition rather than re-order it according to the consequences of deferred maintenance. The discrimination failure of the baseline model is the empirical signature of this tendency. By making the relevant consequences explicit criteria and by exposing the weights through which they are combined, the multi-criteria framework converts an opaque allocation into an auditable one.

6.2 Implications for municipal management and Vision 2030

For a municipality operating under the service-quality and asset-stewardship objectives of Vision 2030 (Kingdom of Saudi Arabia, 2016), the practical value of the framework lies less in producing a single definitive ranking than in supporting a defensible, repeatable budgeting process. Weights can be set to reflect declared policy priorities, sensitivity analysis can be reported alongside the chosen allocation, and the entire chain of reasoning from criterion to score to ranking can be documented for review. This auditability aligns directly with the governance ambitions of the national agenda and with the broader literature linking sustainable, structured project-management practices to better infrastructure outcomes (Maqbool & Jowett, 2022). The framework also accommodates the region's spatial heterogeneity: where preferences differ between dense urban Abha and dispersed mountain governorates, locally varying weights of the kind formalized by Malczewski (2011) can be applied without abandoning the common methodological structure.

6.3 A computational pathway: condition prediction and scaling

The principal practical constraint on full segment-level deployment is the cost and currency of condition data. Manual PCI surveys across more than forty thousand segments are expensive and quickly become outdated, and incomplete or stale condition layers weaken any prioritization built upon them. Machine-learning condition prediction offers a route around this constraint. Piryonesi and El-Diraby (2020) demonstrated that pavement condition can be predicted cost-effectively from inexpensive, readily available attributes, enabling smaller agencies to estimate condition without exhaustive field survey. Integrating such predictive models with the multi-criteria framework would allow the pavement-condition-deficit criterion to be populated and refreshed at scale, transforming the framework from a periodic planning exercise into a continuously updated decision-support system. This computational direction connects the management framework presented here to the wider trajectory of architectural and urban computing, in which data-driven and machine-learning methods increasingly inform the design and stewardship of the built environment.

6.4 Limitations

Several limitations qualify the findings. The illustrative application was conducted at the level of functional classes rather than individual segments, because complete, verified attributes were available in aggregate; segment-level scoring requires the integration of geocoded condition and demand layers that were not yet uniformly available across the network, and the study notes the need for authoritative geospatial data to support this step. The criterion weights used in the demonstration are illustrative rather than the product of a formal expert-elicitation panel, and the expert hierarchy scores, although defensible, are ordinal judgements. Finally, the analysis treats the inventory's recorded values as accurate; data-quality management, as emphasized in the asset-management literature, remains a prerequisite for reliable operational use. These limitations define a clear agenda for subsequent work rather than undermining the framework's logic.

VII. CONCLUSION

This study set out to develop and demonstrate a transparent multi-criteria decision framework for prioritizing road-maintenance investment in a large municipal network, using the official inventory of 41,744 road segments in the Aseer Region of Saudi Arabia. The descriptive analysis established a structural mismatch between road count and maintenance value, and showed that per-asset criticality is concentrated in a small number of high-order roads. A baseline two-criterion model was found to lack discriminatory power, placing roughly nine in ten segments in the lowest priority bands and clustering its high-priority designations in the largest urban centre. The proposed four-criterion framework, grounded in the Analytic Hierarchy Process and weighted linear combination, re-ordered the network's functional classes in policy-meaningful ways and, critically, made the underlying trade-offs explicit and adjustable through sensitivity analysis.

The framework's contribution to municipal management is an auditable allocation process aligned with the governance and service-quality objectives of Vision 2030, rather than a single prescriptive ranking. Its extension through machine-learning condition prediction offers a credible pathway to continuous, segment-level operation. Future work will focus on integrating authoritative geocoded condition and demand layers to enable full network-scale scoring, on conducting a formal expert-elicitation exercise to establish defensible weights, and on validating predicted condition against field survey, thereby moving the framework from demonstration toward routine deployment in the Aseer Municipality and comparable Saudi contexts.

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