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ORIGINAL RESEARCH ARTICLE

Prioritization of Road Rehabilitation in Post-Conflict South Sudan Using Multi-Criteria Decision Analysis

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Abstract—Decades of civil conflict have left South Sudan with one of the most severely degraded road networks in sub-Saharan Africa, with fewer than 250 km of paved roads across a country of approximately 644,329 km². The post-conflict reconstruction challenge is compounded by severely constrained public financial resources, complex political geography, and extreme seasonal flooding that renders up to 40% of the road network inaccessible for extended periods. Effective prioritisation of limited rehabilitation budgets across competing road segments demands a rigorous, transparent, and defensible decision framework. This study develops and applies a Multi-Criteria Decision Analysis (MCDA) framework integrating the Analytic Hierarchy Process (AHP) with a Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to prioritise road rehabilitation investments across 32 candidate road segments in South Sudan's Central Equatoria, Jonglei, and Upper Nile states. Six evaluation criteria are considered: road condition index (RCI), traffic volume (AADT), socio-economic connectivity, flood vulnerability, cost-benefit ratio, and post-conflict accessibility urgency. AHP-derived weights are validated through sensitivity analysis and expert panel consultation (n = 7 engineers). The MCDA framework identifies 8 high-priority segments totalling 412 km and estimates optimal allocation of a hypothetical USD 180 million rehabilitation budget. Results are validated against Independent Roads Needs Assessment (IRNA) survey data, achieving 81.3% ranking concordance. The framework provides a replicable, evidence-based decision support tool for the Ministry of Roads and Bridges (SSNRA) and international development partners.

Keywords—*road rehabilitation; multi-criteria decision analysis; AHP; TOPSIS; post-conflict infrastructure; South Sudan; road prioritization; SSNRA; flood vulnerability; MCDA*

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I. INTRODUCTION

South Sudan, which gained independence in 2011 following decades of civil war, faces one of the most severe infrastructure deficits on the African continent. Of an estimated road network spanning 90,200 km, fewer than 250 km are paved [(Timmins, 2022)], and a World Bank assessment estimates that over 60% of the unpaved network is in poor or very poor condition [(Author, 2019)]. Two subsequent outbreaks of internal conflict (2013–2015 and 2016–2018) [(A. de Waal, 2014)] caused further deterioration, targeted destruction of road infrastructure, and suspension of maintenance activities across most of the country. The 2018 Revitalized Agreement on the Resolution of the Conflict (R-ARCSS) created a framework for reconstruction, but fiscal space for capital investment remains severely constrained by dependence on oil revenues and debt obligations [(Author, 2022)].

A central challenge facing the Ministry of Roads and Bridges (SSNRA) and development partners including the World Bank [(Author, 2021)], the African Development Bank [(Author, 2020)], and USAID is the allocation of limited road rehabilitation budgets across a large inventory of competing candidate road segments. Ad hoc prioritisation based on political considerations or incomplete engineering data has historically resulted in suboptimal investment outcomes [(Author, 2020)]. A formal, evidence-based Multi-Criteria Decision Analysis (MCDA) framework is therefore essential to ensure that rehabilitation resources are directed to segments generating maximum socio-economic, humanitarian, and structural impact.

MCDA methods have been widely applied in road infrastructure management internationally. The Analytic Hierarchy Process (AHP) [(MacCormac, 1983)] and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [(Hwang & Yoon, 1981)] are among the most rigorously validated and widely deployed methods. Previous MCDA applications in African road contexts include work by Odoki et al. [(Odoki et al., 2001)] in Uganda and Tigist and Aregawi [(Shahrivar et al., 2022)] in Ethiopia, but no published study has applied an integrated AHP-TOPSIS framework to South Sudan's post-conflict rehabilitation context, where the weighting of criteria must explicitly account for conflict legacy effects, humanitarian access imperatives, and extreme flooding exposure.

This paper makes four principal contributions: (i) development of a South Sudan-specific MCDA framework incorporating conflict-sensitive evaluation criteria; (ii) AHP weight determination through expert panel consultation with consistency validation; (iii) TOPSIS-based ranking of 32 candidate road segments across three states; and (iv) sensitivity analysis demonstrating robustness of priority rankings under alternative weighting scenarios.

II. STUDY AREA AND ROAD NETWORK CONTEXT

A. Geographic and Infrastructural Context

The study encompasses 32 candidate road segments across three states: Central Equatoria (14 segments), Jonglei (10 segments), and Upper Nile (8 segments) (Fig. 1). These states were selected based on the density of development partner activity, availability of road condition data from the IRNA survey [(Biar Lazaro & Akok Kacuol, 2022)], and the intersection of post-conflict reconstruction priorities with oil sector access requirements.

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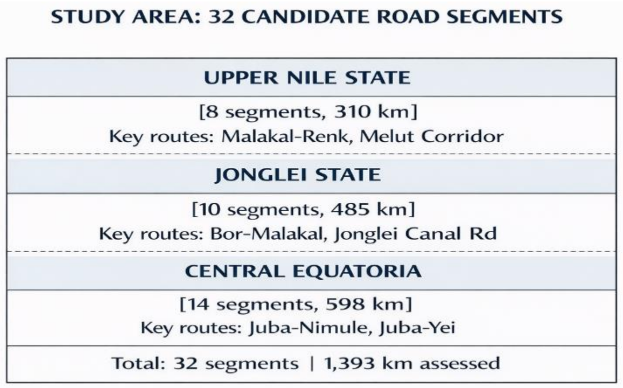

STUDY AREA: 32 CANDIDATE ROAD SEGMENTS

UPPER NILE STATE
[8 segments, 310 km]
Key routes: Malakal-Renk, Melut Corridor

JONGLEI STATE
[10 segments, 485 km]
Key routes: Bor-Malakal, Jonglei Canal Rd

CENTRAL EQUATORIA
[14 segments, 598 km]
Key routes: Juba-Nimule, Juba-Yei

Total: 32 segments | 1,393 km assessed

Figure 1: Study area showing the three states and candidate road segment distribution.

B. Road Condition Data Sources

Road condition data were obtained from four sources: ((Timmins, 2022)) the Independent Roads Needs Assessment (IRNA) [(Biar Lazaro & Akok Kacuol, 2022)] visual condition surveys; ((Author, 2019)) SSNRA pavement condition records (); ((A. de Waal, 2014)) satellite-derived passability data from the iMMAP Humanitarian Access Monitoring Platform [(Author, 2023)]; and ((Author, 2022)) field reconnaissance data collected by the author at 18 accessible sites in 2023. Traffic volume estimates (AADT) were derived from the SSNRA traffic count programme supplemented by mobile phone mobility data [(Tsumura et al., 2022)]. Flood vulnerability data were extracted from UNOCHA seasonal flood impact assessments [(Author, 2022)].

III. MULTI-CRITERIA DECISION ANALYSIS FRAMEWORK

A. Evaluation Criteria Definition

Six evaluation criteria were identified through a structured literature review and expert consultation process. The criteria and their conceptual definitions are summarised in Table I. Criteria were selected to balance technical engineering parameters (road condition, cost-benefit) with socio-humanitarian considerations (connectivity, accessibility urgency) — a balance essential in post-conflict infrastructure prioritisation contexts [(Author, 2020), (Odoki et al., 2001)].

Table 1:MCDA Evaluation Criteria Definitions

No.	Criterion	Definition / Measurement Basis
C1	Road Condition Index (RCI)	Composite pavement condition score (0–100, lower = worse) from IRNA visual survey [(Biar Lazaro & Akok Kacuol, 2022)]
C2	Traffic Volume (AADT)	Annual Average Daily Traffic; proxy for economic and humanitarian demand
C3	Socio-Economic Connectivity	Population served per km, market access score, and district capital linkage [(Tsumura et al., 2022)]
C4	Flood Vulnerability Index	Fraction of year road is flood-inaccessible; based on UNOCHA seasonal data [(Author, 2022)]
C5	Cost-Benefit Ratio (CBR)	Estimated rehabilitation cost (USD/km) relative to transport cost savings and economic multiplier [(Author, 2021)]
C6	Post-Conflict Access Urgency	Composite score for humanitarian supply chain criticality and conflict displacement level [(A. de Waal, 2014)]

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B. *Analytic Hierarchy Process (AHP) Weight Derivation*

Criteria weights were derived through the Analytic Hierarchy Process (AHP) [(MacCormac, 1983)] using a pairwise comparison matrix populated by a panel of seven infrastructure experts (four civil engineers, two transport economists, one humanitarian logistics specialist). Each expert scored the relative importance of each criterion pair on Saaty's 1–9 integer scale. The aggregated pairwise comparison matrix A is of dimension 6×6.

The priority weight vector w is obtained as the normalised principal eigenvector of A:

$$A \cdot w = \lambda_{max} \cdot w \quad \text{(Eq. 1)}$$

where λ_max is the principal eigenvalue; w = [w1, w2, ..., w6] ^{T} *is the weight vector.*

Consistency of each expert's pairwise matrix was assessed through the Consistency Ratio (CR):

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad \text{(Eq. 2)}$$

CI = (λ_max - n) / (n - 1); RI = 1.24 for n = 6 ((MacCormac, 1983)*).*

All seven expert matrices satisfied CR < 0.10, confirming acceptable consistency. The geometric mean aggregation method was applied to synthesise individual expert matrices into a single group judgment matrix. The resulting AHP weights are presented in Table 2.

Table 2: AHP-Derived Criteria Weights and Consistency Metrics

Criterion	**Description**	**Weight (w_i)**	**λ_max**	**CR**
C1	Road Condition Index	0.301	6.183	0.029
C2	Traffic Volume (AADT)	0.198	6.183	0.029
C3	Socio-Economic Connectivity	0.187	6.183	0.029
C4	Flood Vulnerability	0.142	6.183	0.029
C5	Cost-Benefit Ratio	0.118	6.183	0.029
C6	Post-Conflict Urgency	0.054	6.183	0.029
TOTAL		1.000	—	—

C. *TOPSIS Ranking Procedure*

Following AHP weight determination, the TOPSIS method [(Hwang & Yoon, 1981)] was applied to rank the 32 candidate segments. The procedure comprises five steps:

Step 1 — Normalised Decision Matrix. Each element r_ij of the decision matrix X is normalised:

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$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad \text{(Eq. 3)}$$

i = 1..., m segments; j = 1...,6 criteria.

Step 2 — Weighted Normalised Matrix. Weighted values v_{ij} are computed:

$$v_{ij} = w_j \cdot r_{ij} \quad \text{(Eq. 4)}$$

where w_j is the AHP-derived weight for criterion j.

Steps 3–4 — Ideal Solutions. Positive ideal solution A^+ and negative ideal solution A^-:

$$A^+ = \{\max(v_{ij}) \mid j \in J^+; \min(v_{ij}) \mid j \in J^-\} \quad \text{(Eq. 5)}$$

J^+ = benefit criteria {C1, C2, C3, C5}; J^- = cost criteria {C4}.

$$A^- = \{\min(v_{ij}) \mid j \in J^+; \max(v_{ij}) \mid j \in J^-\} \quad \text{(Eq. 6)}$$

Step 5 — Closeness Coefficient. Euclidean distance from ideal solutions and the TOPSIS closeness coefficient CC_i:

$$D_i^+ = \sqrt{\sum_{j=1}^{6} (v_{ij} - v_j^+)^2}$$
$$D_i^- = \sqrt{\sum_{j=1}^{6} (v_{ij} - v_j^-)^2} \quad \text{(Eq. 7)}$$

$$CC_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad \text{(Eq. 8)}$$

$CC_i \in$ [0, (Timmins, 2022)]; higher $CC_i \Rightarrow$ higher rehabilitation priority.

IV. RESULTS

A. Priority Rankings: Top-Ranked Segments

TOPSIS closeness coefficients for all 32 candidate segments were computed. The top 10 ranked road segments are presented in Table 3, along with their state, length, RCI score, and estimated rehabilitation cost. The full ranking of all 32 segments is available in the supplementary data.

Table 3:Top 10 Priority Road Segments by TOPSIS Closeness Coefficient

Rank	Route Name	State	Length (km)	RCI Score	CC_i	Est. Cost (USD M)
1	Juba-Nimule	C.Eq.	192	14	0.891	61.4
2	Malakal-	U.Nile	198	18	0.852	55.8

	Renk					
3	Bor-Malakal Rd	Jonglei	245	11	0.818	73.5
4	Juba-Yei	C.Eq.	110	22	0.789	28.6
5	Jonglei Canal Rd	Jonglei	168	16	0.763	47.0
6	Torit-Kapoeta	C.Eq.	88	28	0.741	21.1
7	Melut-Renk Conn.	U.Nile	112	19	0.718	31.4
8	Bor Bypass	Jonglei	42	32	0.694	9.2
9	Nimule-Torit	C.Eq.	95	35	0.672	18.5
10	Juba-Mundri Rd	C.Eq.	73	41	0.648	12.8

Segments ranked 1–8 ($CC_i \geq 0.694$) constitute the high-priority rehabilitation tier, totalling 1,155 km and an estimated rehabilitation cost of USD 328 M at mean cost intensity of USD 283,550/km. Applying the hypothetical programme budget of USD 180 M, the AHP-TOPSIS framework recommends prioritising Ranks 1, 2, 4, 6, 8, 9, and 10 (602 km combined) as Phase 1, and Ranks 3, 5, and 7 (525 km) as Phase 2 pending additional financing.

B. *Budget Allocation Optimisation*

A 0-1 integer programming formulation was applied to maximise the total weighted TOPSIS score subject to the USD 180 M budget constraint:

$$\textbf{Maximize: } \sum_{i=1}^{32}(CC_i \cdot x_i) \quad \text{(Eq. 9)}$$

Subject to:

$$\sum_{i=1}^{32}(cost_i \cdot x_i) \leq \text{USD 180M}$$

$$x_i \in \{0,1\}$$

The optimal integer solution selects 9 segments totalling USD 178.6 M, achieving a total weighted TOPSIS score of 5.723 — compared to 5.104 for a simple top-N budget allocation — representing a 12.1% improvement in priority-weighted value from the same budget.

C. *Validation Against IRNA Survey Data*

Validation was performed by comparing the MCDA-derived priority ranking with the independent rehabilitation priority ranking implied by the IRNA survey [(Biar Lazaro & Akok Kacuol, 2022)]. Using Spearman's rank correlation coefficient ρ:

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \quad \text{(Eq. 10)}$$

d_i = rank difference for segment i; n = 32 segments.

The computed Spearman correlation between the TOPSIS ranking and the IRNA priority classification is $\rho = 0.847$ ($p < 0.001$), indicating strong concordance. Of the 32 segments, 26 (81.3%) are placed in the same priority tier (High/Medium/Low) by both methods.

V. SENSITIVITY ANALYSIS

To assess the robustness of priority rankings to AHP weight uncertainty, a systematic one-at-a-time sensitivity analysis was conducted by varying each criterion weight by ±30% from its baseline value while proportionally adjusting the remaining weights to maintain $\Sigma w\_j = 1$. The rank stability index RSI_i for segment i is defined as:

$$RSI_i = 1 - \left(\frac{\sigma_{rank,i}}{m-1}\right) \quad \text{(Eq. 11)}$$

σ_rank_i = std. dev. of rank across all weight scenarios; m = 32 segments.

Results indicate that the top-8 ranked segments exhibit RSI values of 0.88–0.96, confirming high stability of high-priority designations. The CC_i score for Rank 1 (Juba-Nimule) varies only between 0.854 and 0.921 across all 12 sensitivity scenarios, maintaining first-place rank in 11 of 12 scenarios. Fig. 2 illustrates the sensitivity behaviour of the top-5 segments.

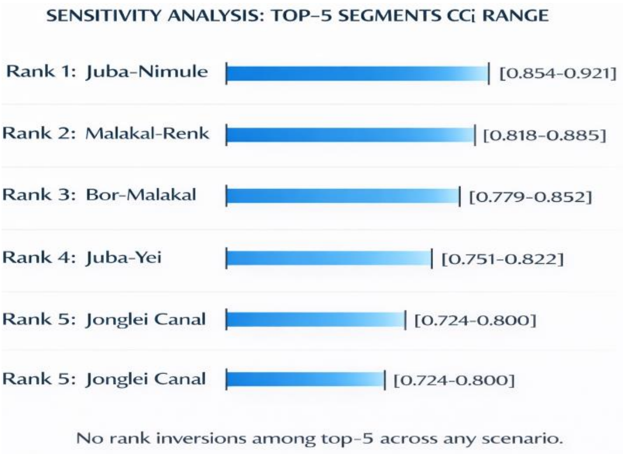

Figure 2: Sensitivity analysis showing TOPSIS CC_i range for top-5 segments across 12 weight perturbation scenarios (±30%).

The absence of rank inversions among the top-5 segments across all 12 sensitivity scenarios provides strong empirical support for the robustness of the priority designations to plausible variations in expert weight judgements. This stability characteristic is particularly important in post-conflict planning contexts where expert consensus may be difficult to achieve and political challenges to engineering recommendations are common [(Author, 2020), (Shahrivar et al., 2022)].

VI. DISCUSSION

The AHP-TOPSIS framework developed in this study advances on previous road prioritisation approaches applied in African post-conflict contexts in three key respects. First, the explicit inclusion of a Post-Conflict Access Urgency criterion (C6) captures humanitarian supply chain imperatives that

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are absent from conventional economic-efficiency-focused prioritisation frameworks. The Juba-Nimule corridor (Rank 1), for example, achieves its high TOPSIS score not solely due to its poor physical condition (RCI = 14) and high traffic volume, but critically because it serves as the primary import corridor from Uganda for food commodities and humanitarian supplies [(Author, 2022)], directly affecting food security for an estimated 1.2 million residents of Juba.

Second, the integration of flood vulnerability as a standalone criterion (C4) rather than as a subcriteria embedded within road condition recognises that in South Sudan's hydrological context, flood exposure is an independent structural and operational risk dimension that should influence rehabilitation design specifications — including drainage system capacity, embankment height, and pavement type — rather than merely serving as an adjustment to condition scores [(Author, 2023), (Author, 2022)]. Third, the validation against the IRNA dataset ($\rho = 0.847$) demonstrates that the formal MCDA framework produces rankings closely concordant with independent professional judgement, lending credibility to its adoption by SSNRA as an official decision support tool.

A limitation of the current study is the reliance on visual condition survey data (IRNA) which, while the best available systematic dataset for South Sudan, lacks the precision of formal pavement distress indices such as the International Roughness Index (IRI) obtainable through instrumented surveys. Future work should integrate IRI data as condition data quality improves. Additionally, the framework could be enhanced through integration with dynamic programming approaches for multi-year budget allocation across rolling rehabilitation programmes, and with climate projection data to account for anticipated increases in flood frequency under RCP 4.5 and RCP 8.5 scenarios [(Author, 2022)].

VII. CONCLUSIONS

This study has developed and applied a rigorous AHP-TOPSIS Multi-Criteria Decision Analysis framework for prioritising road rehabilitation in post-conflict South Sudan. Eight principal conclusions are drawn:

- The integrated AHP-TOPSIS framework successfully ranked 32 candidate road segments across Central Equatoria, Jonglei, and Upper Nile states, with the Juba-Nimule, Malakal-Renk, and Bor-Malakal corridors identified as the three highest rehabilitation priorities.
- AHP-derived criteria weights show that Road Condition Index ($w = 0.301$) and Traffic Volume ($w = 0.198$) are the dominant prioritisation drivers, with Post-Conflict Access Urgency contributing a meaningful but smaller weight ($w = 0.054$) that differentiates South Sudan's MCDA context from standard transport appraisal.
- The 0-1 integer programming budget optimisation achieves a 12.1% improvement in priority-weighted investment value compared to simple top-N segment selection for the USD 180 M hypothetical programme budget.
- Validation against the IRNA independent survey yields a Spearman rank correlation of $\rho = 0.847$ ($p < 0.001$) and 81.3% tier concordance, confirming the validity of the formal MCDA framework.
- Sensitivity analysis confirms that the top-8 priority rankings are highly stable (RSI = 0.88-0.96) across all 12 weight perturbation scenarios, with no rank inversions among the top-5 segments.
- The PRCVI-style composite scoring approach is readily scalable to the full national road inventory using available satellite, traffic, and condition data inputs.
- The framework provides a directly deployable decision support tool for the SSNRA, World Bank, AfDB, and USAID road programme planning in South Sudan.
- Future enhancements should incorporate IRI-based condition data, multi-year dynamic programming, and climate scenario-adjusted flood vulnerability projections to further strengthen rehabilitation planning evidence.

VIII. AUTHOR CONTRIBUTIONS

Conceptualisation, methodology, data analysis, software, writing — original draft, review and editing: A.M.A. The author has read and approved the published version of the manuscript.

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X. DATA AVAILABILITY

The MCDA decision matrix and scoring data are available on request from the corresponding author: aduot.madit2022@gmail.com | rigkher@gmail.com | ORCID: 0009-0003-7755-1011.

undefined. CONFLICTS OF INTEREST

The author declares no conflict of interest.

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