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A Review of Prioritization Methods for Rural Road Network Planning: From Traditional Approaches to Modern MCDM and GIS-Based Frameworks

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ABSTRACT

Rural road networks play a vital role in enabling socio-economic development by improving access to markets, healthcare, education, and other essential services. However, constrained budgets and diverse regional needs make prioritization of road projects imperative to optimize resource allocation and maximize impact. This review paper examines the various prioritization methods applied in rural road network planning, focusing on their conceptual foundations, key evaluation criteria, and methodological approaches. Traditional cost-benefit and ranking techniques are contrasted with modern multi-criteria decision-making (MCDM) frameworks, including the Analytic Hierarchy Process (AHP), fuzzy logic methods and geographic information system (GIS)-based spatial tools. The paper further compares these methods in terms of strengths, limitations, data requirements, and applicability, supported by relevant case studies. Current challenges, such as data scarcity, stakeholder engagement and integration of environmental sustainability, are identified, alongside emerging research directions incorporating digital tools and participatory approaches. By systematically reviewing existing literature, this study aims to inform planners and policymakers on effective, transparent and context-appropriate prioritization strategies to enhance rural road infrastructure development.

Keywords: *Rural Roads; Prioritization; Maintenance; Road Planning; Prioritization Strategies.*

1. Introduction

Rural road systems play a vital role in promoting socio-economic development by improving access to markets, educational institutions, healthcare, and other critical services for rural communities [1,2]. Nevertheless, the planning and growth of these networks frequently face challenges due to restricted financial resources, difficult terrains, and intricate social requirements, which highlights the need for systematic and objective prioritization to make the most efficient use of the funds available [2].

The goal of prioritization in planning rural road networks is to identify and rank potential investment projects based on criteria that enhance economic, social, and environmental benefits while fostering equity and accessibility. Important considerations usually include the population affected, connectivity and coverage, access to social services, economic effects, projected traffic, construction and maintenance costs, environmental concerns and local priorities [3]. Striking a balance among these various objectives is crucial for rural infrastructure policy and often influences the success of projects.

Over the years, methods of prioritization have progressed from basic ranking systems or minimum spanning tree models, which emphasize costs or connectivity, to integrated frameworks that merge cost-benefit analysis, socio-economic metrics, and stakeholder preferences [3, 4]. Contemporary strategies frequently utilize multi-criteria decision-making (MCDM) techniques, like the Analytic Hierarchy Process (AHP) or Fuzzy MCDM, allowing for the simultaneous assessment and weighting of various, often conflicting, criteria in a transparent and participative manner [4] (Hasan and Jaber, 2024; Abdullah and Wang, 2024). Geographic Information Systems (GIS) have enhanced planning processes by facilitating spatial analysis and improving access and coverage optimization [2,5].

The success of any prioritization approach, however, hinges on the specific local context, the availability of data, active stakeholder participation, and the institutional capability to put recommendations into practice. In reality, planning models frequently need to reconcile both top-down directives and grassroots community demands to realize inclusive and sustainable development of rural roads [2].

This review article offers a comprehensive overview of the principles, criteria, and methods of prioritization in rural road planning. It contrasts traditional methods with multi-criteria and GIS-based techniques, extracts insights from significant case studies, and identifies persistent challenges and new opportunities for future research and practice.

2. Research Methodology

To carry out the literature review, we adhered to the approach outlined by [6]. This methodology was chosen because: (1) it offers clear and comprehensive direction for conducting reviews; (2) it has proven effective in similar literature reviews carried out by the authors previously; and (3) it is suitable for application across a wide range of disciplines. The process of selecting publications was carried out in two stages. First, we identified the keywords that would guide the search for relevant papers. After careful deliberation, the following keywords were chosen: rural road, prioritization, maintenance, techniques, approaches, optimization. To get the best search results, the combination of these keywords was applied in search using Boolean operators AND and OR. The following search string queries were used to obtain papers from various databases:

- Rural road AND Maintenance AND (Techniques OR Approach)
- Rural road AND Prioritization AND Planning AND (Techniques OR Approach)
- Rural road AND Maintenance AND Optimization AND (Techniques OR Approach)

To get as many papers available on the internet, related to the topic of prioritization planning techniques in rural road, we used seven different databases for the searching process. The following databases were searched using the defined search string queries: Google Scholar, Scopus, Springer Link, Science Direct, Web of Science, IEEE Xplore, and ASCE Library.

In second stage, after excluding papers that were irrelevant to the review area, the remaining papers were thoroughly analysed. These papers were then systematically organised and categorized to facilitate a more detailed examination.

3. Key Concepts and Criteria for Prioritization

Effective rural road network planning depends on well-defined prioritization criteria and core concepts that ensure limited resources are allocated to projects with the highest developmental impact. These criteria play a vital role in balancing economic viability, social equity, and environmental sustainability principles that underpin both traditional and contemporary planning approaches.

3.1. Physical and Spatial Criteria: Accessibility, Connectivity and Coverage

Accessibility is central to prioritization frameworks, as it determines how easily rural populations can reach essential services such as markets, schools, and healthcare facilities. Many prioritization models use indicators like reductions in travel distance or time to evaluate the effectiveness of proposed road investments [7]. Connectivity complements this by assessing how newly constructed or upgraded roads link remote villages to broader road networks and local service centers, thereby fostering regional integration and improving accessibility on a larger scale [8, 9]. Coverage aims to maximize the reach of investments by targeting the greatest number of individuals, families, or marginalized communities that benefit from improved infrastructure [10].

3.2. Developmental and Socioeconomic Impacts

Beyond these physical and spatial dimensions, prioritization must also consider wider developmental impacts. Economic impacts typically focus on the road’s capacity to reduce transportation costs, enhance agricultural productivity, facilitate trade, and increase income opportunities. These effects are often measured through anticipated improvements in local business activity or market access [11]. Social benefits are also critical metrics, with high-priority projects often enhancing access to public services and explicitly targeting underrepresented or disadvantaged groups. Increasingly, frameworks incorporate social inclusion and equity considerations, particularly concerning women, marginalized populations and geographically isolated communities [12]. Environmental sensitivity is equally important; sustainable planning requires evaluating potential effects on vulnerable ecosystems, biodiversity, flood risk and disaster resilience. Projects that minimize environmental harm or incorporate mitigation strategies are preferred [7].

3.3. Integration, Decision-Making and Stakeholder Participation

The literature identifies several commonly used criteria that guide prioritization decisions. These include the population served, which measures the number of beneficiaries especially in remote and underserved regions [10]; cost and resource efficiency, which encompasses construction, maintenance, lifecycle costs and resource utilization balanced against expected benefits [13]; and proximity to essential facilities such as markets, schools, hospitals, and emergency services [8]. Additionally, traffic volume and demand forecasts inform investment decisions by projecting future road usage based on socioeconomic trends [11]. The alignment of road development with land use and regional growth strategies ensures that investments support both current and anticipated development patterns [7]. Equity and inclusion are also key considerations, as they direct resources toward historically neglected regions and communities [12]. A summary of these key prioritization criteria and their indicators is presented in Table 1.

Table 1: Prioritization Criteria, Associated Indicators, and Purposes.

Reference	**Criteria Category**	**Key Indicators**	**Purpose**
Garg & Kaur (2023)	Accessibility	Travel time/distance reductions	Ease of reaching schools, markets and hospitals
Nisar et al., (2022)	Connectivity	Links to road networks/service centers	Regional integration
Al-Mamun & Paul (2018)	Coverage	Population or households reached	Maximize coverage and social equity
Bhatti & Hanjra (2019)	Economic	Market access, transport cost savings	Enhance livelihoods
Singh et al., (2019)	Social	Service access for marginalized groups	Promote fairness
Garg & Kaur (2023)	Environmental	Risks to ecosystems, flood resilience	Support sustainability

To integrate these diverse and sometimes competing criteria, modern prioritization frameworks employ multi-criteria decision-making (MCDM) techniques such as the Analytic Hierarchy Process (AHP). These methods use weighting systems that reflect planning objectives and stakeholder preferences, enabling transparent and justifiable trade-offs between cost, coverage, economic benefits, and social equity [13, 12].

Finally, stakeholder engagement is considered essential to effective prioritization. Including domain experts, community representatives, and other stakeholders in the process of setting criteria and assigning weights enhances the legitimacy, contextual relevance, and acceptance of decisions. Participatory frameworks have emerged as best practice in many contexts, ensuring that the technical priorities of planners align with the needs and values of local communities [11].

4. Overview of Prioritization Methods

Prioritization methods for rural road network planning are essential to ensure that limited resources are allocated to projects delivering the most significant developmental impact. Throughout the years, approaches have progressed from simple economic assessments to advanced multi-criteria and spatially integrated systems, each presenting distinct benefits and drawbacks.

4.1. Traditional Approaches

Traditional methods primarily focus on economic efficiency and minimum connectivity requirements:

1. Cost-Benefit Analysis (CBA): Projects are ranked based on the ratio of anticipated benefits (such as decreased travel duration, enhanced access, economic improvements) to expenses. Roads with higher benefit-cost ratios (BCR) receive greater priority for funding.

Nonetheless, CBA might overlook non-monetary social and environmental considerations [14].

2. Scoring and Ranking Systems: Road projects earn points according to established criteria (for example, population served, access to markets). Scores are assigned weights and combined to create a priority ranking. While this method is straightforward and transparent, it can oversimplify intricate social or regional concerns [15].

3. Minimum Spanning Tree (MST) Models: These models aim to create networks that connect all intended locations with the least total road length or expense, ensuring fundamental connectivity but usually disregarding qualitative or distributional factors [16].

4.2. Multi-Criteria Decision Making (MCDM) Methods

MCDM approaches allow for holistic evaluation by integrating economic, social, and environmental factors:

1. Analytic Hierarchy Process (AHP): The Analytic Hierarchy Process involves breaking down decision problems into a hierarchy of criteria and sub-criteria. By conducting pairwise comparisons, weights are determined, and project scores are compiled. AHP is particularly useful for integrating stakeholder feedback and managing conflicting priorities [17].

2. Multi-Attribute Utility Theory (MAUT) and Fuzzy MCDM: Multi-Attribute Utility Theory and Fuzzy MCDM utilize mathematical functions or fuzzy reasoning to incorporate both quantitative and qualitative data—effectively addressing the uncertainties and imprecisions often present in rural settings [18].

3. TOPSIS and VIKOR: rank options based on their relative proximity to an “ideal” solution, providing clear compromise rankings when stakeholder goals differ [19].

By accommodating a variety of diverse and even intangible criteria (such as equity or environmental impact), MCDM fosters more nuanced and inclusive decision-making.

4.3. GIS-Based and Spatial Planning Tools

Geographic Information Systems (GIS) technology has become integral to rural road prioritization, offering powerful capabilities to analyze spatial data and support decision-making. GIS facilitates multiple analytical functions that enhance the accuracy and effectiveness of prioritization frameworks.

First, spatial analysis enables the visualization of infrastructure, population distribution, service areas, and physical barriers. This helps planners identify underserved regions and determine optimal routes for new or improved road networks [20]. Second, network analysis within GIS allows for modeling shortest paths, delineating catchment zones, and simulating alternative scenarios. These capabilities improve the evaluation of accessibility and connectivity metrics that directly inform road prioritization rankings. Third, GIS supports the integration of diverse data layers, including socio-economic, environmental, and infrastructural information. This comprehensive data merging fosters localized planning tailored to specific regional contexts, while enhancing the transparency and reproducibility of prioritization processes [21]. Through these functionalities, GIS-based spatial planning tools contribute significantly to more informed, equitable, and sustainable rural road network development.

4.4. Integrated and Hybrid Approaches

Modern prioritization often employs frameworks that combine MCDM, GIS, and participatory methods. For instance, in various Indian states, fuzzy-AHP paired with GIS has been used to design networks that are resilient to flooding and climate change while also taking local socio-economic conditions into account [19]. Workshops with stakeholders and participatory geographic mapping foster community validation, enhancing the relevance and acceptance of the identified priorities [17].

5. Comparative Assessment of Prioritization Methods

A comparative analysis of prioritization techniques is essential for effective rural road network planning, given that each technique differs in complexity, data needs, levels of stakeholder inclusion, and applicability to various regional and planning scenarios. This segment compares the primary approaches as traditional, multi-criteria, and GIS-based methods which highlighting their respective advantages, drawbacks, and examples from practical application.

5.1. Strengths and Limitations

Traditional Approaches:

Cost-benefit analysis (CBA) and minimum spanning tree models are clear and direct, making them suitable for situations with limited information where economic efficiency is the primary concern [22, 23]. Nevertheless, these approaches often overlook wider social and environmental considerations and may inadequately address equity or the preferences of stakeholders [24].

Multi-Criteria Decision Making (MCDM):

MCDM techniques like AHP, Fuzzy MCDM, and TOPSIS enable the simultaneous evaluation of economic, social, and environmental factors. Their adaptability facilitates alignment with various policy goals and local priorities. They are particularly valuable in participatory planning as they can formally incorporate stakeholder feedback and transparently weigh different criteria [25, 26]. However, their main drawback lies in the subjective nature of criteria weighting and the requirement for more extensive data and expert participation.

GIS-Based and Spatial Tools:

GIS methodologies offer robust visualization, spatial analysis, and scenario simulation, significantly improving the precision of accessibility and connectivity assessments [27, 16]. They are most effective when high-resolution spatial data is accessible and have been proven to greatly enhance service coverage evaluations and the identification of underserved regions [26]. Limitations include the availability of data, the need for technical expertise, and the expense of GIS infrastructure in low-resource environments.

5.2. Case Studies: Real-World Evidence

India: The integrated approach of AHP and GIS for prioritization in Punjab showcased the benefits of merging expert insights, socioeconomic metrics, and spatial analysis to create road rankings that better reflect ground realities and meet stakeholder expectations [23].

Nepal: The application of MCDM alongside participatory workshops resulted in road investments that enhanced equitable access for isolated communities, highlighting the significance of including social equity criteria [24].

Flood-Prone Regions: Strategies utilizing Fuzzy-AHP and GIS methodologies have been employed to formulate resilient road network plans in regions at risk of natural disasters, integrating hydrological, economic, and social data for improved prioritization [26].

5.3. Adaptability and Policy Fit

Adaptability: MCDM and GIS methods offer greater adaptability across diverse geographic, institutional, and data settings because of their modular and customizable characteristics.

Transparency and Stakeholder Buy-In: Multi-criteria and participatory approaches are favoured when transparency and public acceptance are essential, as they clearly illustrate trade-offs and incorporate various perspectives [16].

Limitations: Bias can arise from subjectivity in assigning weights, and conventional methods may overlook important qualitative elements. Additionally, the implementation of GIS is constrained where spatial data or technical expertise is insufficient.

Table 2: Comparison Between different methods of prioritization.

Method	Key Advantages	Limitations	Best Use Contexts
Cost-Benefit Analysis	Simple, transparent	Ignores non-monetary factors	Resource-constrained, efficiency-focused
Scoring/Ranking	Easy, quick	Can be subjective, static	Early screening, limited data
Minimum Spanning Tree	Guarantees connectivity	Ignores social/environmental goals	Network extension, basic connectivity
MCDM (AHP/TOPSIS/VIKOR)	Multi-factor, participatory	Weighting subjectivity, data needs	Complex, multi-objective environments
Fuzzy MCDM	Handles uncertainty	Requires expert input	Data-poor or uncertain contexts
GIS-Based Planning	Visual, spatial, integrative	Data-intensive, technical skills	Detailed design, spatially complex areas

5.4. Lessons and Best Practices

The combination of multi-criteria decision-making (MCDM) strategies with geographic information systems (GIS) has proven to be an effective method for achieving more robust and context-sensitive prioritization in the planning of infrastructure and related decision-making activities. This integration allows for the inclusion of both quantitative criteria and spatial elements, improving the reliability of the results. Nevertheless, for such prioritization efforts to be sustainable and broadly accepted, it is vital to adapt locally and actively involve stakeholders, as this ensures that the outcomes mirror the realities on the ground and the needs of the community [23, 26]. Additionally, maintaining transparency in how criteria weights and data sources are documented is essential, as it builds trust among stakeholders, boosts credibility, and enables the methodology to be replicated in future studies. The comparative analysis of the strengths and weaknesses of various prioritization methods based on multiple criteria are shown in Figure 1.

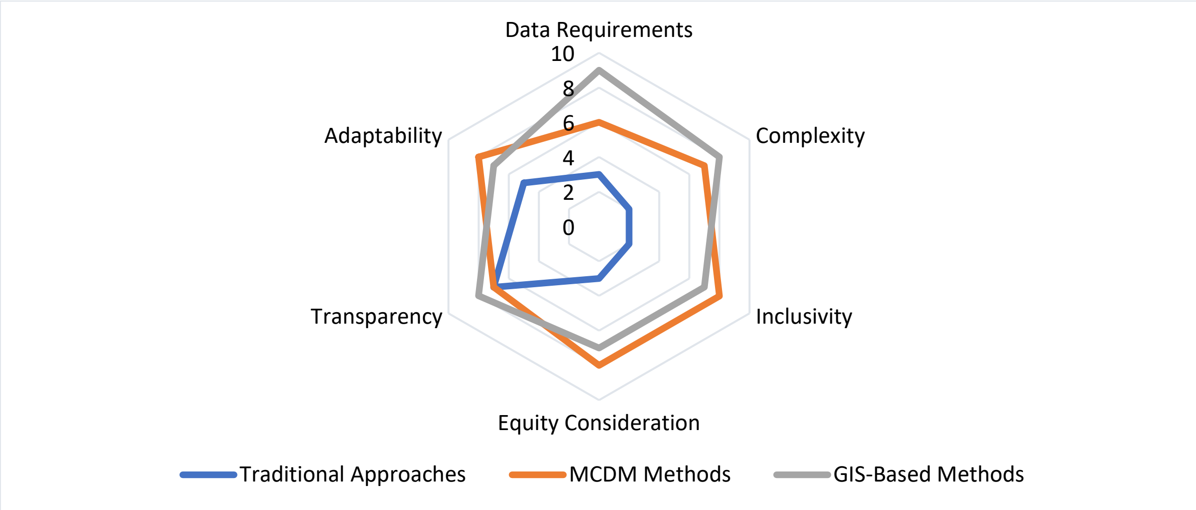

Figure 1: Comparative analysis of the strengths and weaknesses of various prioritization methods based on multiple criteria.

6. Gaps, Challenges, and Future Research Directions

Despite considerable advances in rural road network prioritization methodologies, significant challenges and gaps persist, demanding continued research and innovation. Key among these challenges is the availability, accuracy, and timeliness of essential data. Many rural regions lack up-to-date, high-resolution information on population, road conditions, economic activities, and environmental hazards, which critically impacts the reliability of prioritization outcomes, particularly in data-dependent methods such as GIS and MCDM [16, 28]. To address these issues, improvements in remote sensing, crowd-sourcing, and affordable digital tools are vital. Furthermore, while multiple criteria frameworks and participatory approaches aim to include stakeholder perspectives, real community involvement in defining and weighting criteria is frequently limited by resource, institutional, and temporal constraints [29, 30]. Bridging top-down policies with grassroots needs remains essential to achieve equitable, sustainable results. In addition, integration of environmental sustainability—especially climate adaptation, biodiversity conservation, and disaster resilience into prioritization practices is still incomplete, necessitating more robust indicators, scenario modeling, and multi-sector collaborations [28,29]. A persistent methodological challenge involves subjective weight allocation in MCDM techniques, potentially skewing results without transparent management [31]. Moreover, balancing the complexity of advanced analytical tools like GIS and fuzzy logic with practical usability is difficult, particularly in resource-constrained settings lacking technical expertise and institutional capacity [32]. Adaptability poses another hurdle;

frameworks must flexibly accommodate diverse geographic, institutional, and socio-economic contexts, which is often challenging in low-resource environments.

Simultaneously, emerging digital technologies and sophisticated analytics offer promising opportunities to enhance prioritization. Mobile platforms, cloud services, and open-source GIS tools facilitate efficient, real-time data collection and foster broader stakeholder participation [29]. The adoption of AI and machine learning aids data evaluation and anomaly detection, though maintaining transparency in automated decision-making processes is crucial [28]. Participatory and decentralized governance models supported by digital engagement tools can improve the legitimacy and acceptance of prioritization outcomes. Innovations combining socio-economic, environmental, participatory, and digital data have produced spatially integrated, adaptive planning frameworks that enhance transparency, inclusivity, and accountability in governance [33, 34]. Case studies from diverse regions showcase how context-sensitive prioritization frameworks effectively address local needs and capacities, underscoring the importance of flexible approaches [35, 36]. Recent guidelines emphasize transparent weighting processes and inclusive stakeholder roles to build trust and enable successful implementation [37, 38]. These advancements align with established findings supporting the integration of MCDM and GIS, the necessity of stakeholder engagement, the challenges of subjective weighting and the potential of digital tools and resilience integration in rural road prioritization [38, 39, 40].

7. Conclusion

Prioritization in rural road planning is crucial for achieving cost-effective, equitable, and sustainable infrastructure development, especially in resource-constrained and diverse need settings. The evolution from simple economic appraisals to advanced multi-criteria decision making (MCDM), GIS-based analytics, and participatory methodologies has greatly enhanced the transparency, inclusivity, and local relevance of project selection.

Key takeaways include integrating economic, social, environmental, and spatial criteria to provide holistic and nuanced project rankings [18, 12]. Participatory frameworks that involve community stakeholders improve legitimacy, address local priorities, and enhance implementation success [18, 1]. The use of technology such as GIS, remote sensing, and digital data platforms which support dynamic, evidence-based and spatially informed planning, expanding both the reach and quality of rural road prioritization [32, 12]. Adaptability is essential, as no single method fits all contexts; the choice of approach should be tailored to institutional, geographic, socio-economic settings, and technical capacities [10].

Despite these advances, challenges remain in data gaps, sustained community engagement, climate resilience, equitable access, and replicability in low-resource areas. Emerging opportunities with digital tools, advanced analytics, and participatory governance are likely to further democratize and strengthen rural road planning. Planners are encouraged to adopt integrated, transparent frameworks balancing technical rigor with community input, invest in local data collection and capacity building, and promote policies that incentivize resilience, equity, and continuous methodological improvement. Addressing both technical and contextual factors systematically will improve the socio-economic benefits and sustainability of future rural road investments.

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Conflict of Interest

The authors declare no conflict of interest.

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