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A Socio-Economic Optimization Framework for Rural Road Network Design to Enhance Accessibility

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Abstract - **Rural road networks play a vital role in improving accessibility to healthcare, education, markets, and other essential services, thereby supporting socio-economic development in rural regions. However, designing cost-effective road networks that ensure complete connectivity while accounting for the socio-economic importance of villages remains a significant challenge. This study proposes a socio-economic optimization framework for rural road network design that integrates the Value of Edges (VOE) with the Minimum Spanning Tree (MST) algorithm. Village scores are first computed using population and facility information based on PMGSY and World Bank guidelines. The VOE metric is then calculated for each feasible road link and transformed into optimization weights to guide the MST algorithm in generating a fully connected and cost-effective rural road network. The performance of the optimized network is evaluated using the Value of Network (VON), together with network length and average score per link. The proposed framework was implemented in C# and validated using spatial data from Khanpur Block, Haridwar district, Uttarakhand, India. Results show that the optimized network reduced the total number of road links from 60 to 49, decreased the total network length by 22.49%, increased the average score per link by 22.47%, and improved the Value of Network by 19.92% while maintaining complete connectivity. These findings demonstrate that the proposed framework provides an effective decision-support tool for sustainable and accessibility-oriented rural road network planning.**

Keywords - Rural road network; Optimization Technique; Minimum Spanning Tree; Accessibility; Socio-economic.

I. INTRODUCTION

Rural areas are typically characterized as regions situated outside urban centers, where the majority of residents rely primarily on agriculture for their livelihood. In terms of living conditions, rural areas accommodate a substantial population. While many people from these regions have chosen to pursue urban jobs and lifestyles during the process of urbanization, nearly half of the population continues to reside in rural areas throughout the year. This highlights the necessity to provide essential living conditions and fundamental public services, such as housing, transportation, and environmental considerations, for rural inhabitants [1].

The improvement of rural road networks is crucial for ensuring equitable access to critical resources like healthcare, education, and markets, especially in underserved and remote locations where infrastructure deficiencies severely obstruct socio-economic progress. A well-structured rural road system enhances connectivity in rural regions, facilitates access to various key facilities, and influences the everyday lives of rural residents [2]. The development of the rural road network must be approached with care to maximize user accessibility, allow efficient transportation of goods, and link important facilities while minimizing both construction and maintenance costs [3,4].

In India, it has been demonstrated that rural connectivity plays a crucial role in determining household income, consumption patterns, and alleviating poverty [5–7]. Acknowledging this fact, programs like the Pradhan Mantri Gram Sadak Yojana (PMGSY) initiated by the Ministry of Rural Development [8], along with strategic planning guidelines created in partnership with global organizations such as the World Bank [9], highlight the importance of methodical rural road planning. These guidelines advocate for the identification of a "core network" that ensures every habitation has at least one all-weather road connection. However, financial resources are often inadequate to fulfill all connectivity demands, necessitating that policymakers and planners make investment choices based on priorities. Historically, this prioritization has heavily depended on economic cost–benefit analyses, assessing productivity through metrics like the net welfare gains resulting from lower transportation costs, increased job opportunities, and improved trade [10].

Even with these strategies, designing rural road networks that achieve complete connectivity while minimizing construction cost remains a significant challenge. Graph-theoretic optimization methods, particularly the Minimum Spanning Tree (MST), provide an effective solution by generating a fully connected network with minimum total road length. However, conventional MST-based approaches primarily focus on cost minimization and often overlook the socio-economic importance of road links. Therefore, this study integrates the Value of Edges (VOE) metric into an MST-based framework to design rural road networks that are both cost-effective and socio-economically beneficial while ensuring complete connectivity.

II. LITERATURE REVIEW

Rural road network planning has been extensively studied to develop networks that are cost-effective, sustainable, and equitable. Over the years, academics have utilized traditional algorithms and metaheuristic methods to tackle the complexities involved in road network design.

A. Algorithmic Approaches for Road Network Optimization

Classical graph-theoretic and mathematical optimization algorithms have been widely employed in rural road network planning because of their computational efficiency, ease of

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implementation, and ability to generate reliable solutions for infrastructure development problems. Among these, the Minimum Spanning Tree (MST) algorithm is one of the most commonly adopted approaches for designing cost-effective rural road networks. The MST constructs a connected network by minimizing the total construction cost or road length while ensuring that all nodes remain connected without forming cycles [11,11]. Owing to these characteristics, MST has been extensively applied in rural road planning, including the development of rural transportation networks in Nepal [14], the optimization of road connectivity in hilly and mountainous terrains [15], and the improvement of accessibility to public welfare services such as healthcare and education [13].

Another widely used graph-theoretic approach is Dijkstra's Algorithm (DA), which determines the shortest path between nodes in a transportation network. In rural planning applications, DA has been employed to identify critical villages and service centres using facility-based indices, thereby assisting planners in prioritizing infrastructure investments [16]. Furthermore, it has been utilized to generate need-based road routes by considering service-specific travel distance requirements identified through local community participation, resulting in improved accessibility to essential facilities [17]. In addition to graph-based algorithms, mathematical programming techniques such as Mixed Integer Linear Programming (MILP) have also been applied to rural road network planning. MILP enables planners to optimize multiple planning objectives under budgetary and operational constraints, making it suitable for designing economical all-weather rural road systems. Previous studies have successfully applied MILP in India and Bangladesh to develop road networks that simultaneously improve connectivity, support regional development priorities, and enhance transportation safety while efficiently utilizing available financial resources [18,19].

B. Indian Context: PMGSY

In India, the Pradhan Mantri Gram Sadak Yojana (PMGSY), launched in 2000, is a flagship program aimed at providing all-weather road connectivity to unconnected rural habitations. The scheme has significantly improved access to essential services and markets for millions of rural residents. However, several gaps persist in planning and implementation. In many states, the adoption of advanced planning tools and construction technologies has been slow. As a result, roads often exhibit lower durability, reduced efficiency, and higher maintenance costs. Although national guidelines recommend the use of GIS-based and evidence-driven planning methods, many regions still rely on traditional techniques of route selection and prioritization, leading to suboptimal resource utilization and connectivity outcomes.

These shortcomings underscore the need for technological integration and capacity building at the state and district levels. Strengthening planning processes under PMGSY through graph-theoretic optimization techniques, GIS, and decision-support tools can significantly improve the efficiency, sustainability, and equity of rural road network planning.

C. Research Gaps and Challenges

Although significant progress has been made in rural road network planning, several research gaps remain. Existing studies based on the Minimum Spanning Tree (MST) primarily focus on minimizing construction cost and ensuring complete network connectivity. However, these approaches generally consider only physical distance or construction cost as the edge weight and rarely incorporate the socio-economic importance of villages into the network design process. Consequently, highly beneficial road links connecting villages with greater service availability and population importance may receive the same priority as less significant links.

Another limitation is that many existing approaches evaluate network performance mainly in terms of total length or construction cost, providing limited insight into the socio-economic value of the selected road links. Incorporating a metric that reflects both village importance and construction efficiency can improve the planning process and support more informed infrastructure investment decisions.

To address these limitations, this study integrates the Value of Edges (VOE) metric within an MST-based framework for rural road network design. The proposed approach retains the computational efficiency and guaranteed connectivity of MST while enabling the designed network to better reflect the socio-economic significance of the connected villages.

III. PROBLEM STATEMENT AND OBJECTIVES

Rural areas in developing countries often suffer from inadequate road infrastructure, which restricts access to essential services such as healthcare, education, and markets. Despite the implementation of rural connectivity programmes such as the Pradhan Mantri Gram Sadak Yojana (PMGSY) in India, significant challenges remain in designing road networks that provide complete connectivity while minimizing construction cost and maximizing socio-economic benefits. Conventional rural road planning methods generally emphasize physical distance or construction cost and often overlook the socio-economic importance of the villages being connected.

To address these limitations, this study proposes an MST-based rural road network planning framework. The proposed framework employs the Minimum Spanning Tree (MST) algorithm to generate a fully connected rural road network. Unlike the conventional MST, which considers only edge length, the proposed approach assigns edge weights using the Value of Edges (VOE), a metric that integrates construction length with the socio-economic importance of the connected villages. Consequently, the MST selects road links that simultaneously minimize construction cost and maximize socio-economic benefits. The overall performance of the designed network is subsequently evaluated using the Value of Network (VON).

The proposed framework aims to generate a fully connected rural road network by minimizing the overall edge weight, where the edge weight is represented by the Value of Edges (VOE). This enables the MST algorithm to simultaneously consider construction efficiency and the socio-economic importance of the connected villages during network design.

IV. METHODOLOGY

The proposed methodology integrates the Minimum Spanning Tree (MST) algorithm with the Value of Edges (VOE) metric to design a cost-effective and socio-economically beneficial rural road network. The framework begins by computing village scores based on population and the availability of essential facilities in accordance with PMGSY [20] and World Bank guidelines [21]. These scores are then used to calculate the Value of Edges (VOE) for every feasible road

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link, representing the socio-economic importance of connecting two villages relative to the required road length.

Since the conventional MST algorithm minimizes edge weights, the reciprocal of VOE is assigned as the optimization weight for each road link. Consequently, the MST simultaneously favors shorter road lengths and higher socio-economic importance while ensuring complete connectivity among all villages. The performance of the optimized network is subsequently evaluated using indicators such as total network length, VON and average Score per Link. The overall workflow of the proposed framework is illustrated in Fig. 1.

```
Input:   Village   data   (Population,   Facilities,
Distance Matrix)
Output: Optimized Road Network
BEGIN
    // Step 1: Compute village scores
    FOR each village i DO
        Compute VillageScore(i)
    END FOR

    // Step 2: Calculate Value of Edges (VOE)
    FOR each feasible edge (i, j) DO
        VOE(i,j)
    END FOR

    // Step 3: Assign edge weights
    FOR each feasible edge (i, j) DO
        Weight(i,j)
    END FOR

    // Step 4: Generate optimum network
    OptimizedNetwork ← Kruskal_MST(Graph, Weight)

    // Step 5: Evaluate network performance
    Calculate_TotalLength()
    Calculate_AverageScorePerLink()
    Calculate_VON()

    RETURN OptimizedNetwork,
           TotalLength,
           AverageScorePerLink,
           VON
END
```

Fig. 1. Proposed MST Framework Pseudocode for Rural Road Network Design

A. Village Score

The village score measures the overall availability and quality of services in a settlement. It is computed in accordance with PMGSY [20] and World Bank guidelines [21], with weights assigned to service categories such as education, health, markets, and administrative services [22]. The cumulative facility score reflects a village's relative attractiveness and priority for road connectivity and is determined either by the highest-category score or by the cumulative sum of individual parameter scores, as shown in Table I. Accordingly, the facility-based score (S) of a village is calculated as:

$$\boldsymbol{S} = \sum_{c \in C_{max}} \min\left(\max_{1 \le p \le m_c} S_{c,p}, W_c\right) + \sum_{c \in C_{cum}} \sum_{p=1}^{m_c} \min(S_{c,p}, W_c) \tag{1}$$

Where:

C_{max} = set of categories using the highest-category rule,
C_{cum} = set of categories using the cumulative rule,
$S_{c,p}$ = score of the p^{th} sub-category in category c,
m_c = number of sub-categories in category c,
W_c = weight of category c,

Table I. Habitations/facilities and their proposed weightages as per PMGSY and World Bank Guidelines.

S. No.	Parameter	Category Weight	Sub—category Weight
1	**Population** (Census 2011) of the Habitation/village connected by the Through Route *(score of the highest category)*	30	
	• 5000 and above		30
	• 3000 to 4999		20
	• 1000 to 2999		10
	• Less than 1000		05
2	**Market facilities** *(cumulative score)*	30	
	• Mandi/GrAMs/Rurban Growth Cluster		15
	• Warehouse / Cold Storage / Sugar Mills / Agro Industry		10
	• Collection Centre or pack house		5
3	**Educational facilities** *(score of the highest category)*	15	
	• High School		10
	• Higher Secondary School / Girls High School / ITIs		12
	• Degree College		15
4	**Medical facilities** *(score of the highest category)*	15	
	• Primary Health Centre / Veterinary Hospital		10
	• Bedded Hospital / Community Health Centre		15
5	**Transport infrastructure** *(cumulative score)*	10	
	• Bus Stand		4
	• Administrative Centre (Block, Panchayat Hqr)		4
	• Bank/Fuel Station		2

B. Minimum Spanning Tree-Based Network Optimization

The Minimum Spanning Tree (MST) is a graph-theoretic optimization algorithm that constructs a connected network with the minimum total edge weight while avoiding cycles. Owing to its computational efficiency and ability to guarantee complete connectivity, MST has been widely applied in transportation network design and infrastructure planning. In the proposed framework, MST is employed to generate an optimized rural road network that minimizes construction cost while incorporating the socio-economic importance of the connected villages.

Unlike the conventional MST, which considers only the physical length of road links as edge weights, the proposed framework introduces the Value of Edges (VOE) as a socio-economic measure for evaluating each feasible road link. The VOE combines village importance, represented by the village score and population, with the corresponding road length, thereby prioritizing links that provide greater socio-economic benefits relative to the required construction length. The Value of Edges between villages *i* and *j* is defined as,

$$\boldsymbol{VOE} = \frac{(S_i+S_j)*(P_i+P_j)}{L_{ij}} \tag{2}$$

where:

VOE = Value of Edges between village *i* and *j*,
L_{ij} = Total length of edge between village *i* and *j*.

A higher VOE indicates a more desirable road link because it connects villages with greater socio-economic importance while requiring a shorter construction length. However, since the conventional MST algorithm minimizes edge weights, the optimization weight assigned to each edge is defined as the reciprocal of VOE:

$$\boldsymbol{W_{ij}} = \frac{1}{VOE} = \frac{L_{ij}}{(S_i+S_j)*(P_i+P_j)} \tag{3}$$

where $\boldsymbol{W_{ij}}$ represents the optimization weight associated with the road link between villages *i* and *j*. The MST algorithm then determines the optimum rural road network by minimizing the total optimization weight,

$$min \sum_{i,j \in T} \boldsymbol{W_{ij}} \tag{4}$$

where T denotes the set of edges selected to form the spanning tree. By minimizing the reciprocal of VOE, the proposed framework simultaneously favours shorter road lengths and higher socio-economic importance of the connected villages. Consequently, the generated rural road network achieves complete connectivity while efficiently balancing construction cost and socio-economic benefits. The performance of the optimized network is finally evaluated using the Value of Network (VON), which represents the overall socio-economic value of the optimized network and is computed as

$$\boldsymbol{VON} = \frac{\sum_{(i,j)\in T}(S_i+S_j)*(P_i+P_j)}{L_n} \tag{5}$$

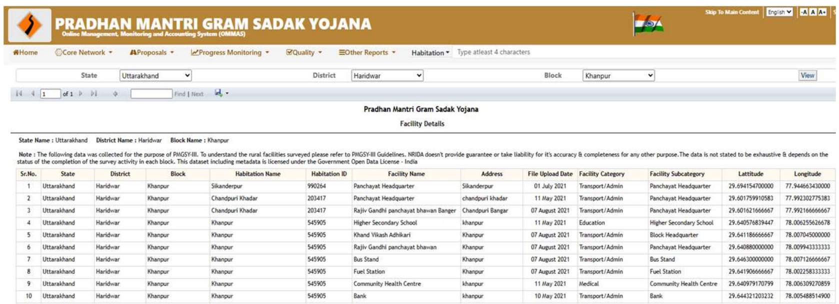
where L_n is the total length of the optimized network and T denotes the set of edges selected in the final network. A higher VON indicates that the optimized network connects villages with greater socio-economic importance while maintaining a shorter overall network length. In addition, the optimized network is evaluated using the total network length and average Score per Link, thereby providing a comprehensive assessment of construction efficiency and overall network performance.

V. CASE STUDY: DESIGN OF OPTIMUM RURAL ROAD NETWORK

A. Study Area

The study area for this research is Khanpur Block, located in Haridwar district, Uttarakhand, India. The proposed MST framework was applied to design an optimized rural road network connecting the villages within the block. The study required village population, facility information, geographic coordinates and feasible road links. A total of 50 villages with a combined population of 53,194 were considered in the analysis. The data were primarily collected from the OMMS Portal [23] database, as shown in Fig. 2 and PMGSY GRRIS [24] linked to the government-initiated PMGSY (Pradhan Mantri Gram Sadak Yojana) program and other layouts were downloaded from PMGSY National GIS Website [25]. These datasets were used to prepare the village database, generate the distance matrix, calculate village scores, and implement the proposed optimization framework.

(a)



(b)

Fig. 2. OMMS Portal for efficient retrieval of population (a) and facility datasets (b).

B. Software Used

The implementation of the proposed methodology was carried out using Microsoft Visual Studio for algorithm development and QGIS (Version 3.42.3) for spatial visualization and analysis. The computations and mapping were performed on a personal computer, and the detailed system specifications are provided in Table II.

Table II. System Specifications

Component	**Specification**
Processor	Intel Core (TM) i7-10700 CPU@2.90GHz (2.90 GHz)
Installed RAM	16GB
System Type	64-bit operating system, x64-based processor
GPU	Intel (R) UHD Graphics 630

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Vol. 15 Issue 08 , August - 2026

Microsoft Visual Studio

Visual Studio is an Integrated Development Environment, and it offers a full-fledged environment for software development, such as code editing, debugging, building, and deployment. It is built and supported by Microsoft. It supports application building for many platforms, such as Windows, Mac, Linux, iOS, and Android. It supports an extensive list of programming languages, such as C#, Visual Basic, F#, C++, HTML, JavaScript, TypeScript, Python and so on. The proposed model was developed using the C# programming language in Microsoft Visual Studio. The software computes village scores, calculates the Value of Edges (VOE), assigns optimization weights and implements the Minimum Spanning Tree (MST) algorithm to generate an optimized rural road network.

Quantum Geographic Information System (QGIS)

QGIS is an open-source, free computer software that enables the creation, editing, visualizing, analyzing, and publishing of geospatial data, as shown in Fig. 3. The visualization of the existing and optimized rural road network of the study area was compiled in QGIS.

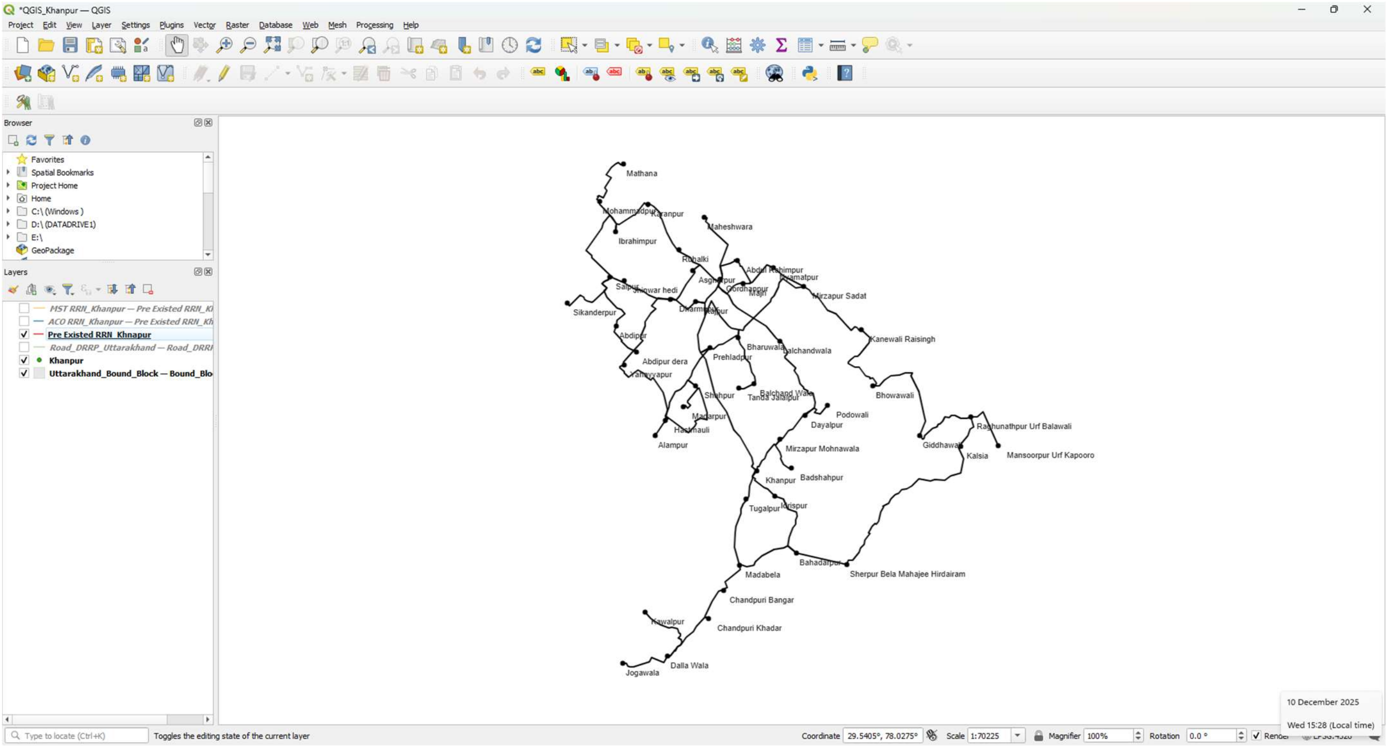


Fig. 3. User Interface of QGIS During Map Creation.

C. Distance matrix for study area

All villages in the study area have been marked on the map in QGIS using the open-layer plugin. A point layer was created in QGIS, where each point denotes a village and its corresponding location on the map. The villages were marked in QGIS as black circles and road between villages shown as black color link, as shown in Fig. 3. A distance matrix was generated for the study area using QGIS and information was collected and stored.

D. Calculation of Village Score

After the generation of distance matrix population data of the villages, the village scores were calculated for each village using the attribute tables obtained from PMGSY national GIS GRRIS. The village score is the summation of the sub-category weightage of all the facilities available inside the village boundary and it is calculated by using eq. (1). The category weightage and subcategory weightage are mentioned in Table 1 for the corresponding parameters. This study incorporated international guidelines of the World Bank on rural development [21] as well as PMGSY guidelines [20] for measuring village scores, by ensuring that the design met international standards of rural development.

E. Finding the Optimum Network

The proposed MST framework was implemented in C# to generate the optimum rural road network. The algorithm first computes village scores based on population and available facilities. The Value of Edges (VOE) is then calculated for every feasible road link and transformed into optimization weights. Finally, the Minimum Spanning Tree algorithm identifies the optimum network that minimizes the total optimization weight while ensuring complete connectivity among all villages. The implementation procedure is summarized below:

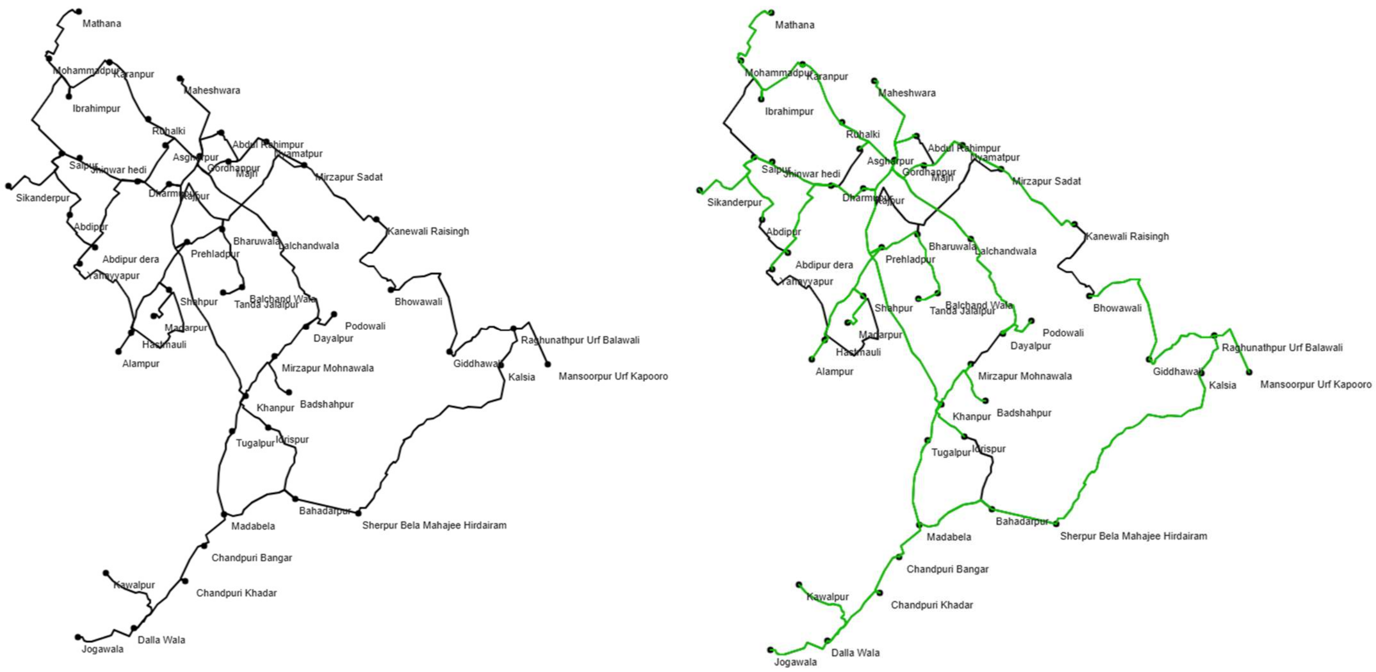
- Prepare the village database and feasible road network.
- Calculate village scores.
- Compute the Value of Edges (VOE) for each feasible road link.

- Compute optimization weights.
- Apply the Minimum Spanning Tree (MST) algorithm.
- Generate the optimized rural road network.
- Evaluate the network using the Value of Network (VON).

VI. RESULTS AND DISCUSSION

Using the proposed MST framework, an optimized rural road network was generated for the Khanpur Block. The optimized network connects all 50 villages, serving a total population of 53,194, while reducing the total number of road links from 60 to 49. The total network length decreased from 117.91 km to 91.39 km, representing a 22.49% reduction in network length. This reduction demonstrates that the proposed framework effectively eliminates redundant road links while preserving complete network connectivity.

In addition to reducing the network length, the optimized network achieved a 19.92% increase in the Value of Network (VON), indicating an improvement in the overall socio-economic value of the selected road links. Furthermore, the Average Score per Link increased from 9.30 to 11.39, corresponding to an improvement of 22.47%. These results demonstrate that the proposed MST framework successfully balances construction efficiency with socio-economic benefits by connecting villages with greater importance while minimizing the overall network length.



(a) (b)

Fig. 4. (a) Existing Rural Road Network. (b) Optimized Rural Road Network.

The existing network connects 50 villages through 60 road links, serving a total population of 53,194, as shown in Fig. 4(a). In contrast, the optimized network connects the same 50 villages using only 49 road links, with a total network length of 91.39 km. In Fig. 4(b), the green links represent the optimized road network selected by the proposed framework, whereas the black links indicate the excluded or redundant road links that were not included in the final optimized network. It demonstrates a significant improvement, with the total length reduced by 22.49% from 117.91 km to 91.39 km. This reduction indicates a more cost-effective and efficient rural road network. Consequently, the decrease in total network length will lead to lower maintenance as well as upgradation costs, enabling the government to utilize the savings for other rural development initiatives. Furthermore, the Value of Network increased by 19.92%, reflecting an improvement in the network's ability to connect maximum villages and facilities effectively, thus enhancing accessibility and service delivery across the region. The 22.47% increase in the Average Score per Link further highlights that the optimized network not only minimizes cost but also maximizes social and functional benefits, ensuring a balanced approach between economic efficiency and community welfare in rural transportation maintenance planning. Comparison and improvement between the existing and maintenance optimal networks are illustrated in Table III.

Table III. Result of Rural Road Planning Algorithm.

Parameter	Pre-existing Network	Optimized Network	Improvement (%)
Population Connected	53194	53194	-
Village Connected	50	50	-
Number of Links	60	49	18.33%
Average Score per Link	9.30	11.39	22.47%
Length of Network(km)	117.91	91.39	22.49%
Value of Network	38097.62	45685.79	19.92%

The effectiveness of the proposed framework was evaluated using the Value of Network (VON), which represents the cumulative socio-economic benefit of the optimized rural road network relative to its total construction length. The increase in VON demonstrates that the optimized network not only minimizes construction length but also improves connectivity among villages with higher socio-economic importance. The combined improvements in network length, Average Score per Link, and VON confirm that the proposed MST framework provides an efficient and sustainable approach for rural road network planning.

VII. CONCLUSION

The proposed Minimum Spanning Tree (MST)-based framework provides an effective approach for designing optimized rural road networks that minimize construction length as well as provide socio economic benefit, while ensuring complete connectivity among villages. By integrating the Value of Edges (VOE) into the edge-weight formulation, the proposed methodology considers both construction efficiency and the socio-economic importance of the connected villages during network optimization. The performance of the optimized network is subsequently evaluated using the Value of Network (VON), which provides an overall measure of the socio-economic effectiveness of the final rural road network.

The proposed model was developed using the C# programming language and implemented with QGIS using real-world spatial data. The results demonstrate that the framework can generate a fully connected and cost-effective rural road network while improving overall network value. Owing to its computational efficiency and straightforward implementation, the proposed framework can support the planning of new rural road networks as well as the expansion and modernization of existing road infrastructure under programmes such as PMGSY.

Although the proposed framework produces an optimized and fully connected rural road network, certain limitations remain. The present study does not explicitly consider terrain conditions, environmental constraints, land acquisition issues, or regional variations in construction costs, which may influence the practical implementation of road projects. Furthermore, dynamic factors such as future population growth, traffic demand, seasonal accessibility, and long-term maintenance requirements have not been incorporated into the optimization process.

Future research may extend the proposed framework by integrating terrain-based GIS analysis, environmental constraints, variable construction costs and multi-objective optimization techniques. In addition, incorporating real-time spatial data, remote sensing information, and machine learning approaches could further enhance the adaptability, robustness, and decision-making capability of the proposed framework for sustainable rural road network planning.

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