

Multi-Objective Analysis of Cost and Social Benefits in Rural Road Networks

J. K. Shrestha, A. Benta, R. B. Lopes, and N. Lopes

Abstract—This paper presents a multi-objective model for addressing two main objectives in designing rural roads networks: minimization of user operation costs and maximization of population covered. As limited budgets often exist, a reasonable trade-off must be obtained in order to account for both cost and social benefits in this type of networks. For a real-world rural road network, the model is solved, where all non-dominated solutions were obtained. Afterwards, an analysis is made on the (possibly) most interesting solutions (the ones providing better trade-offs). This analysis, coupled with the knowledge of the real world scenario (typically provided by decision makers) provides a suitable method for the evaluation of road networks in rural areas of developing countries.

Keywords—Multi-objective, user operation cost, population covered, rural road network.

I. INTRODUCTION

TRANSPORTATION cost of goods and services to rural areas of developing countries is always an important issue for decision makers (DM). Often, these costs are related with the following underlying problems. Establishment of an appropriate rural road network: This is guided by different constraints such as topographical conditions, environmental quality, economic efficiency, and social equity. Accordingly, these factors are considered in the development of road networks, using objectives such as connectivity of settlements [1], maximization of accessibility to settlements [2], maximization of equity (distribution) [2]-[4], robustness of network [5], [6] and maximization of covering of settlements and public facilities [7] during planning of a rural road network.

Minimization of operation cost in the road network: This depends on the length of links and surface level of road links (earthen, gravel, or asphalt). The better the surface level the lesser will be the vehicle operating cost. Hence, fixing of surface level of road links are directly related with minimization of operating cost. Furthermore, the amount of CO₂ emission depends on the travel distance and condition and surface level of the road, consuming a lot of natural

resources such as fuel, energy, land, and minerals related which raise serious environmental concerns. However, this effect may be less critical in rural areas, where traffic congestion is not an issue.

The scope of this work is to study existing or already planned rural road networks. Establishment of appropriate road networks is not considered here. In an already defined road network, minimization of transportation cost depends on the length and surface type and condition of the road links.

In addition to this, in real world scenarios, DM's have to consider social issues. For rural areas, there could be a strategy to upgrade surface level of road links which cover more population. This is one of the measures of social equity in terms of transportation; it provides opportunities for social and economic activities in rural areas.

This paper considers the rural road network upgrading problem (from lower surface level – earthen or gravel – to a higher surface level – gravel or asphalt) with two objectives: minimization of user operation cost and maximization of population covered by the network. The first one corresponds to an economic efficiency objective and the second corresponds to a social objective. As the problem has more than one objective; a multi-objective approach is used.

The usual surface level of roads in rural areas is earthen, which may need to be upgraded to gravel or asphalt. This issue is addressed in Heng et al. [8] where three surface levels are also considered.

This paper is organized as follows. The mathematical formulation of the problem is presented in Section II. Section III gives solution technique for the problem. This section also presents the application of the proposed model in a rural road network, for link selection and upgrading, in a real case in Nepal. Finally, conclusions of the study are presented in Section IV.

II. PROBLEM FORMULATION

Mostly, road links in rural road networks have earthen surfaces, causing high user operation costs and, accordingly, high costs for goods and services. Hence, the surface level of road links needs to be upgraded to higher surface level (gravel or asphalt) to bring down these costs. To formulate the problem, the road network is discretize to a set of nodes and links. The nodes are connected by road links with one of the surface level (either of earthen, gravel or asphalt).

The multi-objective transportation cost optimization problem can be formulated considering the rural road network as an undirected graph $G = (N, L)$. Where, N and L are the sets of nodes and road links respectively. The mathematical

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formulation considers the road surface with options for earthen, gravel and asphalt.

The following notations are used. S is the set of road surface options $S=\{s1, s2, s3\}$ for earthen, gravel, and asphalt respectively. P_{ij} and W_{ij} are, respectively, the population served by link (i, j) and the weight to the link (i, j) . d_{ij} is the distance from node i to node j . c_{ij}^s is the operating cost per unit flow of traveling over surface type $s \in S$ on link (i,j) . O_{ij}^s is the operating cost on link (i, j) over surface type $s \in S$, where $O_{ij}^s = d_{ij}c_{ij}^s$. B is the available investment budget, and I_{ij}^s is the cost of improving link (i, j) with surface type $s \in S$. x_{ij}^s are integer decision variables, taking the value of 1 if a link (i, j) is built with surface type $s \in S$, 0 otherwise.

The model to be developed aims to achieve the least operation cost, while maximizing the population covered by the upgraded rural road network, subject to an investment constraint. Thus, the multi-objective transportation cost optimization problem can be formulated as follows:

Minimize

$$Z_1 = \sum_{s=1}^3 \sum_{(i,j) \in L, i < j} W_{ij} O_{ij}^s x_{ij}^s \quad (1)$$

Maximize

$$Z_2 = \sum_{s=1}^3 \sum_{(i,j) \in L, i < j} P_{ij} x_{ij}^s \quad (2)$$

Subject to

$$\sum_{s=1}^3 \sum_{(i,j) \in L, i < j} I_{ij}^s x_{ij}^s \leq B \quad (3)$$

$$\sum_{s=1}^3 x_{ij}^s = 1 \quad \forall (i, j) \in L, \quad i < j \quad \forall s \in S \quad (4)$$

$$x_{ij}^s \in \{0,1\} \quad \forall (i, j) \in L, \quad \forall s \in S \quad (5)$$

The first objective function (1) is written as to consider the minimization of user operating cost, and intends to achieve economic efficiency. If the links are prioritized, it can be considered as weights (W_{ij}) to give the importance to the specific links in the road network. Otherwise, the value of W_{ij} can be assumed as unitary. The second objective, maximization of population covered by the upgraded links, is written as (2), and aims at achieving social efficiency. The model sets a road surface with option of earthen, gravel and asphalt so that transportation operation cost in the network is a minimum in (1) and maximizes the population coverage in (2).

Equation (3) ensures that the improvement/construction expenditure of rural road network is constrained to an investment budget. The budget indicates physical restriction as the total number of upgraded links depends on it. Further, the term of link improvement/construction expenditure ensures that the budget is spent to build only one link either (i, j) or (j, i) as the graph is undirected. It is possible to investigate different decisions using different budget levels. Constraints (4) define that one link is to be upgraded with only one type of

surface level. These constraints also guarantee that all links are to be connected with one of the surface options. Decision variables x_{ij}^s are defined in (5).

III. SOLVING AND APPLYING THE MULTI-OBJECTIVE PROBLEM

This problem (a multi-objective optimization problem – MOOP), as does not have compatible objectives (the provided objectives conflict with each other), is not able to provide a single optimal solution. Instead, we must search for the set of Pareto optimal solutions (non-dominated solutions).

For obtaining the non-dominated set, the problem can be solved using a weighted sum program [9]. In the following application of the problem, MPL for Windows 4.2 as the modeling language with CPLEX 10.0's as the mixed integer programming solver, was used for solving the weighted sum program.

The application of the problem is carried out in the rural road network (real existing network) shown in Fig. 1, which is in the Gorkha district of Nepal. There are 21 links and 22 nodes in this network. The available investment budget, for the test instance, is fixed as Nepalese Rupees (NRs) 400 million (1 Pound = 130 NRs).

The weight for each link is calculated based on an indirect travel cost in terms of person-km [10] and presented in Table I. Operating cost per unit flow over earthen, gravel, and asphalt surface of the links are taken as NRs 50.64, NRs 45.64, and NRs 36.79, respectively [11]. The upgrading cost from earthen surface level to gravel surface level is taken as NRs 5 million per kilometer and from gravel surface level to asphalt surface level as NRs 10 million per kilometer.

An analysis can be conducted at different budget levels. However for the test instance, solution of the model is obtained for the budget level of NRs 400 millions.

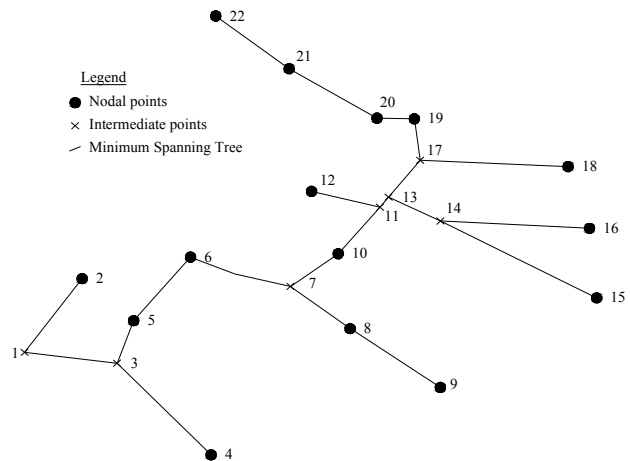


Fig. 1 Test rural road network

TABLE I
LENGTH OF LINKS, POPULATION SERVED BY LINKS AND WEIGHT OF LINKS

Links	Length (km)	Population served	Weight
1-2	5.75	4501	1.90
1-3	3.52	58936	100.00
3-4	6.00	7478	3.29
3-5	3.34	51458	81.51
5-6	3.44	48021	68.92
6-7	5.70	43029	56.82
7-8	2.69	9263	3.48
7-10	4.12	33766	35.37
8-9	4.20	5383	1.66
10-11	2.49	31520	25.17
11-12	1.74	4408	0.56
11-13	0.70	27112	18.86
13-14	1.50	8968	5.93
13-17	2.78	18144	11.54
14-15	7.73	4040	4.94
14-16	7.35	4928	2.65
17-18	5.57	5465	2.23
17-19	2.10	12679	5.62
19-20	1.20	10257	3.67
20-21	3.28	7236	2.77
21-22	5.12	2740	1.03

The Pareto optimal solutions of the test rural road network are listed in Table II. The solution space between the two objective functions, minimization of user operation cost (Z_1) and maximization of population coverage (Z_2) is indicated in Fig. 2. There are ten solutions in the Pareto frontier for the test rural road network: the non-dominated solutions at the budget level.

Table III shows that each solution has a set of links with recommended surface level. The letter “a” stands for asphalt, “g” stands for gravel, and “e” stands for earthen surface level of the road links in the table.

There are ten interesting decision options for the chosen budget level, from which the DM can choose from. However, she/he may be more interested in the efficient solutions that provide the best trade-offs. The trade-off relationships can be easily visualized and interpreted by using the plot of non dominated solutions (Fig. 2).

TABLE II
RESULTS OF NON-DOMINATED SOLUTIONS AT THE TEST BUDGET LEVEL

Solutions	Z_1 (minimum)	Z_2 (maximum)
s1	73,060	396,592
s2	70,690	395,292
s3	69,981	393,867
s4	69,936	390,884
s5	69,740	388,939
s6	68,717	378,985
s7	66,001	377,658
s8	61,005	372,275
s9	60,302	361,601
s10	60,208	357,193

TABLE III
ROAD LINKS RECOMMENDED FOR UPGRADING FROM RESULTS OF NON-DOMINATED SOLUTIONS AT THE TEST BUDGET LEVEL

Links	Solutions									
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10
1-2	g	g	g	g	g	g	e	e	e	e
1-3	g	g	a	a	a	g	a	a	a	a
3-4	g	g	g	g	g	g	a	g	e	e
3-5	g	a	g	g	g	g	g	a	a	a
5-6	g	g	g	g	g	g	a	a	a	a
6-7	g	g	g	g	g	a	g	a	a	a
7-8	g	g	g	g	g	g	a	a	g	g
7-10	g	g	g	g	g	a	a	a	a	a
8-9	g	g	g	a	g	g	a	e	e	e
10-11	g	g	g	g	g	g	a	a	a	a
11-12	g	a	g	e	g	g	a	g	g	e
11-13	g	a	g	a	g	g	g	g	a	a
13-14	g	g	g	g	g	a	a	a	a	g
13-17	g	g	g	g	g	a	g	g	a	a
14-15	g	e	g	e	a	g	e	e	a	a
14-16	g	g	g	g	e	e	e	e	e	e
17-18	g	g	e	g	e	g	e	e	e	e
17-19	g	g	g	g	g	e	g	g	g	a
19-20	g	g	g	g	g	g	g	g	g	a
20-21	g	g	g	g	g	g	g	g	e	e
21-22	e	g	g	g	g	e	e	e	e	e

Looking at Fig. 2, and the solutions representation in the decision space (depicted in Figs. 3-5), three solutions appear to be the most interesting: s3, s7, and s8. When the DM wants to keep user operating costs low, giving more emphasis on economic efficiency, she/he may choose solution s8 (Fig. 5). However, upgrading the corresponding links in the road network avoids the most populated areas and therefore, may be socially undesirable. If she/he wants to cover more population, thus giving more emphasis to social efficiency, The DM may choose solution s3 (Fig. 3). However, the transportation cost of the goods and services in the network will be significantly higher as user operation costs will be increased. If she/he wants objective function values to be in between the two options, solution s7 (Fig. 4) may be the most interesting. Hence, a deeper analysis of the trade-offs between the objectives is always necessary.

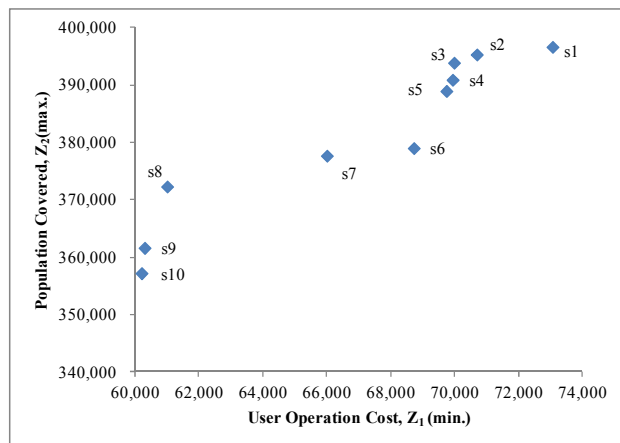


Fig. 2 Pareto frontier for the test budget level

To compare different situations, the trade-offs between the values of the two objective functions can be analyzed for the

complete non-dominated set. From this, we can examine how much we have to penalize the value of one objective function, in order to improve the other. However, in this problem, the DM may be interested in solutions with lower values for the first objective (Z_1) and higher values for the second objective (Z_2). A small increase of the value of Z_1 is intended to produce the biggest increment possible on the value of Z_2 . Hence, solution s8 may be most preferred as, with a small increase in the value of Z_1 over solutions s9 and s10, the increase in Z_2 is significantly higher. Solution s7 also has an increase in value of Z_2 , however, there is a high increase in the value of Z_1 for a smaller increment in value of Z_2 which may not be preferred. The same situation can be observed for solution s6. Beyond solution s6, again, small increases in the value of Z_1 gives rise to significant increases in the value of Z_2 (in solutions s3, s4 and s5). Further, solutions s1 and s2 have the similar situation as of solutions s6 and s7 in that the increase in the value of Z_1 is high for small increases in the value of Z_2 which may also not be intended.

In this way, it is possible to explore interesting alternatives rather than a unique solution to the problem. Also, there are several possible decisions, where the improvement of the value of one objective does not cause a major increase of the value of the other one. The DM can therefore examine several different solutions, with different trade-offs, and in this way, make a more informed decision. It should be noted that the final choice of the solution to be implemented will always belong to the DM.

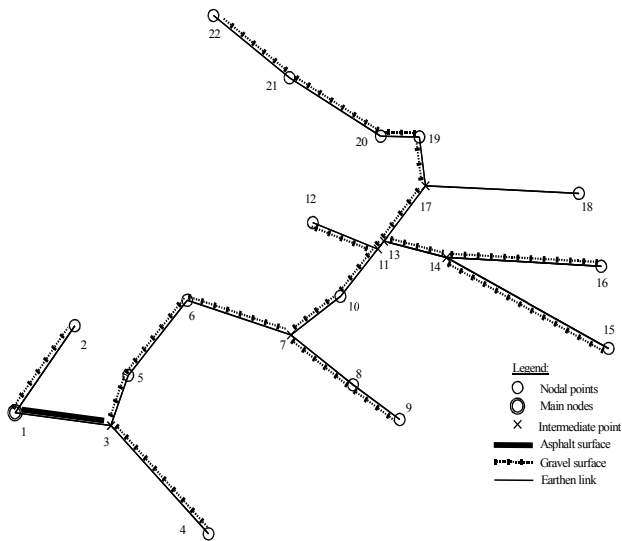


Fig. 3 Graphical representation of solution s3

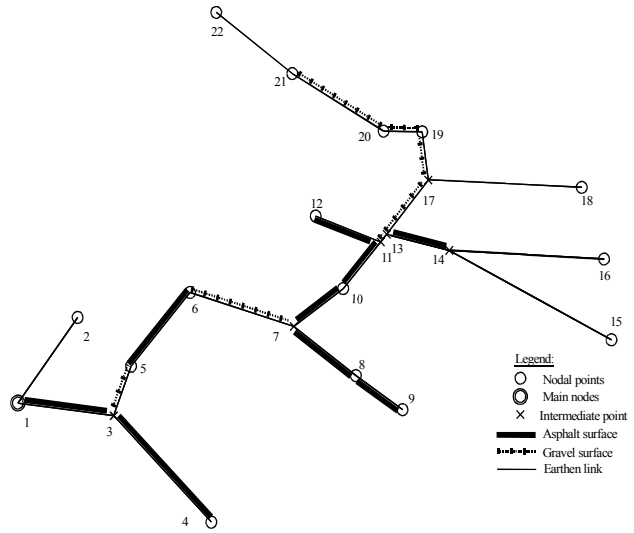


Fig. 4 Graphical representation of solution s7

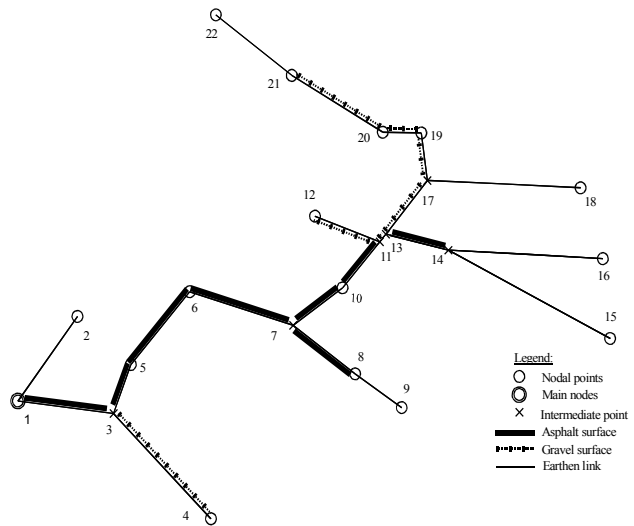


Fig. 5 Graphical representation of solution s8

IV. CONCLUSION

This work proposed an optimization model to achieve minimum transportation cost by establishing a suitable road surface level in rural road networks. The two most important aspects in rural roads (user operating cost and population coverage) were used simultaneously, thus becoming a multi-objective decision model. Consequently, the Pareto optimal solutions of the problem were obtained, giving some interesting trade-offs between the two objectives. This allows the DM to choose, from a set of significant alternatives, the solution(s) which better reflects aspects (possibly not considered in the mathematical model) of the real world scenario.

The multi-objective transportation cost optimization model, applied to the rural road network problem, can give realistic decision alternatives which can be more practical for rural areas in different decision making scenarios (e.g. when

different budget levels are available).

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