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Multi-Objective Optimization of National Highways in Nepal: A Case Study in Gandaki Province

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Abstract
This study presents the multi-objective approach to national highway network planning in developing and mountainous country Nepal where it is difficult to find traffic and highway related data. This approach considers accessibility and robustness objectives simultaneously for highway network planning. Robustness of a network is determined based on the accessibility to major cities during the monsoon season when almost all highway links are disturbed to the some extent. The construction of new highways and/or upgrading of the existing highways are proposed for fulfilling the objectives The application of the approach is demonstrated on real national highway network in Gandaki Province of Nepal. The outcomes indicate that the proposed approach provides numerous pareto-optimal solutions to policy makers and is suitable for highway network planning. This methodology can be applied to mountainous areas of other developing nations.

Keywords
Multi-objective optimization, Accessibility, Robustness

1. Introduction

1.1 Background

In Nepal, underdevelopment and rising regional inequality are frequently attributed to insufficient and uneven transportation infrastructures. In order to meet the government's development goal, the 15th five year plan envisions that by the end of the plan period, the number of households with access to transport within a distance of 30 minutes will have increased from 82 to 95 percent [1]. Traffic disturbance due to landslides on highways for several hours is common during the monsoon season (June-September) in Nepal [2]. In order to provide the smooth passenger and freight movements throughout the year, highways need to be upgraded to appropriate standard. However, due to technical as well as budgetary constraints, policy makers have to select the best alternative considering the most relevant objectives. This goal can be accomplished through highway network optimization.

Most of the previous studies in road network optimization can only be adapted in developed and data-rich environments slightly constrained by topography. This study propose a highway network optimization methodology using easily accessible data taking into account the accessibility of all population center and robustness of highway network based on accessibility to major economic and health service center during the monsoon season when almost all highways are disturbed to certain level. This approach helps policy makers in selecting highway links for upgrading or new construction in data-poor environments constrained by topography. The application of the approach is illustrated for a road works planning of hypothetical test network as well as real national highway network in Gandaki province of Nepal.

1.2 Research Objectives

The study is being carried out to propose a methodology to optimize the national highway network upgrading and extension problem in Nepal. Specific objectives of the study are:

- To develop a multi-objective approach for national highway network planning in Nepal.
- To develop efficient technique to solve the model.
- To apply the model for a road works planning of hypothetical test network as well as real national highway network in Gandaki province of Nepal.

2. Literature Review

The ease of accessing activities via a specific transportation system can be broadly characterized as accessibility [3]. Based on the previous studies, Páez et al. (2012) [4] categorized accessibility indicators in three broad classes: cumulative opportunities, gravity-based, and utility based. The gravity based approach has been extensively used in urban and geographic studies [3]. In the gravity model, the number of opportunities accessible from a given location, considering spatial impedance, is measured [5].

Network robustness can be defined as the extent to which the transportation network can continue to operate in various interferences on transport elements [6]. Assessing the reduction in network performance due to the disturbances is a common approach in robustness analysis [7]. Robustness and vulnerability are the closely related concepts [8]. Taylor et al. (2006) [9] proposed a methodology for analyzing the vulnerability of strategic road networks due to loss of specific links by using the accessibility indices as parameters of vulnerability analysis.

Substantial researches have been found on optimization-based road network planning models. Generally, the network design problems have two types of solutions: a discrete form concentrating on the addition of new road links to an existing road network, and a continuous form focusing on upgrading of existing links [8]. Most of the road network design problems are built on efficiency objective, such as minimization of travel costs or maximization of user benefits. Recently, there is more focus on incorporating robustness objective in road network planning model. There are few literatures on multi-objective road network planning considering both efficiency and robustness objective simultaneously. Santos et al. (2010) [8] have presented the regional road network planning combining efficiency (accessibility maximization) and robustness objective.

There are even limited studies that deal with the accessibility and robustness objectives simultaneously in road network planning in mountainous region of developing world like Nepal. Shrestha et al. (2014) [10] presented the multi-objective optimization model for upgrading of rural(local) road network in hilly regions of Nepal. Their objectives were to minimize the overall user operating cost and to maximize the population served by the network. Banick et al. (2021) [11] formulated a multi-modal (vehicle and walking mode) cost-time model to assess the rural road construction options based on accessibility enhancements towards service centers during dry and monsoon seasons .

Due to lower density of highways in Nepalese context, new links have to be added in order to increase the accessibility and also we have to consider the robustness objective so that people can have access to the major facility centers during monsoon season. This study considers both accessibility and robustness objective in the multi-type (single lane, double lane etc.) highway network planning in the context of Nepal.

3. Methodology

The method (figure 1) used in this study to plan the national highway network adheres to the principals outlined below.

- Planning decisions consist of upgrading existing road links or adding new road links.
- Accessibility and robustness maximization are the two objectives taken into considerations
- Construction and upgrading costs should not exceed the available budget

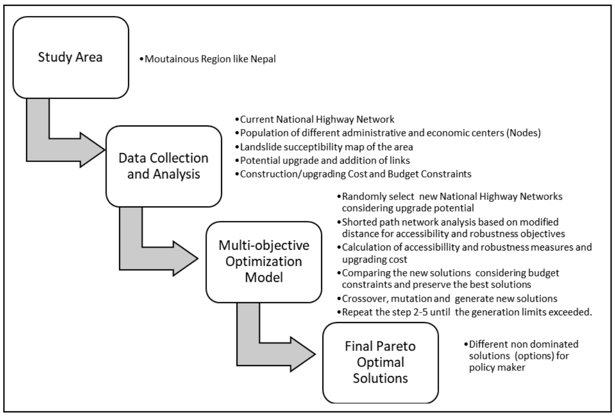

Figure 1: Framework of Methodology

3.1 Study Area

Nepal is a relatively small country (147,181 km2) administratively divided into 7 provinces which are further divided into 77 districts and 753 municipalities/village municipalities. The altitude in Nepal shows an extreme variation of heights (from 58m to 8848m) across the whole the country [12].

Geographically, Nepal can be divided into three strips (Plain, Mid-Hills and Mountains) running the full width. The hills and mountains cover the 83 % of area of the country [10]. Huge vertical variations within short horizontal span possess an extreme topography, steep unstable slopes, deep gorges causing a high risk for landslides, rock falls etc. [13].

In Nepal, around 80 % of annual precipitation falls during monsoon season (June – September) [14]. The heavy rainfall in combination with unstable steep slopes of the hill region causes massive landslides and floods during the monsoon season. During that period, earthen sections of highways become slippery and undulated which make difficult for vehicle to travel along the road [13]. Most of the highways, which are the main mode of transportation in Nepal follow the river routes and are blocked by landslides, flooded or washed away during monsoon season. For example, in 2003 Narayanghat – Mugling highway was blocked for two weeks due to landslides and slope failures [2].

National highway network of Nepal consists of 80 national highways having total length of 14,913 km. Some highways (around 20 % of total length) are still in planning stage and only 50 % of total length have bituminous surface [15].The total population of the Nepal as per Census 2011 is 26.5 million of which hilly and mountainous regions accommodate about 50 % of total population [16].

Due to extreme topography, road construction/ expansion is a difficult and costly job. As follows, a national highway network planning model is proposed taking into account the characteristics of the region.

3.2 Problem Formulation

A national highway network consists of the set of nodes and interconnected links which may be upgraded to the different types (double lanes, four lanes etc.) as shown in table 1. In addition to upgrading current links, adding new links is also taken into consideration.

3.2.1 Accessibility Measure

The accessibility of the location (node) i may be measured with slight modification in Hansen's Accessibility Index [5] in normalized form as shown in equation 1 [9].

$$A_i = \frac{1}{\sum_{j\varepsilon N\backslash i} P_j} \sum_{j\varepsilon N\backslash i} \frac{P_j}{d_{ij}(y)} \quad (1)$$

Where,
A_i is accessibility measured at node i;
P_j is population of node j;
d_{ij} is the shortest distance between node i and node j obtained after multiplying the link distance with a factor based on the road type (table 1);
$y = \{y_{lm}\}$ is a matrix of binary variables equal to one if link l is set at road type m and zero otherwise and
N is a set of nodes in the road network.

The weightage (table 1) to be applied for distance of links for assessment of accessibility was calculated by dividing the average speed of reference road type (road type 3) by average speed of that road type and the average speed of the road type was adopted from Nepal Road Standard [17]. Similar workout can be found in Banick et al. (2021) [11]. Here, we also considered the four lane highway for planning of highways in mountainous area of Nepal, because traffic volume in major highways like Prithivi Highway is expected to exceed the capacity of double lane highway in near future.

Table 1: Weightage for distance of road link based on travel speed of road type [17]

Road Type	Average Speed	Weightage for distance
Potential (1)	-	Large value say 10000
Single lane earthen road (2)	10 km/h	3.00
Single lane bituminous road (3)	30 km/h	1.00
Double lane bituminous road (4)	40 km/h	0.75
Four lane bituminous road (5)	60 km/h	0.50

3.2.2 Robustness Measure

The robustness analysis of the highway network proposed in this study is based on the accessibility metrics [9]. A network is said to be more robust if summation of accessibility, during monsoon season, of all the nodes towards major nodes where there are large opportunities for education, employment and emergency services like health service is maximum. Accessibility of nodes during monsoon season is determined by equation 2 as shown below.

$$R_i^m = \frac{1}{\sum_{j\varepsilon Np\backslash i} P_j} \sum_{j\varepsilon Np\backslash i} \frac{P_j}{d_{ij}^m(y)} \quad (2)$$

Where,
R_i^m is accessibility measured at node i during monsoon season;

P_j is population of node j;
d_{ij}^m is the shortest distance between node i and node j obtained after multiplying the link distance with a factor based on the road type (table 1) and with a factor based on road link susceptibility towards landslide during monsoon season (table 2);
$y = \{y_{lm}\}$ is a matrix of binary variables equal to one if link l is set at road type m and zero otherwise and
N_p is a set of major nodes in the road network.

The probability of occurrence of landslide is higher in high risk zone in comparison with low risk zone. Here, we categorized the study area into three zones: high risk, moderate risk and low risk based on susceptibility to landslides as shown in table 2 [12]. The road construction activities (deforestation, hillside cutting, dumping of construction spoil, quarrying, rerouting of the natural drainage system etc.) itself can have huge impact on the fragile mountainous area [18]. Pantha et al. (2010) [2] found that landslides are densely located in proximity of highway. Singh et al. (2014) [19] concluded that in mountainous region, landslides are occurring more frequently as a result of extensive human activities including road upgrading and widening. According to a recent study, landslides caused by rains are twice as likely to happen within 100 meters of the road as landslides caused by earthquakes [20]. Tanyaş et al. (2022) [21] conducted a study in Arhavi, Turkey to access the effect of road construction on mass movement and found that 90.1 % of mass movement in the area was linked to the road construction works. Also the study found that the majority of mass movements (51 % of total size identified) were associated with major road construction despite it constituted only 10.8 % of total road length in the area.

In developing countries like Nepal, inadequate geotechnical investigation and faulty construction/ widening techniques are major factors for natural as well as cut slopes' instability[22]. During the monsoon season in 2010, India's national highway NH-58 witnessed huge slope failures along the section where road widening projects were either completed or running [23]. After completion of widening project in 2018, Mugling-Narayanghat Highway of Nepal has been witnessing a series of landslides blocking the traffic movements for several hours during monsoon season [24].

There is a tendency to leave the cut slopes nearly vertical without proper geotechnical investigation [19]. Higher the width of road, higher will be the earthworks which results in deeper and steeper cut slopes in mountainous regions which are the main causes of slope failure blocking the movements of traffic. This issue is more severe in high risk zone and then in medium risk zone in comparison to low risk zone. Therefore, four lanes roads which constitute the deeper and steeper cut slopes are more vulnerable to landslides than single lane and double lane roads. Banick et al. (2021) [11] reduced (up to 60% for paved roads and up to 85% for earthen roads depending upon road conditions) the dry season speed for monsoon season by using the modifiers proposed by Banick and Kawasoe (2019) [25] and measured the accessibility towards service centers during monsoon season. Banick and Kawasoe (2019) [25] validated the speed reduction modifiers by comparing modeled travel times with travel time actually incurred by households. Based on the above discussions, we assumed that during monsoon season, travel speed decreases by 40%, 20%, 10% and 5% in low risk zone, 60%, 30%, 40%, 65% in moderate risk zone and 80%, 40%, 60% and 80% in high risk zone for 2-5 road types respectively and weightages for link distances were calculated accordingly as shown in table 2.

Table 2: Weightage for distance of road link based on road link susceptibility towards landslide during monsoon season

Road Type	Weightage for distance for different hazard zones		
	Low Risk	Moderate Risk	High Risk
Potential (1)	Large Value	Large Value	Large Value
Single lane earthen road (2)	1.67	2.50	5.00
Single lane bituminous road (3)	1.25	1.43	1.67
Double lane bituminous road (4)	1.11	1.67	2.50
Four lane bituminous road (5)	1.05	2.86	5.00

3.2.3 Multi-objective Optimization

The multi-objective optimization of the highway network maximizes the accessibility and robustness objectives through the interference in the existing highway network (construction of new road links of given type or the upgrading of existing road link to higher type) taking into account the available budget.

The decision variable will be the link type (road type).

If link type of certain section of highway is changed, accessibility and robustness of the highway network will automatically alter. In this way, the objective functions will be directly impacted by modifying a link type. Each link in the highway network will be given an initial link type as a reference. All links will be divided into different link sets. Each link set comprises links which should be upgraded to same type. All possible link type will be assigned for each link based on the topography and risk zone. Available budget is the constraint applied to the model.

Table 3: Construction and upgrading cost for different road type per km in NRs (millions) in low risk zone

Existing road type	Upgraded road type				
	1	2	3	4	5
Potential (1)	-	20	50	120	350
Single lane earthen road (2)	-	-	30	100	300
Single lane bituminous road (3)	-	-	-	80	250
Double lane bituminous road (4)	-	-	-	-	200
Four lane bituminous road(5)	-	-	-	-	-

The construction and upgrading cost of the road also depends on the terrain type. In this study, we used the construction and upgrading cost for different categories of road in low risk zone as shown in table 3 calculated based on average cost estimates of some real road projects(upgrading of different sections of Midhill highway and Mugling – Pokhara section of Prithivi highway) in Nepal. For medium and high risk zones, values in table 3 will be multiply by factor 1.25 and 1.5 respectively assuming that in medium and high risk zones more investment is required for slope stability in comparison to low risk zone.

The optimization model can be formulated as shown in equation 3 and 4:

Maximize

$$Z_1 = \sum_{i\varepsilon N} A_i \quad and \quad Z_2 = \sum_{i\varepsilon N} R_i^m \tag{3}$$

Subject to

$$\begin{gathered} \sum_{m\varepsilon M_l} y_{lm} = 1, \forall l\varepsilon L \quad , \quad \sum_{l\varepsilon L}\sum_{m\varepsilon M_l} c_{lm} * y_{lm} \leq B \\ and \quad y_{lm}\varepsilon\{0,1\}, \quad \forall l\varepsilon L, \quad m\varepsilon M_l \end{gathered} \tag{4}$$

Where,
Z_1 and Z_2 are objective function value for accessibility and robustness objective;
A_i is accessibility measured at node i as per eq. 1;
R_i^m is accessibility measured at node i during monsoon season as per eq. 2;
N is a set of nodes in the road network;
$y = \{y_{lm}\}$ is a matrix of binary variables equal to one if link l is set at road type m and zero otherwise;
M_l is the set of possible road types for road link l;
L is the set of road links;
c_{lm} is the cost required to set link l at road type m and B is the total available budget.

3.3 Solution methods

In multi-objective optimization, there are several optimal solutions called Pareto optimal (non-dominated) solutions rather than just one optimal solution. For these solutions, the one objective cannot be improved without degrading the other objective [26]. The optimization model presented above is quite difficult to solve. Heuristic methods are generally used to solve the network optimization model. One of the most effective heuristic techniques for solving network design problems is genetic algorithms (GA). In this study we used the non-dominated sorting genetic algorithm II (NSGA-II) [27] building on the earlier application of Possel et al. (2016) [26].

3.3.1 NSGI-II framework

NSGA-II framework designed to solve the multi-objective highway network optimization problem is shown in figure 2. A population of N feasible solutions are randomly selected which forms the current population. Uniform crossover [26] operation is performed on randomly selected parents from the current population to create an offspring population. Parents for crossover operation are selected based on the objective function values. Offspring population just created undergoes the mutation operation [26]. Crossover and mutation operations continue until the N feasible offspring are generated. The current population and offspring population are then merged, and the N best solutions from the merged population are determined. This completes the one generation and the N best solutions make up the current population for the next generation. This process continues for several generations until the terminating criteria (maximum generation) are met. Every individual in a population is a set of possible link types and called a chromosome. Each component (link type) of this chromosome is known as a gene.

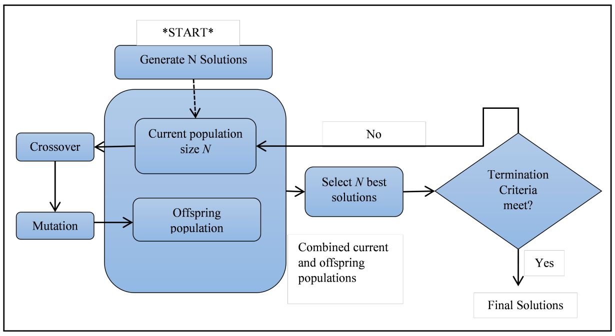

Figure 2: The NSGA-II framework followed in this study

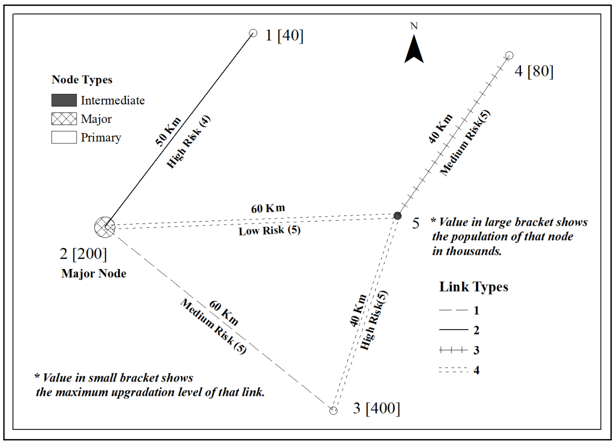

Figure 3: Hypothetical network for case study I

4. Application and Result

Methodology and solution approach presented in section 3 were implemented in two case studies. In order to validate the framework, firstly, the methodology was applied in a small hypothetical network for which all possible solutions can be assessed. Secondly, the methodology was applied to a real highway network of Gandaki province, Nepal.

4.1 Case study I: small hypothetical network

The details of road network for this case study are shown in figure 3. It consists of 4 population nodes (including 1 major node), 1 interconnecting node and 5 links. There are 180 numbers of possible link type combinations for no budget limitation out of which 11 Pareto optimum solutions could be found due to its relative small size. This case study was used to validate the proposed methodology of highway network optimization.

Using the above data, the proposed model was executed in MATLAB R2018b. Parameters (population size - 50, maximum generation - 50, uniform crossover probability - 0.6 and one gene mutation probability - 0.05) considered for genetic algorithm (NSGA-II) in this case study were based on parameters used by Possel et al. (2016) [26]. The total construction and upgrading cost to upgrade/construct all the road links to the highest possible types is NRs 70,250 million. Comparison of total Pareto-optimal solutions found manually and through the NSGA-II framework at different budget levels shows that the framework can find the most of the Pareto optimal solutions for this hypothetical test network.

4.2 Case study II: national highway network in Gandaki province of Nepal

Real world highway network of Gandaki province was assessed in the second case study. Gandaki province, one of the seven provinces of Nepal, is located at central part of Nepal and comprises of 11 districts. Likewise, there are 85 local governments (1 metropolitan City, 26 municipalities and 58 rural municipalities) in this province. The total area of the province is 21,976.34 km2 covering the 14.93% of total area of Nepal [12]. According to the census 2011, the total population of the area is 2,403,757 [16]. There is an extreme variation of altitude and the total area can be divided into three strips (Plain, Mid-Hills and Mountains) running the full width. It is one of the maximum rainfall regions of Nepal. Due to varied topography and heavy monsoon rain, the Gandaki province is more inclined to natural hazards like landslides. This province clearly resembles the characteristics of Nepal.

4.2.1 Input Data

Highway network of Gandaki province considered for this case study consists of 34 population nodes (including 4 major nodes), 18 interconnecting nodes and 75 links as shown in figure 4. Major facility centers (Narayanghat, Butwal and Kathmandu) outside the Gandaki province and highways connecting those centers were also incorporated in the highway network planning. 11 new roads which are not in the current highway network were also proposed for construction/upgrading . 1 out of 75 links is already upgraded to four-lane standard. Therefore, the remaining 74 links were categorized into 42 link sets so that consecutive links would be upgraded to same type. One recent study divided the Gandaki province into three hazard zones based on the landslide susceptibility [12] and based on this study report hazard zone of the each link was concluded. Hazard zone of highway links outside the Gandaki province was assumed based on the hazard zone of similar locality in Gandaki province.

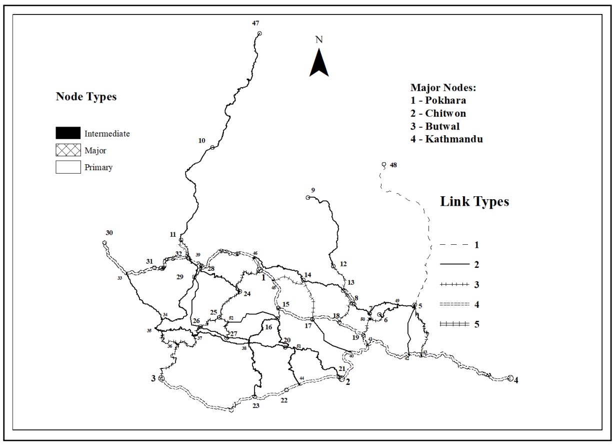

Figure 4: National highway network of Gandaki province considered for case study II

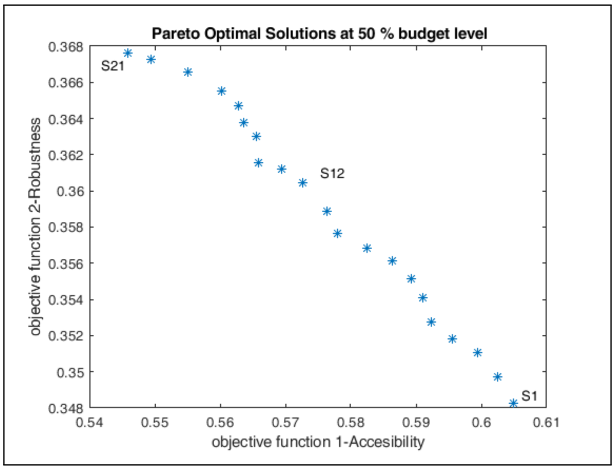

Figure 5: Pareto-front at 50 %t budget levels for highway network of Gandaki province considerd for case study II

Five link types (road types) were used similar to the first case study. Node populations were calculated based on census data [16] of the area that is supposed to be served by the node. The population of border nodes Korola (47) and Larke Pass (48) were calculated based on the population of Zongba and Gyirong County of neighboring country China to impart the importance of these nodes [28]. Construction and upgrading cost of road link from one link type to another link type was taken from table 3. There are $1.997 * 10^{19}$ numbers of possible link type combinations with no budget limitations.

4.2.2 Results and Discussion

Using the above data and NSGA-II parameters used in first case study, the proposed model was executed in MATLAB R2018b. The total construction and upgrading cost to upgrade/construct all the road links to the highest possible types is NRs 526,265.475 million. The Pareto-optimal solution at 50 % budget level is shown in figure 5. The graphical representation of the solution S12 is shown in figure 6. It can be observed that link of major highways: Prihivi highway (Pokhara (1) to Mugling (41)), East West highway (Chitwan (2) to Butwal (3)), Narayanghat – Mugling highway (Chitwan (2) to Mugling (41)), Midhill highway (Aarughat (5) to Maldhunga (39)) are suggested to be upgraded to four lane highways. Shortest routes proposed to be added on highway network: Talchowk (45) to Bhorletar (14) and Bhorletar (14) to Damauli (17) are suggested to be upgraded to four lane highways. Other shortest routes proposed to be added on highway network: Kushma (28) to Galyang (14), Aarughat (5) to Benighat (42) and Damauli (17) to Ghumaune (40) are suggested to be upgraded to two lane highways.It can be concluded that the proposed framework provides numerous solutions (figure 5) to the policy makers in planning the highway links construction/upgrading. From various alternative solutions, decision makers can select the best solution which fits well with the current context.

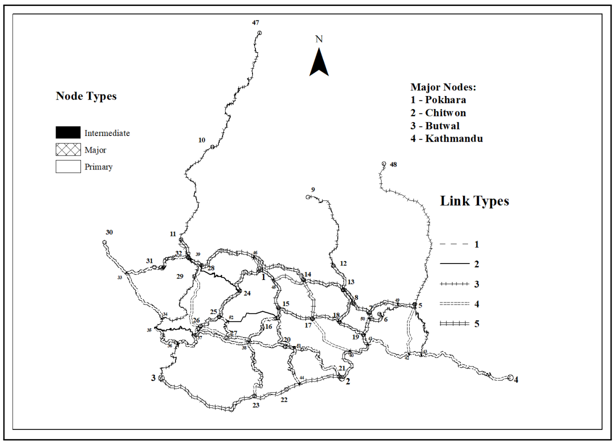

Figure 6: Graphical representation of solution S12

5. Conclusion

In this paper, a methodology is proposed for highway network planning in a mountainous country Nepal considering the accessibility and robustness objective simultaneously using easily accessible data in data-poor environment. Frequent obstructions of highways during monsoon season in Nepal have drawn the necessity of incorporating robustness objective while planning the highway network. Robustness measure proposed in this study is based on the accessibility to major cities during the monsoon season. The construction of new highways and/or upgrading of the existing highways have been taken as a decision variable.

NSGA-II framework is proposed for solving the model. The efficiency of the NSGA-II framework was tested on a small hypothetical test network and the results show that framework is capable of finding most of the pareto-optimal/non-dominated solutions. The usefulness of the approach was demonstrated for a real highway network of Gandaki province, Nepal at different budget levels. Pareto optimal solutions were obtained which provides the policy makers with set of different solutions allowing them to select the solution which best fit into the current scenario. This approach can also be applied in road network planning of regions having similar characteristics of Nepal.

6. Recommendations

Further research can be done in the following sectors.

- Robustness assessment based on permanent link failure of the road in monsoon season which is the most case in Nepal can be taken into consideration.
- The weightage of node can be taken into consideration so that the road connecting major nodes get priority for upgrading.
- Other modes of transportation like airways can be incorporated while accessing accessibility.

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