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A RELIABILITY-BASED RESOURCE ALLOCATION MODEL FOR TRANSPORTATION NETWORKS AFFECTED BY NATURAL DISASTERS

ABSTRACT

This paper is concerned with the development of a resource allocation model for road networks under supply uncertainty caused by natural disasters. An optimization model is proposed to determine which links should be invested for the system to perform better while encountering natural disasters such as earthquake. The connectivity reliability and travel time reliability of origin-destinations (ODs) are selected as performance measures to do so. The Monte-Carlo simulation method is used to estimate the reliability measures and the model is solved by the genetic algorithm. The proposed model is implemented on a test network to demonstrate the results.

KEYWORDS

resource allocation, travel time reliability, connection reliability, Monte Carlo simulation, genetic algorithm

1. INTRODUCTION AND PREVIOUS RESEARCH

One of the most important issues after the occurrence of a disaster, such as earthquake, is to provide a transportation system so that the emergency trips can be made successfully. This issue is, first, concerned with the problem that the Origin-Destination (OD) pairs possessing emergency demand flows should remain connected after the event and, second, the injured people should be transported to hospitals within a pre-specified time interval threshold. In uncertain conditions, where the network link capacities or demand flows are not known in advance and are rather random variables, the reliability measures would be more appropriate assessment indicators for the network performance. Therefore, in this paper, we have considered the connectivity reliability and travel time reliability to evaluate the network reliability in the aftermath of a disaster. These two reliability measures have repeatedly been used in previous works, but not in a unique framework simultaneously. In this paper, we have incorporated these reliability indices, each of which as a constraint, in mathematical programming for improving the network performance.

The connectivity reliability is defined as the probability that a pair of nodes in a network remains connected. A special case of this index (as in our current application) is the terminal reliability that is concerned with the existence of at least one path between each origin-destination (OD) pair [1]. Some methods for analyzing the connectivity reliability of transport networks have been presented in previous studies in which a probabilistic and binary state have been assumed for the performance of links [2-5]. The state of a link is usually expressed by a binary variable, which is equal to 1 if the link operates normally and 0 if it fails. This state variable may also indicate more than two states [5].

The travel time reliability is defined as the probability that a trip between a given origin-destination (OD) pair can be made successfully within a pre-specified time interval [6]. Travel time reliability can also be defined as a function of the ratio of travel times under degraded and non-degraded states [2]. This definition introduced an important key for some of the following studies. Several travel time reliability studies have focused on the concept of 'budget time' where the travellers are assumed to experience different perceived costs relative to their different sensitiveness to the mean and variance of travel time [7, 8]. This mean-variance approach has been originally investigated to develop travel choice (route and departure time choice) utility functions [9, 10]. The travel time reliability can be also studied in more precise (stochastic time-dependant) frameworks. The ‘Schedule reliability’ was introduced as the probability of on-time against late or early arrivals [11]. However, such precise measures require in-detail information about travellers’ behaviour in response to the source of uncertainty, which is still under investigation.

The main purpose of developing performance indicators, such as the connectivity reliability and the travel time reliability, is to evaluate the network performance under uncertainty and, if needed, to allocate resources in order to meet the desired levels of the performance indicators. For this purpose, the so-called bi-level mathematical programming has been used where the resource allocation is carried out in the upper level problem and the traffic assignment in the lower problem. To the best of our knowledge, the first attempt to introduce network reliability to the network design problem was performed by Chootinan et al. [12]. They presented a continuous network design to maximize the new capacity-reliability index as the probability that each link operates below its capacity. They used the Probit-based assignment and genetic algorithm for the lower and upper level problems, respectively. Sanchez-Silva et al. [13] developed a pseudo-Markov chain model for measuring the changes in the network accessibility index. Their model maximizes the network reliability index based on a set of possible actions which is described in terms of failure and repair rates of links. Chen et al. [14] proposed an alpha-reliable network design problem to minimize the total travel time budget required to satisfy the total travel time reliability constraint. They used the notion of α-value-at-risk to optimize the performance associated with a set of demand scenarios whose collective probability of occurrence is α. This approach is to some extent similar to the robust optimization later used by Yin et al. [15] in which a solution is sought in order to tolerate the changes of travel demand, up to a given bound known a-priori, and the resulting robust network will perform much better against the worst-case scenario while ensuring a near-optimal average performance. Recently, Shariat-Mohaymany and Babaei [16] developed a reliability-based network design problem to minimize the connectivity reliability considering link capacity degradations based on a new technique for evaluating the reliability of link performances.

In real-world applications it has become important for decision makers to take into account multiple criteria (objectives) rather than single criteria in order to select suitable projects or determine relevant maximum allowable budget levels. Accordingly, we have used terminal reliability and travel time reliability as two important criteria for evaluation of networks under supply (capacity) degradation resulting from a special disaster scenario when providing transportation system for the emergency trips in the aftermath of the disaster. Our definition for terminal (as a particular case of connectivity) reliability and travel time reliability is the same as those presented in [1] and [6], respectively. We have forced these reliability indicators to be satisfied as lower bound constraints in a mathematical programming model that seeks to minimize the required budget.

The general framework for choosing an acceptable set of links for investment is first to select an investment scenario and then to examine whether the performance measures satisfy the constraints. If so, the scenario is labelled as “appropriate” and could be accepted. Otherwise, a new scenario should be studied in the same way. To find the optimal scenario, an appropriate optimization method should be applied. *Figure 1* indicates the general algorithm for investment decision-making.

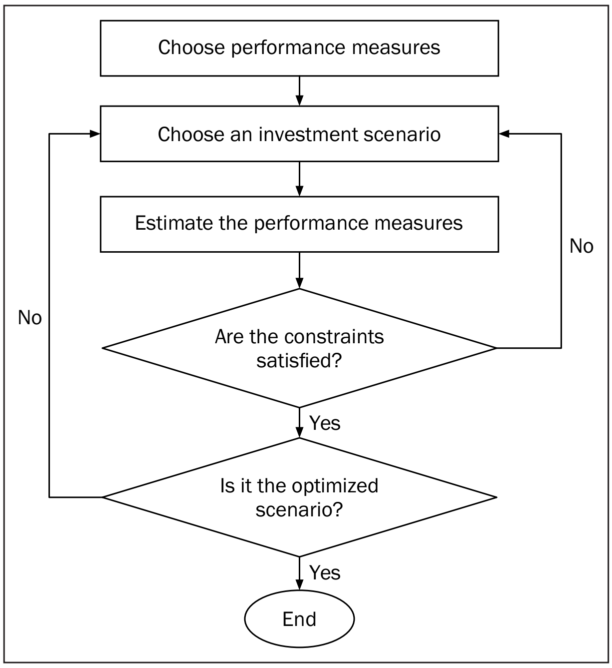

Figure 1 - General algorithm for investment decision-making

Therefore, the network is expected to meet the desired level of performance by means of upgrading the most effective links which are determined through the general above algorithm. Herein, the performance is quantified by two measures of reliabilities: connectivity and travel time. In other words, the optimal investment leads to a reliable network which, after a disaster, still connects the ODs through predefined logic travel time intervals.

The remainder of the paper is organized as follows. In the next section, the network performance measures used in this study are selected and the method for approximating them is illustrated. In Section 3 the model is proposed, assumptions are clarified and the solution algorithm is presented. This model is then illustrated through a numerical example in the next section. Finally, the study is closed by conclusion and suggestions.

2. NETWORK PERFORMANCE MEASURES

In the next two sub-sections, the measures chosen to indicate the network performance are defined and the algorithm to approximate these measures is illustrated.

2.1 Choosing network performance measures

As mentioned before, in order to supply the emergency service demand, it is essential that different parts of the network remain connected. Moreover, the connected routes are expected to provide an appropriate quality for transportation. In other words, each trip should be made in a predefined standard travel time. Therefore, both connectivity and travel time are important criteria. Due to the probable nature of the network facing disaster, in this study, their corresponding reliability parameters with the following definitions are considered as network performance measures:

R_{c_w}: Connectivity reliability of the OD pair w. This measure indicates the probability that w is connected through at least one operating route.

R_{t_w}: Travel time reliability of the OD pair w. This measure indicates the probability that the demand of w is transferred within a pre-defined standard threshold of time.

2.2 Reliability approximation

Links of a network are vulnerable to disasters such as earthquake. Exposed to a disaster, they may operate perfectly, operate in a degraded manner or fail totally, each with a given probability. In this study, to estimate the reliability of the OD travel time and OD connectivity, accordingly, the two issues are examined in each state of the network generated by Monte Carlo Simulation. A state of the network here means the set of link conditions, in a deterministic manner; namely, a particular state of a network represents its realization where the links are in one of the defined states.

Monte Carlo simulation is an algorithm in which the probable situation of the network converts to thousands of deterministic states. In each state it is examined whether the state is acceptable or not. Finally, the ratio of the number of accepted states to the number of total generated states indicates the reliability of the concerned measure (e.g. connectivity or travel time). An acceptable state in case of connectivity is defined as the state in which the given pair of OD is connected. Similarly, in case of travel time, an acceptable state is defined as the state in which the OD travel time is within a pre-defined interval. This interval could be defined using a coefficient like λ. Multiplying λ by the initial travel time gives an upper boundary of the acceptable travel time interval. Smaller λ gives shorter interval which means considering stronger measures to preserve the initial normal situation of the network.

λ is usually determined by decision maker authorities due to the importance of the network or a certain expectation which can be itself a challenging object and could be different for separate ODs.

Based on the above explanations an algorithm is used to reliability approximation as follows:

Step 0: Choose the Coefficient λ for each OD so that $\lambda \cdot T_{w,0}$ gives the maximum acceptable travel time in the respective OD. ($T_{w,0}$ is the travel time considering the free flow travel time between the origin-destination w.)

Step 1: Set $n = 0$, n is the simulation iteration counter.

Step 2: Generate one of the possible states of the network. Roulette Wheel is a helpful method for state generation.

Step 3: Assign the demand to the network

Step 4: Calculate the travel time between each OD. (T_w)

Step 5: For each OD, check if it is connected. If so, the current state is acceptable considering connectivity of the ODs.

Step 6: For each OD, check if the travel time is below the maximum acceptable travel time ($T_w \leq \lambda \cdot T_{w,0}$). If so, the current state is acceptable considering travel time of the ODs.

Step 7: If $n \leq N$, $n = n + 1$ and go to step 2. N is the required number of iterations for simulation.

Step 8: Estimate connectivity reliability for each OD using the following equation:

$$R_{c_w} = \frac{Number\ of\ Acceptable\ states\ (in\ which\ w\ is\ connected)}{Number\ of\ Total\ Generated\ States} \tag{1}$$

Step 9: Estimate travel time reliability for each OD using the following equation:

$$R_{t_w} = \frac{Number\ of\ Acceptable\ states\ (satisfying\ T_w \leq \lambda T_{w,0})}{Number\ of\ Total\ Generated\ States} \tag{2}$$

3. RESOURCE ALLOCATION PROBLEM FOR INVESTMENT ASSIGNMENT

After the problem statement and after choosing an appropriate method for approximating the reliability of the network, as important criteria to be controlled in decision-making, in section 3.1 the network improvement model is proposed. Solving the model, it is necessary to assign the demand to the network and to calculate the travel time of each OD. In this regard, Section 3.2 discusses the appropriate assignment method applied in this paper. Finally, Section 3.3 presents a solution algorithm for the proposed resource allocation problem.

3.1 Model formulation

Suppose each link has three modes of performance as follows:

1 - Normal: The link is not damaged and performs normally with its full capacity.

2 - Degraded: The link is damaged and performs with half the capacity.

3 - Failed: The link has failed totally and does not perform in the network anymore.

The performance function of each link is a discrete function reflecting the probability of occurrence of the above mentioned modes. These functions are determined considering the structural and operational state of links which would be case-dependant. In addition, suppose there is one level of investment available for each link. Investing on a link leads to performance function improvement. For example, a bridge which is rehabilitated can perform more reliably encountering a destructive event than in its current situation. Now the question to be answered is: which links of the network should be invested into so that the reliability measures were preserved in accordance with the predefined values. The problem is modelled as:

$$Minimize \sum_{i=1}^{n} I_i \theta_i \tag{3}$$

s.t.

$$R_{t_w} \geq \alpha \quad \forall w \in W$$

$$R_{c_w} \geq \beta \quad \forall w \in W$$

where:

R_{t_w} – travel time reliability of the origin-destination w;

R_{c_w} – connectivity reliability of the origin-destination w;

I_i – investment on link i;

W – set of all pairs of ODs in the network;

$\theta_i = 1$ if link i is invested into and 0 otherwise;

α – lower threshold of travel time reliability of OD pair w;

β – lower threshold of connectivity reliability of OD pair w;

i – each link of the network;

n – number of links of the network.

Note that the proposed model is in fact a bi-level model. In the upper level, it is to minimize the total investment required to improve the network so that the connectivity and travel time reliability of each OD reach at least the pre-defined reliability measures. As the travel time reliability depends on the demand assigned to each route, in the lower level, an appropriate assignment method is to be employed to specify each link flow. It should be noted that, in real circumstances each link of a transportation network may experience several different levels of service. Although in this study three modes for each link (normal, degraded and failed) have been assumed, the model is not dependent and limited to the number of modes assumed for each link in this paper.

Moreover, in a real network there can be more than one level of investment possible for each link. The presented model can be applied in such problems as well. It means that employing the model will determine how much resource should be assigned to which links to satisfy all the constraints in an optimized decision. Thus, the resource allocation model will be converted to a resource prioritization model without any change. In such cases, I_i shows the level of investment for link *i*.

3.2 Assignment method

As obligatory in the model, the investment on the network should be applied in such a manner that the connectivity and travel time be satisfied for all the ODs in the network. In order to approximate these reliabilities, as mentioned in Section 2.2, for each state it is necessary to assign the demand and then to calculate the travel time of each OD.

Accordingly, it is supposed that after an event occurs, the users are informed about which links have failed and which are still working. Although they know all the operating links that are not in their perfect (normal) situation; they do not have any information about other links that are operating in a degraded manner due to limited dissemination of exact information. Therefore, optimistically, they choose their route based on the shortest travel time of the working links hypothesizing that all of the links are still performing perfectly. Furthermore, all the users want to reach their destination in the shortest time possible. The free flow travel time of links has been assumed to be the base of specifying the shortest paths.

Apparently, the demand after a natural event is for emergency services and less than regular demand of the network. Furthermore, here the network is studied exactly after the occurrence of the disaster. In such cases, no equilibrium is expected due to the fact that the travellers have not enough time to get familiar with the degraded manner of the network and the equilibrium travel times as expected in long-run applications. Additionally, as mentioned, the emergency demand chooses the route based on their previous experiences while they are sure that they are not informed of the precise current situation of the links. Therefore, all-or-nothing method is employed herein as an appropriate method of assignment problem as the lower problem.

It should be noted that, although each user chooses her/his route based on the free flow travel times, the travel time they experience is different due to the following reasons:

1 - The congestion caused by other drivers choosing the same route.

2 - The degraded links included in the route which perform with their half capacity. Therefore, the route travel times should be determined considering the effect of congestion imposed to links. It is well-known that the travel time of each link is a function of the ratio of its volume to its capacity. This function is called volume-delay function. Here, the Bureau of Public Road link travel time has been applied:

$$t_{ij}(v_{ij}, c_{ij}) = t_{0i}\left(1 + a\left(\frac{v_{ij}}{c_{ij}}\right)^4\right) \tag{4}$$

where:

i – the link index;

j – mode of performance;

a – coefficient of (v/c);

c_{ij} – capacity of link i with mode performance j;

v_{ij} – flow of link i with mode performance j;

t_{0i} – free flow travel time of link i;

t_{ij} – travel time of link i with mode performance j;

Finally, the real experienced travel time of each OD is calculated as:

$$T_w = \sum_{i}^{i \in A_w} \sum_{j=1}^{J} t_{ij}\gamma_i \tag{5}$$

where:

T_w – travel time of origin-destination w;

t_{ij} – travel time of link i with mode performance j;

j – performance mode of links;

J – set of possible performance modes of links;

$\gamma_i = 1$ if link i performs in mode j and 0 otherwise;

A_w – the set of links forming the shortest path between origin-destination w.

3.3 Solution algorithm

The genetic algorithm is employed to find the optimized investment scenario because of its high performance in discrete integer problems (*Figure 2*).

In each generation, the fitness of each chromosome should be calculated using the travel time and connectivity reliabilities. Related steps are shown in the dashed box in *Figure 2*.

The fitness function is as follows:

$$Fitness = \begin{cases} M - \sum_{i=1}^{n} I_i\theta_i & \text{if constraints are satisfied} \\ 0.01 & \text{otherwise} \end{cases} \tag{6}$$

where:

M – a large number to convert the minimization problem to maximization one;

$\sum_{i=1}^{n} I_i\theta_i$ total investment for the concerned chromosome;

The algorithm will continue until convergence condition occurs. The answer shows the best combination of the links to be invested so that all constraints of the model are satisfied where the least number of links are chosen to be invested.

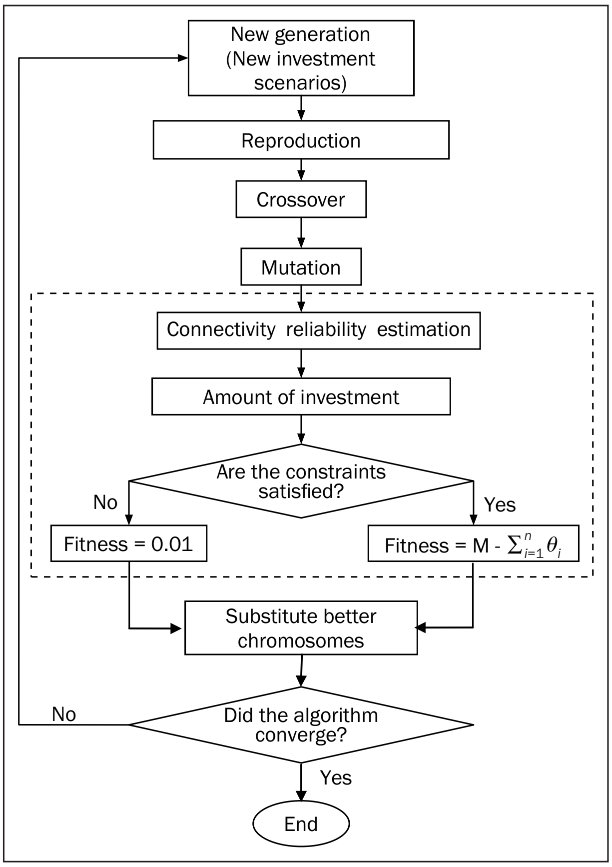

Figure2 - Adapted genetic algorithm as the solution for investment problem

4. NUMERICAL EXAMPLES

This section presents a numerical example to illustrate the proposed model. First, a small network (test network) is chosen and with several runs, mutation and crossover rates of the genetic algorithm are tuned. The best rates which lead to convergence to the optimum answer are determined 0.6 and 0.3 for crossover and mutation rate, respectively. These rates are then borrowed for the main network example as well. The well-known Sioux Falls network (*Figure 3*) is the next used in order to demonstrate the efficiency of the model for use in a real situation. Note that the adopted rates of GA in

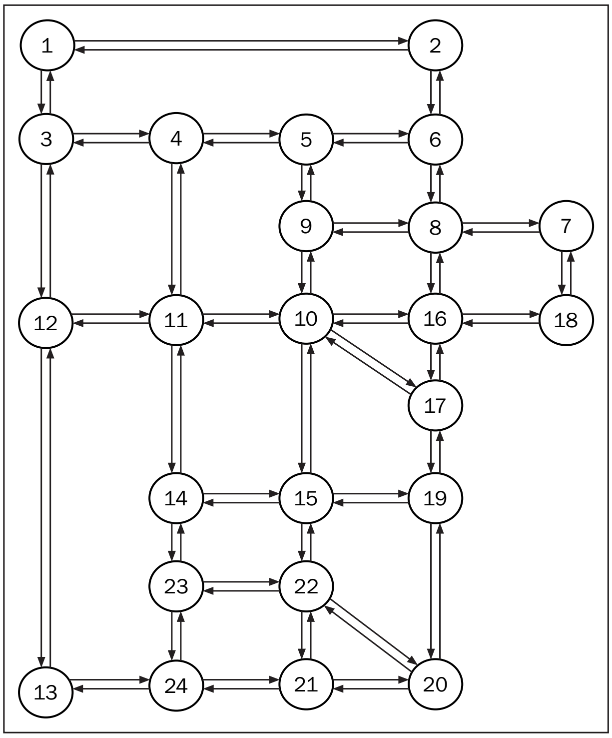

Figure 3 - Sioux Falls network

the first example are used for the second example as well.

As it is shown in *Figure 3*, all links are directed. Because it is very probable that an earthquake harms two sides of a road at the same rate, each pair of directed links are substituted by a two-way link. Therefore, the 76-link network decreases to a 38-link one which leads to an easier, quicker optimization process. Origins, destinations and the demand of each OD are given in *Table 1*. *Table 2* shows other specifications of the network including links ID, initial capacities, free flow travel times. Coefficient α in equation 4 is considered 0.15. *Table 3* shows the discrete performance function for links before and after the investment.

Here, $\lambda = 2.5$ and $M = 100$ is chosen. Minimum desired travel time and connectivity reliability, $\alpha = 0.85$, $\beta = 0.95$ are chosen, respectively. The genetic algorithm with pre-determined optimized rates and 20 chromosomes in each generation was employed. After 39 iterations, the algorithm reached the solution indicating that links (2, 4, 6, 9, 17, 19, 21, 23, 29, 30, 36, 38) must be invested into. This solution indicates the least investment required for satisfying all 60 constraints of the proposed model (30 for connectivity reliability and 30 for travel reliability of each 30 ODs).

As shown in *Table 4*, the connectivity reliability before investment varied between 79% in OD 2 to 86% in OD 29.

Optimal investment on 12 links (less than 30% of the total links of the network) leads to improvement of all OD connectivity reliabilities up to above 95% and even 99% for several ODs. In other words, after an earthquake, in the worst case, it is possible for an OD not to be connected by 5% at the most. This shows that there is a correlation between the connectivity reliability and the travel time reliability, as the optimal solution results in connectivity reliabilities to be greater than the minimum defined 95% (almost often near 99%) to satisfy the minimum travel time reliability of 85%. In other words, it is normally expected that the optimal solution should result in a minimum investment level so that the pre-defined 85% and 95% reliability levels are met; but, as seen in Tables 4 and 5, such a solution has not been obtained. The investment increased the travel time reli-

Table 1 - Origin-destinations and demands

OD#	Origin	Destination	Demand	OD#	Origin	Destination	Demand
1	1	4	4	16	13	23	2
2	2	4	2	17	15	10	2
3	4	1	2	18	15	12	2
4	4	2	2	19	15	13	2
5	4	10	2	20	15	18	2
6	4	12	3	21	15	20	3
7	10	4	2	22	15	23	3
8	10	12	2	23	18	10	3
9	10	15	4	24	18	15	2
10	10	18	3	25	20	15	3
11	12	4	3	26	20	23	3
12	12	10	3	27	23	12	2
13	12	23	2	28	23	13	2
14	12	15	2	29	23	15	2
15	13	15	2	30	23	20	2

Table 2 - Links specifications

Link ID	Free Flow Travel Time	Initial Capacity	Link ID	Free Flow Travel Time	Initial Capacity
1	6	25.9002	20	4	4.8765
2	4	23.4035	21	6	13.512
3	5	4.9582	22	8	4.9935
4	4	17.1105	23	2	5.2299
5	2	17.7828	24	4	23.4035
6	4	4.948	25	2	4.824
7	4	23.4035	26	3	25.9002
8	6	4.9088	27	5	5.1275
9	5	10	28	4	15.6508
10	2	4.8986	29	4	4.9248
11	10	5.0502	30	4	10.315
12	3	7.8418	31	4	5.0023
13	3	13.9158	32	4	5
14	5	5.0458	33	2	5.0785
15	2	23.4035	34	2	23.4035
16	6	4.9088	35	5	5.0757
17	5	10	36	4	5.0913
18	5	5.1335	37	3	4.8854
19	3	19.6799	38	6	5.0599

ability of each OD up to 89% through average 17% improvement.

Figures 4 and 5 show the improvement of connectivity and travel time in the network. *Figure 5* indicates well that a good investment can make a network more uniform in different parts by finding the weakest links and recovering the shortcomings of the network.

Table 3 - Performance function before and after investment

	Normal	Degraded	Failed
Before investment	0.50	0.25	0.25
After investment	0.90	0.07	0.03

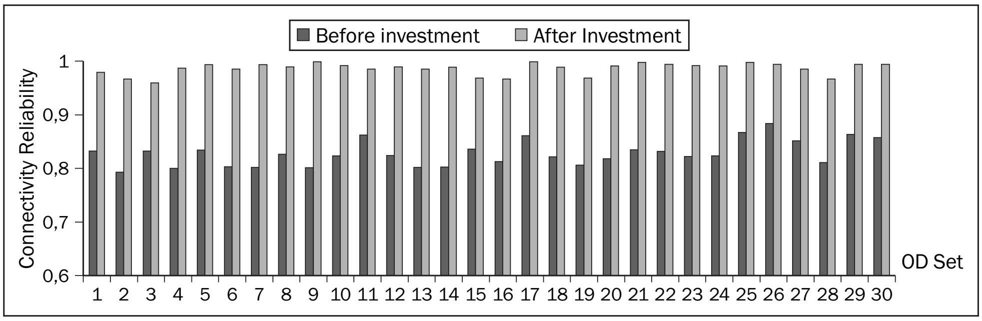

Figure 4 - Investment effects on connectivity reliability

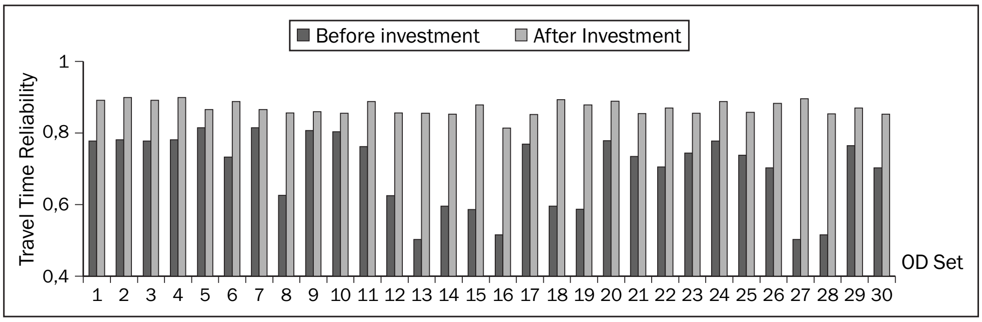

Figure 5 - Investment effects on travel time reliability

Table 4 - Investment effects on connectivity reliability

OD	Connectivity Reliability			OD	Connectivity Reliability		
	Before investment	After investment	Improvement (%)		Before investment	After investment	Improvement (%)
1	0.8325	0.9794	11.69	16	0.8124	0.9666	13.41
2	0.7932	0.9668	11.43	17	0.8613	0.9988	16.63
3	0.8325	0.9594	11.69	18	0.8214	0.9888	15.63
4	0.8002	0.9868	11.43	19	0.8061	0.9686	13.61
5	0.8344	0.9934	16.09	20	0.8182	0.9910	15.85
6	0.8033	0.9852	15.27	21	0.8345	0.9976	16.51
7	0.8020	0.9934	16.09	22	0.8316	0.9942	16.17
8	0.8263	0.9892	15.67	23	0.8221	0.9918	15.93
9	0.8012	0.9988	16.63	24	0.8231	0.9910	15.85
10	0.8235	0.9918	15.93	25	0.8671	0.9976	16.51
11	0.8622	0.9852	15.27	26	0.8836	0.9942	16.17
12	0.8241	0.9892	15.67	27	0.8516	0.9850	15.25
13	0.8021	0.9850	15.25	28	0.8110	0.9666	13.41
14	0.8022	0.9888	15.63	29	0.8636	0.9942	16.17
15	0.8361	0.9686	13.61	30	0.8575	0.9942	16.17

Table 5 - Investment effects on travel time reliability

OD	Travel Time Reliability			OD	Travel Time Reliability		
	Before investment	After investment	Improvement (%)		Before investment	After investment	Improvement (%)
1	0.7772	0.8910	11.38	16	0.5150	0.8536	29.86
2	0.7812	0.8990	11.78	17	0.7684	0.8520	8.36
3	0.7772	0.8910	11.38	18	0.5954	0.8928	29.74
4	0.7812	0.8990	11.78	19	0.5866	0.8786	29.2
5	0.8146	0.8650	5.04	20	0.7784	0.8884	11
6	0.7322	0.8878	15.56	21	0.7344	0.8540	11.96
7	0.8146	0.8650	5.04	22	0.7046	0.8694	16.48
8	0.6260	0.8562	23.02	23	0.7434	0.8552	11.18
9	0.8064	0.8596	5.32	24	0.7778	0.8882	11.04
10	0.8034	0.8552	5.18	25	0.7378	0.8578	12
11	0.7622	0.8878	12.56	26	0.7026	0.8826	18
12	0.6246	0.8556	23.1	27	0.5026	0.8952	39.26
13	0.5026	0.8552	35.26	28	0.5150	0.8536	33.86
14	0.5952	0.8526	25.74	29	0.7646	0.8694	10.48
15	0.5864	0.8786	29.22	30	0.7026	0.8526	15

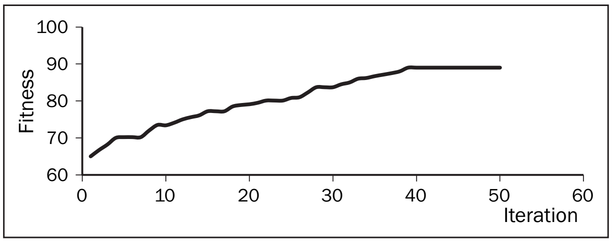

Figure 6 - GA convergence

Figure 6 shows how the GA algorithm improves the answer in each iteration and converges to the best scenario after 39 iterations.

5. CONCLUSION

The paper aimed to upgrade optimally a set of links in order to convert the current network to a more reliable one which will be expected to operate at a desired level of performance after a disaster occurrence.

In this regard, first, the connectivity reliability and the travel time reliability of each origin-destination were selected as performance measures of the network. Although these measures have been used previously in several studies, they have never been used simultaneously within a single framework. Then, a resource allocation model was proposed to select the optimal set of links to be upgraded through a proper investment to obtain a more reliable network in order that the selected measures (OD connectivity and travel time reliability) meet their minimum thresholds.

This study shows that it is possible to upgrade different parts of the network with different specifications and different levels of service, which may be performed by gradual expansion of the network over the years, to achieve the same pre-defined acceptable level of quality. This leads to a more uniform network operation. Applying a similar attitude in very limited accessible resource cases, it is possible to make the most important OD pairs reliable. The results show that there is a correlation between the connectivity reliability and the travel time reliability. Additionally, our algorithm assumes that the network component failures are independent of each other, while in real circumstances, the network components are usually correlated. These two sources of correlations can be considered as important issues for future research, in order to achieve more real solutions in investment decision-making problems.

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چکیده

ارائه مدلی جهت تخصیص سرمایه گذاري در شبکه حمل و نقل بر مبناي قابلیت اطمینان

در این مقاله، مدلی جهت تخصیص سرمایه گذاری به شبکه حمل و نقل جاده ای با در نظر گرفتن عدم قطعیت خدمت دهی کمان های شبکه ناشی از حوادث طبیعی ، ارائه شده است. حل این مدل مشخص می کند کدام کمان ها در شبکه در اولویت سرمایه گذاری قرار دارند به نحویکه سرمایه گذاری روی آن ها منجر به عملکرد بهتر سیستم در شرایط بروز حوادث طبیعی از جمله زمین لرزه می گردد. قابلیت اطمینان اتصال و دسترسی در هر زوج مبدا-مقصد به عنوان شاخص های کارآیی انتخاب شد و روش شبیه سازی مونت کارلو جهت برآورد قابلیت اطمینان و الگوریتم ژنتیک جهت حل نهایی مدل بکار گرفته شد. در نهایت در یک مثال عددی، مدل، در یک شبکه حمل و نقلي به کار گرفته شده است.

واژگان کلیدی
تخصیص سرمایه گذاري، قابلیت اطمینان زمان سفر، قابلیت اطمینان دسترسي، شبیه سازي مونت‌کارلو، الگوریتم ژنتيك

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