THE ALGORITHM FINDING OPTIMAL ROAD SECTIONS FOR THE INVESTMENT AGAINST DISASTERS UNDER THE BUDGET CONSTRAINT: A CASE OF ULSAN CITY IN SOUTH KOREA

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Abstract: There has been growing interest in minimizing damages by disasters, but the countermeasure in traffic engineering has been limited to the passive researches such as evaluating transportation network. The algorithm suggested by this paper was the active countermeasure to find directly the optimal road sections for investment against catastrophes using the optimization process and the simulation. This was composed of three modules such as scenarios, model, and aggregation. First, scenarios were made by the assumption of unusual behaviors under ‘life or death’ situation. Second, the object function using the number of dead people and the budget constraint were included into the optimization equation. Then, the results of iterated scenarios were aggregated to the best alternative, using the possibility of disaster occurrence. Lastly, it is applied using the network and production of Ulsan City in South Korea. The result of case study supported the usefulness and availability of this algorithm.

Key Words: countermeasure of disaster, optimal algorithm, network design

1. INTRODUCTION

1.1 Backgrounds & Objectives
Recently, there has been growing interest in minimizing damages caused by disasters such as an earthquake, a storm wave, a terrorist act, and so on. There are many countermeasures in some kinds of research areas, but one of important topics in traffic engineering study is to guarantee the escaping routes when a catastrophe occurs. Therefore, a vulnerability index was suggested by Erik Jenelius[1], and Jungyul Sohn[2] developed an accessibility index under the flood damage. However, these researches were just related with the evaluation of road network under sudden accidents, and did not find an active countermeasure such as suggesting the optimal escaping route, finding the priority investment road section, etc.
In addition, some structural techniques against earthquake have been studied nowadays. If these technologies were applied to all road networks, it could have not been better. However, there are two big obstacles in the actual world. One is that road networks except new planning cities were somewhat accomplished, and the other that a budget for construction of seismic structures is not limitless. Therefore, it needs the optimal strategy for investment.

Then, this paper aims at making not a passive but an active countermeasure, and setting up the optimal strategy for implementation of the structural technologies against disaster under a budget constraint. First, a scenario is assumed that a catastrophe happens, and MOE (a measure of effect) is determined. Then, the object function is set up using MOE under some assumptions such as budget and time constraint. Finally, the function applied to real network is solved using the minimum-path algorithm and the simulation technique. Then, the results of this process are the priority road sections for investment against disaster under a budget constraint.

**1.2 Contents & Scope**

An algorithm of this paper is composed of three parts: Scenarios, Model, Aggregation. First, some assumptions and scenarios are decided when a catastrophe happens, and the basic data such as O/D matrix, network investigated. Secondly, “do nothing scenario” that some road networks are randomly destructed are made, and “the optimal alternative in each scenario” which recoveries should be taken on “do nothing scenario” are searched using the optimization of the object function. Then, the results of each simulated scenario are aggregated, and “the optimal investment alternative” is suggested. Lastly, the case of Ulsan city in South Korea is explored by this algorithm.
Then, the time scope of this algorithm is from when breakdown of some road sections is occurs to when the second attack rises. The spatial boundary is the damaged area and the extrication point.

2. THEORETICAL REVIEW

There were some researches how to evaluate a road network in traffic engineering such as Erik Jenelius[1], Jungyul Sohn[2], Stephanie E. Chang[7] and so on. This kind of researches has been focused on the measurement of transportation system performance, and it needs to find how to use these evaluation methods actively. Thus, this paper aims to make an algorithm to find the optimal road sections for investment considering previous studies.

Jenelius[1] suggested the concept of ‘link importance’ and ‘site exposure’ to make operational measures. Those measures can be used as making rank of roads for maintenance and repair. Then, the measures were composed of ‘equal opportunities perspective’ and ‘social efficiency perspective.’ He considered the normal situation in ordinary times and Nicholson and Du(1994) and others suggested similar concepts. However, the scope of this paper is focused on the unusual case, disconnected roads and escaping from a disaster. Thus, in this paper, only ‘social efficiency perspective’ is applied because efficiently saving human-being life is most important in ‘life or death’ situation.

Jungyul Sohn[2] evaluated the significance of highway network links in Maryland under the flood damage using an accessibility approach. He suggested the methodology to evaluate road network by index including only distance or both distance and flow-rate. Then, he calculated and compared the accessibility index of two cases: before flood damage and after flood damage. However, he didn’t suggest how to deal with abnormal situations. Therefore, in this
paper, new index are developed using the minimum-path and the production of fugitives, and the methodology comparing before- and after-index are applied.

Moreover, there have been many researches about facility location and transportation network design related with this research, but they also have focused on the usual situation. The previous general approach is not proper to the unusual case, so this paper made new approach using a basic methodology in operation research area.

### 3. ALGORITHM

#### 3.1 Scenario

The scenario is made in order to make the extreme case under disasters, because the purpose of this algorithm is to find the priority road sections for investment against a catastrophe. That is to say, the function of this scenario is not a description of the real world but a model to evaluate the alternatives against the destruction of road networks.

The first assumption is about the irrationality of human-being under a ‘life or death’ situation. It means that most of people use the minimum-path at the risk situation, though it is better that people uses the optimal path at the state of user equilibrium. Also, those people know the disconnected road on their way, so they change the minimum-path considering the disconnected link.

Then, it is assumed that the first attack destroys some parts of road network, and the second attack is powerful enough to ravage all sections. Therefore, all the people in the damaged area should escape from this district. The time between the first and the second, is defined “the escaping time” and those who can’t escape in the escaping time are dead.

Some network index such as total time, total length, average time per person, average length per person, the quantity of damage, has the possibility to be MOE(measure of effect). However, under the disasters, a human life should be the first consideration. That is why the number of people who can escape under the scenario is chosen as the MOE of this algorithm.

#### 3.2 Model

The objective function is constructed as in Equation (1). This equation finds the link set to maximize the difference of dead people, who can’t escape in the escaping time, between before-countermeasure and after-countermeasure under budget constraint.

\[
\text{Maximize } Z = \sum_i \sum_f f_{ij}^b \delta_{ij}^b - f_{ij}^a \delta_{ij}^a
\]

Subject to

\[
t_{ij}^a \geq T
\]

\[
t_{ij}^b \geq T
\]

\[
\sum_i \sum_j c_{ij} v_{ij} \leq C
\]

Where,

\[
T = \text{Escaping constraint time}
\]

\[
b = \text{Before countermeasure}
\]

\[
a = \text{After countermeasure}
\]
Flow rate from i to j link
\( f_{ij} \)

Time from starting point to escaping point
\( t_{od} \)

Budget constraint
\( C \)

Countermeasure cost from i to j link
\( c_{ij} \)

Disconnected links set
\( D \)

\( \delta_{ij} = 1 \) if link ij is a part of path od, and \( \delta_{ij} = 0 \) otherwise.

\( \nu_{ij} = 1 \) if link ij is a part of path set D, and \( \nu_{ij} = 0 \) otherwise.

3.3 Aggregation of Scenarios
The best alternative set is decided from the object function in each scenario, so it needs to aggregate these results. The breakdown of road section is randomly distributed, so each scenario has the different disconnected link set extracted from the investigated breakable links. Therefore, in each scenario, results are changed, and the aggregation of results needs to find the final optimal roads for the investment.

The strategy using the possibility weight is suggested in this paper, in order to find the best aggregated set as in Equation (2).

First, the possibility (not probability), as which scenario i happens among the disconnected road sets, is applied to the weight for scenario i. This value is calculated by the past statistic data, the similar region data, or the investigation of the road endurance data. In the case study, the road data was used to find the possibility i. In order to make the road endurance data to the possibility i, the each endurance data were collected, and the distribution was estimated from that, and the possibility i was extracted from the distribution.

Secondly, the weight value, \( E_i P_i \), is calculated, and the best alternative sets of each scenario are collected and sorted as the candidate set.

Then, the object function value of every subset of the candidate set is calculated to find the best alternative set (\( B' \)).

\[
\text{Maximize} \quad Z = \sum_i \delta_i E_i P_i \quad (2)
\]

Where,
- \( \delta_i = 1 \) if \( B_i = B' \), and 0 otherwise
- \( B' \) = Best alternative of this algorithm
- \( B_i \) = Best alternative in scenario i
- \( E_i \) = Escaping people in scenario i
- \( P_i \) = Possibility for scenario i to come true

4. RESULT (A CASE OF ULSAN CITY IN KOREA)

4.1 Data Description
The O/D and network data of the case study is from the data of Ulsan city in South Korea that was investigated in the report, “Road Maintenance Plan of Ulsan City, Ulsan City, 2003.” In the case of escaping, there is no attraction because no people go to the risk area, so only the
value of production is included. Then, the value of that index is assumed as the number of household, for all the people of the same house escape at the same time using the same car. The network is composed of 58 ordinary zones, 11 escaping zones, 593 nodes, 1709 links. The index number and XY coordinates are included to the data of Zone and Node, and “From-node number”, “To-node number”, “Length”, “Lane”, “Delay Function(BPR function)” and “Capacity” are recorded in the data of link.

When the disaster occurs, there exists also traffic flow on the road link, so the default link flow rate is assumed as 30% of the link capacity. Then, the rank of roads is meaningless in the case of escaping from the disaster, and the escaping speed of all roads is calculated using the BPR Function of the connection road, the lowest rank of road function set. Lastly, the escaping time is determined as 0.5 hour considering the assumed average time delay of the second attack from the first.

Then, 200 scenarios were simulated, and from 20 to 30 links, which are included to the major roads and are easy to break down by an earthquake, were randomly disconnected in each case. After that, eight links, which are major bridges of Ulsan City, were included to the recovery set. In case of all scenarios, it was assumed that the budget constraint was 100,000,000(won), and the recovery cost was 100,000,000(won/km).
Table 1 Recovery Candidate Link

<table>
<thead>
<tr>
<th>Index</th>
<th>From</th>
<th>To</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3991</td>
<td>3946</td>
<td>0.52</td>
</tr>
<tr>
<td>2</td>
<td>3984</td>
<td>3957</td>
<td>0.36</td>
</tr>
<tr>
<td>3</td>
<td>3975</td>
<td>3999</td>
<td>0.38</td>
</tr>
<tr>
<td>4</td>
<td>1310</td>
<td>3988</td>
<td>0.55</td>
</tr>
<tr>
<td>5</td>
<td>3946</td>
<td>3991</td>
<td>0.52</td>
</tr>
<tr>
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<tr>
<td>7</td>
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<td>3975</td>
<td>0.38</td>
</tr>
<tr>
<td>8</td>
<td>3988</td>
<td>1310</td>
<td>0.55</td>
</tr>
</tbody>
</table>

4.2 Result

The final result of this algorithm is the best alternative link set to make an investment against a catastrophe, and the intermediate result is the candidate link sets. In order to validate the object function value, differences between total time-differences and object function values before and after countermeasures in each scenario were compared (Figure 4.) The unit of the function was 100 persons, and that of time is minute. The graph of Figure 4 showed that the total time difference has no relation with the object function value. It means that the total time difference can’t be the index to evaluate transportation network performance conceptually. Furthermore, the distance sum of minimum path, the average travel time which is represented by the total time are not able to express the efficiency of countermeasures.

Then, the original value of the function and the weight value by the possibility to take place were compared in Figure 5, and unit was percent which meant the difference divided by the weight value. Also, the original values were larger than the weight values because the possibility was set up from 0 to 1 like probability. The difference percent was between 0% and 9%, and it explained that the possibility of occurrence could change the result of the original value. Thus, the logical distribution of the possibility should be set up for this algorithm to be available.
At last, the results of this algorithm are given in Table 2, and the best alternative links are illustrated in Figure 5. There were the 5 candidate link sets although this algorithm was iterated by 200 times. It was caused by existence of the budget constraint and definition of the major roads to be managed. The aggregation results showed that the forth candidate link set was the best alternative, which consisted of link 2, link 3, link 6, and link 7 in Table 1, and also in Figure 5.

Table 2 Recovery Candidate Link Set and Aggregation result

<table>
<thead>
<tr>
<th>Index</th>
<th>Link Index</th>
<th>Aggregation Result (persons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>5</td>
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<td></td>
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<td></td>
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<tr>
<td>2</td>
<td>4</td>
<td>2</td>
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<td></td>
<td>8</td>
<td>6</td>
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</tr>
<tr>
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<td>8</td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

Figure 5 Comparison between the object function value and the possibility weight value
5. DISCUSSION

This algorithm has three modules: Scenarios, Model, Aggregation. That makes it flexible to variable situations especially under breakdown of roads by a disaster. Moreover, the concept of this algorithm, which governs each module of this method, is minimizing damages of escaping persons in a point of the social optimization’s view and the optimization of investment under budget constraint.

The general concept of network design and evaluation assumes both the social optimization and the state of user equilibrium, but the behavior of people changes under catastrophe. They do not have the opportunity that makes them experience under the state of user equilibrium, and they should escape in a given time. Thus, they use the minimum-path to the escaping gates, and the countermeasures for disasters are established on the social optimization concept. Then, in real world, there is always the budget constraint, so it must be considered importantly. Therefore, the budget constraint is included into the optimization equation with the escaping time.

A disaster occurs rarely, and breakable road sections are randomly destructed. Thus, the general approach about the normal network is difficult to apply to this situation, so this algorithm assumes the Catastrophe Scenarios. Then, the optimal alternative of each scenario are produced by the optimization model, and the each results are aggregated to the best alternative in a given network and productions. This process guarantees the most efficient investment alternative against unexpectedly damages.

The final result of case study produced the links in Figure 5 as the optimal road sections for investment. These links are two major bridges of Ulsan City among the candidate bridges, and
the production is aggregated densely near these bridges. Also, the position of these links is the central of the city, and the critical links of the minimum-path from south to north. These facts support the availability of this algorithm.

In conclusion, the above-mentioned the structure, the concept, the methodology, and a case study result seem to guarantee the usefulness and availability of this algorithm.

6. CONCLUSION AND RECOMMANDATIONS

This paper have made the algorithm to find the optimal road sections for investment against disasters and applied it to the real network and production of Ulsan City in South Korea. This algorithm consisted of three modules such as making scenarios, constructing the optimization function, aggregating the results, based on ‘social optimization of those who behave unusually’ and ‘the budget constraint.’ Each module supported the availability of this algorithm, and the case result produced the best investment alternative, which is reasonable. This algorithm is useful to decide the priority road sections for investment against disasters under the budget constraint.

However, there needs more researches about the characteristics of human-being under ‘life and death’ situation, the possibility of disaster occurrence, the integration of the real structural techniques, and the validity and applicability of this algorithm in other cases.

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REFERENCES


