Repair Crew Scheduling Considering Variable Disaster Aspects

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Abstract.
Human beings have suffered from disasters continuously, therefore, the post-disaster efforts to reduce additional damages have been widely conducted. In this study, we focused on the repair crew scheduling to set a plan for repairing destroyed roads. Rural areas were considered because of limited link members of supply chain networks, and rural isolation caused by road destruction is the main concern of this study. To reflect the intrinsic nature of a disaster in the short-term, additional damages and variable damage rates were considered. The repair crew scheduling problem considering variable disaster aspects was proposed to minimize total damages caused by isolation. A small-scale experiment was conducted and the result showed that our model can be used to effectively reduce further damages compared to previous research.

Keywords: repair crew; humanitarian logistics; relief scheduling; mixed integer program

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1 Introduction

Human beings have long suffered from catastrophes such as natural or man-made disasters. During the post-disaster period, disaster damages prevent rapid relief activities and it is generally complicated to recover damages [1]. Among disaster damages, especially in rural areas to which accessible routes are limited, road destruction is significantly fatal because roads are not only social support routes but also the supply routes for relief goods [2, 3]. Yan and Shih [2] focused on network repair and distribution of relief goods simultaneously. In the follow-up paper [4], they developed an ant colony system (ACS) algorithm to compensate for the limitations of previous studies. Duque et al. [5] developed the network repair crew scheduling and routing problem (NRCSRP) to minimize the weighted sum of total times for relief in isolated disaster areas.

However, previous research about repair planning has mainly focused on reducing the time to supply relief goods or initial relief without considering variable characteristic of the short-term situation. In the short period in post-disaster, damage conditions vary depending on types of disaster and recovery situations. For example, earthquakes cause not only immediate damages but also additional damages that develop over time [2, 6]. Damages also differ by type of disaster and the conditions where it occurs. Particularly in cases of casualties, appropriate action is required within a specific timeframe to prevent further damages. For these reasons, we developed a repair crew scheduling problem by extending the work of NRCSRP [5]. We propose the repair crew scheduling problem considering variable disaster aspects (RCSPVDA). We assumed that the damage patterns in different isolated areas follow different damage functions, and that a single supply hub and a single repair crew are assigned to all sites in the area. This model minimizes the sum of total damages caused by isolation conditions.

This paper is organized as follows: Section 2 introduces the repair crew scheduling problem and Section 3 illustrates the mathematical formulation. Section 4 presents the example of a small size problem. We provide a conclusion on this study in Section 5.

2 Model description

The model follows the definition similar to that provided by Duque et al. [5], and the mathematical formulation is based on that introduced by Duque et al. [7]. The road network is defined as an undirected network, $G(V, E)$. V is defined as a node set that includes damaged node set, V_r, and isolated node set, V_d. We assume that damaged nodes should be repaired by the repair crew. Passing through damaged nodes is impossible without repair. For damaged node $i \in V_r$, it take s_i unit times to repair. After repair, the node functions as a normal node. Without loss of generality, the definition of damaged nodes includes both destroyed roads and damaged areas. Before isolation conditions are resolved, victims in inaccessible areas are afflicted with lack of necessaries. Two main factors were considered to analyze total damages of isolated areas: (1) disaster damages from the initial and following disasters, (2) isolation damages caused by lack of accessibility preventing relief activities.

To consider the variable aspects of disasters in node $i \in V_d$, which is the main contribution of our study, we considered the golden time, g_i. The golden time is a given time bound within which an appropriate responsive management should be conducted. For instance, the golden time includes the last time to avoid additional disasters or to save lives from critical injuries. It is assumed that the golden time of each node is known. In addition, one-to-one correspondence between the golden time and an isolated node is assumed. If an appropriate action is not conducted to an isolated node until the golden time, extra disasters deteriorate the isolated node. Direct physical damages from disasters are denoted as p_i, such as earthquake or tsunami. As time goes by without being treated, we assume the damage increases linearly, but the rates of increment are different before and after the golden time. We assume that the damage rate before the golden time, w_i^1, is less than or equal to the damage rate after the golden time, w_i^2. Fig.1 illustrates cumulative damages before and after the golden time. Focusing on the discontinuity of the first graph, we can see that it implies the occurrence of the additional disaster after the golden time. The second graph shows the change of the damage rate after the golden time.

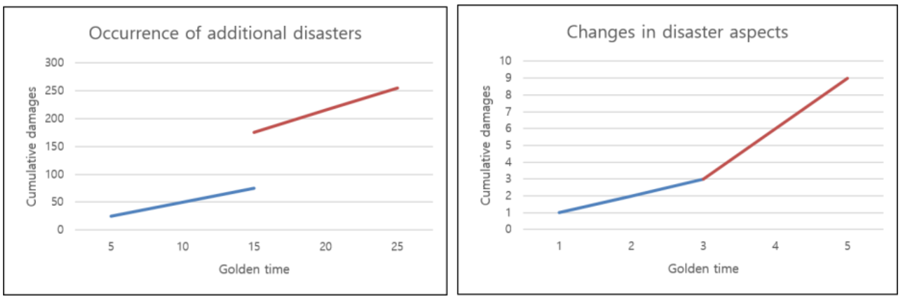

Fig. 1. Examples of cumulative damages with varying disaster aspects.

A supply hub denoted by ss is an origin node in which a repair crew begins his or her activities. Destination Node sd is a dummy node which indicates the repair crew has completed tasks; if the repair crew reaches the destination node, it implies that all the plan of the repair crew has been done. Fig. 2 represents an instance of a network with damaged nodes. It takes t_{ij} unit times for the repair crew to move from node i to node j, depicted between nodes in Fig. 2. The apparent structures of the original and model networks are not the same because damaged arcs in the original network were converted into damaged nodes in the model network. For example, Nodes 5 and 7 in the model network are identical to the damaged arcs in the original network. Depending on the conditions of nodes around, the undamaged nodes can be either accessible from the supply node or not. When all links of a node are damaged, the node is in isolation.

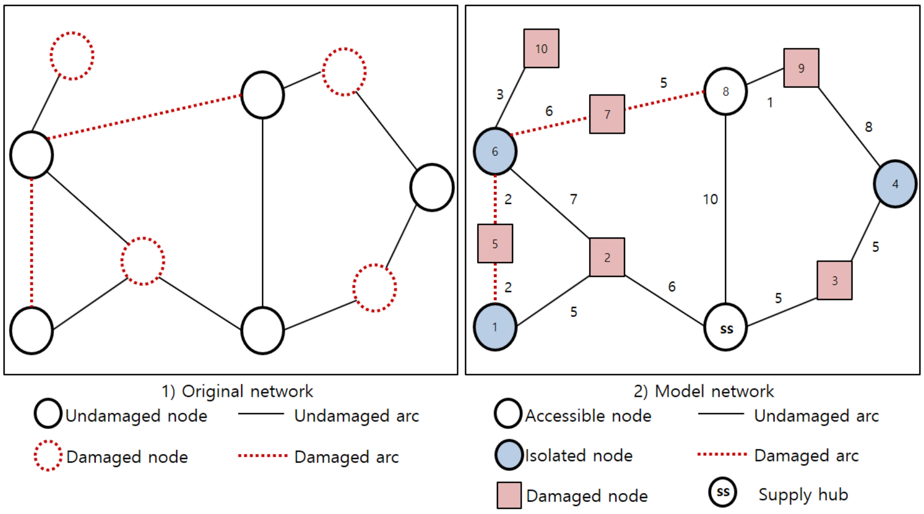

Fig. 2. Example of a damaged road network.

3 Mathematical formulation

Additional definition of sets, parameters, and decision variables are as follows:

Sets

A	Set of damaged node pairs (i,j); logically possible sequences of repairing nodes; $\forall i \in V_r + ss, \forall j \in V_r + sd, (i,j) \neq (ss,sd)$

Parameters

s_i	Repair time for damaged node $i, \forall i \in V_r$
F_i	Parameters for calculation; cumulative damage differences before and after g_i in node $i, \forall i \in V_d$; $F_i = p_i + g_i \cdot (w_i^1 - w_i^2)$

Decision variables

x_{ij}	1, if a repair crew repair moves to node j after repairing node $i, \forall (i,j) \in A$ 0, otherwise
r_{kl}^{ij}	1, if a repair crew moves from node k to node l when a repair crew moves to node j after finishing repairs at node $i, \forall (i,j) \in A, \forall k,l \in V$ 0, otherwise
a_k^{ij}	1, if a repair crew passes node k when a repair crew moves to node j after finishing repairs at node $i, \forall (i,j) \in A, \forall k \in V_k, k \neq i \neq j$ 0, otherwise
y_{kl}^{j}	1, if isolated node j, is linked to a supply chain with road from node k to node l, $\forall\, j \in V_d, \forall k,l \in V$ 0, otherwise
b_k^{j}	1, if isolated node j, is linked to a supply chain with passing node $k, \forall j \in V_d, \forall k \in V$ 0, otherwise
c_i	1, if additional disasters occur in node $i, \forall i \in V_d$ 0, otherwise
z_i	Time when node i is repaired, $\forall i \in V$
u_i	Time when isolated node i is linked to the supply chain, $\forall i \in V_d$
v_i	Time when a repair crew arrives at damaged node i before it is repaired, $\forall i \in V$
d_i	Total damages in node $i, \forall i \in V_d$

We include a part of our formulation, and the formulation was based on the previous research [7]. The mathematical formulation is as follows:

Minimize $\sum_{i \in V_d} d_i$ (1)

Subject to

$$\sum_{i \in V} x_{ssj} = 1 \qquad (ss, j) \in A \qquad (2)$$

$$\sum_{i \in V} x_{isd} = 1 \qquad (i, sd) \in A \qquad (3)$$

$$\sum_{i \in V, (i,j) \in A} x_{ij} = \sum_{k \in V, (j,k) \in A} x_{jk} \qquad \forall j \in V_r \qquad (4)$$

$$\sum_{i,j \in V, (i,j) \in A} x_{ij} = |V_r| + 1 \qquad (5)$$

$$\sum_{k \in V} r_{ik}^{ij} = x_{ij} \qquad \forall i, j \in V, (i,j) \in A \qquad (6)$$

$$\sum_{k \in V} r_{kj}^{ij} = x_{ij} \qquad \forall i, j \in V, (i,j) \in A \qquad (7)$$

$$\sum_{k \in V} r_{kl}^{ij} + \sum_{m \in V} r_{lm}^{ij} = 2 \cdot a_l^{ij} \qquad \forall i, j, l \in V, (i,j) \in A, \; l \neq i \neq j \neq sd \qquad (8)$$

$$z_i + \sum_{k,l \in V} t_{kl} \cdot r_{kl}^{ij} + M \cdot (x_{ij} - 1) \leq v_j \qquad \forall (i,j) \in V, (i,j) \in A \qquad (9)$$

$$v_i + s_i = z_i \qquad \forall i \in V_r \qquad (10)$$

$$z_k + M \cdot (b_k^i - 1) \leq u_i \qquad \forall i \in V_d, \forall k \in V_r \qquad (11)$$

$$z_k + M \cdot (a_k^{ij} - 1) \leq z_j \qquad \forall i, j \in V, \forall k \in V_r, (i,j) \in A \qquad (12)$$

$$u_i - g_i \leq M \cdot c_i \leq M + u_i - g_i \qquad \forall i \in V_d \qquad (13)$$

$$w_i^1 \cdot u_i \leq d_i \qquad \forall i \in V_d \qquad (14)$$

$$w_i^2 \cdot u_i + F_i + M \cdot (c_i - 1) \leq d_i \qquad \forall i \in V_d \qquad (15)$$

The objective function (1) minimizes the sum of total damages in isolation. Constraints (2) to (5) define the flow of the repair crew. Constraints (6) to (8) denote the routes of the repair crew. Note that flow constraints related to isolated nodes are excluded because they are similar to those of the repair crew. The detailed information can be referred to [7]. Constraint (9) restricts the arrival time of the repair crew to the next damaged node and Constraint (10) denotes the time to finish repairing a damaged node. Constraint (11) ensures the time to link an isolated node i to other nodes. Constraint (12) enforces the time sequence to repair a damaged node. Constraint (13) ensures the case which an isolation time of node i is greater than the golden time. Constraints (14) and (15) denote total damages when an isolated time of node i is less or greater than the golden time, respectively.

4 Small-scale example

A small-scale example and solution is presented to help explain the proposed model. We used the same network shown in Fig. 2. Ten nodes are in the network; however, we need to add a dummy node, sd. For this reason, the network node set is $V = \{0, \dots, 11\}$. Nodes 2, 3, 5, 7, 9, and 10 are damaged nodes, therefore, $V_r = \{2,3,5,7,9,10\}$. In addition, Nodes 1, 4, and 6 are isolated nodes; $V_d = \{1,4,6\}$. We set the repair times for damaged nodes as 6, 5, 3, 2, 7, and 4, respectively. Likewise, we also set parameters related to isolated nodes as follows: $w_i^1 = \{5,3,2\}, w_i^2 = \{6,5,3\}, p_i = \{0,100,0\}$, and $g_i = \{20,25,15\}$. To explain the difference between the NRCSRP and the RCSPVDA, experiments were conducted under the same conditions. However, the NRCSRP did not take into account w_i^2, p_i, and g_i. Therefore, the solution for the NRCSRP may not be competitive if disaster rates are different before and after the golden time. The damaged nodes directly related to isolation damage are 2 and 3. Therefore, the problem is the same as if we were prioritizing the two nodes. After repairing these two nodes, which means that the isolated nodes are linked to the supply chain, the way to repair the remaining damaged nodes is arbitrarily chosen because the choice of order does not cause additional damages.

The optimal routes of the NRCSRP was 0-2-0-3 and that of the RCSPVDA was 0-3-0-2. The detailed results of the experiment in terms of damages caused by isolation are presented in Fig. 3. Under static damage conditions, the solution of the NRCSRP is logical because repairing damaged Node 2 links isolated Nodes 1 and 6 to the supply chain, and the sum of their damage rates is 7, which is larger than the damage rate of isolated Node 4. The repair crew arrived to Node 2 at time 6, and it took 6 unit times to repair the node. Therefore, both isolated Nodes 1 and 6 were linked to the supply chain at time 12, and the cumulated damages were 120 ((5+3+2)×12). The operation of the repair crew was ended after linking Node 5 to the supply chain at time 28 with the total damages 168 (120+16×3). On the other hand, under the routes 0-3-0-2, Node 5 was linked first at time 10, and then, Nodes 1 and 6 were linked at time 27. The total damages of the routes 0-2-0-3 (168) were much lower than that of the routes 0-3-0-2 (219). In contrast, under variable disaster conditions, the situation can be the opposite as those of the static situation. Although the damage rate in the isolated Node 4 was lower than the sum of damage rates of the others, the isolated node has the highest priority because additional detrimental events were predicted that would be unavoidable unless the node was treated first. It can be seen that cumulative damages dramatically increased at time 25 under the routes 0-2-0-3, and direct disaster damages could be avoided under the routes 0-3-0-2 with relatively high isolation damages; the isolation damage rate of Nodes 6 and 1 increased at times 15 and 20, respectively. Therefore, the routes of the repair crew schedule in the RCSPVDA was 0-3-0-2. As a result, the total damages of the NRCSRP is 274 and those of the RCSPVDA is 238, showing that consideration of variable disaster aspects can help reduce further damages.

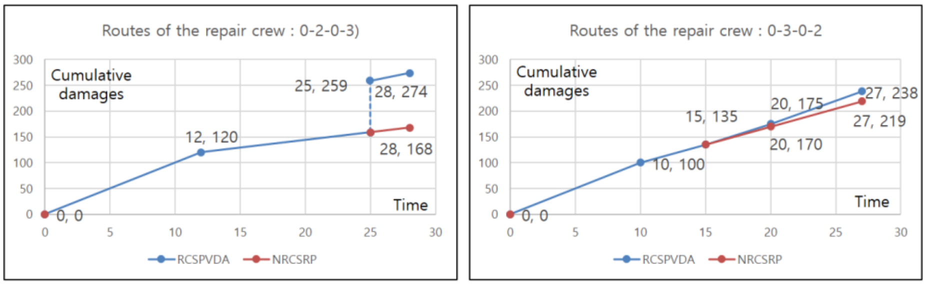

Fig. 3. Cumulative damages with respect to operation time in different routes.

5 Conclusion

We introduced a repair crew scheduling problem considering variable aspects of disasters. We assumed that disaster aspects in each isolated area can be changed after a certain time, and this point is the main contribution of our study. A repair crew who leaves at a supply node was delegated to minimize further damages in the post-disaster period. The small-scale example showed that the RCSPVDA can be effectively used to reduce disastrous damages. However, the mathematical model is limited to solve small-scale problems because of the complexity problem. Therefore, developing efficient heuristic algorithms are interesting research topics.

Acknowledgements
This research was supported by the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning [grant number 2015R1A2A1A15053948].

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