Reliable Transportation of Humanitarian Supplies in Disaster Response: Model and Heuristic

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Abstract

When a region is hit by a severe disaster, humanitarian supplies must be provided to victims/evacuees efficiently throughout the entire disaster and post-disaster periods. The emergency packages include but not limited to food, water, sanitation supplies, medicine, medical equipment, etc. Delivery of the humanitarian aids from suppliers to shelters must be done within certain time limits. Though helicopters are used for transporting a fraction of the daily requirements, the capacity of small aircrafts limits the throughput of this mode. Ground transportation modes are still playing a major role in the humanitarian logistics. Because of the severe weather during and after disaster, e.g. storm after hurricane or after-shock after an earthquake, it is common to have failures on the road and infrastructure, such as flooding, surface cave-in and sedimentation, which may delay the traffic or even make part of the network unusable. The expected reliability of a route is one of the main variables when planning a trip. The route choice coheres with the choice of the departure time to reach a destination in time with an acceptable probability. To increase the possibility of providing supply to evacuees under uncertainty without disruptions is a challenging problem. An efficient and reliable routing and scheduling model needs to be developed for both disaster and post-disaster conditions. In this study, we address a sub-problem of the general humanitarian supply-chain problem, which is the humanitarian response planning for a fleet of vehicles with reliability considerations. Routing and scheduling of humanitarian supply transportation is formulated as a mathematical model. To apply this routing and scheduling method in real operations with on-line information, efficient algorithms are necessary. A genetic algorithm based heuristic is proposed to solve the problem in reasonable computational time. The performance of the mathematical optimization model and heuristic algorithm are evaluated using test networks. The results show that the proposed approach can provide prompt delivery while reducing the risk of undesirable delay caused by uncertainty. The algorithm can provide high quality solution within short computational time to fulfill the on-line operation requirement.

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Keywords: Humanitarian response; Vehicle routing; Scheduling; Reliability

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1. Introduction

In the wake of devastating events such as Hurricane Katrina in the United States (2005), Earthquake in Haiti (2010), earthquake and tsunami in Indian Ocean (2004) and Japan (2011), planning for humanitarian supplies and response operations have largely been the concern of emergency management agencies. Under these severe disaster situations, deficiency in the flow of supplies may have direct consequences. Recent research in the humanitarian relief and development have put great emphasis on issues providing a more reliable, efficient logistic and information infrastructure that are best addressed through increased inter-agency cooperation. While a large body of the most recent research is focused on the preparation, planning of disaster evacuation and alleviation, little attention has been put on humanitarian response problem during and after disasters. Humanitarian response is the procedure in which the relief aids is delivered by agencies according to preset humanitarian principles. These agencies include government agencies as well as local and international non-government organizations. Humanitarian supplies can be categorized to urgent/immediate distribution, low priority distribution and non-priority items. For each supply priority and each agency, corresponding response strategies is needed.

Though helicopters are used for transporting a fraction of the daily requirements, the capacity of small aircrafts limits the throughput of this mode. Ground transportation modes are still playing a major role in the humanitarian logistics. Compared to traditional transportation problem, humanitarian response problem has its own features throughout the entire procedure. First, there is approximately no lead time in preparation stage. Second, the transportation on road is subject to high risk and low reliability due to sever climate or incomplete information of road condition. The impact of delivery is at high stakes, usually directly related to human lives and health. Selecting proper performance measures is another issue. As an example, when transporting medical supplies, the measures can be amount of delivery in a given time, reliability of the scheme, total cost of the transportation or the shortest time that the first batch is delivered. Selection of performance measures may depend on the applicable humanitarian principles and decision maker’s preference.

This paper focuses on routing and scheduling a fleet of trucks that transport high priority humanitarian distribution over an unreliable road network under different risk scenarios.

2. Problem Statement

To dispatch a disaster response fleet, there are multiple performance measures involved in making an optimal plan including cost, average response time, reliability, and the arrival time of the first truck. When complete information on road condition is available, finding optimal routing and scheduling plan for the humanitarian response problem is not very different from ordinary vehicle routing problems. However, due to the uncertainty in road conditions, if a particular segment of the route becomes partially or completely unusable, the response time may increases dramatically. In the sample network illustrated in Figure 1, two humanitarian response trucks need to ship medical supplies from origin node 1 to destination node 5. The length of each link is shown in Figure 1. When all the links are in good condition, the cost of path 1-2-4-5 is 3 and that of path 1-3-4-5 is 4. The decision maker can easily pick the shortest path for truck delivery. The problem becomes more complicated by considering probability of link failure. Such failure can be a result of disaster caused flooding, road sink, bridge collapse and etc. In the same network shown in Figure 1, link (2, 4) has a probability of failure equal to 0.5 and link (3, 4) has a failure probability of 0.2. Assume the link failure probabilities are independent and these failures cannot be identified in advance. When a truck identifies the link failure, it will go back to the precedent node and select another route.
In this example there are four scenarios corresponding to different combinations of road conditions. Table 1 demonstrates the probabilities and expected travel time for each truck under these four potential scenarios when path1-2-4-5 is taken (scheme 1). Table 2 shows the corresponding results when both truck are assigned to path 1-3-4-5 (scheme 2). Alternatively, when each truck is assigned to a different path (scheme 3), the corresponding calculation results are shown in Table 3. When there is at least one link in good condition, the expected response time under these three dispatching schemes are 3.9, 3.7 and 3.8 respectively. So does this mean that dispatching scheme 2 is superior? From a humanitarian response planner’s perspective, it is important to have the supplies delivered as soon as possible and it is also crucial to select a reliable dispatching scheme given all uncertainties. In this example, assigning two trucks to two different routes increases the chance for at least one truck to reach destination while the average response time for the whole operation is maintained. In this sense, the third dispatching scheme is more preferable.

Figure 1. A simple humanitarian response network

Table 1. Probabilities and Expectations of 4 Scenarios (Path 1Æ2Æ4Æ5 for 2 trucks)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Link(2, 4) Fails</th>
<th>link(3, 4) Fails</th>
<th>Probability</th>
<th>Expectation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>Yes</td>
<td>0.1</td>
<td>∞</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>No</td>
<td>0.4</td>
<td>(6, 6)</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>Yes</td>
<td>0.1</td>
<td>(3, 3)</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>No</td>
<td>0.4</td>
<td>(3, 3)</td>
</tr>
</tbody>
</table>

Table 2. Probabilities and Expectations of 4 Scenarios (Path 1Æ3Æ4Æ5 for 2 trucks)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Link(2, 4) Fails</th>
<th>link(3, 4) Fails</th>
<th>Probability</th>
<th>Expectation</th>
</tr>
</thead>
<tbody>
<tr>
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<td>∞</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>No</td>
<td>0.4</td>
<td>(4, 4)</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>Yes</td>
<td>0.1</td>
<td>(5, 5)</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>No</td>
<td>0.4</td>
<td>(4, 4)</td>
</tr>
</tbody>
</table>
Table 3. Probabilities and Expectations of 4 Scenarios (2 routes for 2 trucks)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>link(2, 4) Fails</th>
<th>link(3, 4) Fails</th>
<th>Probability</th>
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<td>No</td>
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<td>0.1</td>
<td>(3, 5)</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>No</td>
<td>0.4</td>
<td>(3, 4)</td>
</tr>
</tbody>
</table>

This study provides a solution for routing and scheduling a humanitarian fleet such that the expected response time is minimized while concurrent traversal of unreliable links is avoided. Similar to real world transportation networks, the links are assumed to have time dependent travel time.

3. Literature Review

Responding to the increasing occurrence of man-made and natural disasters, and on the perception that quality of relief is inadequate [1], more attention has been attracted to humanitarian response in order to improve the process of delivering aid [2]. The speed of delivery or responsiveness has been identified as a desired effect [3],[4]. Altay and Green [5] conduct a literature survey and identify some directions of future research. Humanitarian response problem can be deemed as a special type of shortest path problem with multiple objectives and specific requirements. There are not many publications dedicated to humanitarian response. However while considering reliability in the operations, research in hazmat transportation can be both relevant and useful due to similarity in accounting for risk in route and schedule design process.

Authors of [6] formulate a multi-objective problem of minimizing risk and cost and distributing risk equitably for a hazmat transportation problem and a set of Pareto-optimal solutions is determined. Weather condition was considered in hazmat transportation as well [7]. The impact of weather systems on hazmat routing by analyzing the effects of a weather system for a single link is studied [8]. Authors present an approach to find a least risk path for hazmat transportation on a network. In their heuristic, the dispatching scheme will be altered to avoid the weather system effects by parking at a strategic location or by using alternate links that are not influenced by the weather system. Similar ideas can be adopted in the humanitarian response problem. Berdica [9] further defines the vulnerability of the road transportation system in humanitarian response. Different from the traditional reliability assessment where reliability is only linked to the probability of failure, they define the reliability to be adequate serviceability under the operating conditions at a given time. Reliability of the transportation network should be a parameter in cost benefit analysis process [10]. The integration of reliability and vulnerability, costs and benefits to address the uncertainty in decision making is crucial in humanitarian response.

4. Mathematical Model

A mathematical optimization model is presented for solving the humanitarian response planning problem. Inputs to the model are the characteristics of the underlying network. As mentioned before, many performance measures for traditional commercial supply chains do not suit the distinct characteristics of the humanitarian supply chain. In this objective function addresses promptness and reliability of the transportation operations. The following measures are used in the modeling:

- Total transportation time of delivering humanitarian supplies; and
- Reliability of transportation scheme
In a time dependent directed network \(G(A, V, C(t), P(t))\), where \(A\) is the set of arcs, \(V\) is the set of vertices, \(C\) is the set of travel time on arcs at time \(t\) and \(P\) is the set of failure probability on arcs at time \(t\). Given the origins (locations of supplies) and destinations (locations of demands), to find the best routing and scheduling scheme; a mathematical formulation is presented based on the following assumptions:

- Both origin and destination for each truck are known.
- Humanitarian trucks are only allowed to wait on certain nodes.
- Population data which will be influenced by the humanitarian supplies are known.
- Failure probabilities of links in a given time interval are known.

Total cost is composed of three main parts:

1. Fixed cost: the cost to dispatch a truck. This part is not considered in the objective function since the number of trucks that need to be dispatched is known.
2. Travel cost: total travel time cost and travel distance cost usually are considered as travel cost. In this study, only total travel time cost is considered due to special nature of humanitarian response.
3. Reliability cost: the reliability cost is composed of two main parts:
   - a) Population that will be affected by the humanitarian supplies;
   - b) Sharing unreliable road: as discussed in previous section, when the road is under unreliable condition, routing multiple trucks on the same road intersection during the same time interval should be avoided.

Taking all the factors described above into consideration, the problem is formulated as a linear integer optimization problem.

**Notation**

**Sets**

- \(V\) : set of humanitarian trucks, \(k = 1, 2, \ldots, ||V||\)
- \(H\) : set of time windows
- \(N\) : set of nodes
- \(A\) : set of links
- \(O\) : set of origins
- \(D\) : set of designations

**Parameters**

- \(O_k\) : the origin of truck \(k\)
- \(D_k\) : the destination of truck \(k\)
- \(M\) : a large number
- \(c_{ijk}(h)\) : travel time of truck \(k\) from node \(i\) to node \(j\) in time window \(h\)
- \(TWE_h\) : starting time of time window \(h\)
- \(TWL_h\) : ending time of time window \(h\)
- \(POP_{ih}\) : aggregated affected population at destination \(i\) in time window \(h\)
- \(Prob_{sh}\) : failure probability of road link \(s\) in time window \(h\)
\( f_1, f_2 \): cost functions

\( p_{pop} \): penalty parameter of affected population

\( p_{prob} \): penalty parameter of failure probability

\( p_s \): penalty parameter of sharing unreliable road links in same time window

**Decision Variables**

\( X_{ijk} \): 1, if the truck \( k \) will travel from node \( i \) to node \( j \)

0, otherwise,

\( a_{ik} \): Arrival time of truck \( k \) at node \( i \),

\( R_{ik} \): Waiting time of truck \( k \) at node \( i \),

\( TWN_{ikh} \): 1, if truck \( k \) arrives at nodes \( i \) in time window \( h \)

0, otherwise

\( TWN_{ikh}^d \): 1, if truck \( k \) departure from nodes \( i \) in time window \( h \)

0, otherwise

\( TWA_{ukh} \): 1, if vehicle \( k \) travel on arc \( u \) in time window \( h \)

0, otherwise

\( TNE_{ikh} \): 1, if the arrival time of truck \( k \) at node \( i \) is later than the starting time of time window \( h \)

0, otherwise

\( TNE_{ikh}^d \): 1, if the departure time of truck \( k \) at node \( i \) is later than the starting time of time window \( h \)

0, otherwise

\( TNL_{ikh} \): 1, if the arrival time of truck \( k \) at node \( i \) is earlier than the ending time of time window \( h \)

0, otherwise

\( TNL_{ikh}^d \): 1, if the departure time of truck \( k \) at node \( i \) is earlier than the ending time of time window \( h \)

0, otherwise

\( S_{ih} \): 1, no less than 1 trucks stay on node \( i \) in time window \( h \)

0, otherwise

The formulation is presented as following:

Minimize \( f_1 + f_2 \) \hspace{1cm} (1)

Where

\( f_1 = \sum_k p_{prob}(a_{D_{ik}} - a_{O_{ik}}) \) \hspace{1cm} (2)

\( f_2 = \sum_{i \in D} \sum_{k \in V} \sum_{h \in H} TWN_{ikh} \cdot Pop_{ih} \cdot p_{pop} + \sum_{i \in A} \sum_{h} Prob_{ih} S_{ih} \) \hspace{1cm} (3)
Subject to:

Origin constraints:

\[ \sum_{j \in N - \{S_k\}} X_{S_{ik}k} - \sum_{j \in N - \{S_k\}} X_{jS_{ik}} = 1 \quad \forall \ k \in V \] (4)

Destination constraints:

\[ \sum_{i \in N - \{D_k\}} X_{id_{ik}} - \sum_{i \in N - \{D_k\}} X_{di_{ik}} = 1 \quad \forall \ k \in V \] (5)

Flow conservation:

\[ \sum_{i} X_{ijk} = \sum_{j} X_{jik} \quad \forall \ k \in V \ i, j \in N - \{S_k \cup D_k\} \] (6)

Arrival Time on node:

\[ M \cdot (1 - X_{ijk}) + a_{jk} - a_{ik} - c_{ijk} - R_{ik} \geq 0 \quad \forall \ k \in V \ i, j \in N \] (7)

\[ M \cdot X_{ijk} - a_{jk} \geq 0 \quad \forall \ k \in V \ i, j \in N \] (8)

\[ a_{ik} + R_{ik} + c_{ijk} - a_{jk} \geq 0 \quad \forall \ k \in V \ i, j \in N \] (9)

Find the time window when arriving on node:

1. Check the start point of time window

\[ a_{ik} - TWE_{ih} \leq M \cdot TNE_{ikh} \quad \forall \ k \in V \ i \in N \ h \in H \] (10)

\[ TWE_{ih} - a_{ik} \geq M \cdot (1 - TNE_{ikh}) \quad \forall \ k \in V \ i \in N \ h \in H \] (11)

2. Check the end point of time window

\[ TWL_{ih} - a_{ik} \leq M \cdot TNL_{ikh} \quad \forall \ k \in V \ i \in N \ h \in H \] (12)

\[ a_{ik} - TWL_{ih} \geq M \cdot (1 - TNL_{ikh}) \quad \forall \ k \in V \ i \in N \ h \in H \] (13)

3. Find the right time window which satisfying (10) to (13).

\[ TNE_{ab} + TNL_{ab} - 1 \leq M \cdot TWN_{ab} \quad \forall \ k \in V \ i \in N \ h \in H \] (14)

\[ 2 - TNE_{ab} - TNL_{ab} \leq M \cdot (1 - TWN_{ab}) \quad \forall \ k \in V \ i \in N \ h \in H \] (15)

Find the time window of the departure time

1. Check the start point of time window

\[ a_{ik} + R_{ik} - TWE_{ih} \leq M \cdot TNE_{ih}^d \quad \forall \ k \in V \ i \in N \ h \in H \] (16)

\[ TWE_{ih} - a_{ik} - R_{ik} \geq M \cdot (1 - TNE_{ih}^d) \quad \forall \ k \in V \ i \in N \ h \in H \] (17)

2. Check the end point of time window
3. Find the right time window which satisfying (16) to (19).

\[ TNE_{ik} + TNL_{ik} - 1 \leq M \cdot TWN_{ik} \quad \forall k \in V, \ i \in N, \ h \in H \]  

\[ 2 - TNE_{ik} - TNL_{ik} \leq M \cdot (1 - TWN_{ik}) \quad \forall k \in V, \ i \in N, \ h \in H \]  

Connection of node flow and arc flow

\[ Arc_{uk} - X_{ijk} = 0 \quad \forall \ k \in V, \ u \in A, \ i = Archead_{u}, \ j = Arctail_{u} \]  

\[ TWA_{ukh} - TWN_{ukh} = 0 \quad \forall \ k \in V, \ u \in A, \ i = Archead_{u}, \ j = Arctail_{u} \]

Penalty of Sharing the Segment:

\[ \sum_{k \in V} TWA_{ukh} - 1 < M \cdot S_{ukh} \quad \forall \ k \in V, \ u \in A, \ h \in H \]  

Equations (1) give the general format of the objective function. It is the weighted total cost which is composed of four parts: travel distance, travel time, risk exposure and risk accumulation costs.

Equations (2) to (3) describe the four cost functions considered in this model. The reliability cost is formed by the affected population on destinations nodes and the unreliable road sharing cost.

Constraints (4) to (6) satisfy the flow conservation at each node. Constraints (7) to (9) define the time dependant arrival time at each node. They are the translation of the relationship shown below in (25), which cannot be accepted by most optimization software.

\[ a_{ik} = \begin{cases} a_{ik} + R_{ik} + c_{ijk}(h) & \text{if vehicle } k \text{ will travel to node } j \text{ from } i \\ 0 & \text{otherwise} \end{cases} \]  

Constraints (10) to (21) provide the exact time window number of the arrival time and departure time at each node. Constraints (10) and (11) define all time windows whose start time is no later than the arrival time to be 1, and constraints (12) and (13) define all time windows whose end time is no earlier than the arrival time to be 1. Constraints (14) and (15) define a time window to be 1 when the arrival time 1 is between its start time and end time. Constraints (16) to (21) define the time window for each departure time. Constraints (22) and (23) connect the node information and link information. Constraints (24) define the penalty for sharing an unreliable link. Constraints (25) define the penalty index sharing intersection.

This mathematical model is solved to optimality using optimization software CPLEX for small size problems; however both problem size and running time significantly increase as the problem size increases.
5. Solution Algorithm

Humanitarian response in disaster situation as a problem of dispatching trucks via an unreliable network can be deemed as a special case of shortest path problem with multiple objectives. In this section a multi-objective routing algorithm to determine the path that minimizes both the travel time and the reliability cost is discussed. The problem is transformed to a single objective problem by introducing a set of weights. The underlying network is time dependent so a backtracking shortest path algorithm is applied for solving the routing part. In this approach Single trip scenarios are developed iteratively and intelligently to address the problem of multiple shipments. Output of the algorithm is routing and scheduling of a fleet of humanitarian trucks over the transportation network.

The routing algorithm is a modified version of Cooke-Halsey (1966) algorithm in which link weights are calculated dynamically based on a travel time function. When calculating the label for each node j, population of destination and the probability of failure of the candidate link at the potential arrival time as well as time-dependent travel time on link i-j are taken into account. A drawback to this method is the sensitivity of the solution to the weights assigned to objective function elements. We maintain two labels for each node, one label represents objective function value and the other label represents the earliest possible time of arrival at the node. The proposed algorithm to find the best route is as following.

5.1 Algorithm HRBP, G= (N, A)

Step 0:

\[
\begin{align*}
&f_{j0} = 0 \\
&f_i = \infty, \forall i \in N, i \neq i_o \\
&P = \{i_0\} \\
&T = \{\text{all } i \in N, i \neq i_o\} \\
&k = i_0
\end{align*}
\]

Step 1:

\[
\begin{align*}
&f_j = \min\{f_j, f_k + \lambda_1d_{kj}(\tau_k) + \lambda_2POP_D + \lambda_3Penalty_j(\tau_k + d_{kj}(\tau_k))\}, \text{update } \tau_j \\
&\tau_k = \text{Earliest arrival time at } k \\
&k = \arg\min\{f_j\}, j \in T \\
&P = P \cup \{k\}, T = T - \{k\} \\
\end{align*}
\]

where:

POP_j : population of the destination node

Penalty_j(t) : Penalty associated with failure risk of the link at time t

\(\lambda_1, \lambda_2, \lambda_3\) : parameter

Repeat step 1 until \(T = \emptyset\ and\ P = N\)

5.2. Link-Truck time window matrix

The time stamps that a humanitarian truck enters and exits each link are saved in a Link-Truck matrix. When routing and scheduling the next truck, the algorithm looks into this matrix to measure the time span in which the
new truck shares unreliable links with the previously routed ones. Each truck may have intermediate stops only at nodes and may not visit each node more than once. Every time that HRBP is solved for a truck, the corresponding column in the aforementioned matrix is updated based on the solution. Similarly, changes in truck schedule will be reflected in the relative cells.

5.3. Reliability penalty function

A main goal of this research is to analyze and model the problem in order to simultaneously decrease the total supply delivery delay and increase the reliability of routing plan. The objective function may be penalized for delay in delivering the supplies to the destination. Delay is measured by the difference between the shortest path travel time and the calculated path travel time. This penalty is imposed as people-minute affected by the delay and is a function of population of the destination. Another penalty is assigned to simultaneous presence of trucks on the links with high failure probability. The value of the penalty is calculated based on the probability of the failure and the number of trucks on the link. When the routing algorithm looks forward to pick up the next node, potential arrival time at the candidate node will be passed to the risk penalty function as a parameter to obtain the highest level of risk imposed by the previously routed trucks at that node. Penalty function performs a reliability assessment on the respective row in Link-Truck time window matrix and calculates the highest number of trucks sharing one unreliable segment. Based on the type of supplies and nature of the problem, this number is transformed into a penalty value using a penalty parameter. In a decision support system this penalty parameter may be used to tune the solution to the desired level of reliability. In simple words the higher the penalty, the higher the reliability. There is a trade-off between the level of reliability and total cost of the solution. This paper assumes that this transformation is exponential of degree $m$, which implies a road sharing of N trucks is $N^m$ times less desirable than a similar situation without road sharing. This penalty function can be tuned based on the nature of the problem and other regulations.

5.4. Rescheduling and rerouting

Origin, destination and departure time from origin are known for each truck. A path from an origin node to a destination includes several intermediate stops. It is assumed that a humanitarian supply carrier can have rest or delay only at nodes. Staying at a node extends the departure time of the truck at the corresponding node and consequently the total travel time.

Although the algorithm tries to avoid sharing unreliable road segment when solving the routing problem, the goal is not always achievable. Figure 2 demonstrates an example that both trucks are traveling from 1 to 2 with same departure time. In Figure 2.a no matter how much penalize is imposed on node 2 to avoid sharing road segment, it will be part of the solution, since there does not exist an alternative path. Even in the presence of alternative path, due to level of risk reflected in weighted objective function it may not be selected.

However changing the schedule of the second truck will simply solve the problem. Since the trucks will be having 30 minutes of overlap, had we delayed truck 2 for 30 minutes they would become 30 minutes apart from one another. Doing that, there is no more than one truck using the unreliable segment in that time window.

It is important to mention that rescheduling is not always cheap, because it comes at the cost of delay in delivering the supplies. It must also be seen as part of the big picture when inappropriate rescheduling at one node might cause trouble for upcoming links rather than helping it. Final solution for the single truck consists of the most desirable combination of departure time from each node and the route taken to the destination.
5.5. Heuristic approach

Given a time dependent transportation graph $G = (N, A)$, a population vector, a set of humanitarian supply trucks $V$, a set of OD pairs and a set of departure times, the heuristic finds a set of routes and schedules which minimizes the total travel time and the total population-minute delay in delivering the supplies while maximizing the reliability of the operations. It uses HRBP routing algorithm combined with the scheduling technique discussed earlier. The parameters in the model include the weight coefficients of travel time, population and penalty of the low reliability.

**Step 0: Initialization**
- Set Link-Truck time window, Penalty weight

**Step 1: select an OD pair from OD set**
- Mark OD as selected
- Assign a truck $V$ to the OD
- Set truck departure time
- Call HRBP algorithm ($V$)

**Step 2: for every link visited by $V$**
- Update $LTW_{n,v}$

**Step 3: While there is a sharing on unreliable road $>$ Max-Acceptable-Sharing-Level**
- Call rescheduling algorithm ($V$)

**Step 4: if all OD pairs are selected stop, else go to step 1**

5.5. OD pair ordering and optimization

In each step, the heuristic selects one OD pair and fixes the route and the schedule for the corresponding truck, and then moves to next OD pair until all pairs are done. The order in which trucks are chosen affects the final solution. In a fleet of $N$ trucks or $N$ origin-destination pairs, $N!$ different possible arrangements exist. The proposed heuristic is integrated with a Genetic Algorithm approach to determine the best arrangement. GA
encoding consists a set of chromosomes in which the value of gene i represents the priority weight of corresponding truck in the sorted OD list. The evaluation of each chromosome is done by running the heuristic using the encoded priorities. This allows revising the previously fixed routes and exploring all possibilities.

Priority weight \( w \) for truck \( i \) determines the rank in which truck will be routed.

\[
\text{The GA encoding:} \quad \begin{array}{c|c|c|c|c|c}
     & W_{i-1} & W_i & \cdots & \vdots & \end{array}
\]

Figure 3. Sample Network of a Disaster Area

6. Numerical Example

Figure 3 shows the layout of a sample disaster area. Shelters are located at nodes 4 and 8 and humanitarian supply depots are at nodes 13 and 15. The numbers on the links represent the probability of failure of the network segment and are assumed to be given. Historical data and topographical GIS maps may be used to assess the probability of failure of the road segments for different situations. Characteristics of the example network are given in appendix A. In this example it is assumed that two humanitarian trucks will be dispatched from each depot to each shelter, which makes a total of 8 trucks. This can be the case if each depot keeps certain type of humanitarian supplies, e.g. food or medicine. The problem is solved for different reliability scenarios. In the first scenario the objective is to minimize total time on network without considering the probability of failure. The next three scenarios represent the solution for different levels of reliability. By increasing the desired reliability level, trucks are routed in a way that sharing high risk segments by multiple trucks on the same time is not favoured. This can be achieved either by rerouting the trucks or by changing their departure time such that their
The simultaneous presence on the less reliable roads is minimized. Number of evacuees at shelter 4 and 8 is 2000 and 1000 respectively. The more the population in a shelter, the higher priority will be in humanitarian response. Table 4 shows the routing results for all the scenarios. In scenario I, the total travel time is 4683 units. When the reliability level increases, the concurrent traversal of multiple vehicles on less reliable links (with higher failure rate) is avoided. In scenarios 3 and 4, those links with higher failure rate are removed from the routing scheme. Though the total travel time increased, reliability of the dispatching scheme is improved. The algorithm supports real-time information. If in the middle of the transportation a road segment becomes unavailable or its failure probability increases the algorithm can optimize the partial solution for the rest of the operation.

Table 4. Heuristic Results of Numerical Example

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7. Conclusions and Future Research

This research, focused on reliable routing and scheduling of humanitarian supplies over a time dependant network. While minimizing the total travel time, sharing unreliable road segment is avoided to increase the reliability of the operations. By weighing the various components of cost involved in the operation, a mathematical integer programming model is developed to integrate routing and scheduling of the humanitarian trucks. For small networks, optimal solution can be provided by solving the mathematical model. A heuristic is proposed to deal with the large size problems. If time window interference exists, the algorithm decides whether to pick up a different route or resolve the problem by making stop at one of the intermediate nodes. The outcome is a scheduling and routing sequence. A genetic algorithm is used to optimize the OD pair ordering and ranking. A time-dependant shortest path based solution approach is embedded in this genetic algorithm for chromosome evaluation. The results show that the algorithm can provide good quality solutions for larger network and fleet size. The model and heuristic are flexible in accommodating multiple commodity and regulation parameters, which means each truck can have its own risk time window or parameter sets based on the commodity type on board.

Since the proposed heuristic uses a weighing approach to reduce multi-objective optimization problem to a single-objective version, it is highly sensitive to the weight parameters. An appropriate set of weights is needed through a comprehensive reliability assessment research and sensitivity analysis. In an interactive decision support system, the decision maker can tune the parameters to find desired routing and scheduling plan, according to the nature of humanitarian supplies and regulations.

References

[9]. Berdica, K. An introduction to road vulnerability: what has been done, is done and should be done, Transport Policy, 2002, 9: 117-127.
## Appendix A. Characteristic of the network

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