Dynamic Vehicle Routing for Relief Logistics in Natural Disasters

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1. Introduction

This chapter will introduce the dynamic vehicle routing problem for relief logistics in natural disasters such as earthquakes or typhoons. Natural disasters often cause huge fatalities and property damages. It is apparent that the coordinated and orderly delivery/pickup of available resources helps to mitigate property damages and save lives. Without performing quick and appropriate disaster relief logistics, the losses could be worsened. These relief resources, including food, water, medicine, and other equipment, may be misplaced at first due to the chaos and need to be rearranged in later time, according to the latest situation.

Disaster relief logistics using the vehicle routing approach has not attracted much attention and, hence, literature on this topic is relatively rare. Barbarosoglu et al. (2002) present a mathematical model for helicopter mission planning during a disaster relief operation. The decisions inherent in the problem decompose hierarchically into two sub-problems where tactical decisions are made at the top level, and the operation routing and loading decisions are made at the based level. Consistency between the decomposed problems is achieved with an iterative coordination procedure, which transfers anticipated information for the base level to improve the top-level decisions. The existence of conflicting objectives in this hierarchical structure requires the development of a multi-criteria analysis, and an iterative procedure is designed with top-level decision makers to assess the preference of alternative non-dominated solutions.

Mohaymany et al. (2003) propose a method to obtain the "emergency paths" that is based on two "life loss mitigation criteria". One is minimization of travel time between rescue and relief centers and the help-needing population, and the other is maximization of rescue and relief forces‘ service capability to all help-needing population. The main elements considered in the process of emergency paths selection include the highly populated areas and vulnerable and hazardous areas on the one hand, and rescue and relief centers on the other. The proposed path selection process is performed by using some developed computer programs in the GIS environment.

Özdamar et al. (2004) offer a planning model that is to be integrated into a natural disaster logistic decision support system. The model addresses the dynamic time-dependent transportation problem that needs to be solved repetitively at a given time interval during ongoing aid delivery. The model regenerates plans incorporating new requests for aid

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materials, new supplies, and transportation means that become available during the current planning time horizon. The plan indicates the optimal mixed pickup and delivery schedules for vehicles within the considered planning time horizon, as well as the optimal quantities and types of loads picked up and delivered on these routes.

Thomas and White (2004) analyze the problem of constructing a minimum expected total cost route from an origin to a destination that anticipates and responds to service requests if they occur while the vehicle is en route. This problem is modeled as a Markov decision process and several structured results associate with the optimal expected cost-to-go function and an optimal policy for route construction are presented.

Pettit and Beresford (2005) present research that proposes a refined model for logistics requirements in emergency conditions, taking account of existing response models, both military and non-military. The composite model appears to be robust and workable in a range of geopolitical and operational circumstances.

Yi and Özdamar (2007) describes an integrated location-distribution model for coordinating logistics support and evacuation operations in disaster response activities. The logistics planning considered involves dispatching commodities (e.g., medical materials and personnel, specialized rescue equipment and rescue teams, food, etc.) to distribution centers in affected areas and evacuation and transfer of wounded people to emergency units. The proposed model is a mixed integer multi-commodity network flow model that treats vehicles as integer commodity flows rather than binary variables.

Gong et al. (2007) consider ambulance allocation and reallocation models for a post-disaster relief operation. They formulate a deterministic model that depicts how a casualty cluster grows after a disaster strikes and consider the objective of minimizing the makespan to determine allocation and reallocation of ambulances.

A real-time time-dependent vehicle routing problem with time windows has been formulated as a series of mixed integer programming models (Chen et al., 2005), which provides some basic knowledge of this chapter. A clear definition of “critical node” is proposed, which defines the scope of the remaining problem along the time-rolling horizon. The concept of critical nodes distinguishes the real-time vehicle routing problem with time windows (VRPTW) from the traditional VRPTW to a high degree. A heuristic comprising route construction and route improvement is proposed. Following the same line, Chang et al. (2003) further extended an earlier version of their work to accounts for simultaneous delivery/pickup demands while neglecting time-dependent assumption of travel times.

In summary, in the disaster relief operations, the logistic coordinator may not be aware of all information for route scheduling at the time when the routing process begins. Dynamic information, including delivery/pickup demands and travel times, may change after the initial routes have been constructed, and such kinds of information are known only in a real-time manner. When a new demand appears, the main task of the logistics coordination center is to include the new demand into the current routing schedule. In addition, if travel times have changed due to an unexpected incident, in order to fulfill time window constraints and achieve a lower cost objective, scheduled routes must be re-scheduled based on the positions of the vehicles. The logistics coordination center needs an answer urgently in order to respond in real time to both the real-time demands and travel times.

2. Model formulation for disaster relief operations

In this chapter, the dynamic vehicle routing problem for relief logistics in natural disasters (DVRP-RL) is described as follows. The demands for relief goods, including delivery or pickup, may vary in real time and are probably unpredictable. The change of travel times may be predictable (e.g., recovery of a road, regulation of traffic, or recurrent traffic) or unpredictable, such as traffic incidents. The predictable travel time can be described as a function of "time of day" and the pattern of this function may change due to unpredictable incidents. At each demand site (or "node" in the following), several kinds of relief goods with different levels of emergency and deadlines are required and both delivery and pickup operations may be needed simultaneously. The excess relief goods or rescue equipment picked up at one site may be reused in any of the following sites of the same tour. For a quick response to future demands, a dispatched vehicle may not have to return to the depot unless it needs to be refilled with relief goods. It may wait at their last stop until they receive the next order from the logistics coordination center.

In order to capture the dynamic characteristics of the DVRP-RL, we adopt the concept in Chen et al. (2005) and formulate the DVRP-RL as a series of mixed integer programming models in the rolling time horizon. Each model represents a special VRPTW at a particular instant when travel times or demands have changed. Once a new demand appears or the travel time changes, the domain of the remaining problem should be redefined and the problem needs to be solved again. The concept of "critical node" is adopted to delineate the scope of the remaining problem along the rolling time horizon. A vehicle may depart from either the depot or the critical node and visit other unserviced nodes afterward. The goal of the model at any particular time instant τ is to find a set of minimum cost vehicle routes, which originate from the critical nodes or the depot, $N_c(\tau) \cup \{0\}$, and visit all other unserviced nodes, $N_u(\tau)$.

Figure 1 illustrates where the critical nodes is located. A critical node is defined as a node that is currently being serviced or to which a vehicle is heading. Once a vehicle has left a serviced node, the node will be removed from the planned route thereafter. Only unserviced nodes will be considered in the scheduled vehicle routes. Therefore, the critical node plays an important role in distinguishing between serviced nodes and unserviced nodes. Critical nodes need to be identified instantly when a real-time demand or travel time has changed so that the route can be reconstructed.

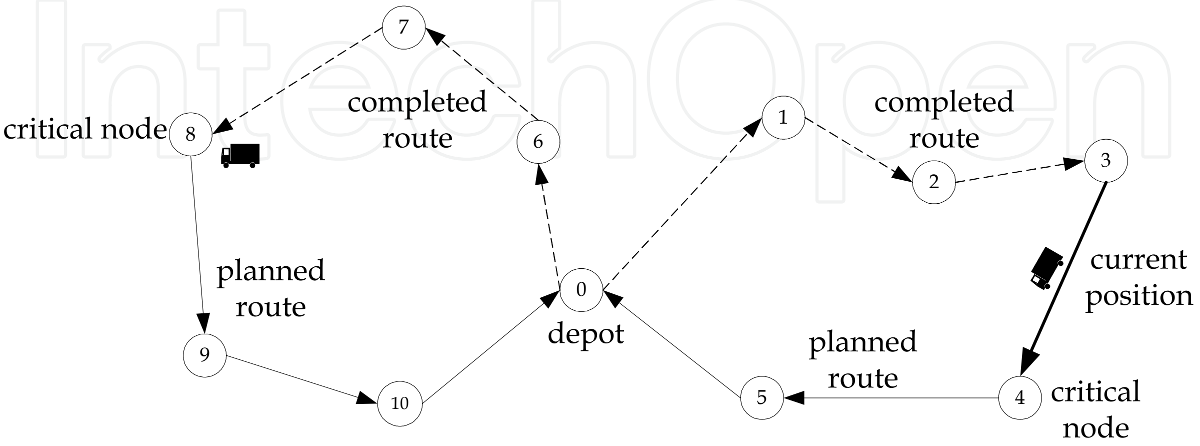

Fig. 1. Vehicle routes and critical nodes (Chen et al., 2005)

For ease of reference, notations are listed below:

Parameters and constants:

τ : time when real-time information (travel times or demands) occurs plus a small computation time

$c_{0j}(d_{0k})$: travel time between depot *0* and node *j* when vehicle *k* departs from the depot at time d_{0k}

$c_{ij}(d_i)$: travel time between nodes *i* and *j* at departure time d_i

C_k : full capacity of vehicle *k*

l_i : deadline at node *i*

q_{im} : delivery demand of commodity *m* at node *i*

$\hat{q}_{im}$: pickup demand of commodity *m* at node *i*

$\overline{Q}_{mk}$: total loads of commodity *m* for vehicle *k* when dispatching from the depot

$\overline{Q}_{mk}(\tau)$: remaining loads of commodity *m* for vehicle *k* at time τ

s_i : service time at node *i*

W_i : unit penalty of late arrival at node *i*

Sets:

{0} : depot

$N_c(\tau)$: set of critical nodes at time τ

$N_u(\tau)$: set of unassigned (or unserviced) nodes at time τ

$N_{cu}(\tau)$: set of critical nodes and unassigned nodes at time τ

$N_{u0}(\tau)$: set of the depot and unassigned nodes at time τ

$N_{cu0}(\tau)$: set of the depot, critical nodes and unassigned nodes at time τ

K : set of all vehicles, which is the union of two sets, i.e., in the depot and en route

$K_0(\tau)$: set of vehicles in the depot at time τ

M : set of all commodities needed in the disaster area

Variable:

a_i : time arriving at node *i*

d_i : time to depart node *i*

d_{0k} : time for vehicle *k* to depart from the depot

x_{ijk} : 1, if vehicle *k* departs node *i* toward node *j*; 0, otherwise

Q_{jmk} : remaining loads of commodity *m* when vehicle *k* arrives at node *j*

Whenever real-time demands have appeared or time-dependent travel times have changed, the submodel of DVRP-RL at this instant τ needs to be solved for an initial solution within a small computation time, which is very close to zero and will be neglected in the following. The submodel of DVRP-RL at time τ, denoted as VRP-RL, can be formulated as a mixed integer model, as follows:

$$\min_{\{x_{ijk}\}\in\Omega} z(\tau) = \sum_{j\in N_{u0}(\tau)} \sum_{k} \left(\sum_{i\in N_{cu}(\tau)} c_{ij}(d_i) x_{ijk} + c_{0j}(d_{0k}) x_{0jk} \right) + \sum_{i\in N_u(\tau)} W_i(\max(a_i - l_i, 0)) \quad (1.)$$

where Ω is the feasible region represented by the following constraints.

Flow conservation constraints:

$$\sum_{j}\sum_{k} x_{ijk} = 1 \qquad \forall i \in N_{cu}(\tau) \tag{2.}$$

$$\sum_{i}\sum_{k} x_{ijk} = 1 \qquad \forall j \in N_{u}(\tau) \tag{3.}$$

$$\sum_{i} x_{ihk} - \sum_{j} x_{hjk} = 0 \qquad \forall\, h \in N_{u}(\tau), k \in K \tag{4.}$$

$$\sum_{j} x_{ij\bar{k}_i} = 1 \qquad \forall i \in N_{c}(\tau) \tag{5.}$$

$$\sum_{j} x_{0jk} \le 1 \qquad \forall k \in K_{0}(\tau) \tag{6.}$$

$$x_{ijk} \in \{0,1\} \qquad \forall i \in N_{cu0}(\tau), j \in N_{u0}(\tau), k \in K \tag{7.}$$

Vehicle capacity constraints:

$$Q_{imk} \ge q_{im} \qquad if \quad \sum_{j} x_{ijk} = 1 \qquad \forall i \in N_{u}(\tau), m \in M, k \in K \tag{8.}$$

$$\sum_{m} (Q_{imk} - q_{im} + \hat{q}_{im}) \le C_{k} \qquad if \quad \sum_{j} x_{ijk} = 1 \qquad \forall i \in N_{u}(\tau), k \in K \tag{9.}$$

Definitional constraints:

$$a_{j} = d_{i} + c_{ij}(d_{i}) \qquad if \quad x_{ijk} = 1 \qquad \forall i \in N_{cu}(\tau), j \in N_{u}(\tau), k \in K \tag{10.}$$

$$a_{j} = d_{0k} + c_{0j}(d_{0k}) \qquad if \quad x_{0jk} = 1 \qquad \forall j \in N_{u}(\tau), k \in K \tag{11.}$$

$$d_{i} = \begin{cases} \max(\tau, a_{i} + s_{i}) & if \quad \sum_{k} x_{i0k} = 0 \\ \infty \quad if \quad \sum_{k} x_{i0k} = 1 & \end{cases} \qquad \forall i \in N_{cu}(\tau) \tag{12.}$$

$$d_{0k} = \tau \qquad \forall k \in K_{0}(\tau) \tag{13.}$$

$$Q_{jmk} = Q_{imk} - q_{im} + \hat{q}_{im} \qquad if \quad x_{ijk} = 1 \qquad \forall i \in N_{u}(\tau), j \in N_{u}(\tau), m \in M, k \in K \tag{14.}$$

$$Q_{jmk} = \overline{Q}_{mk}(\tau) - q_{im} + \hat{q}_{im} \qquad if \quad x_{ijk} = 1 \qquad \forall i \in N_{c}(\tau), j \in N_{u}(\tau), m \in M, k \in K \tag{15.}$$

$$Q_{jmk} = \overline{Q}_{mk} \qquad if \quad x_{0jk} = 1 \qquad \forall j \in N_{u}(\tau), m \in M, k \in K \tag{16.}$$

The objective of the VRP-RL, shown in Eq. (1), is to minimize the total travel time of all tours and the total penalty due to late arrivals. The unit penalty W_i reflects the relative importance of node *i* for late arrival. Eq. (2) requires that only one vehicle can leave a critical node or unserviced node *i* once. Eq. (3) denotes that only one vehicle can arrive at unserviced node *j* once. Eq. (4) states that for each unserviced node *h*, the approaching vehicle must eventually leave this node. Eq. (5) requires that vehicle $\bar{k}_i$, which has arrived at or is approaching a critical node, must also leave this node once. Note that vehicle $\bar{k}_i$ is known at time τ. Eq. (6) requires that each vehicle can leave the depot once at most. Eq. (7) designates x_{ijk} as a 0-1 integer variable. x_{ijk} equals 1 if vehicle *k* departs node *i* toward node *j*. Otherwise, x_{ijk} equals 0.

Eq. (8) indicates that if node *i* is serviced by vehicle *k*, i.e., $\sum_j x_{ijk} = 1$, then the remaining load of commodity *m* of vehicle *k* at node *i* must be greater than or equal to the demand of commodity *m* at node *i*. Eq. (9) indicates that if $\sum_j x_{ijk} = 1$, then the updated load of vehicle k at node i after delivery and pickup must be less than or equal to the full capacity of vehicle *k*.

Eq. (10) and Eq. (11) define the arrival time at node *j*. Eq. (12) defines the departure time at node *i*. If $i \in N_u(\tau)$ then the departure time is set as $d_i = a_i + s_i$. On the other hand, if $i \in N_c(\tau)$, two scenarios must be further considered. (i) If node *i* is not the last node, i.e. $\sum_k x_{i0k} = 0$, then the departure time is set as $d_i = \max(\tau, a_i + s_i)$. The only situation that the departure time will take on the value of τ is when the vehicle that is waiting at the last node *i* receives a new order from the logistic coordination center and must depart for the next node immediately. (ii) If node *i* is the last node, i.e. $\sum_k x_{i0k} = 1$, then the departure time is set as $d_i = \infty$, referring to infinity. This logical expression is meant that vehicle *k* can stay at the last node *i* until the next order from the logistics coordination center has been received. For those vehicles that have to return to the depot to refill, pickup demands at the depot will be virtually created for them. Eq. (13) defines the departure time at the depot. Eq. (14) states for unserviced node *i* that if vehicle *k* is heading to node *j*, then the remaining load of commodity *m* of vehicle *k* at node *j* will be equal to the updated load of commodity *m* minus the delivery and plus the pickup at node *i*. Eq. (15) is identical to Eq. (14) except that the unserviced nodes are substituted by critical nodes. Eq. (16) defines the initial load of commodity *m* for the vehicle *k* dispatched from the depot.

Note that with departure time set as $d_i = \infty$ in Eq. (13), link *i*→0 will never be traversed in the solution at this instant, and hence link travel time between any node *i* and the depot, $c_{i0}(d_i)$, should not be included in the objective function. Consequently, model (1) is naturally modified as follows.

$$\min_{\{x_{ijk}\}\in\Omega} z(\tau) = \sum_{j\in N_u(\tau)} \sum_k \left(\sum_{i\in N_{cu}(\tau)} c_{ij}(d_i) x_{ijk} + c_{0j}(d_{0k}) x_{0jk} \right) + \sum_{i\in N_u(\tau)} W_i(\max(a_i - l_i, 0)) \quad (17.)$$

3. Solution algorithm

We propose a two-phase heuristic comprised of routes construction and routes improvement for the DVRP-RL. For real-time operations, an anytime algorithm is desired. In other words, the solution procedure must have the ability to stop at any time and provide an acceptable solution. A unified solution procedure for the DVRP-RL is shown in Figure 2.

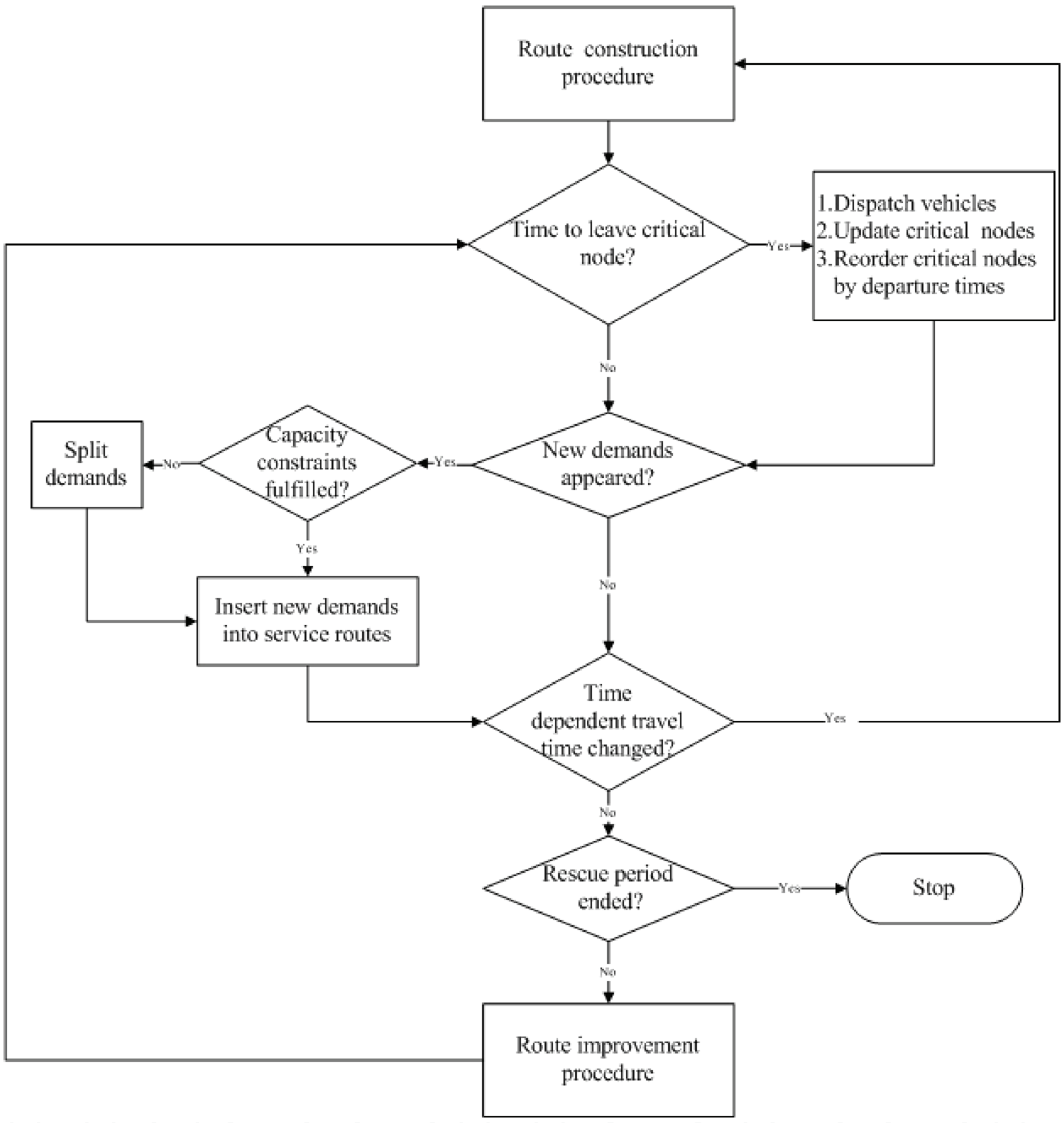

Fig. 2. Unified framework of solution procedure

The route construction and route improvement procedures are two major phases in the unified solution procedure. Between these two phases, we constantly check whether the following incidents happen.

i. Departure time of earliest critical node has arrived.
ii. New demand has appeared.
iii. Time-dependent travel time has changed.
iv. Disaster relief operation has ended.

The change of time-dependent travel times refers to the change of the travel time function, not merely current travel time itself. The operating maneuvers, such as dispatching en route or on-call vehicles to the next demand site, reconstructing routes, improving the quality of the existing routes, and so forth, are repeatedly applied. Note that the computation time allowed for route construction and improvement is usually short due to the requirement of real-time response. It is necessary to adopt a fast solution algorithm for use. In our solution procedure, the insertion method is used for route construction, while the Or-opt node exchange algorithm is adopted for route improvement.

For the VRPTW, the insertion method has been proven effective in constructing static routes (Solomon, 1987). So we adopted the insertion method with modifications for the DVRP-RL in the phase of route construction, as follows.

Step 1: Input data

Input real-time demands of each commodity $\left\{ q_{im}, \hat{q}_{im} \right\}$, deadlines $\left\{ l_i \right\}$, service times $\left\{ s_i \right\}$, time-dependent travel times $\left\{ c_{ij}(d_i) \right\}$, and time instant τ.

Step 2: Identify the scope of the remaining problem

Classify nodes into critical nodes $N_c(\tau)$ and unassigned nodes $N_u(\tau)$.

Step 3: Find the inserting node with the smallest insertion cost

Find the inserting node (and its corresponding insertion position) that has the smallest insertion cost among all unassigned node $u \in N_u(\tau)$.

Step 4: Insert the selected node and update the relevant data

Update the system by inserting selected node *u* into the position with *smallest* accrued cost in an appropriate route and redefine relevant data, such as departure time and arrival time for each affected node. Once inserted, node *u* is then removed from set $N_u(\tau)$.

Step 5: Stopping check for assignment

If set $N_u(\tau)$ is empty, the phase of route construction terminates. Otherwise, compute the remaining delivery/pickup capacity. If no vehicles can fulfill capacity constraints for nodes in $N_u(\tau)$, split a large demand into several small parts for partial service. Go to Step 3.

After the routes are constructed, many existing route improvement methods can be applied, such as 2-opt and Or-opt, which may combine with other meta-heuristics.

Due to the fact that insufficient supplies in relief logistics is very common, the demand at one node can be split into several parts and each part corresponds to a "virtual" node with a different deadline and a different level of emergency. In this way, partial delivery is possible so that the limited relief can be distributed to more demand sites to ease the impact of the disaster, though the demands are not fully satisfied.

4. Computational results

The test problem set used in Chen et al. (2005) is adopted with additional columns added to accommodate real-time delivery/pickup demands of each commodity and the levels of emergency. We only perform the test of problem numbered R103 for illustration. It is assumed that two kinds of commodities are considered for delivery/pickup. The predictive traffic condition is characterized by a step-wise travel time function, which is exactly the same as the one used in Chen et al. (2005). During the disaster relief logistics, the number of unexpected road incidents/recoveries is set as four, at each of which a new travel time function will result. The whole vehicle capacity is set as 200 pallets for each vehicle, and the initial loads of a vehicle at the depot are 80% of the whole vehicle capacity. In other words, 80 pallets for each commodity are loaded when a vehicle is departing the depot. Other information associated with each node, including the severity of emergency, which is further divided into three levels denoted as A, B, and C, is summarized in Table 1. Nodes in the class of “A” belong to the highest level of emergency and once its deadline is missed, the penalty is also the highest.

Appearing Time	Node no.	Level of emergency	Pickup commodity		Delivery commodity		Deadline
			Type	Quantity (pallets)	Type	Quantity (pallets)	
0	1	B	1	10	2	8	204
0	2	C	2	7	1	5	202
0	3	B	1	13	2	17	197
0	4	A	2	19	1	22	159
0	5	A	1	26	2	38	199
0	6	C	1	3	2	2	109
0	7	B	2	5	1	5	198
0	8	B	1	9	2	13	105
0	9	A	1	16	2	16	107
0	10	B	1	16	2	17	134
0	11	C	2	12	1	10	77
0	12	A	2	19	1	12	205
0	13	A	2	23	1	32	169
0	14	A	1	20	2	12	187
0	15	C	2	8	1	5	71
0	16	B	2	19	1	18	190
0	17	C	1	2	2	3	167
0	18	C	2	12	1	17	204
0	19	A	2	17	1	9	187
0	20	C	2	9	1	5	188
0	21	B	1	11	2	10	201
0	22	A	2	18	1	11	107
0	23	A	2	29	1	19	78
0	24	C	2	3	1	4	190
0	25	C	2	6	1	6	182
0	26	A	1	17	2	25	208
0	27	B	1	16	2	15	47
0	28	B	1	16	2	17	213
0	29	C	2	9	1	13	190
0	30	A	2	21	1	28	81
0	31	A	1	27	2	40	202
0	32	A	1	23	2	16	186
0	33	B	2	11	1	8	47
0	34	A	1	14	2	21	183
0	35	B	2	8	1	9	153
0	36	C	1	5	2	3	51
0	37	B	2	8	1	7	198

Appearing Time	Node no.	Level of emergency	Pickup commodity		Delivery commodity		Deadline
			Type	Quantity (pallets)	Type	Quantity (pallets)	
0	38	B	2	16	1	15	93
0	39	A	2	31	1	18	54
0	40	B	1	9	2	10	95
0	41	B	2	5	1	3	107
0	42	C	2	5	1	5	41
0	43	B	1	7	2	10	185
0	44	A	2	18	1	15	79
0	45	B	1	16	2	16	42
0	46	C	2	1	1	1	184
0	47	C	2	27	1	21	185
0	48	A	2	36	1	49	192
0	49	A	1	30	2	35	118
0	50	A	2	13	1	250	203
0	51	C	2	10	1	10	193
0	52	C	2	9	1	9	208
0	54	B	1	18	2	18	197
0	57	B	2	7	1	4	196
0	59	A	2	28	1	28	202
0	60	C	2	3	1	2	201
0	61	B	2	13	1	19	194
0	63	B	2	10	1	12	185
0	64	C	2	9	1	9	83
0	65	A	2	20	1	12	61
0	71	C	2	15	1	12	180
0	72	A	2	25	1	22	197
0	73	C	2	9	1	13	199
0	75	B	2	18	1	15	192
0	81	A	1	26	2	36	192
0	82	C	1	16	2	21	196
0	83	C	2	11	1	11	198
0	85	A	1	41	2	42	196
0	86	A	2	35	1	37	184
0	89	B	2	15	1	15	211
0	90	B	1	3	2	2	187
0	91	C	2	1	1	1	194
0	92	C	2	2	1	1	28
0	94	A	2	27	1	34	207
0	95	C	1	20	2	12	205
0	96	A	1	11	2	8	204
0	97	B	2	12	1	12	202
0	98	C	1	10	2	7	198

Appearing Time	Node no.	Level of emergency	Pickup commodity		Delivery commodity		Deadline
			Type	Quantity (pallets)	Type	Quantity (pallets)	
10	67	A	1	25	2	13	93
10	78	C	1	3	2	3	106
11	62	B	2	19	1	18	68
12	69	C	1	6	2	4	60
19	79	A	2	23	1	31	102
19	80	C	1	6	2	8	192
23	87	B	1	26	2	31	103
28	76	B	1	13	2	7	83
31	68	A	1	36	2	33	152
32	88	C	2	9	1	8	84
33	100	B	2	17	1	19	195
35	99	A	1	9	2	6	93
38	58	C	2	18	1	24	210
44	53	B	1	14	2	13	105
48	66	A	2	25	1	28	137
50	77	B	1	14	2	9	189
55	84	C	1	7	2	7	111
62	56	B	1	6	2	5	140
88	55	C	1	2	2	1	146
91	74	B	2	8	1	9	159
125	93	A	2	22	1	24	198
136	70	C	1	5	2	7	192

Table 1. Delivery/pickup information at demand sites

In order to show the capability for partial delivery, we set the delivery demand at node 50 equal to 250 pallets, which is greater than the vehicle capacity of 200 pallets. It is obviously that only partial demand, preset as 50 pallets, can be satisfied by the first incoming vehicle. The unsatisfied delivery demand, say 200 pallets, will stand at the same node with the same deadline and wait for service during the solution process. If the unsatisfied delivery demand can still not be satisfied by the second incoming vehicle, the partial delivery will be performed again. This process will be repeated until the entire delivery demand at this node has been totally satisfied.

The testing result shows that acceptable initial routes responding to the change of real time information were obtained in a very short time – less than one second for a problem with 100 nodes. The quality of the solution is further improved after the initial routes were obtained. This computational efficiency implies that the proposed model and associated algorithm are very suitable for real-time disaster relief logistics because of its quick response requirement.

The testing result is shown in Table 2, in which the number of vehicles is limited to 10. It shows that node 50 is serviced by three different vehicles – i.e., vehicles 1, 2, and 6 – and their respective delivery quantities are 50, 100, 100 pallets, implying that partial delivery is actually made. It is also found that 28 out of 100 nodes cannot be serviced by their deadlines; however, the routing schedule persists with late arrivals. In fact, late arrivals can be avoided by increasing the number of vehicles, as in Figure 3. The number of late arrivals decreases apparently as the number of vehicles increases. All nodes can be serviced by the deadlines if the number of vehicles increases to 17.

Veh. No.	Route	Commodity 1 (pallets)			Commodity 2 (pallets)		
		$\bar{Q}_{mk}$	$\sum_i q_{im}$	$\sum_i \hat{q}_{im}$	$\bar{Q}_{mk}$	$\sum_i q_{im}$	$\sum_i \hat{q}_{im}$
1.	0→27→50→30→20→10→63→ 90→11→64→70	80	114	40	80	41	61
2.	0→28→12→76→77→ 3→79→ 78→68→50→26→80→29	80	156	118	80	119	51
3.	0→42→87→92→99→94→37→ 98→100→91→85→93→59→17	80	119	88	80	89	110
4.	0→45→8→83→60→5→84→ 61→16→86→96→18	80	104	69	80	82	93
5.	0→40→21→72→23→22→75→ 74→53→58→2	80	105	34	80	33	123
6.	0→33→51→9→69→1→50→ 34→81→50→24	80	122	72	80	85	37
7.	0→65→35→71→66→32→19→ 82→47→46	80	92	39	80	37	113
8.	0→44→38→14→43→6→13→ 95→97→57→15	80	83	50	80	36	84
9.	0→ 4→39→67→56→41→55→ 25→54→73	80	62	51	80	37	70
10.	0→36→49→62→88→31→48→ 7→89→52	80	104	62	80	78	93

$\bar{Q}_{mk}$: initial loads on the vehicle
$\sum_i q_{im}$: total amount of delivered commodity m on the vehicle
$\sum_i \hat{q}_{im}$: total amount of pick-up commodity m on the vehicle

Table 2. Computational results (No. of vehicles = 10)

To show the importance of real-time information, we created a benchmark solution that does not take into account the change of real-time travel times. In other words, the scheduled routes in the benchmark solution remain unchanged regardless of how the real-time travel times vary – that is, without considering real-time information. The number of nodes encountering late arrival is 39 in the benchmark solution as opposed to 28 nodes in the original test solution. In addition, the total penalty of late arrival obtained in the benchmark problem is about 1.9 times as high as that of the original test problem.

It is also worth mentioning that some relief goods or rescue equipments at a demand site may be no longer desired and, therefore, can be picked up for use in the following nodes of the same route. For example, in Table 2 the total quantity of delivery for commodity 1 by vehicle 1 is 114 pallets, which is greater than its initial loads, 80 pallets, implying that at least some delivery demands are fulfilled by the pickup commodity from previous nodes of the same route.

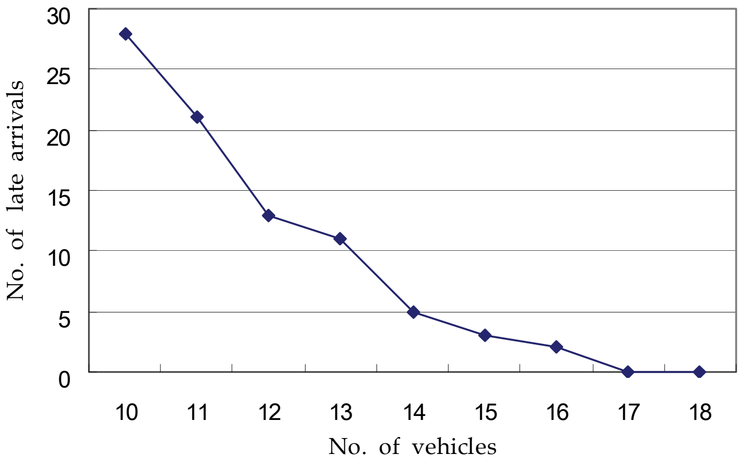

Fig. 3. Number of late arrivals under different fleet size

5. Conclusion

In the operations of relief logistics in natural disasters, there are several features that are different from the traditional VRPTW, such as unexpected road damage and recovery, real-time information and response, partial delivery, re-allocation of resource, different level of emergency, and so on. The model and algorithm of DVRP-RL are proposed to meet these requirements and provide an efficient solution for relief logistics. Some contributions are summarized as follows:

1. Real-time information such as road incidents, road/bridge damage recoveries, or delivery/pickup requests can be considered from time to time to regenerate a better route schedule.
2. When a visited demand site needs further disaster relief, it will be regarded as a new demand and taken back to the unserviced node list. This situation is quite common in a disaster relief operation if the damage resulting from the natural disaster continues.
3. Delivery and pickup demands are considered simultaneously. In addition, the excess relief goods or rescue equipment picked up at one site can be reused in the following sites of the same route. In reality, the coordination and reallocation of relief resource between different demand sites is essential in disaster relief operations.
4. Partial or full delivery/pickup operations, which are critical in the disaster relief logistics, can be accommodated in the solution procedure.
5. Relative importance of a demand node for late arrival is reflected in the corresponding unit penalties due to missing the deadline. When late arrivals are inevitable, the service sequence among those nodes can be determined based on the magnitude of the corresponding unit penalties.
6. Without having to return to the depot, a vehicle can stay at the last node, waiting for the next order from the logistics coordination center, and hence, has more flexibility for disaster relief operations in natural disasters. This treatment is useful especially when the depot is distant from the disaster area.
7. Supply shortages were implicitly considered by setting the deadline and classifying all demand nodes into several levels of emergency.

Two suggestions are made in the following for future research.

1. The optimal initial loads of vehicles need further study, especially in a real-time situation.
2. Anticipatory routing, which analyzes the problem of constructing a minimum expected cost route from an origin to a destination, anticipates and then responds to service requests.

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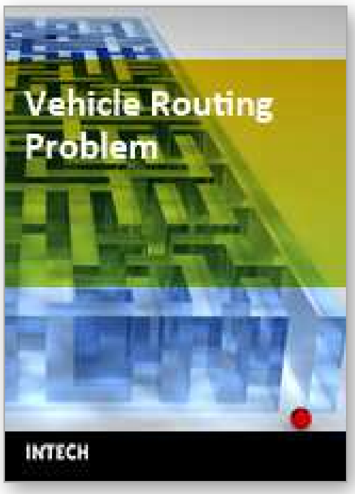

Vehicle Routing Problem

Edited by Tonci Caric and Hrvoje Gold

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The Vehicle Routing Problem (VRP) dates back to the end of the fifties of the last century when Dantzig and Ramser set the mathematical programming formulation and algorithmic approach to solve the problem of delivering gasoline to service stations. Since then the interest in VRP evolved from a small group of mathematicians to a broad range of researchers and practitioners from different disciplines who are involved in this field today. Nine chapters of this book present recent improvements, innovative ideas and concepts regarding the vehicle routing problem. It will be of interest to students, researchers and practitioners with knowledge of the main methods for the solution of the combinatorial optimization problems.

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