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SPLIT DELIVERY-BASED ROUTING RECOVERY MODEL FOR PERISHABLE PRODUCT DISTRIBUTION DELAY IN TIME-DEPENDENT NETWORK

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Abstract. *During the execution of vehicle routing plan for perishable product distribution, unexpected disruption events may bring about transportation delay in some routes and thus cause the initial routing scheme infeasible. To eliminate negative effects on major participators, a split delivery-based routing recovery model (SDRRM) is established in accordance with disruption management principle for inter-route recourse, where the perishable nature of products and alternative path choice are considered. To our knowledge, split delivery under this context that the total remaining load is just equal to the total demand of unserved customers has not been investigated yet. Moreover, a tabu search algorithm with novel neighborhood structures is devised to solve this problem. The effectiveness of the proposed model and algorithm is demonstrated by comparison results.*
Keywords: Perishable product, Disruption management, Split delivery, Tabu search

1. **Introduction.** To accommodate the fast pace of life in a convenient way, substantial life necessities are purchased via Internet instead of picking in person. Among them, perishable products account for a large percentage, such as fresh fruits, vegetables, meals, and flowers. For this category of products, their quality deteriorates continually during transportation due to the perishable nature. As the value of products delivered is affected by their freshness, it is practical to capture the distinguishing nature in the proposed model for distribution activities.

There are some papers modeling perishable product distribution as the well-known vehicle routing problem with time windows (VRPTW) [1-3]. Also several researchers considered time-dependent traffic flow and studied time-dependent vehicle routing problem with time windows (TDVRPTW) for perishable product distribution [4-6]. In reality, some unexpected disruption events sometimes also cause troubles to vehicles en route, such as traffic block and vehicle breakdown. However, there are only some papers concentrating on routing recovery of general product delivery or perishable products delivery regardless of perishability. Li et al. [7] introduced a real-time vehicle rerouting problem with time window to handle vehicle breakdown, which minimizes a weighted sum of operation, service cancellation and route disruption costs. A similar problem tackling vehicle breakdown was investigated by Mu et al. [8], but without considering customers' time windows. By considering the uncertainty of human behaviors and adopting hierarchical cluster analysis to segment customers, Ding et al. [9] constructed a disruption management model for delivery delay in multiple stages. Wang et al. [10] developed a combinational disruption recovery model for a combination of delivery disruption events, where various delivery disruptions are transformed into new-adding customer disruption and the effects on the real-world participators were measured. Nikolić and Teodorović [11] studied a scenario that unexpected high demands in some nodes make regular distribution infeasible. In these papers, the main recourse approaches to disruption events are dispatching new vehicles or loading vehicles full before they leave the depot. They are not practical to perishable product distribution due to perishability, which in practice constricts that vehicles leave the depot with load just equal to the total demand. Therefore, when transportation delay occurs in some routes, split delivery would be an effective recourse approach to diminish the negative effects on related agents. In our work, we adopt disruption management principle and propose SDRRM to tackle perishable product distribution delay, which integrates the time-dependent traffic flow and selection of alternative paths between each couple of nodes. Encouraged by the effectiveness and simple implementation of tabu search in solving vehicle routing problems [12], we propose a tabu search algorithm with elaborate neighborhood structures to deal with the specific split delivery, which is different from the traditional split delivery only considered in the initial routing plan [13].

The paper is organized as follows. SDRRM is developed in Section 2, followed by the proposed algorithm in Section 3. A computational experiment is shown in Section 4. Section 5 draws conclusions and provides several topics for further research.

2. Problem Statement and Formulation.

The following visits of vehicles in transit are associated to the traffic condition at occurrence time of disruption events. Therefore, a computation framework of responding to transportation delay is suggested. For each vehicle in transit, the travel time from its current site to the next visit node is calculated with real-time speed, and other travel times are still calculated with time-dependent speed.

2.1. Time-dependent road network.

When the dynamics of traffic flow is significant, particularly in busy urban areas, there is a need to select an optimal travel path from several alternatives rather than only the path with the shortest distance, which depends on the specific time of the day. We construct the logistics network by a multigraph. There are H_{ij} (≥ 1) arcs from node i to node j and each arc is represented by a triple (i, j, h), where the third number h indicates the arc identifier.

Given a start time t_i from node i and the length d_{ijh} of arc (i, j, h), its travel time can be calculated by Equation (1), and thus arrival time is equal to $t_j = t_i + \tau_{ijh}(d_{ijh}, t_i)$.

$$\tau_{ijh}\left(d_j, t_{curr}\right) = \begin{cases} t_{res} + \tau_{ijh}(d_j - d_{res}, t_{curr} + t_{res}), & d_{res} < d_j \\ d_j / v_{ijhm}, & d_{res} \geq d_j \end{cases} \tag{1}$$

where t_{curr} and t_{res} are respectively the current time and remaining time of current time period, i.e., $t_{res} = T_{ijh(m+1)} - t_{curr}$ & $t_{curr} \in [T_{ijhm}, T_{ijh(m+1)})$. d_j and d_{res} denote respectively the length from present site to node j and distance that can be covered within t_{res}, i.e., $d_{res} = t_{res} v_{ijhm}$. Equation (1) is used to compute travel time of traversing remaining length d_j from current time t_{curr}.

2.2. SDRRM.

For convenience of further explanation, some notations about the condition at occurrence time $DisT$ of disruption events are illustrated as follows. IK: The set of vehicles in transit. Q_k: Remaining load of vehicle $k \in IK$. p_k: Virtual node representing the site of vehicle k, $P = \{p_1, p_2, \ldots, p_k, \ldots, p_{|IK|}\}$. C: The set of unfulfilled nodes. C^+: Copies of the depot as return centers of vehicles, $N = C \cup C^+$. D_i: Unsatisfied demand of node i. x^k_{ijh}: Delivery sequence of initial routing scheme, which equals 1 when arc (i, j, h) is traversed by vehicle k, 0 otherwise. $\bar{x}^k_{ijh}$: Decision variable of routing recovery plan, which decides the delivery sequence of vehicle k. t_{ik}: Visit time of node i by vehicle k. q_{ik}: Delivery quantity for node i by vehicle k.

The disruption measurements of customers, providers and drivers are sequentially analyzed in the followings. Firstly, split delivery is an appropriate way to provide the products in time. However, each customer expects that his/her demand is entirely satisfied by minimal visits to reduce the trouble of receiving shipments. Hence, the visit frequency and time of each unserved customer should be taken trade-off in the routing recovery plan. In addition, each customer has different importance to the decision maker, and thus discrepant concerns will be paid to them. Therefore, besides highlighting the care of justice for each customer by setting a maximum tolerance of delay time, the routing recovery scheme should minimize the sum of weighted service dissatisfaction. The objective function of total dissatisfaction is written as follows with a changed constraint.

$$F_1 = \sum_{i \in C} w_i \left(\mu_1 \left(\sum_{j \in N} \sum_{h \in H_{ij}} \sum_{k \in IK} \bar{x}_{ijh}^k - 1 \right) \mu_2 \max\left\{ t_{ik} - l_i, 0 \right\} \cdot q_{ik} \Big/ D_i(l_i - e_i) \right)$$

$$t_{ik} \le l_i + L, \ \forall i \in C, \ k \in IK$$

where w_i is the importance degree of customer i. Coefficients μ_1, μ_2 are relative weights of visit frequency and time, respectively. Factor L in the constraint is defined as maximum tolerance of delay time.

Secondly, providers are particularly interested in reducing transportation cost and product deterioration loss. Regardless of the constant cost of initial routing plan in new traffic condition, the deviation of total relevant delivery cost is described as follows:

$$F_2 = \theta_1 \sum_{i \in C^+} t_{ik} + \theta_2 \sum_{i \in C} \sum_{j \in N} \sum_{h \in H_{ij}} \sum_{k \in IK} t_{ik} q_{ik} \bar{x}_{ijh}^k$$

where θ_1 and θ_2 are variable cost per unit travel time derived from transportation operations and deterioration loss of per unit product, respectively.

Thirdly, drivers are usually well primed with the assigned delivery routes. Adjustment of driving routes will trouble the drivers and make them feel tired of new paths. Hence, the new routing scheme should seek to maintain the initial routing scheme. The deviation of total driving paths is described as follows:

$$F_3 = \sum_{i \in C \cup P} \sum_{j \in N} \sum_{h \in H_{ij}} \sum_{k \in IK} \max\left\{ \bar{x}_{ijh}^k - x_{ijh}^k, 0 \right\}$$

Let M be a sufficiently large number. **SDRRM** is formulated as follows:

$$\min\left\{ F_1, F_2, F_3 \right\} \tag{2}$$

$$\text{s.t.} \ \sum_{i \in C} \sum_{h \in H_{i,n+k}} \bar{x}_{i,n+k,h}^k = 1 \quad \forall k \in IK \tag{3}$$

$$\sum_{j \in N} \sum_{h \in H_{ij}} \bar{x}_{p_k jh}^k = 1 \quad \forall k \in IK \tag{4}$$

$$\sum_{i \in C \cup P} \sum_{h \in H_{ij}} \sum_{k \in IK} \bar{x}_{ijh}^k \ge 1 \quad \forall j \in C \tag{5}$$

$$\sum_{i \in C \cup P} \sum_{h \in H_{ij}} \bar{x}_{ijh}^k = \sum_{i \in N} \sum_{h \in H_{ji}} \bar{x}_{jih}^k \quad \forall j \in C, \ k \in IK \tag{6}$$

$$\sum_{k \in IK} q_{ik} \ge D_i \quad \forall i \in C \tag{7}$$

$$\sum_{i \in C} q_{ik} \le Q_k \quad \forall k \in IK \tag{8}$$

$$q_{ik} \le M \sum_{j \in N} \sum_{h \in H_{ij}} \bar{x}_{ijh}^k \quad \forall i \in C, \ k \in IK \tag{9}$$

$$t_{jk} \geq t_{ik} + s_i + \sum_{h \in H_{ij}} \tau_{ijh}(d_{ijh}, t_{ik} + s_i) - M \sum_{h \in H_{ij}} (1 - \bar{x}_{ijh}^k)$$
$$\forall i, j \in N,\ k \in IK \quad (10)$$

$$t_{ik} \geq e_i - M \sum_{j \in N} \sum_{h \in H_{ij}} (1 - \bar{x}_{ijh}^k) \quad \forall i \in N,\ k \in IK \quad (11)$$

$$t_{ik} \leq l_i + L + M \sum_{j \in N} \sum_{h \in H_{ij}} (1 - \bar{x}_{ijh}^k) \quad \forall i \in N,\ k \in IK \quad (12)$$

$$t_{p_k,k} = DisT \quad (13)$$

$$\bar{x}_{ijh}^k \in \{0, 1\},\ t_{ik} > 0,\ \forall i, j \in N,\ k \in IK \quad (14)$$

Equation (2) aims to minimize the triple deviations, and the lexicographic principle is used to solve them with the order of importance $F_1 \succ F_2 \succ F_3$. Equations (3)-(6) ensure the flow conservation of vehicles in transit. Equation (3) restricts the used vehicles finally back to the depot. Equation (4) forces the vehicles at virtual nodes to move ahead to unserved customers or the depot. Equation (5) states that each customer can be visited by more than once. Equation (6) ensures that the vehicle has to leave a customer after finishing its service. Equations (7)-(9) are customer demands and vehicle delivery capacity constraints. Equation (7) guarantees that the remaining demand of each customer is fulfilled. Equation (8) restricts the total delivery quantity of a vehicle en route is no more than its remaining load. Equation (9) ensures the delivery quantity for a customer is offered by one vehicle visiting it. Equation (10) requires the service start time of a customer respects the vehicle visiting sequence. Equations (11) and (12) impose that the customer service has to be started between its earliest allowable time and maximum limitation with tolerable delay. Equation (13) realizes the start times of recovery routes with the occurrence time of disruption events. Equation (14) introduces the involved binary and non-negative variables.

3. **Tabu Search Algorithm.**

As a variant of TDVRPTW, SDRRM is an NP-hard problem. We design a tabu search algorithm with novel neighborhood structures compliant with the special split delivery.

3.1. **The framework of tabu search algorithm.**

Step 1: Acquire an initial solution from the instant result of executing the initial routing scheme, and initialize tabu tenures and the penalty coefficient.

Step 2: Generate inter-route neighborhoods. Repeat the following steps until the iteration termination condition is met.

Step 3: Improve the best non-tabu neighbor solution or feasible neighbor solution meeting the aspiration criterion.

Step 4: Update the incumbent solution, best so far solution, tabu tenures and the penalty coefficient. Go to Step 2.

3.2. **Solution evaluation.**

The delivery capacity constraints of vehicles are away satisfied according to neighborhood structures described in Section 3.3. For an infeasible solution violating time windows, a penalty item is added on the first objective function F_1, that is, evaluation function of F_1 is $O(S) = F_1 + \beta \cdot \Delta T$, where ΔT is total time excess. For a solution represented as $S = \{R_1, R_2, \ldots, R_k\}$, the total time excess is computed by $\Delta T = \sum_{R \in S} \sum_{i \in R} \max\{t_i - l_i, 0\}$, where the departure time from node i is noted as $l_i + s_i$ if its service start time meets the condition $t_i > l_i$, otherwise, equals $t_i + s_i$. Penalty coefficient β is initially set as 1, and after each iteration its value is divided by $1 + \gamma$ ($\gamma \in (0, 1]$) if time window constraint of the incumbent is respected, otherwise, multiplied by $1 + \gamma$.

3.3. **Neighborhood search.** Three inter-route operators and one intra-route operator are introduced to explore more extensive solution space. The former includes cross exchange, node exchange, inter-route relocation while the latter is intra-route relocation. In every iteration, one of inter-route operators is randomly selected to be executed, and then the updated incumbent solution is improved by the intra-route operator. Particularly when cross exchange operator moves a string of consecutive visit nodes, reversing its sequence is also carried out to enrich the neighborhood solutions. To meet the constraint of delivery capacity, each neighborhood does not change the total delivery quality in each route. Nodes with oblique lines in Figures 1 and 2 denote the virtual nodes.

1) Cross exchange

From two randomly selected routes, two strings of consecutive visit nodes are extracted. The total delivery quantity of the two strings is compared first. While the string with less quantity is directly shifted into the other route, the string with more delivery quantity leaves the redundancy in its source route and only shifts a sub-string with equal amount into the other route. Figure 1 depicts the way this operator works.

2) Node exchange

As a special case of cross exchange operator, only one node is extracted from each selected route, and then the node with more delivery quality is essential to be divided into two same visit nodes. The delivery quantity of exchanged nodes remains equal to ensure the total delivery quantity of each vehicle coincides its load. Figure 2 describes the process.

3) Inter-route relocation

This operation is confined into two routes with more than one same visit node. A split visit node in one route is combined into the same visit node in another route, and the

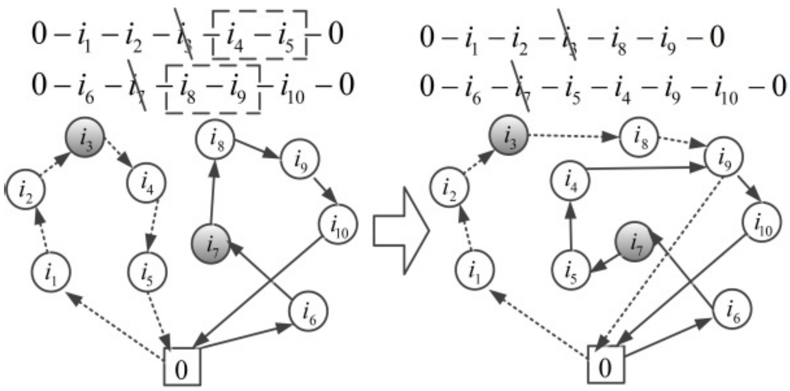

Figure 1. Cross exchange operator

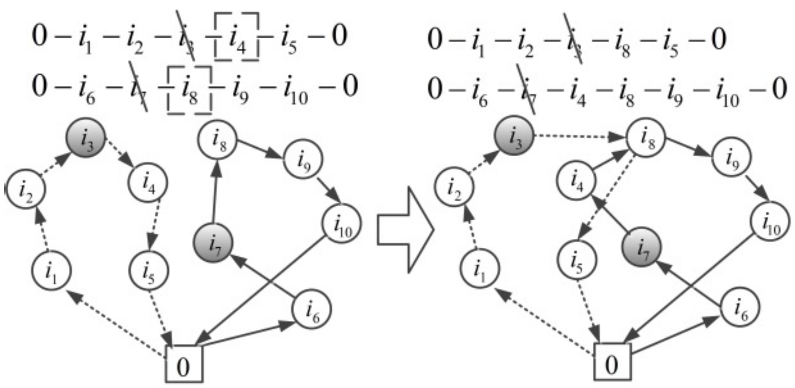

Figure 2. Node exchange operator

route with delivery increase transfers a part of visit nodes with equal delivery quantity back to the former route.

4) Intra-route relocation

In one route, a node is randomly removed from its primary site into another site. In this way, the visit sequence of a route is reordered in hope of exploiting a large solution space.

3.4. **Tabu list and stopping criteria.** In each iteration, the non-tabu solution with best evaluation value is accepted unless one feasible solution meets an aspiration criterion. When a move is employed, its inverse operation is set tabu for the next δ iterations, $\delta \in [1, \sqrt{n}]$. For cross exchange operator, the two ends of the exchanged string are set tabu. To decrease frequency of split, only non-split node is allowed to be set tabu. The proposed algorithm is terminated when maximum response time $LimT$ runs out or the number of consecutive non-improving iterations reaches $NoImp$.

4. **Numerical Example.** All proposed procedures are implemented in Matlab R2014a and run on a PC with a Core i3, 2.13 GHz CPU and 4 GB of memory. By comparing the results of experiments with different values of algorithm parameters, $LimT$ and $NoImp$ are respectively set as 1 min and 5 to produce good solutions in relatively shorter time.

In order to analyze the effectiveness of the proposed model and algorithm, we conceive an example by the first 25 customers of instance R101 of Solomon data [14]. Each couple of nodes has $2 \sim 3$ arcs with length of a percent $\lambda \in [0.7, 1.3]$ of the Euclidean distance. The importance degrees of customers follow a discrete uniform distribution $U(1, 3)$. By dividing the planning horizon into three equal intervals, five speed functions of the same pattern $(1-\varepsilon, 1+\varepsilon, 1-\varepsilon)$ are derived, $\varepsilon \in \{0.0, 0.1, 0.2, 0.3, 0.4\}$. Then each arc is randomly assigned a speed profile to construct a time-dependent network. When disruption events occur, real-time speed of an arc is set as a percentage λ of its time-dependent speed.

By computing an initial routing model, 7 vehicles are arranged to deliver the signed orders. Their routes are listed as follows: Route 1 (0-12-9-20-1-0), Route 2 (0-14-16-6-13-0), Route 3 (0-23-3-4-25-0), Route 4 (0-11-19-8-17-0), Route 5 (0-5-7-18-10-0), Route 6 (0-2-15-22-24-0) and Route 7 (0-21-0). Suppose that all dispatched vehicles were traveling at the specific sites (i.e., virtual nodes P) at time 67, which are marked with solid circles in Figures 3 and 4. It was found that vehicles 3 and 5 were both affected by traffic accidents and their transportation delay times are 30.5 and 26, respectively.

According to SDRRM and global rescheduling method which reoptimizes the disruption problem regardless of the deviations from the initial routing scheme, two rescue schemes are generated in Table 1 with illustrations of Figures 3 and 4. The objective function values of SDRRM are $F_1 = 1.4272$, $F_2 = 1478.2$, $F_3 = 11$ while the objective function values of global rescheduling method are $F_1 = 10.4491$, $F_2 = 1398.2$, $F_3 = 13$. These solutions are better than that obtained by the framework of simulated annealing. Here coefficients are set as follows: $\mu_1 = 0.1$, $\mu_2 = 0.9$, $L = 30$, $\theta_1 = 1$ and $\theta_2 = 0.015$.

Table 1. Detailed results of two different recovery methods

Vehicle	Disruption recovery routing	Global rescheduling routing
1	0-12-p_1-9-20-1-0	0-12-p_1-9-20-1-0
2	0-14-p_2-16-6-13-0	0-14-p_2-16-***6***-17-13-0
3	0-p_3-23-22-4-***25***-0	0-p_3-23-22-***4***-25-0
4	0-11(p_4)-19-7-***8***-17-0	0-11(p_4)-19-8-***6***-0
5	0-5-p_5-18-***8***-10-0	0-5-p_5-18-7-10-0
6	0-2-p_6-15-3-24-***25***-0	0-2-p_6-15-3-24-***4***-0
7	0-21-p_7-0	0-21-p_7-0

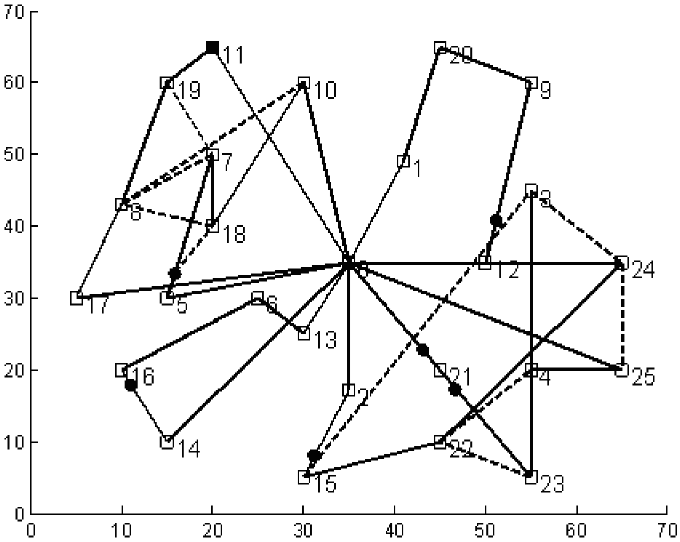

FIGURE 3. The disruption recovery scheme

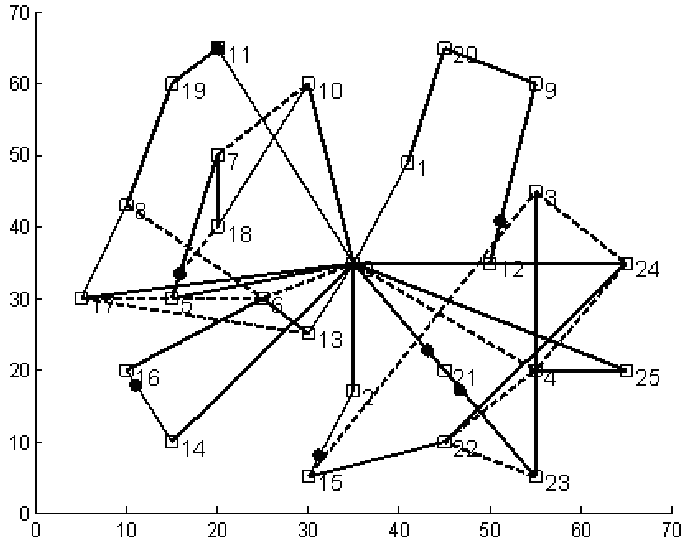

FIGURE 4. The global rescheduling scheme

It is clear that there are two split nodes in both solutions. By comparison, the disruption recovery scheme has few negative effects on customers at approximately equal cost while the global rescheduling scheme brings about a large influence on customers with little cost savings. It can be inferred that SDRRM is more appropriate for real applications.

5. **Conclusions.** Since the perishability of products decides the load of scheduled vehicles to just meet the total demands of assigned customers, split delivery may be an effective method for inter-route recourse when transportation delay occurs. With time-dependent travel times and multiple paths covering two nodes considered, SDRRM is formulated based on disruption measurements. Combined with some specific neighborhood structures, a tabu search algorithm is adapted to solve this problem. The effectiveness of the proposed model and algorithm is demonstrated by a numerical example.

The problem may be extended to the distribution of multiple perishable products using multi-compartment or refrigerator vehicles. In addition, many forms of disruption events are necessary to be investigated in perishable products distribution.

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