Vehicle Routing Optimization toward Green Logistics

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In the logistics industry, labor shortage has been highlighted as a major social issue. However, there is also a need to respond to carbon neutrality, and efforts are being accelerated in this area as well. A typical example is the switch to EV trucks. Unfortunately, more time is expected to be needed before their use becomes practical and widespread. On the other hand, efforts to reduce CO_2 emissions through efficient transport and delivery are also attracting attention. In particular, some small and medium-sized enterprises, which account for more than 90% of logistics companies, have not adopted the use of IT in their operation, and many inefficient analog methods remain. Improving this situation will contribute to carbon neutrality.

Aiming to reduce CO_2 emissions associated with store delivery operations, OKI has developed a vehicle routing optimization technology that provides efficient delivery. The technology has been applied to an actual delivery operation for verification, and the result of its effect in reducing CO_2 emissions is presented in this article.

Vehicle Routing Optimization

(1) What is Store Delivery Operation?

Logistics transport operation covers a wide range from trunk line transport to branch line transport. Trunk line transport is delivery from a depot (delivery base), where large quantities of shipments from the surrounding area are collected, to other depots. Branch line transport is the collection and delivery of shipments within an area. This article focuses on store delivery, which is a form of branch line transport.

Figure 1 is a schematic presentation of store delivery that logistics companies perform on a daily basis. Logistics companies use multiple vehicles to transport specified quantities of shipments from the depot to numerous destinations. In addition to weight and volume, the unit of shipments is sometimes counted as the number of standard containers. In many cases, the delivery time frame to each destination is specified. One delivery round is defined as the process in which a vehicle leaves the depot and returns after visiting several delivery destinations. Vehicles may make several delivery rounds a day. The maximum shipment, that is, the maximum load, a vehicle can deliver in one delivery round is fixed, and it is not possible to exceed this limit.

The order in which a vehicle visits the delivery destinations is referred here as the vehicle route. An example of a vehicle route is the path connected by arrows of the same color and shape in **Figure 1**. A routing plan describes which route each vehicle will use. There are many possible vehicle routes for delivering the shipments requested by each destination without excess or deficiency. The total travel distance by all vehicles will differ depending on the vehicle route. As the total travel distance becomes longer, fuel cost will increase, and at the same time, CO_2 emissions will be higher.

Vehicle routing optimization is defined in this article as creating a routing plan that minimizes the total travel distance. If conditions such as destinations and load demand hardly change, the routing plan can be created only once at the beginning of the rounds and the deliveries carried out according to that plan each time. Conversely, if the conditions change each time, the optimal vehicle route will also change, and it becomes necessary to create a routing plan accordingly. In either case, the creation of the routing plan is often done manually by the vehicle dispatcher based on their experience and intuition. Since manual planning is not always efficient, this is where improvement is needed.

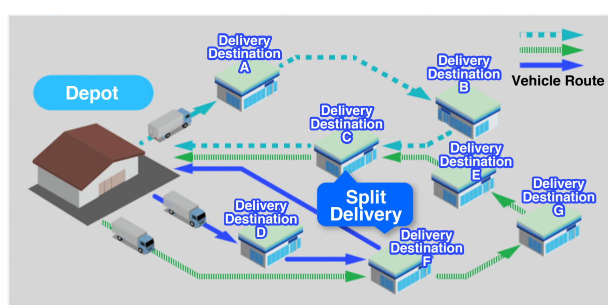

Figure 1. Store Delivery

(2) What is Split Delivery?

Split delivery is a delivery method that uses two or more vehicles to deliver shipments to a certain destination. **Figure 2** shows the difference between split delivery and non-split normal delivery. In the example, the maximum load of the vehicles is set as 4 containers, and the number of containers to be delivered to three destinations is 2, 4, and 2, respectively. The distances between the depot and destinations are as indicated in the figure. In normal delivery, individual vehicles visit and deliver shipments to each of the three destinations. On the other hand, in split delivery, shipments to be delivered to the center destination is split into two shipments and delivered by two vehicles. This way, the delivery can be made using less vehicles and shorter total travel distance. However, split delivery has a disadvantage in that route planning becomes complicated because a decision must be made as to which destination shipments should be split and in what ratio, which is unnecessary in normal delivery. Since it is difficult to manually create a routing plan that takes into account these complicated conditions, an autonomous computation scheme needs to be established.

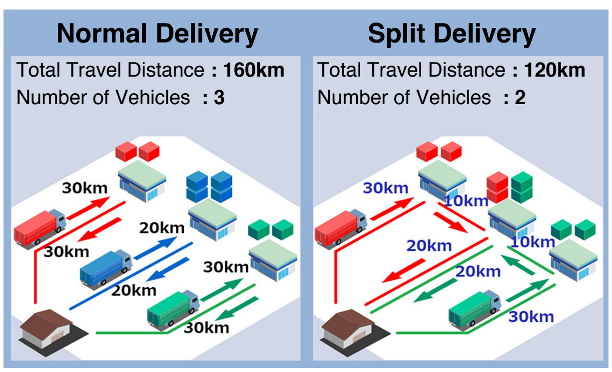

Figure 2. Normal and Split Deliveries

(3) Formulation of Split Delivery Vehicle Routing Problem

The problem of creating an optimal routing plan described above will be solved using mathematical optimization. Mathematical optimization is a method of finding a solution that minimizes or maximizes the value of an objective function under given constraints[1]. In order to solve a real-life problem (in this case, route planning) using mathematical optimization, it is first necessary to formulate the real-life problem into a mathematical optimization problem. A mathematical optimization problem consists of constants, variables, objective functions, and constraints.

The problem of finding the optimal vehicle route that applies split delivery is called the "split delivery vehicle routing problem" and has been generalized[2]. The formulation of this problem results in the equations (1) through (14) given below.

(Constants)

- m: Number of vehicles
- n: Number of destinations
- b: Maximum number of delivery rounds
- h_i: Maximum number of vehicles that can visit destination i
- i, j: Subscripts representing depots or destinations (0, n+1 are depots, others are destinations)
- v: Subscript representing vehicle
- f: Subscript representing delivery round
- d_i: Quantity demanded by destination i
- c_{ij}: Travel distance from destination i to j
- e_i: Earliest arrival time for destination i
- l_i: Latest arrival time for destination i
- t_{ij}: Travel time from destination i to j
- q: Maximum load of vehicle

(Variables)

- u_{ivf}: Integer variable representing the time vehicle v arrives at destination i on the f-th delivery round
- w_{vf}: Binary variable indicating whether or not vehicle v uses the f-th delivery round
- x_{ijvf}: Binary variable indicating whether or not vehicle v traveled from destination i to j on the f-th delivery round
- y_{ivf}: Binary variable indicating whether or not vehicle v traveled to destination i on the f-th delivery round
- z_{ivf}: Integer variable for the shipment quantity that vehicle v delivers to destination i on the f-th delivery round

(Objective function)

$$\min \sum_{i,j,v,f} c_{ij} \cdot x_{ijvf} \quad \begin{pmatrix} i = 0\sim n, j = 0\sim n, \\ v = 1\sim m, f = 1\sim b \end{pmatrix} \tag{1}$$

Equation (1) is the objective function of the problem to be solved. It represents the minimization of the vehicle's total travel distance.

(Constraints)

$$y_{0vf} = w_{vf} \quad (f = 1\sim b, v = 1\sim m) \tag{2}$$

$$w_{vf} \geq w_{vf+1} \quad (f = 1\sim b, v = 1\sim m) \tag{3}$$

Equations (2) and (3) indicate that the delivery rounds of each vehicle are loaded in order from the first round.

$$\sum_{v,f} y_{ivf} \geq 1 \quad (i = 1\sim n, v = 1\sim m, f = 1\sim b) \tag{4}$$

$$\sum_{v,f} y_{ivf} \leq h_i \quad (i = 1\sim n, v = 1\sim m, f = 1\sim b) \tag{5}$$

Equations (4) and (5) indicate that delivery destination $\boldsymbol{i}$ is visited by at least one vehicle but no more than $\boldsymbol{h_i}$ vehicles.

$$\sum_{v,f} z_{ivf} = d_i \quad (i = 1\sim n, v = 1\sim m, f = 1\sim b) \tag{6}$$

Equation (6) indicates that the shipment quantity to be delivered to destination $\boldsymbol{i}$ and the quantity demanded by destination $\boldsymbol{i}$ are the same.

$$z_{ivf} \leq d_i \cdot y_{ivf} \quad (i = 1\sim n, v = 1\sim m, f = 1\sim b) \tag{7}$$

Equation (7) indicates that only vehicles that visit destination $\boldsymbol{i}$ can deliver shipments to that destination.

$$\sum_{i} z_{ivf} \leq q \quad (i = 1\sim n, v = 1\sim m, f = 1\sim b) \tag{8}$$

Equation (8) indicates that the shipment quantity delivered by one vehicle per round is equal to or less than the maximum load.

$$\sum_{i} x_{ijvf} = y_{jvf} \begin{pmatrix} i = 0\sim n, j = 0\sim n, \\ v = 1\sim m, f = 1\sim b \end{pmatrix} \tag{9}$$

$$\sum_{j} x_{ijvf} = y_{ivf} \begin{pmatrix} i = 0\sim n, j = 0\sim n, \\ v = 1\sim m, f = 1\sim b \end{pmatrix} \tag{10}$$

Equations (9) and (10) are constraints that the vehicle route is the route of the delivery round. Equations indicate that when a vehicle visits a depot or delivery destination, it has already or will afterwards visit another delivery destination or depot.

$$u_{ivf} + t_{ij} - M(1 - x_{ijvf}) \leq u_{jvf}$$
$$(i = 0\sim n, j = 1\sim n+1, v = 1\sim m, f = 1\sim b, M \text{ is a large number}) \tag{11}$$

Equation (11) indicates that when a vehicle visits two delivery destinations in succession, the difference in arrival times is greater than or equal to the travel time between the delivery destinations.

$$u_{0v1} = 0 \ (v = 1\sim m) \tag{12}$$

Equation (12) indicates that the departure time of the first delivery round from the depot is 0.

$$u_{0vf} \geq u_{n+1\,v\,f-1} \ (v = 1\sim m, f = 2\sim b) \tag{13}$$

Equation (13) indicates that the depot departure time of the second and subsequent delivery rounds is greater than or equal to the depot arrival time of the immediately preceding delivery round.

$$e_i \leq u_{ivf} \leq l_i \quad (i = 0\sim n, v = 1\sim m, f = 1\sim b) \tag{14}$$

Equation (14) indicates that the arrival time at delivery destination $\boldsymbol{i}$ is greater than or equal to $\boldsymbol{e_i}$ and less than or equal to $\boldsymbol{l_i}$.

(4) Vehicle Routing Optimization Tool

The split delivery vehicle routing problem formulated above has been implemented as a computer program, and prototyped into a "vehicle routing optimization tool." The tool solves the problem based on the given input data (equivalent to the constants in the formulation) and automatically outputs the routing plan. It was implemented using Python® 3[*1)] and operates on a cloud computer (4-core CPU operating at 3.1 GHz). The problem was solved using the mathematical optimization solver "Gurobi Optimizer® 9.1[*2)]."

Demonstration Experiment

A demonstration experiment was conducted with the cooperation of LONCO JAPAN Co., Ltd. to verify the effect of the vehicle routing optimization tool in reducing CO_2 emissions. The experiment took place at an actual site where LONCO JAPAN carries out store delivery operations almost on a daily basis.

The experimental conditions and methods are as follows. The target store delivery site is a certain region in Japan, and the delivery destinations are fixed at about 50 stores. Deliveries are made once a day, and the quantity of shipments to each delivery destination varies from day to day. Since shipments are delivered in fixed-size containers, the unit of shipments is the number of containers. About 15 vehicles are used for delivery, all of which are diesel-powered vehicles. The routing plan was drafted by LONCO JAPAN's dispatch staff using the prototype "vehicle routing optimization tool." Due to the time constrain imposed by work operation, the time allotted to the tool for calculation was at most 10 minutes. The actual deliveries were carried out according to the drafted routing plan, and the total travel distance of the vehicles was measured. The total travel distance of the vehicles was calculated based on the

*1) Python is a registered trademark of Python Software Foundation. *2) Gurobi Optimizer is a registered trademark of Gurobi Optimization, LLC.

trajectories collected using OKI's SaaS-type ITS service LocoMobi® 2.0[*3]. For comparison, a similar experiment was conducted on a different day in which the dispatcher drafted a conventional routing plan without the tool.

The results of the experiment are shown in **Figure 3**. The figure shows the relationship between the total number of containers distributed in one delivery and the total traveled distance. It can be seen that the number of containers varies from day to day, and the total traveled distance increases almost linearly according to the number of containers. It is also apparent that the total traveled distance is shorter when the tool is used. The magnitude of that effect depends on the number of containers, and as the number increases, the effect tends to become higher. In this experiment, the average number of containers was 948. Using this value as a representative figure, the difference between the total traveled distance per delivery with the tool and the conventional method was estimated to be 224km on average (equivalent to 5.1% of the conventional total traveled distance). Since the operation is carried out at this site throughout the year, the difference equates to 81,780km when converted to a yearly value.

This distance reduction was converted into CO_2 emissions. According to the study presented in reference 3), the fuel consumption of current heavy-duty trucks is approximately 3km per liter. Additionally, from reference 4), the amount of CO_2 emitted per liter of diesel fuel is said to be 2.6kg-CO_2. Using these values, an estimated 193kg per day, or approximately 70.4 tons per year of CO_2 can be reduced at this site when the vehicle routing optimization tool is used in the operation.

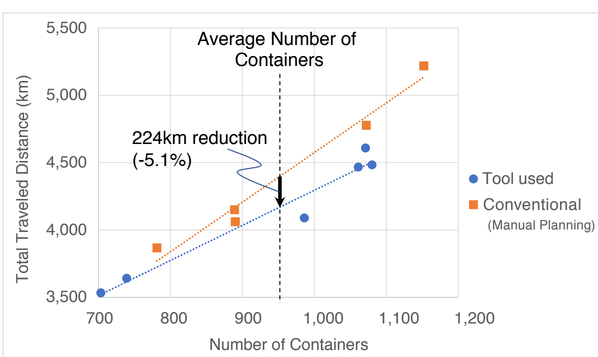

Figure 3. Demonstration Experiment Results

Conclusion

OKI's vehicle routing optimization technology currently under research and development has been introduced. Based on the result of experiments conducted at an actual store delivery site, it was estimated that the site can reduce CO_2 emissions by approximately 70.4 tons per year with the use of the technology. OKI will continue its effort in the development of technologies that contribute to a green society. ◆◆

References

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TIPS 【Glossary】

LocoMobi 2.0
A SaaS-type ITS service that collects and analyzes vehicle location information. Using roadside sensors to acquire signals sent from the vehicle-mounted device, it is possible to generate the driving trajectory of the vehicle.

Mathematical optimization solver
Software containing algorithms for solving mathematical optimization problems.

*3) LocoMobi is a registered trademark of Oki Electric Industry Co., Ltd.