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Vehicle Routing Problem for Multi-Transportation Modes

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Abstract - This paper reveals a current business situation where several types of subcontracting transportation are used for delivery services in forwarding companies. Each subcontracting option contains different cost structure and constraint set, which makes transportation planning more complex. This problem comprises new aspects which extend the traditional vehicle routing problem (VRP). A heuristics algorithm is proposed for simultaneously solving the combination of optimization problems in vehicle routing and scheduling.

Keywords - Vehicle Routing Problem; Meta-heuristics

I. INTRODUCTION

Many companies give high attention to minimize their transportation cost of goods because it is considered as a major share of the total logistics cost. The importance of the transportation is reasoned by [1] revealing that transportation cost accounts for almost 60% of logistics cost. The VRP is defined as "the problem to discover a route for a fleet to service a set of customers at the lowest cost possible, given a set of constraints [2]". A number of problems and constraints arising in logistics business such as time window (TW) or multiple depots have also been taken into account in extension of the simple VRP problem. There has been a wealth of proposals of further types as surveyed in Ref [3]-[5]. Typical types of such constraints are summarized as follows:

- Demand: Deterministic/Stochastic
- Product: Single/Multiple
- Purpose: Delivery/Pick-up
- Time Window: Hard/Soft
- Capacity: Homogeneous/Heterogeneous
- # of trucks: Limited/Unlimited
- Routing: Single/Multiple
- # of depots: Single/Multiple

Even with such types of models, however, there are still some realistic constraints missing in existing models.

In today's business, a shift toward JIT delivery and an increasing in diversification and fluctuation in customer demands have caused more and more uncertainty in transportation requests. This makes difficulty for the forwarding companies to manage and optimize their transportation task to the maximum possible benefits, which include both satisfying an uncertainty of customer request and minimizing transportation cost. To deal with these situations, most companies have been shifting their business from asset-oriented to non-asset-oriented.

This paper introduces a complex situation in vehicle routing and scheduling where combining usage of different types of subcontracting transportation is applied in the forwarding companies. A simulated annealing (SA) algorithm is presented for solving this special type of problem and a real-life case is also applied for illustration. Section 2 discusses practical current business situation that influences the VRP. An introduction to multiple types of transportation is conducted in Section 3. The constraints that have to be taken into account in vehicle planning are described in Section 4 followed by algorithm and mathematical model to solve the problem in Section 5. Section 6 shows a computational analysis and results then conclusion in Section 7.

II. ROUTING AND SCHEDULING IN FOR MULTI-TRANSPORTATION MODES

In the typical VRP, a company is supposed to have enough trucks on their own in order to use them to fulfill all of the delivery requests they receive. With a highly uncertain demand regarding transportation volume which varies over time, however, it is hard to predict and to have enough capacity to meet the demand. Conventionally there are fixed costs to having more own vehicle fleet which normally associate with manpower. Fewer vehicles mean less monetary investment and expenditure. Therefore, most forwarding companies have tendency to reduce the number and to hold a minimal amount of their own trucks, and when it is necessary, external carriers are used in order to gain enough transportation capacity to fulfill the remaining transportation requests. Some companies even have none of their own fleet but rely only on external transportation resources. Such an outsourcing of transportation requests is often referred to as subcontracting. Figure II shows multiple transportation assignment used to fulfill the demand.

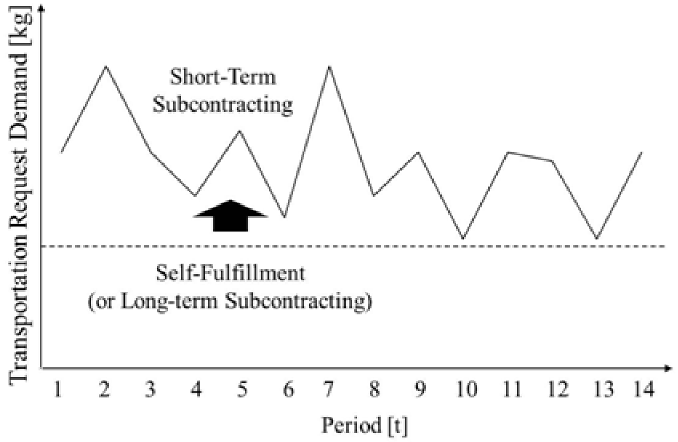

Fig 1. Transportaion mode mix for multi-period deliveries

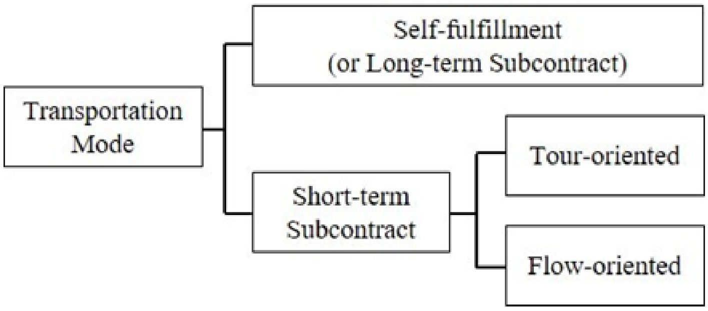

Fig 2. Transportation Modes

The traditional VRP model does not consider the integration of subcontracting issue. When engaging the external carriers, the companies not only determine the routing and scheduling their own fleet but also have to appropriately assign the customer requests with proper number of trucks necessary for each subcontracting transportation service. Terms of payment and conditions of service, which are different for each service type depending on agreement of the forwarding companies and subcontractors, also have to be specified. In effect, it is more complicated in managing vehicle routing especially when involving several subcontracting types with diverse terms and conditions of payment and service. Consequently it is important for the research in investigating the VRP that involves subcontracting.

Apart from the subcontracting aspect, a large number of requests are another issue arising in growing competitive logistics market. Since modern communication technology makes information transfer much easier than it used to be, this allows customers to place the orders for delivery requests several times within a day. Therefore, the forwarding companies have to manage daily variation in large amount of their orders in order to ensure that they have enough transportation resources to provide all customer requests.

There are several types of subcontracting options as proposed in Refs [6],[7], each of which has different structures of cost and constraints set. This paper introduces three types of subcontracting transportation modes used in Japanese forwarding companies. Utilization of own fleet or renting vehicles in a long period to fulfill the requests is defined as self-fulfillment or long-term subcontracting while engaging the external carriers is called short-term subcontracting. The short-term subcontracting consists of two types: tour-oriented and flow-oriented as shown in Figure II.

The first transportation type is self-fulfillment, which the company uses own trucks. It also includes long-term subcontracting, such as monthly contract of truck rental, which the company could perform the transportation planning in a similar way as the own vehicle fleet by signing long-term contracts with the subcontractors who provide up to an agreed number of vehicles. In this category, the vehicles are stationed in one of their depots, and fulfill pick-up and/or delivery requests with round routes. Often, there are different types of fleet $k = 1, \cdots, K$ with particular capacity Q_k . The costs consist of fixed costs F_k , and variable costs C_k . Fixed costs could contain monthly truck rental fee, or payment for drivers while variable costs depend on the distance of the routes. Compared to other modes, this type has higher fixed costs and lower variable costs. Thus, the company aims to utilize the fleet of this type to a maximal extent.

The second type is tour-oriented short-term subcontracting which the subcontractors are involved for full truckload shipment (FTL). In this category, trucks are rented during specified short-term period T (e.g., T = 24 hours) to fulfill transportation requests with round routes, and are then returned at their original locations. A rental fee is calculated separately for each route as regards the fleet size and the travel distance specified in tariff table. This tariff table provides a list of agreed fixed tariff rates under non-linear consideration of loads and lengths of the tours that the subcontracting company charges for its delivery services. A typical tariff table for tour-oriented subcontracting type is shown in Figure II. The tariff rate per load travel is higher than the cost rate of the first transportation mode as it covers a part of the fixed costs of the subcontractor.

In the tariff table, rental fee $C(Q_i, D_j)$ are specified according to the truck load section $Q_i \in \{Q_1, \cdots, Q_m \mid Q_1 \le Q_2 \le \cdots \le Q_m\}$ and the travel distance section $D_j \in \{D_1, \cdots, D_n \mid D_1 \le D_2 \le \cdots \le D_n\}$. For each trip k with the distance d_k and truckload quantity q_k, a section pair (Q_i^k, D_j^k) is chosen from the specified section set (Q_i, D_j). The choice is based on the minimum resource usage basis as long as resource usage must not exceed the section limit, $i.e. Q_i^k = \inf\{Q_i \mid q_k \le Q_i\}$, and $D_j^k = \inf\{d_k \le D_j\}$. For example of transportation in Japan, the maximum truckload limit is twenty tons due to the government restriction and the longest distance available on tariff table is 3,000 kilometers.

To determine the cost for each trip, the truckload quantity q_k is measured by the maximum load quantity, and the distance d_k is measured only for drives for the delivery within a trip. For example in Figure II, truck k picks up order quantities q_1, q_2, q_3 at location 0, then makes a delivery to customer 1,2,3 respectively. The truck then goes to location 4 to pick up order quantity q_5 to deliver to customer 5. After that, the truck k returns to the original location 0. In this example, the truckload for the tour k is given by $q_k = \max\{q_1 + q_2 + q_3, q_5\}$, which is a summation of load q_1, q_2 and q_3. The travel distance is calculated as $d_k = d_{01} + d_{12} + d_{23} + d_{45}$ as in Figure II (a). Since the truck is rented within specific time period and has to be returned at the origin point, operation time constraints (OTC) are to be imposed. In this case, the total travel time must not exceed specified rental term as: $t_k = t_0 1 + t_1 2 + t_2 3 + t_3 4 + t_4 5 + t_5 0 \le T$, where t_{ij} denotes travel time from location i to location j.

The third type is flow-oriented short-term subcontracting. In this category, transportation requests are fully outsourced to the external carriers so the forwarding companies are not responsible for the vehicle scheduling. As is the same with tour-oriented subcontracting, an outsourcing fee is extracted from the tariff table according to the corresponding amount of goods to be transported and length of the transportation, but the rate is higher than the tour-oriented type. This type is advantageous especially for transport requests with tight constraints. Another attractive feature of this mode is that there are many more sections of truckload and travel distance. Hence, it is appropriate to fulfill less-than-truckload (LTL) transportation requests that have the much smaller order quantity for the fleet capacity, yet are difficult to combine with other orders.

Combining the usage of own fleet and subcontracting offers two main advantages for the forwarding companies [6]. Firstly, as high uncertainty in transportation requests varies in short time periods, company could cut the fixed cost of its under-utilized own fleet by using subcontracting services which provide flexible capacity of transportation resources. Secondly, there will be more effectiveness and better capacity utilization in the vehicle tours because demand can be delivered in different transportation modes and non-compatible demands can also be delivered less-than-truckload by subcontract [8]. The movements of empty truck are minimized leading to a reduction of transportation costs. The Challenge for analysis is to determine the fulfillment plan for all customer requests with less service cost for the company.

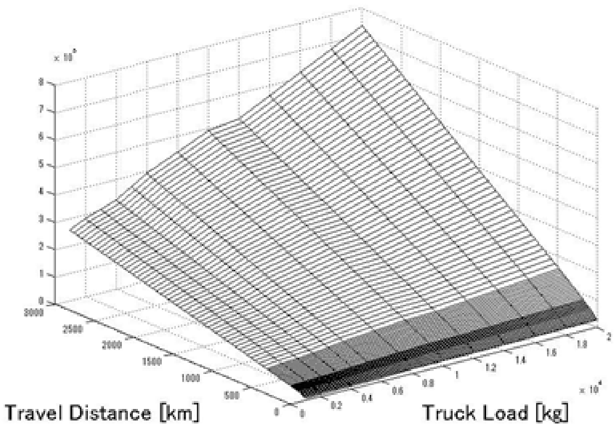

Fig 3. Tariff Table for Tour-oriented Subcontracting

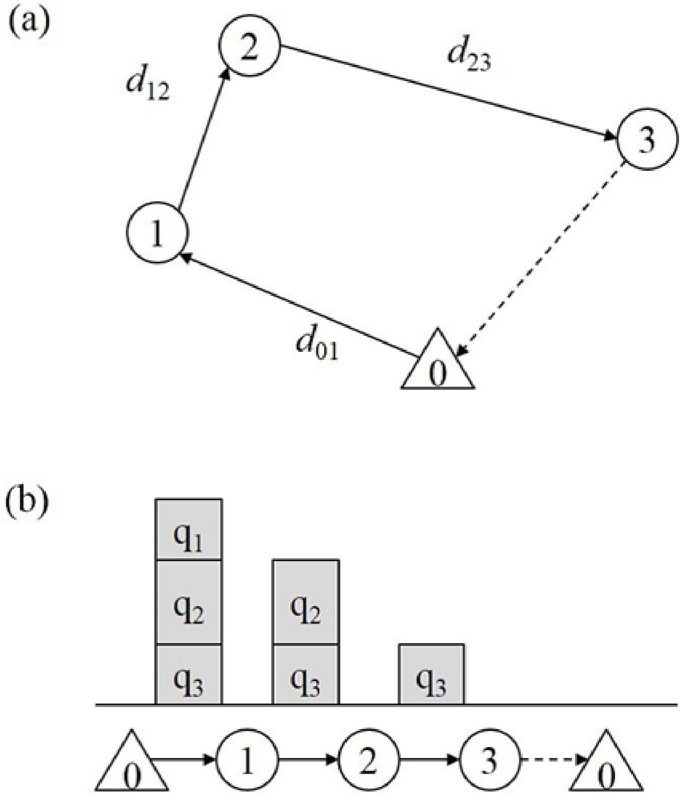

Fig 4. Transportation Modes

III. CONSTRAINTS IN PRACTICE

In this section, we describe realistic constraints that are taken in to account in this paper. Theses constraints have significant importance in practice for the vehicle routing and scheduling.

A. Multiple Subcontracting Service

Table I illustrates the different characteristics of each transportation mode. With short-term subcontracting, there are no fixed and variable costs connected with the tour. The cost of this type is corresponding to the utilization of trucks and the company only holds the costs when truck is used. As the costs of both tour and flow-oriented are based on the tariff tables which load quantity is already considered, thus the capacity of the truck is not taken into account. While in self-fulfillment or long-term subcontracting, the transport loading must not exceed the capacity of available vehicle. The operation time constraint has to be imposed on the self-fulfillment and tour-oriented short-term subcontracting types in order to return the trucks to original point, but for flow-oriented short-term subcontracting as it is fully outsourced therefore the constraints with respect to vehicle scheduling such as OTC and TW are not considered in this type.

Table I. Comparison of transportation modes

characteristics					
transportation modes		fixed cost	variable cost	capacity	operation time
Long Term (self-fullfilment)		drivers' wage, depreciation	fuel	yes	yes
short Term	flow-oriented	tariff-based		no	yes
	tour-oriented	tariff-based		No	No

B. Fleet-type constraints

Often in practice, it is necessary to assign special types of fleet for particular delivery requests. A typical example is cold chain distribution where perishable food products are to be maintained in good temperature condition during delivery process. There are three types of temperature segments: frozen, chilled and normal. For frozen and chilled products, the fleet with refrigerator needs to be assigned. Therefore, when assigning fleet to delivery orders, feasibility with respect to temperature needs to be considered.

Another big challenge is the fleet-size constraints for customers. In typical transportation assignment where there are customers with limited parking spaces, narrow aisles, or low ceilings for the warehouses, making a delivery with trucks that exceed those space limitations is not allowed. This makes optimization many more complicated, especially when making deliveries with tour-oriented subcontracts. With tour-oriented subcontracts, fleet-size is determined only after the assignment of orders for the fleet has been established. However, the feasibility with respect to fleet-size is dependent on the customers included in that assignment.

IV. PROPOSED ALGORITHM

Considering the above-mentioned issues make the problem much more complicated. Since the VRP itself is a NP-hard problem and known to be difficult, it seems very difficult to solve the problem with exact methods. Even with heuristic methods, however, there are still difficulties with respect to scalability. Most heuristics algorithms in the academic literature are designed to solve problems with several hundreds of requests within a few hours. In practice, however, over several thousands of order are posted. The maximum number of requests we observed is about 500,000 requests a day. Further, there are opinions for computing time that it should be less than ten minutes to be applicable in practice without user’s stress. Therefore, developing heuristics that could achieve a good trade-off between computation time and solution quality is another topic to consider.

This study shows a method to find a solution for the VRP extended by the short-term subcontracting transportation mode. It is, in clarification, a combinatorial optimization problem in transportation planning of the forwarding companies fulfilling their customer requests by applying two predefined types of transportation namely tour-oriented, and flow-oriented short-term subcontracting. The goal is to find an optimal solution that minimizes total delivery cost while serving a set of customers. In this problem, entire delivery requests of the two transportation modes correlate with total transportation costs of all routes that are used to deliver product from depots to customers, while the normal VRP only minimizes cost of single transportation type with only one single route from depot to each customer.

A. Mathematical Formulation

The problem is to simultaneously determine customer requests to vehicles, number of vehicles, travel distance and travel time per route, and the corresponding sequence of serving customers for each vehicle so that the all customer demands are satisfied and overall transportation cost is minimized. Given delivery depots where trucks pickup demand orders within time windows, known locations, demands, time windows, and loading and unloading time of customers, tariff tables for both tour and flow-oriented subcontracting which specified capacity of vehicles and travel distances, customers’ demand and travel distance cannot exceed section limit of truckload quantity and travel distance in tariff table, and vehicles must return to the origin within the time limit specified in rental condition for tour-oriented subcontracting type. The amount of payment for the transportation fee to the subcontractors is calculated by based on a fixed tariff rate per load and distance. The main objective is to construct a vehicle routing and scheduling with lowest possible fulfillment cost without violating any constraints. Mathematical models of the subcontracting problem are shown as follow.

minimize

$$\sum_{k \in K} f(q_k, d_k) x_{uvk} + \sum_{v \in V} f(q_v, d_v) x_v \tag{1}$$

subject to

$$q_k \le Q_l^T, l \in M, k \in K \tag{2}$$

$$d_k \le D_j^T, j \in N, k \in K \tag{3}$$

$$q_v \leq Q_l^F, i \in M', v \in V \tag{4}$$

$$d_v \leq D_j^F, j \in N', v \in V \tag{5}$$

$$q_k = \max\{\sum_{v \in V} q_v x_{uvk'}\}, \forall u \in U \cup V, \forall k \in K \tag{6}$$

$$d_k = \sum_{u \in U \cup V} \sum_{v \in U \cup V} d_{uv} x_{uvk'}, \forall k \in K \tag{7}$$

$$_{u \in U \cup V} \sum_{v \in U \cup V} x_{uvk}(t_{uv} + s_u + g_u) \leq T, \forall k \in K \tag{8}$$

$$_{u \in U \cup V} \sum_{v \in U \cup V} x_{uvk}(t_u + t_{uv} + s_u + g_u) \leq t_v, \qquad \forall k \in K \tag{9}$$

$$e_u \leq t_u \leq l_u, \forall u \in U \cup V \tag{10}$$

$$_{k \in K} \sum_{u \in U \cup V} x_{uvk} = 1, \forall v \in V \tag{11}$$

$$_{v \in U \cup V} x_{uvk} - \sum_{v \in U \cup V} x_{vuk}, \forall k \in K, \forall u \in U \cup V \tag{12}$$

$$_{k \in K} \sum_{u \in U \cup V} x_{uvk} + x_v = 1, \forall v \in V \tag{13}$$

$$x_{uvk} = \{0,1\}, \forall u \in U, \forall v \in V, \forall k \in K \tag{14}$$

$$x_{uvk'} = \{0,1\}, \forall u \in U, \forall v \in V, \forall k \in K \tag{15}$$

$$x_v = \{0,1\}, \forall v \in V \tag{16}$$

M : set of truck capacity in tour-oriented tariff table

M' : set of truck capacity in flow-oriented tariff table

N : set of travel distance in tour-oriented tariff table

N' : set of travel distance in flow-oriented tariff table

K : set of all routes for tour-oriented

K' : set of all routes for flow-oriented

U : set of all depots

V : set of all customers

Q_i^T : truckload capacity in tour-oriented tariff table, $i \in M$

D_j^T : travel distance in tour-oriented tariff table, $j \in N$

Q_i^F : truckload capacity in flow-oriented tariff table

D_j^F : travel distance in flow-oriented tariff table

q_k : total truckload quantity of route $k, k \in K$

q_v : quantity demand of customer $v, v \in V$

d_k : total distance of route $k, k \in K$

d_v : distance of route $k, k \in K'$

d_{uv} : distance between point u and v, $u, v \in U \cup V$

t_{uv} : travel time between point u and v, $u, v \in U \cup V$

t_u : arrival time at point $u, u \in U \cup V$

s_u : loading time at point $u, u \in U \cup V$

g_u : unloading time at point $u, u \in U \cup V$

e_u : earliest arrival time at point $u, u \in U \cup V$

l_u : latest arrival time at point $u, u \in U \cup V$

T : rental period for tour-oriented

$x_{uvk} = 1$ if truck k travels from point u to v, 0 otherwise

$x_{uvk'} = 1$ if truck k picks up requests r_v at depot u and consecutively delivers to customer v, 0 otherwise

$x_v = 1$ if the requests r_v is assigned to be fulfilled by truck k, 0 otherwise, $k \in K'$

The objective function (1) is to minimize the total transportation cost for fulfilling all customer demand. The first term of objective function is cost of using tour-oriented subcontracting. The second term is cost of using flow-oriented subcontracting. Constraints (2)-(5) specify the minimum usage of truckload quantity and travel distance according to the section limit in tariff table. The truckload quantity of tour-oriented type is measured as Eq. (6), and the distance is measured only for delivery route within a trip in Eq. (7). Eq. (8) is maximum travel time constraint and Eq. (9),(10) define the time windows. Each customer has to be assigned a single route according to constraint (11). The flow conservation constraint is expressed in (12). Eq. (13) makes sure that each request has to be fulfilled either by tour-oriented or by flow-oriented. The binary requirement on the decision variables are given by Eqs. (14)-(16).

B. Solution Approach

Since the simulated annealing algorithm has been applied to a wide variety of highly complicated combinatorial optimization problems including the VRP and has been proved that it could solve difficult problems and generally gives an acceptable good solution in a relatively short time [9]-[16], it was selected as the basis for developing technique for the VRP with short-term subcontracting transportation mode. The SA is a local search-based heuristic for the optimal state which is maximal or minimal value of the cost function by comparing the current solution with a random solution from a specific neighborhood. It accepts small probability of worse solutions during iterations for the purpose of being trapped into a local optimum. The probability decreases over the very slow decrease of temperature which could last infinitely long [17]. The advantage of the SA is that it can deal with arbitrary systems, can incorporate many cost functions and complex move functions, and statistically guarantees finding an optimal solution [18].

In this study, we generate the initial solution set with piston routes then apply standard SA procedure combined with local search to solve the VRP with short-term subcontracting problem. A random neighborhood structure which includes two types of trial moves, i.e. insert and swap, is used for improving the current solution by checking for best feasible positions of a customer in all routes. The insert move is carried out by randomly removing a customer from one route and putting it into another route. The removing customer is inserted between other two customers or between depot and customer of the receiving route. This type of move originates a solution with one route less if that route contains only one customer which is removed from the route. In order to minimize the number of vehicles, new routes are not allowed to create unless no feasible solution is detected. A swap move is performed by randomly exchanging the positions of two customers that belong to two different routes wherever the cost is lower.

Four parameters in annealing schedule that have to be predetermined for application of SA are initial temperature T_0, number of iterations I_n, cooling rate α, and final temperature T_F. In the beginning of the SA procedure, the current temperature is set to be the same as T_0. Then, at each iteration of each temperature the algorithm improves the current best solution by randomly searches for the next solution that decreases the objective function value f. An increase in f which is defined as σf is accepted with a probability $p = exp(\sigma f / T)$. After running n iterations, the current temperature T is decreased according to α. Finally, the algorithm is terminated when the temperature reaches T_F. The general flowchart showing the implementation of VRP with subcontracting using SA is shown in Figure IV-B.

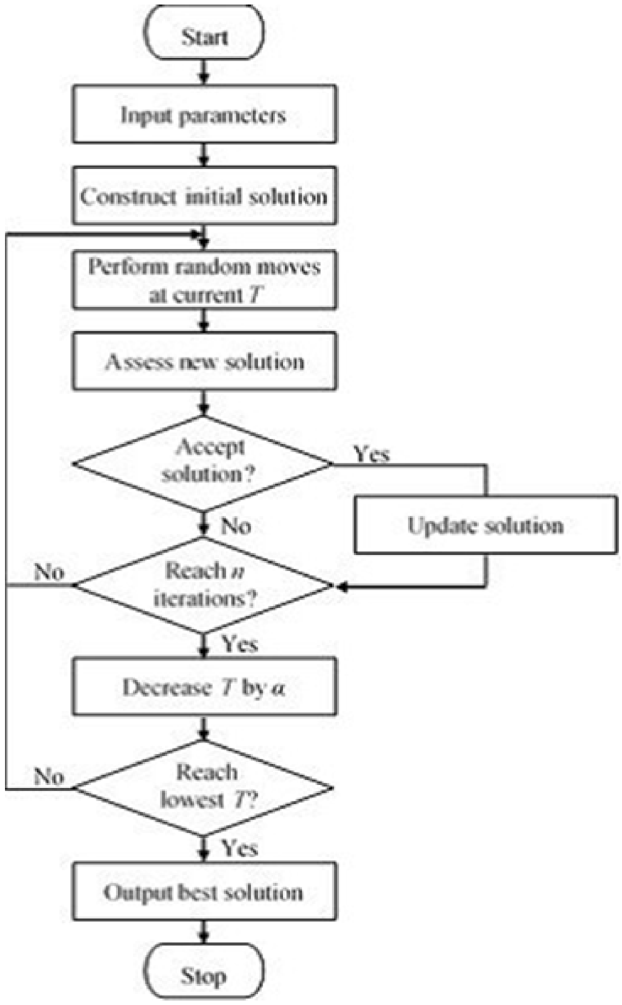

Fig 5. Flowchart of SA Implementation

V. APPLICATION

Table II. Computation Result

	# of vehicles	distance (km)	time (min)	cost (JPY)
Initial State	1,088	119,222	412,223	29,014,340
Total Resource Usage	821	108,631	373,955	25,472,510
- Tour-oriented	222	48,204	141,790	9,908,860
- Flow-oriented	599	60,427	232,165	15,563,650
Improvement	24.5%	8.9%	9.3%	12.2%

We have analyzed the forwarding company in Japan using the short-term subcontracting mode of transportation for its delivery operations. The company receives a varying number of orders from its customers each day and plans the shipment of these daily variations of volume of transportation requests on a monthly basis. In order to ensure that enough resources will be provided profitably for the fulfillment, the company has to make decision on the selection of requests whether to be performed by using the tour-oriented or the flow-oriented short-term subcontracting. The aim of this computational analysis is to point out that the proposed SA algorithm could generate solutions for the VRP with subcontracting transportation modes.

A real-problem data set is applied for computational analysis. The company has distribution center to serve 44 customers. The depot has business hours from 7:20 a.m. to 1:20 p.m., and there is time window for each customer. The data of total customer daily demand for one month is 3,088 requests which accounted for almost 2,300 tons. The tariff tables for both service of tour and flow-oriented are referred from the Ministry of Land, Infrastructure, Transport and Tourism. The following parameters of SA procedure are set for the computation analysis: T_0 = 1,000, T_F = 1, α = 0.99, I_n = 300. Then a daily fulfillment plan for whole month is generated including the numbers of trucks required for both subcontracting modes and the routing for tour-oriented type using the SA heuristic. The number of vehicle used, total transportation distance and time, and total fulfillment cost of an initial state and after improvement are summarized and presented in Table 3.

The number of truck and total travel distance could be reduced around 24.5% and 8.9% respectively. The travel time of each route consists of the travel time between two stops and the loading/unloading time of each stop. The total travel time is improved 9.3% from the initial solution. The total cost could be reduced by 12.2% which considered favorable result as [19] stated that numerous practical applications of the VRP could reduce transportation costs for major companies from 6% to 15%. Table 3 also shows a breakdown of the resource usage of each short-term subcontracting type. As the tariff rate of tour-oriented is lower than flow-oriented short-term subcontracting, there is a potential of resources saving if the company could increase the utilization of the tour-oriented subcontracting.

VI. CONCLUSION

This paper addressed an extended and more practical version of the VRP. We presented a practical complex situation of current business in the forwarding companies where an integrated transportation approach is used to fulfill the transportation requests. In transportation planning, the company is required to find the optimal blend of different types of transportation options available. It has to assign each request to an appropriate mode of transportation and decide the operations for the usage of each mode with its specific type of freight calculation for the payment of subcontracting by taking into account the amount of requests on each period. We proposed the simulated annealing approach for the process of constructing an entire fulfillment plan and the solution of combinatorial optimization problem in the VRP with short-term subcontracting mode with the objective to minimize the overall transportation delivery cost. The real-problem data set which contains a large number of requests for computational analysis was applied for illustration. We showed that the overall operational cost and the resource usage could be significantly reduced by integrating the usage of subcontracting.

In order to account for the market trends and the change in demand, therefore, the company could increase the efficiency of transportation planning and enhance the flexibility and service quality by a rigorous analysis of the extended vehicle routing and scheduling problem. The challenge is to look for better optimize solution and the improvement heuristic for the transportation management strategy that could match the capacity and service requirements across the utilization of multiple transportation modes. Moreover, the development of analysis that integrate the utilization of own vehicle fleet would allow the forwarding companies to determine the optimal number of own vehicles for a long-term planning at a strategic level.

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