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A Meta-heuristic Approach for VRP with Simultaneous Pickup and Delivery Incorporated with Ton-Kilo Basis Saving Method

Yoshiaki Shimizu and Tatsuhiko Sakaguchi

Abstract Under growing concerns with sustainable society, green or low carbon logistic optimization is becoming a keen interest to provide a plausible solution aiming at qualified service in global and competitive distribution system. As a key technology for such deployment, this chapter proposes a hybrid method of simultaneous pickup and delivery VRP aiming at rational framework available for real world applications. In its general procedure, the initial solution is derived from a modified saving method that consider the cost accounting known as Weber model or a bi-linear model of distance and weight. Then, it is updated by a modified tabu search to improve the tentative solution as much as possible. The idea is further extended to a non-linear or generalized Weber model. Numerical experiments are taken place to validate effectiveness of the proposed method through comparison.

Keywords Simultaneous pickup and delivery VRP · Hybrid meta-heuristic approach · Weber model · Modified saving method

1 Introduction

Under growing concerns with sustainable society, green or low carbon logistic optimization is becoming a keen interest to provide a fruitful solution aiming at qualified service in global and competitive distribution system. As a key technology for such deployment, we have engaged in the practical studies on vehicle routing problems (VRP) noticing that the transportation cost and/or CO_2 emission actually depend not only distance but also loading weight. This bi-linear cost accounting (unit cost times loading weight times traveling distance) is known as

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the Weber model and applied popularly to the conventional location/allocation problems belonging to a strategic level problem. Regarding operational problems like VRP, however, this idea has never been considered previously. Giving a general solution procedure in terms of a modified saving method for the Weber model, we developed a hybrid method so that we can practically cope with various types of VRP, i.e., delivery, direct pickup, and drop by pickup both for single depot and multi-depot problems (Shimizu 2011a, b). Against this, it is almost impossible to cope with those problems by conventional mathematical programming approaches. This chapter extends such our idea to a simultaneous pickup and delivery VRP (VRPSPD), and propose a novel saving-based hybrid method that is amenable for various real world applications.

The rest of the chapter is organized as follows. In Sect. 2, we briefly describe problem statements with a review of the related studies. Giving problem formulation in Sect. 3, we explain the proposed method in Sect. 4. Section 5 shows numerical experiments carried out to validate the effectiveness of our method. Finally, we give some conclusions in Sect. 6.

2 Problem Statement and Review of the Related Studies

Let us consider such a logistic network composed of single depot and multiple customers as illustrated in Fig. 1. Thereat, every vehicle starting from the depot visits its client customers via circular route, and return to the original depot so that a certain objective function can be optimized under some prescribed constraints. This generic problem has been studied popularly as VRP. It is a well-known combinatorial optimization problem, which minimizes the total distance traveled by a fleet of delivery vehicles under various constraints.

One of the recent studies on VRP is an extension from the generic customer demand satisfaction and vehicle payload limit. The other concerns have been paid to multi-depot problem (Chen et al. 2005) and multi-objective formulation (Jozefowiez et al. 2008). As a special variant of VRP, many researches are recently interested in VRP with pickup and delivery from certain aspects. They are classified into the following three categories (Nagy and Salhi 2005).

- Delivery first, Pickup second (VRPB): pickup only after delivered,
- Mixed Pickup and Delivery (MVRP): delivery and pickup in any sequence along the routes,
- Simultaneous Pickup and Delivery (VRPSPD): simultaneous delivery and pickup.

In this study, we concern VPRSPD since this is the most practical and general compared with the others. The VRPSPD refers to MVRP when either of pickup demand or delivery demand is placed at each customer.

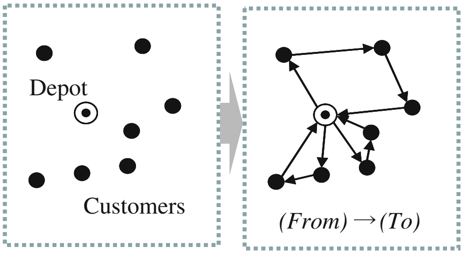

Fig. 1 Logistic network design problem concerned here

The first work in this area is studied by Min (1989) who proposed a cluster-first route-second approach and made a case study in public library A universal mix integer programming mathematic model is formulated associated with time windows and travelling distance constraints by Cao and Lai (2007) and it is solved using an improved genetic algorithm (IGA). Xie et al. (2007) gave an inserting criterion based on travelling distance. Ai and Kachitvichyanukul (2009) applied a particle swarm optimization (PSO) with multiple social structures. Subramanian et al. (2010) applied a parallel technique using multi-start heuristic. It is based on a variable neighbourhood descent procedure with a random neighbourhood ordering in an iterated local search (ILS) framework. Catay (2010) proposed an ant colony algorithm employing a new saving-based visibility function and pheromone updating procedure. Being interested in cost saving and environmental protection, Lai and Cao (2010) solved the problem with time windows by an improved differential evolution. A new meta-heuristic method called bacterial foraging optimization algorithm (BFOA) is applied by Hezer and Kara (2011) under the condition of total distance travelled. Capacitated vehicle routing problem (CVRP) is studied on the branch-and-cut algorithm by Subramanian et al. (2011). Noticing the importance of VRPSPD in reverse logistics, Jun and Kim (2012) proposed a sweep-based route method to generate better initial solution that could be improved by the following procedure associated with inter and intra routes. Goksal et al. (2013) used PSO under the variable neighbourhood descent algorithm (VND). Table 1 summarizes the VRPSPD related works mentioned above, describing their main contributions and/or approaches.

Due to difficulty of solution, however, only small problems formulated by no more than 400 customers are solved in numerical experiments to validate effectiveness of the respective method. Moreover, they have never adopted the transportation cost accounting by the Weber model. Real world applications of VRPSPD are frequently encountered in the distribution system of bottled drinks, groceries, LPG tanks, laundry service of hotels, some reverse logistics, etc. Since in these cases, we cannot ignore the weight expect for a few exceptions, the present approach has a practical significance compared with the previous studies mentioned above.

Table 1 Related studies associated with VRPSPD

Work	Year	Contributions and/or approach
Min	1989	First work, a cluster-first route-second approach
Cao and Lai	2007	MIP model, with time windows and traveling distance constraints, improved genetic algorithm
Xie, Qiu and Zhang	2007	Inserting criterion based method on traveling distance
Ai and Kachitvichyanukul	2009	PSO with multiple social structures
Subramanian et al.	2010	Parallel approach, a variable neighborhood descent in local search
Catay	2010	Ant colony algorithm employing a new saving-based visibility function and pheromone updating procedure
Lai and Cao	2010	Time windows, improved differential evolution
Subramanian et al.	2011	Branch-and-cut algorithm
Hezer and Kara	2011	Bacterial foraging optimization algorithm
Jun and Kim	2012	Sweep-based route method to generate better initial solution
Goksal, Karaoglan and Altiparmak	2013	Particle swarm optimization, variable neighborhood descent algorithm

3 Problem Formulation

The Weber model for VRPSPD is formulated by the following combinatorial optimization problem.

(p.1) min

$$\sum_{v \in V} \sum_{m \in M} \sum_{m' \in M} c_v d_{m'm} (g_{mm'y} + w_v) z_{mm'v} + \sum_{v \in V} F_v y_v$$

Subject to

$$\sum_{m \in M} z_{kmv} \leq 1, \quad \forall k \in K;\ \forall v \in V \tag{1}$$

$$\sum_{m' \in M} z_{mm'v} - \sum_{m' \in M} z_{m'mv} = 0,\ \forall m \in M;\ \forall v \in V \tag{2}$$

$$\sum_{j \in J} z_{jj'v} = 0,\ \forall j' \in J;\ \forall v \in V \tag{3}$$

$$\sum_{v \in V} \sum_{k \in K} g_{jkv} z_{jkv} \leq U_j x_j,\ \forall j \in J \tag{4}$$

$$g_{mm'v} \leq W_v z_{mm'v}, \ \forall m, \ m' \in M; \ \forall v \in V \tag{5}$$

$$\sum_{m \in M} \sum_{m' \in M} z_{mm'v} \leq L y_v, \ \forall v \in V \tag{6}$$

$$\sum_{k \in K} g_{kjv} = \sum_{k \in K} \sum_{k' \in K} p_k z_{kk'v}, \ \forall j \in J; \ \forall v \in V \tag{7}$$

$$\sum_{v \in V} \sum_{m \in M} g_{mkv} - \sum_{v \in V} \sum_{m \in M} g_{kmv} = q_k - p_k, \ \forall k \in K \tag{8}$$

$$\sum_{v \in V} g_{mm'v} = \sum_{v \in V} (u_{mm'v} + s_{mm'v}), \ \forall m, \ m' \in M \tag{9}$$

$$\sum_{v \in V} \sum_{m \in M} u_{kmv} - \sum_{v \in V} \sum_{m \in M} u_{mkv} = p_k, \ \forall k \in K \tag{10}$$

$$\sum_{v \in V} \sum_{m \in M} s_{kmv} - \sum_{v \in V} \sum_{m \in M} s_{mkv} = q_k, \ \forall k \in K \tag{11}$$

$$\sum_{j \in J} \sum_{k \in K} z_{jkv} = y_v, \ \forall v \in V \tag{12}$$

$$\sum_{j \in J} \sum_{k \in K} z_{kjv} = y_v, \ \forall v \in V \tag{13}$$

$$\sum_{m \in \Omega} \sum_{m' \in \Omega} z_{mm'v} \leq |\Omega| - 1, \ \forall \Omega \subseteq M \backslash \{1\}, \ |\Omega| \geq 2, \ \forall v \in V \tag{14}$$

$$\begin{aligned} x_j \in \{0, \ 1\}, \ \forall j \in J; \ y_v \in \{0, \ 1\}, \ \forall v \in V \\ z_{mm'v} \in \{0, \ 1\}, \ \forall m, \ m' \in M; \ \forall v \in V \\ g_{mm'v} \geq 0, \forall m, \ m' \in M; \forall v \in V \end{aligned}$$

Notations of this problem are shown below.

Variables

- $g_{mm'v}$ [ton]: total load of vehicle v on the path from $m \in M$ to $m' \in M$
- $s_{mm'v}$ [ton]: delivery load of vehicle v on the path from $m \in M$ to $m' \in M$
- $u_{mm'v}$ [ton]: pickup load of vehicle v on the path from $m \in M$ to $m' \in M$
- $x_j = 1$ if candidate depot j is opened; otherwise 0
- $y_v = 1$ if vehicle v is used; otherwise 0
- $z_{mm'v} = 1$ if vehicle v travels on the path from $m \in M$ to $m' \in M$; otherwise 0

Parameters

- c_v [cost unit/ton/km]: transportation cost per unit load per unit distance of vehicle v

- p_k [ton]: pickup demand of customer k
- q_k [ton]: delivery demand of customer k
- $d_{mm'}$ [km]: path distance between $m \in M$ and $m' \in M$
- F_v [cost unit]: fixed charge for working vehicle v
- L [-]: auxiliary constant (large integer number)
- w_v [ton]: unladen weight of vehicle v
- U_j [ton]: maximum capacity of depot j
- W_v [ton]: maximum capacity of vehicle v

Index set

- J: depot; K: customer; V: vehicle; $M = J \cup K$, Ω: sub-tour

Here, objective function is composed of routing transportation cost and fixed charges of vehicles. On the other hand, each constraint means as follows: each vehicle cannot visit the customer twice (Eq. 1); coming in vehicle must leave out (Eq. 2); making a path between depots is avoided (Eq. 3); upper holding capacity at depot and upper bound load capacity for vehicle are given by Eq. 4 and Eq. 5, respectively; vehicle must travel on a certain path (Eq. 6); load of the returned vehicle must be equal to the total pickup loads (Eq. 7); Equation 8 and Eq.9 are material balances at each depot and path, respectively; difference from the foregoing visit is described by Eq. 10 and Eq. 11 for pickup and delivery, respectively; each vehicle leaves only one depot and return there (Eq. 12 and Eq. 13); Equation 14 gives a sub-tour elimination condition. Integrality conditions and positive conditions are imposed on the respective variables.

It is well known that this kind of problem belongs to an NP-hard class, and becomes extremely difficult to obtain a rigid optimal solution for real-world size problems. Hence, it is meaningful for those applications to provide a practical method that can derive a near optimum solution with reasonable computational efforts. Actually, we propose a hybrid method composed of the ordinary and meta heuristic methods.

4 Hybrid Approach for Practical Solution

4.1 Transportation Cost Accounting

As a key component of the hybrid method mentioned above, we applied the modified saving method whose cost accounting relies on the bilinear model known as the Weber model (Ton-Kilo basis). It is described as $c_v d_{ij}(w_v + q_j)$. Here w_v and q_j are unladen weight of vehicle v and demand of customer j as weight, respectively. In order to evaluate the cost from a more flexible viewpoint, the above formula is possible to extend to the generalized Weber model descried as $c_v \gamma d_{ij}^{\alpha}(w_v + q_j)^{\beta}$ where α and β denote the elastic coefficients for the distance and weight, respectively and γ is a constant.

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Moreover, for practical evaluation of economy, it is suitable to account the fixed-charge of working vehicle F_v besides transportation cost. Eventually, we can evaluate the total cost TC by the following equation.

$$TC = \sum_{i=1}^{|V|} TR_i + |V| \cdot F_v \tag{15}$$

where

TR_i denotes circular transportation cost of root i, and |V| total number of roots (necessary vehicle).

4.2 Proposed Method

To practically work with the above problem, we used the procedure outlined below. In this procedure, we apply two major components termed modified saving method and modified tabu search in a consecutive manner as follows.

Step 1 Derive the initial solution of VRPSPD by the modified saving method.
Step 2 Improve the above solutions by the modified tabu search.

Though the algorithm of the modified saving method itself is same as the original one, we need to note the following two special ideas in cost accounting. The first one is to derive the saving value on the Ton-Kilo basis. Referring to Fig. 2, the saving value between customer i and j is given by Eqs. (16) and (17) for Weber model and generalized Weber model, respectively. Apparently, the generalized model reduces to the ordinary when $\alpha = \beta = \gamma = 1$.

$$s_{ij}/c_v = d_{0i}(p_i - q_j + w_v) + d_{0j}(-p_i + q_j + w_v) - d_{ij}(p_i + q_j + w_v) \tag{16}$$

$$\begin{aligned} s_{ij}/(c_v\gamma) = {} & (q_i + w_v)^\alpha d_{0i}^\beta + (p_i + w_v)^\alpha d_{i0}^\beta + (q_j + w_v)^\alpha d_{0j}^\beta + (p_j + w_v)^\alpha d_{j0}^\beta \\ & -(q_i + q_j + w_v)^\alpha d_{0i}^\beta - (p_i + q_j + w_v) - (p_i + p_j + w_v)^\alpha d_{j0}^\beta \end{aligned} \tag{17}$$

Here, let the suffix be 0 for depot, $s_{ii} = 0$, and $d_{ij} = d_{ji}$.

The second one comes to the assertion that it is more economical to visit the new customer even if its saving value would become negative as long as its absolute value stays within the fixed charge of vehicle.

Moreover, for the simplicity of the algorithm, we assume the pickup load is less equal to the delivery one, i.e. $p_i \le q_i, \ \forall i \in I$. This is a mild condition when looking at the cases of the bottled drinks and so on mentioned already. Then, Eqs. (19) and (20) are certainly satisfied under Eq. (18). In other word, it is enough to notify only the condition Eq. (18) as the loading constraint of vehicle.

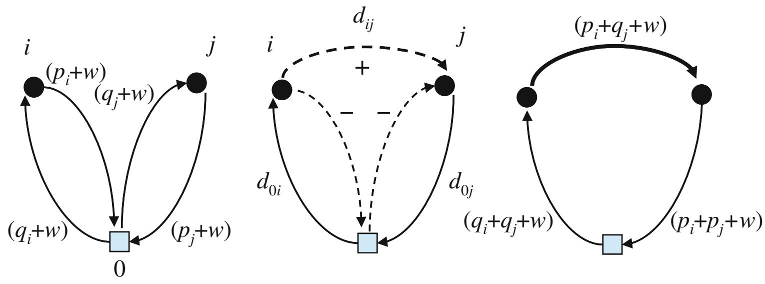

Fig. 2 Scheme to derive Ton-Kilo basis saving value

$$q_i + q_j \leq W_v \tag{18}$$

$$p_i + p_j \leq W_v \tag{19}$$

$$p_i + q_j \leq W_v \tag{20}$$

Since the (modified) saving method derives only an approximated solution, we try to improve it by applying the modified tabu search. There, we employed a few neighborhood operations known as insert, exchange and 2-opt both within each loop and between the loops. Actually, one of those operations is randomly selected under the control of tabu list whose length varies along with the problem size. Moreover, in the original algorithm of tabu search, only the improved neighbourhood solution can survive as long as it would not be involved in the tabu lists. In the modified method, however, even a degraded solution can be allowed to be a new tentative solution. This decision is made based on the probability whose function is known as Maxwell-Boltzmann and used in simulated annealing (Kirkpatrick et al. 1983). It is described as follow.

$$p = \begin{cases} 1 & if\ \Delta e \leq 0 \\ \exp(-\Delta e/T) & if\ \Delta e \leq \varepsilon \\ 0 & if\ \Delta e > \varepsilon \end{cases} \tag{21}$$

where

Δe and ε denote the amount of degradation of objective function value and a certain small value, respectively. Moreover, temperature T will be decreased geometrically along with the iteration.

Regardless of using the ordinal or the generalized models, the proposed method can work with in the same framework. It only requires to replace the saving value given by Eq. (16) with Eq. (17) in Step 1. In contrast, the foregoing mixed-integer bi-linear formulation turns to the non-linear one for the generalized model. This will expand the difficultly of solution greatly.

Table 2 Outline of parameter setting

Distance between customers	[2, 50]
Customer demand	$[2,100]/|K|^{0.25}$
Unladen weight	10
Payload	1,000
Fixed operating cost	50,000

5 Numerical Experiment

Numerical experiments were carried out to validate the effectiveness of the proposed method. In my best knowledge, there have been never existed the studies concerned with Ton-Kilo basis anywhere. Hence, we prepared the benchmark problems by ourselves. First, we randomly generated the prescribed numbers of customers within the rectangular region. Then, a depot is located in its center. The distances between the depot and customers and also those between every customer are given by Euclidian basis. Moreover, demands of each customer for delivery are randomly given within the prescribed ranges. Then, the pickup demands are set like $p_i = (0.3 + 0.7\ \text{rand}())q_i$ so that $p_i \leqq q_i, \forall i \in I$ will be satisfied. The outline of those parameter setting is summarized in Table 2. We used PC with CPU: Intel(R) Celeron(R) 430 1.8 GHz, and RAM: 1 GB. The following discussions are made by averaging the results over 10 samples.

As an alternative to satisfy the requirement both on delivery and pickup of every customer, we can attain such final goal by doing them separately. In this case, we need to solve the delivery (D) and pickup (P) problems independently, and to sum those results to evaluate the total performance. Actually, we compared the results between SPD and such independent dealing (IP&D) through the procedure outlined in Fig. 3.

We summarize the results in Tables 3 and 4. They involve such large problems that have never been solved elsewhere. In the tables, the numbers in *Rate* column denote the improved rates of the final solution from the initial solution derived from the modified saving method. Due to the high non-linearity, results of the generalized model are poor (less than half) compared with those of the ordinary one. Due to the elastic coefficients [$\alpha = 0.894$, $\beta = 0.750$; ($\gamma = 1.726$)], however, the cost itself is less than that of the Weber model except for one exception.

The values in *IMP* column are given by 100(cost(IP&D)-cost(SPD))/cost (IP&D). They show how much we can save the cost by the simultaneous transport from the independent case. In any cases, we know it is able to decrease more than 60 % for the Weber model and till nearly 60 % for the generalized model. We should notice that the number of routes or necessary vehicles is also around 60 %. These results reveal the great advantage of the simultaneous transportation over the independent one.

In comparison, CPU time and iteration number of SPD also stay a bit below 50 % of those of IP&D. As a common property of the combinatorial optimization, CPU time itself expands rapidly according to the increase in problem size. Even

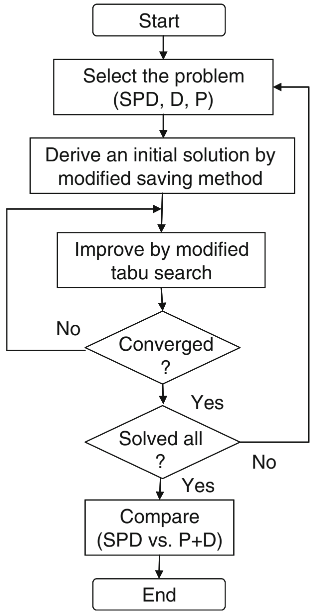

Fig. 3 Flow of the evaluation process

Table 3 Result for Weber model

	Size (–)	Cost (cost unit)	CPU (s)	Route# (–)	Iteration# (–)	Rate (–)	IMP (%)
Simultaneous	10	5.43E + 04	0.012	1.0	8.11E + 02	0.207	65.6
(SPD)	100	2.12E + 05	0.292	3.9	6.33E + 04	0.241	66.0
	300	4.84E + 05	3.502	9.0	5.64E + 05	0.214	61.3
	500	6.66E + 05	11.899	12.5	1.52E + 06	0.214	63.8
	1000	1.08E + 06	64.769	20.6	5.95E + 06	0.220	65.0
Independent	10	1.58E + 05	0.024	2.0	1.66E + 03	–	–
(IP&D)	100	6.24E + 05	0.563	6.8	1.31E + 05	–	–
	300	1.25E + 06	7.229	13.5	1.20E + 06	–	–
	500	1.84E + 06	24.551	20.3	3.40E + 06	–	–
	1000	3.09E + 06	138.634	32.9	1.38E + 07	–	–

for the largest problems, however, we can solve them within a reasonable time. Moreover, we show the convergence profiles in Fig. 4. Due to the high non-linearity, it seems the generalized case (open circle key) will not improve sufficiently compared with the original case, especially for the larger size problems.

To improve this poor performance in advance, it had better introduce the additional neighborhood operations that can derive more distant neighbors in the modified tabu search. As a whole, however, we can claim the proposed method can derive near optimum solutions of VRPSPD within reasonable computation times.

Table 4 Result for generalized Weber model

	Size (−)	Cost (cost unit)	CPU (s)	Route# (−)	Iteration# (−)	Rate (−)	IMP (%)
Simultaneous	10	5.31E + 04	0.018	1.0	8.22E + 02	0.083	58.8
(SPD)	100	2.06E + 05	1.425	3.9	6.33E + 04	0.105	58.9
	300	4.62E + 05	16.509	8.8	5.59E + 05	0.096	58.4
	500	6.65E + 05	50.753	12.7	1.47E + 06	0.091	58.9
	1000	1.12E + 06	251.795	21.4	5.91E + 06	0.089	59.8
Independent	10	1.29E + 05	0.04	2.0	1.66E + 03	–	–
(IP&D)	100	5.01E + 05	3.32	6.6	1.31E + 05	–	–
	300	1.11E + 06	43.106	14.0	1.23E + 06	–	–
	500	1.62E + 06	136.652	20.6	3.40E + 06	–	–
	1000	2.79E + 06	702.3	33.1	1.37E + 07	–	–

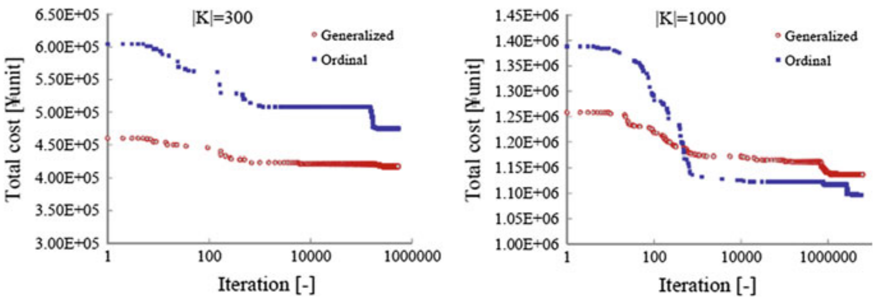

Fig. 4 Profiles of convergence

6 Conclusion

As a key technology for sustainable logistics under agile manufacturing and qualified service in distribution system, we have proposed a novel method for VRPSPD available for various real world applications. It is deployed in the framework proposed previously by making the best use of the components termed modified saving method and modified tabu search in a hybrid manner. Numerical experiments are carried out to validate the effectiveness of the proposed method.

In future studies, it is necessary to make earnest efforts for improving the solution ability especially for the generalized model. We also aim at extending the idea to cope with the problems more in general framework and consider various more practical conditions. For example, multi-depot, time window and duration distance are plausible conditions for such approach. Moreover, it is meaningful to turn our interest to multi-objective optimization that could associate with trade-off analysis among economics, risks, services, environment issues, etc.

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Appendix A

The saving values on Ton-Kilo basis for the other types are summarized in Table A-1.

Table A-1. The Ton-Kilo basis saving values

Type	Weber model	Generalized Weber model
Delivery	$q_j(d_{0j} - d_{0i} - d_{ij}) + w_v(d_{0j} + d_{i0} - d_{ij})$	$\{(w_v + q_i)^\alpha - (w_v + q_i + q_j)^\alpha\}d_{0i}^\beta + (w_v + q_j)^\alpha(d_{0j}^\beta - d_{ij}^\beta) + w_v^\alpha d_{i0}^\beta$
Pick up	$p_i(d_{i0} - d_{j0} - d_{ij}) + w_v(d_{0j} + d_{i0} - d_{ij})$	$\{(w_v + p_j)^\alpha - (w_v + p_i + p_j)^\alpha\}d_{j0}^\beta + (w_v + p_i)^\alpha(d_{i0}^\beta - d_{ij}^\beta) + w_v^\alpha d_{0j}^\beta$

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