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Location-inventory-routing Problem in a Context of City Logistics: A Case Study of Jakarta

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ABSTRACT

City logistics idea is to develop an effective, efficient, and environmentally friendly logistics system. The development of city logistics is related to energy consumption, traffic congestion, economic and environmental problems. As one of the megacities in the world, Jakarta faces an inventory problem which is low availability of only 76%. Jakarta also faces the problem of transportation that is traffic congestion. The problems show that it is needed to develop city logistics in Jakarta. City logistics developed in this paper is related to decisions of location, inventory, and routing problems or LIRP (location-inventory-routing problem) in short. The LIRP takes into account multi-products, multi suppliers, and traffic congestion as an external parameters. This paper aims to develop a heuristic method to solve the LIRP. The heuristic method is based on simulated annealing (SA) algorithm. Existing literature shows that this paper's heuristic method to solve the LIRP has never been developed before. From applying the heuristic method in Jakarta, the coordination concept of city logistics reduces the vehicle number by 73%, and the consolidation concept of city logistics increases the availability from 76% to 95%.

Keywords: city logistics, location-inventory-routing problem, heuristic method, simulated annealing algorithm, traffic congestion

1. INTRODUCTION

City logistics idea is to develop an effective, efficient, and environmentally friendly logistics system *(Taniguchi et al.*, 2012). According to Benjelloun *et al.* (2010), the development of city logistics is related to problems such as energy consumption, traffic congestion, economic problem, and environmental problem. As one of the megacities in the world, Jakarta faces an inventory problem which is low availability that is only 76%. Jakarta also faces a transportation problem that is traffic congestion *(*Saragih *et al.*, 2019). Those problems show that developing city logistics in Jakarta is needed to increase availability and decrease congestion. Development of city logistics related to availability and congestion problems has never been developed before. Traffic congestion is important in developing urban logistics systems because of the increasingly severe traffic conditions in many cities worldwide (Crainic *et al.*, 2004; Das & Mitra, 2018).

Entities involved in the supply chain of Jakarta are traditional markets, wholesale markets, and provinces of suppliers. The single-tier city logistics system is the system of city logistics developed in this paper. The system also consists of three entities. They are the point of demand, logistics facilities, and supplies (Benjelloun & Crainic, 2009). Point of supplies are provinces of suppliers, which are called suppliers, logistics facilities are wholesale markets that are substituted with urban consolidation centres or UCCs (Browne *et al.*, 2005), and point of demands are traditional markets, called retail markets. Fundamental concepts of city logistics used in this paper are consolidation and coordination (Crainic *et al.*, 2009). City logistics initiatives used are cooperative freight transportation system and public logistics terminal (Taniguchi & Van Der Heijden, 2000). The products are fruits and vegetables, and the demands are probabilistic, following a normal distribution.

In the real system, the wholesale markets are located in the city, while UCCs in the city logistics system are outside of the city. Therefore, the optimal locations for UCCs needs to be determined (Gholamian & Nasri, 2019; Mokrini *et al*., 2019). The consolidation concept solves the logistics problem's low availability by increasing service levels and optimally controlling inventory on the three entities involved. The coordination concept is used to solve traffic congestion, a transportation problem, by decreasing the number of vehicles by using vehicles together. Due to the use of cars together, it is necessary to determine the optimal vehicle route to serve the retail markets. Based on those descriptions, the city logistics model developed in this paper is related to decisions of location, inventory, and routing problems or location-inventory-routing problem (LIRP) in short. The model takes into account multi-products, multi suppliers, and traffic congestion as an external parameter. The model was given in Saragih *et al*. (2018).

Since LIRP belongs to the class of NP-hard problems, it needs a heuristic method to apply it in Jakarta. This paper aims to develop a heuristic method to solve the LIRP. The heuristic method is based on simulated annealing (SA) algorithm. Existing literature shows that this paper's heuristic method to solve the LIRP has never been developed before. Two stages of heuristic method are developed in this paper to solve the problem. The stages are constructive and improvement stage. The heuristic method is developed from Saragih *et al*. (2019). Simulated annealing (SA) algorithm is used to improve the solutions at the improvement stage.

2. LITERATURE REVIEW

This section describes papers related to LIRP in the last 10 years. Sajjadi & Cheraghi (2011) solved LIRP using simulated annealing that consisted of multi echelons, multi products, and probabilistic demands. Decisions of inventory were made at depots and customers. Guerrero *et al*. (2013) solved LIRP using local search and randomized extended Clarke and Wright algorithm. The problem consisted of single echelon, single product, and deterministic demand. Similar to Sajjadi & Cheraghi (2011), in Guerrero *et al*. (2013), decisions of inventory were made at depots and customers. Nekooghadirli *et al*. (2014) solved LIRP using multi-objective meta-heuristic algorithms. The problem consisted of multi echelons, multi products, and probabilistic demands. Decisions of inventory in Nekooghadirli *et al*. (2014) were made only at distribution centers. Zhang et al. (2014) solved LIRP where decisions of inventory were made at customers only. Zhang *et al.* (2014) used simulated annealing and local search to solve the problem that consisted of multi echelons, single product, and deterministic demand.

Tang *et al.* (2016) solved LIRP using multi-objective particle swarm optimization where the inventory decisions were made only at warehouses. The problem in Tang et al. (2016) consisted of multi echelons, single product, and probabilistic demand. In addition, Tang *et al.* (2016) considered carbon emissions as external parameters. Ghorbani & Akbari Jokar (2016) solved LIRP using simulated annealing and imperialist competitive that consisted of multi echelons, multi-products, and probabilistic demands. Decisions of inventory were made at depots and customers. Zhalechian *et al*. (2016) solved LIRP using variable neighborhood search and self-adaptive genetic algorithm. The problem consisted of multi echelons, multi-products, and probabilistic demands. The inventory decisions of were made only at distribution centres. External parameters considered in Zhalechian *et al*. (2016) were fuel consumption, carbon emissions, wasted energy, CO_2 emissions, and the social impacts. Hiassat *et al*. (2017) solved LIRP for a problem that consisted of single echelon, single product, and deterministic demands using a genetic algorithm. The inventory decisions were made only at customers. Rayat *et al*. (2017) solved LIRP using archived multi-objective simulated annealing where only distribution centres made inventory decisions. The problem consisted of multi echelons, multi-products, and deterministic demands.

Using the Lagrangian relaxation algorithm, Rafie-Majd *et al.* (2018) solved LIRP for a problem consisting of multi echelons, multi-products, and deterministic demands. The inventory decisions were made at customers only. Vahdani *et al.* (2018) solved LIRP using non-dominated sorting genetic algorithm II and multi-objective particle swarm optimization. The problem consisted of multi echelons, multi-products, and probabilistic demands. The inventory decisions were made at distribution centres/warehouses. Saragih *et al.* (2019) solved LIRP using simulated annealing for a problem that consisted of multi echelons, single product, and probabilistic demand. Decisions of inventory were made at retailers, depots and suppliers. Bagherinejad & Najafi-Ghobadi (2019) solved LIRP using a genetic algorithm and an evolutionary simulated annealing algorithm. The problem consisted of multi echelons, single products, and deterministic demand. The inventory decisions were made at retailers and warehouses.

Farias *et al.* (2020) solved LIRP using Branch-and-Cut algorithm and two-phase heuristic for a problem that consisted of multi echelons, single product, and deterministic demand. Decisions of inventory were made at customers, distribution centers, and supplier. Rahbari *et al.* (2020) solved LIRP using general algebraic modeling system for a problem that consisted of multi echelons, single product, and deterministic demand. Decisions of inventory were made at all echelons. Karakostas *et al.* (2020) solved LIRP using general variable neighborhood search for a problem that consisted of single echelon, single product, and deterministic demand. Karakostas *et al.* (2020) considered external parameters which were fuel and CO_2 emissions. The summary of papers related to location-inventory-routing problem can be seen in Table 1.

The heuristic method developed in this paper is to solve LIRP in a context of city logistics. The problem is taking into account multi products, multi suppliers, and traffic congestion as an external parameter. From Table 1, it can be concluded that this work has never been done before.

Table 1 Papers related to LIRP in the last 10 years

Papers	Number of products		Decisions of inventory			Parameters		Number of echelons	
	Single	Multi	Customers/ Retailers	Depots/ Distribution centers/ Warehouses	Suppliers/ Plants	Internal	External	Single	Multi
This paper		√	√	√	√	√	√		√
Karakostas et al. (2020)	√		√			√	√	√	
Rahbari et al. (2020)	√		√	√	√	√			√
Farias et al. (2020)	√		√	√	√	√			√
Bagherinejad & Najafi-Ghobadi (2019)	√		√	√		√		√	
Saragih et al. (2019)	√		√	√	√	√			√
Vahdani et al. (2018)		√		√		√		√	
Rafie-Majd et al. (2018)		√	√			√			√
Rayat et al. (2017)		√		√		√			√
Hiassat et al. (2017)	√		√			√		√	
Zhalechian et al. (2016)		√		√			√		√
Ghorbani & Akbari Jokar (2016)		√	√	√		√			√
Tang et al. (2016)	√			√			√		√
Zhang et al. (2014)	√		√			√			√
Nekooghadirli et al. (2014)		√		√		√			√
Guerrero et al. (2013)	√		√	√		√		√	
Sajjadi & Cheraghi (2011)		√	√	√		√			√

3. MODEL FORMULATION

To evaluate the performance of the heuristic method developed in this paper, solution from small data is compared with optimal solution from mathematical model of Saragih *et al*. (2018). The model of Saragih et al. (2018) consisted of suppliers, UCCs, and retail markets. The illustration of the system studied is given in Figure 1. The model was also taking into account multi products, multi suppliers, and traffic congestion as external parameter. The model of Saragih *et al*. (2018) is given at the Appendix.

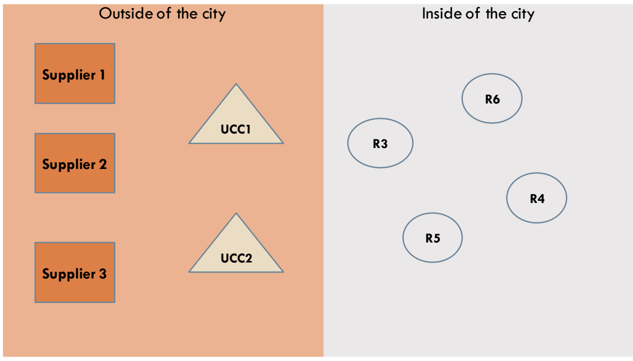

Figure 1 The illustration of system studied

4. THE PROPOSED HEURISTIC METHOD

The proposed heuristic method was developed from Saragih et al. (2019), as shown in Figure 2. The difference is at a constructive stage which results in the initial solution. The constructive phase of the heuristic method from Saragih *et al*. (2019) was only for a single product. This weakness is improved at the proposed heuristic method since the LIRP in this paper considering multi-products. This improvement can be seen from the formulation to obtain the initial solution for inventory decisions. The initial solution for location decisions is obtained randomly, vehicle routing decisions is obtained using the nearest neighbour algorithm, and inventory decisions are obtained using the economic order quantity (EOQ) formulation. The formulation to calculate the value of initial Q_{ip} is:

$$Q_{ip} = \sqrt{\frac{2A_{ip}D_{ip}}{h_{ip}}}, \forall p \in P, \forall i \in \quad (1)$$

The formulation to calculate initial T is:

$$T = \frac{Q_{ip}}{D_{ip}} \quad (2)$$

The formulations to calculate initial Q_{jp} and initial Q_{kp} are:

$$Q_{jp} = TD_{jp}, \forall p \in P, \forall j \in J \quad (3)$$

$$Q_{kp} = T\mu_{kp}, \forall p \in P, \forall k \in K \quad (4)$$

The formulations to calculate initial NP_{jp} and initial NP_{kp} are:

$$NP_{jp} = \frac{TD_{jp}}{Q_{jp}}, \forall p \in P, \forall j \in J \quad (5)$$

$$NP_{kp} = \frac{T\mu_{kp}}{NP_{jp}Q_{kp}}, \forall p \in P, \forall k \in K \quad (6)$$

The constructive stage results initial solution improved using SA algorithm at improvement stage. The improvement is done by modifying the decisions of location, inventory, and routing in three phases. They are phase of location, inventory, and routing.

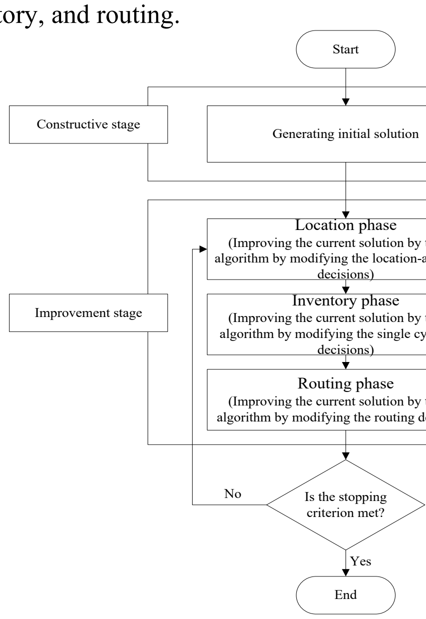

Figure 2 Flowchart of the proposed heuristic (Saragih *et al*., 2019)

5. COMPUTATIONAL EXPERIMENTS

Computational experiments are performed to evaluate the performance of the proposed heuristic. For small cases, the data used for the instances are similar to Saragih *et al*. (2019) and they are given in Table 2. In addition to Table 2, the service level used is 95%, vehicle capacity is 20, and truck capacity is 30.

Table 2 Data used for small cases

Data	Distribution	Range of the values
Means of demands	Uniform	[10, 30]
Variances of demands	Uniform	[4, 6]
Ordering costs	Uniform	[4, 6]
Holding costs	Uniform	[2, 3]
Shortage costs	Uniform	[10, 15]
Transportation costs	Uniform	[1, 5]
Lead times	Uniform	[0.2, 0.3]

The proposed heuristic is coded in MATLAB R2013a. It is run on an *Intel Core i7 4.00 GB* (2.10 GHz) *processor*. The mathematical model of Saragih et al. (2018) is solved using LINGO 12.0. Computational results can be seen in Table 3 and it can be seen that the average gap resulted in terms of total cost is 5.1%.

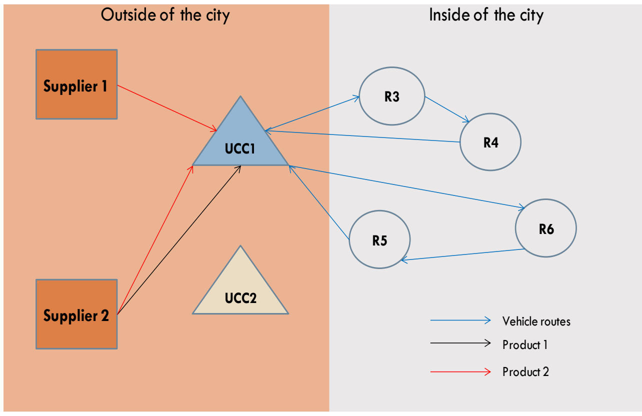

Figure 3 The illustration of solution for instance #1

Instance #1 consists of 2 suppliers, 2 UCCs, 4 retail markets, and 2 products. The illustration of the solution of instance #1 is given in Figure 3. It can be seen from Figure 3 that opened UCC is UCC 1. Supplier 1 and supplier 2 supply the opened UCC for both products. Suppliers do not supply closed UCC which is UCC 2. Opened UCC supplies all the retail markets according to their lot sizes for every product. The closed UCC which is UCC 2 does not supply any retail markets. The vehicle routes are formed to serve retail markets from UCC 1 and they are only from opened UCC. There are two vehicle routes formed to serve the retail markets. The first one is UCC1–R3–R4–UCC1 and the second one is UCC1–R6–R5–UCC1.

Table 3 Computational results

No.	# Supplier	# UCC	# Retail markets	The mathematical model		The proposed heuristic		Gap (%)*
				Total cost (Rp/day)	CPU times (s)	Total cost (Rp/day)	CPU times (s)	Total cost
1	2	2	4	**1790**	1508	1924	29	7.5
2	3	2	4	**2145**	545	2200	34	2.6
3	2	3	4	1915	86400 limit	1925	28	0.5
4	3	3	4	1796	86400 limit	2200	29	22.5
5	2	2	5	2314	86400 limit	2387	30	3.2
6	3	2	5	2831	86400 limit	2733	24	-3.4
7	2	3	5	2305	86400 limit	2445	29	6.1
8	3	3	5	2680	86400 limit	2731	31	1.9
Average								5.1

*Gap (%) = 100 x (proposed heuristic's total cost – the mathematical model's total cost) / the mathematical model's total cost)

6. APPLICATION OF THE PROPOSED HEURISTIC IN JAKARTA

As it was mentioned previously, the proposed heuristics is applied to the food supply chain system of Jakarta to design city logistics than can increase availability and decrease congestion as well. The food supply chain system consists of 12 suppliers, four potential UCCs, 165 retail markets, and 10 products. The retail markets are scattered throughout the city. The potential UCCs are the wholesale markets from which the retail markets get the products. The locations of the potential UCCs are outside the city and suppliers are provinces that supply products to the UCCs. The locations of the potential UCCs are Tangerang, South Tangerang, Bekasi, and Tanjung Priok Port. To design the city logistics, the optimal locations for potential UCCs need to be determined. At the opened UCCs, the consolidation concept is applied to solve the logistics problem's low availability by increasing service levels and optimally controlling inventory on the three entities involved. The coordination concept is also applied to the opened UCCs to solve traffic congestion, a transportation problem, by decreasing the number of vehicles by using vehicles together. Due to the use of cars together, it is necessary to determine the optimal vehicle route to serve the retail markets. Table 4 gives the suppliers and their products.

The results of some retail markets are given in Table 5. Decision variables at retail markets are the lot size of the products as well as the safety stocks, and the order frequency. Since there are 165 retail markets and 10 products, Table 5 only shows some of them. The examples of the products are avocado and tomato.

Table 4 Suppliers and their products

No.	Provinces	Products
1	North Sumatera	Mango, orange
2	West Sumatera	Avocado
3	Jambi	Duku
4	South Sumatera	Duku
5	Lampung	Durian
6	Banten	Duku
7	West Java	Avocado, mango, tomato, potato, carrot
8	Central Java	Avocado, durian, potato, shallot, chilli
9	Yogyakarta	Avocado, durian, shallots, chilli
10	East Java	Avocado, mango
11	Bali	Mango
12	West Kalimantan	Orange

Table 5 Results of the retail markets

Markets	Demands (Kg/Day)		Lot size (Kg)		Safety stock (Kg)		Frequency of order	
	Avocado	Tomato	Avocado	Tomato	Avocado	Tomato	Avocado	Tomato
1	211	1533	84.4	613.2	15.8	105.04	1	1
2	211	1533	84.4	613.2	16.55	117.71	1	1
3	174	1264	69.6	505.6	12.11	84.53	1	1
4	174	1264	69.6	505.6	11.98	94.27	1	1
5	57	415	22.8	166	3.98	31.23	1	1
6	57	415	22.8	166	4.41	30.32	1	1
7	57	415	22.8	166	3.93	28.07	1	1
8	57	415	22.8	166	3.76	30.32	1	1
9	127	920	50.8	368	9.5	70.55	1	1
10	127	920	50.8	368	9.85	69.89	1	1
11	88	636	35.2	254.4	6.84	48.24	1	1
12	88	636	35.2	254.4	6.9	46.86	1	1
13	88	636	35.2	254.4	6.77	42.94	1	1
14	88	636	35.2	254.4	6.97	45.91	1	1
15	21	149	8.4	59.6	1.42	10.62	1	1
16	21	149	8.4	59.6	1.35	11.4	1	1
17	21	149	8.4	59.6	1.35	11.5	1	1
18	21	149	8.4	59.6	1.34	11.18	1	1
19	21	149	8.4	59.6	1.37	11.18	1	1
20	21	149	8.4	59.6	1.34	11.4	1	1
21	21	149	8.4	59.6	1.62	12.12	1	1
22	21	149	8.4	59.6	1.42	10.38	1	1
23	343	2489	137.2	995.6	23.05	185.57	1	1
24	60	439	24	175.6	4.11	30.11	1	1
25	60	439	24	175.6	4.43	33.43	1	1
26	60	439	24	175.6	4.52	29.4	1	1
27	60	439	24	175.6	4.29	31.81	1	1
28	79	576	31.6	230.4	5.47	42.85	1	1
29	79	576	31.6	230.4	5.96	39.35	1	1
30	239	1736	95.6	694.4	17.89	136.69	1	1
31	155	1124	62	449.6	10.36	83.84	1	1
32	155	1124	62	449.6	11.09	84.66	1	1
33	155	1124	62	449.6	11.78	82.18	1	1
…	…	…	…	…	…	…	…	…
154	50	364	20	145.6	3.61	29.5	1	1
155	50	364	20	145.6	3.83	25.27	1	1
156	50	364	20	145.6	3.46	29.5	1	1
157	50	364	20	145.6	3.58	25.55	1	1
158	50	364	20	145.6	3.69	24.09	1	1
159	50	364	20	145.6	3.9	26.93	1	1
160	50	364	20	145.6	3.9	25.27	1	1
161	60	437	24	174.8	4.56	35.16	1	1
162	60	437	24	174.8	4.81	32.42	1	1
163	60	437	24	174.8	4.06	31.12	1	1
164	231	1682	92.4	672.8	15.37	118.91	1	1
165	231	1682	92.4	672.8	17.96	123.97	1	1
Total	11657	84710	4663	33884	860	6248		

The results of the UCCs are given in Table 6 and Table 7. Decision variables at UCCs are the lot size of the products, the order frequency, the vehicle routes, and the opened UCCs. As it can be seen in Table 6, all UCCs are opened.

Since all UCCs are opened, decision variables related to inventory need to be determined at all UCCs. Similar to the retail markets, the examples of the products are avocado and tomato.

Table 6 Results of the UCCs (part 1)

UCC	Demands (kg/day)		Lot size (kg)		Frequency of order	
	Avocado	Tomato	Avocado	Tomato	Avocado	Tomato
1	2364	17176	945	6870	1	1
2	2783	20221	1113	8088	1	1
3	3310	24052	1324	9621	1	1
4	3201	23261	1280	9304	1	1
Total	11657	84710	4663	33884		

Table 7 shows decision variables related to the vehicle routes. From opened UCCs, vehicle routes are formed to deliver the products to retail markets allocated to each UCC according to their lot sizes. It can be seen from Table 7 that there are 18 routes formed to serve all the retail markets. For vehicle 1, it starts from UCC1-R27-R7-R41-UCC1. Similar explanation is applied to vehicle 2 until vehicle 18.

Table 7 Results of the UCCs (part 2)

UCCs	Vehicle capacity (Kg)	Vehicles (Unit)	Route of the vehicles
1	8000	1	1 27 7 41 1
		2	1 36 34 39 35 1
		3	1 38 73 161 162 169 1
		4	1 168 5 6 1
2	8000	5	2 138 137 142 135 140 141 136 132 128 131 112 2
		6	2 110 114 118 117 116 119 124 127 2
		7	2 145 103 150 154 157 156 159 129 130 2
		8	2 133 134 109 108 143 139 2
		9	2 14 37 2
3	8000	10	3 65 60 61 58 63 62 70 51 54 57 59 3
		11	3 52 50 56 55 53 42 45 44 48 49 46 43 47 67 72 3
		12	3 64 166 167 165 66 69 68 71 91 86 98 100 101 28 3
		13	3 40 30 31 29 8 9 20 24 18 3
		14	3 26 13 10 11 12 3
4	8000	15	4 155 153 163 160 164 158 99 97 89 90 93 92 96 94 87 88 83 85 84 4
		16	4 95 102 104 125 126 120 121 149 123 148 122 146 147 144 4
		17	4 151 152 105 106 107 77 80 76 78 79 81 33 32 82 75 74 4
		18	4 111 115 15 17 16 23 22 21 25 19 113 4

The results of the suppliers are given in Table 8. Decision variables at suppliers are the lot size of the products, the cycle time, and the allocation of opened UCCs to each supplier. It can be seen from Table 8 that the cycle time is 0.4 days or 9.6 hours. It means that the delivery of the products is performed every 9.6 hours or 2.5 times a day. Since all UCCs are opened, suppliers supply all the UCCs for its product. For example, supplier 1 has a demand of 0 kg/day for both avocado and tomato. It means that supplier 1 does not have the products. On the other hand, supplier 2 has a demand of 11,657 kg/day for avocado. It implies that supplier 2 has the product. According to Table 4, the demand for the product at each supplier only emerges if the supplier has the product. The demand for the product at each supplier is derived from opened UCCs allocated to the supplier. The demand at opened UCC is derived from retail markets allocated to the opened UCC.

Table 8 Results of the suppliers

Supplier	T (day)	Demands (kg/day)		Lot size (kg)	
		Avocado	Tomato	Avocado	Tomato
1	0.4	0	0	0	0
2		11657	0	4663	0
3		0	0	0	0
4		0	0	0	0
5		0	0	0	0
7		0	0	0	0
8		0	84710	0	33884
9		0	0	0	0
10		0	0	0	0
11		0	0	0	0
12		0	0	0	0

6.1 Discussion

This paper uses consolidation and coordination concepts which are the fundamental concepts of city logistics. The consolidation concept is concerned with consolidation of goods from the suppliers at the UCCs, distribution of the goods from the UCCs to the retail markets, and controlling inventory in the supplier, the UCCs, and the retail markets. After the proposed heuristic is applied to the food supply system of Jakarta, it is possible to maintain the service level which is decided by 95% by using the consolidation concept. This concept can increase the availability from 76% to 95%.

The second fundamental concept of city logistics used in this paper is the coordination concept. The coordination concept is concerned with the use of vehicles together at the UCCs. This is also known as the cooperative goods transportation system. The use of vehicles together reduces the number of vehicles which in turn reducing the congestion. Similar to the consolidation concept, after the proposed heuristic is applied to the real system, the number of vehicles required is 18 vehicles per delivery or 45 vehicles per day (Table 7). Without the coordination concept, which means that the suppliers can directly serve the retail markets since they use their own vehicles, then 165 vehicles are needed per day. The coordination concept can reduce the number of the vehicles by 73%.

7. CONCLUSIONS

This paper's proposed heuristic based on SA has solved LIRP that considers multi-products, multi suppliers, and traffic congestion as an external parameter. This paper's heuristic method to solve the LIRP has never been developed before. The gap in average resulted between the proposed heuristic, and the model is 5.1%. The food supply chain of Jakarta is the system where the proposed heuristic is applied. It consists of 12 suppliers, four potential UCCs, 165 retail markets, 10 products.

The number of vehicles required in the new design of supply chain system is 18 vehicles per delivery or 45 vehicles per day. Without the coordination concept of city logistics, the number of vehicles required was 165 vehicles per day. The coordination concept can reduce the number of vehicles by 73%. In the other way, the consolidation concept of city logistics can increase the availability from 76% to 95%. For future work, developing a more efficient heuristic to solve the problem in this paper can be an interesting topic. Considering time windows and heterogeneous fleet also can be topics for future work.

APPENDIX

The mathematical model of Saragih et al. (2018) is given as follows.

Notations

K	retail markets set
J	potential UCCs set
N_j	capacity levels available to UCC $(j \in J)$ set
I	suppliers set
P	products set
V	vehicles set
M	merged set of retail markets and potential UCCs, i.e. $K \cup J$
k	retail markets index
j	UCCs index
n	capacity levels available to UCC index
i	suppliers index
p	products index
v	vehicles index
μ_{kp}	demand mean at retail market k for product p (kg/day) $(\forall k \in K, \forall p \in P)$
σ_{kp}^2	demand variance at retail market k for product p (kg^2/day^2) $(\forall k \in K, \forall p \in P)$
h_{kp}	cost of inventory holding of retail market k for product p (Rp/kg/day) $(\forall k \in K, \forall p \in P)$
a_{kp}	cost of ordering of retail market k for product p (Rp/order) $(\forall k \in K, \forall p \in P)$
lt_{kp}	retail market's lead time k for product p (day) $(\forall k \in K, \forall p \in P)$
s_{kp}	cost of shortage of retail market k for product p (Rp/kg) $(\forall k \in K, \forall p \in P)$
α	level of service for retail market
z_α	standard normal deviate such that $P(Z \le z_\alpha) = \alpha$
$f(z_\alpha)$	ordinate of z_α
$\psi(z_\alpha)$	partial expectations of z_α
f_j^n	fixed cost of UCC j with capacity level n (Rp/day) $(\forall j \in J, \forall n \in N_j)$
b_j^n	capacity with level n for UCC j (kg/day) $(\forall j \in J, \forall n \in N_j)$
d_{kl}	distance between node k and node l (km)
t_{kl}	time loss between node k and node l (hour)
ca	cost of transportation (Rp/km)
cb	time value (Rp/hour)
h_{jp}	cost of inventory holding of UCC j for product p (Rp/kg/day)$(\forall j \in J, \forall p \in P)$

a_{jp} cost of ordering of UCC j for product p (Rp/order) $(\forall j \in J, \forall p \in P)$

lt_{jp} UCC's lead time j for product p (day) $(\forall j \in J, \forall p \in P)$

vc vehicle capacity (kg)

h_{ip} cost of inventory holding of supplier i for product p (Rp/kg/day) $(\forall i \in I, \forall p \in P)$

a_{ip} cost of ordering of supplier i for product p (Rp/order) $(\forall i \in I, \forall p \in P)$

lt_{ip} supplier's lead time i for product p (day) $(\forall i \in I, \forall p \in P)$

b_{ip} supplier capacity i for product p (kg/day) $(\forall i \in I, \forall p \in P)$

w cost of transportation of truck (Rp/truck)

pp truck capacity (kg)

B customers' number contained in set K, i.e. $B = |K|$

NP_{kp} frequency of order at retail market k for product p $(\forall k \in K, \forall p \in P)$

E frequency of order for every retail market and product

Q_{kp} retail market's lot size k for product p (kg) $(\forall k \in K, \forall p \in P)$

Q_k total lot size of retail market k (kg)

MK_{kp} shortage number of retail market k for product p (Unit) $(\forall k \in K, \forall p \in P)$

RK_{kp} retail market's reorder point k for product p (Unit) $(\forall k \in K, \forall p \in P)$

SS_{kp} retail market's safety stock k for product p (Unit) $(\forall k \in K, \forall p \in P)$

M_{kv} auxiliary variable defined for retail market k for subtour elimination in route of vehicle v $(\forall k \in K, \forall v \in V)$

$U_j^n \begin{cases} 1 \text{ if UCC } j \text{ is opened with capacity level } n \\ 0 \text{ otherwise} \end{cases}$ $(\forall j \in J, \forall n \in N_j)$

$Y_{jk} \begin{cases} 1 \text{ if retail market } k \text{ is assigned to UCC } j \\ 0 \text{ otherwise} \end{cases}$ $(\forall j \in J, \forall k \in K)$

$R_{klv} \begin{cases} 1 \text{ if } k \text{ precedes } l \text{ in route of vehicle } v \\ 0 \text{ otherwise} \end{cases}$ $(\forall k, l \in M, \forall v \in V)$

D_{jp} UCC's demand j for product p (kg/day) $(\forall j \in J, \forall p \in P)$

NP_{jp} frequency of order at UCC j for product p $(\forall j \in J, \forall p \in P)$

Z frequency of order at every UCC and product

Q_{jp} UCC's lot size j for product p (kg) $(\forall j \in J, \forall p \in P)$

Q_j total lot size of UCC j (kg)

RK_{jp} UCC's reorder point j for product p (kg) $(\forall j \in J, \forall p \in P)$

X_j truck number at UCC j (Truck) $(\forall j \in J)$

$R_{ijp} \begin{cases} 1 \text{ if supplier } i \text{ supplies UCC } j \text{ for product } p \\ 0 \text{ otherwise} \end{cases}$ $(\forall i \in I, \forall j \in J, \forall p \in P)$

D_{ip} supplier's demand i for product p (kg/day) $(\forall i \in I, \forall p \in P)$

Q_{ip} supplier's lot size i for product p (kg) $(\forall i \in I, \forall p \in P)$

Q_i total lot size of supplier i (kg) $(\forall i \in I)$

RK_{ip} supplier's reorder point i for product p (kg) $(\forall i \in I, \forall p \in P)$

X_i truck number at supplier i (truck) $(\forall i \in I)$

V_{ijp} amount of demand of UCC j for product p supplied by supplier i $(\forall i \in I, \forall j \in J, \forall p \in P)$

TC total cost (Rp/day)

T single cycle time (day)

The model

Objective function:

$$\min TC = \sum_{j\in J}\sum_{n\in N_j} f_j^n U_j^n + \frac{E}{T}\sum_{v\in V}\sum_{k\in M}\sum_{l\in M}(d_{kl}ca + t_{kl}cb)R_{klv} + \sum_{k\in K}\sum_{p\in P}\left[\frac{a_{kp}\mu_{kp}}{Q_{kp}} + h_{kp}\left(\frac{Q_{kp}}{2} + SS_{kp}\right) + s_{kp}MK_{kp}\left(\frac{\mu_{kp}}{Q_{kp}}\right)\right] + \sum_{j\in J}\sum_{p\in P}\left[\frac{a_{jp}D_{jp}}{Q_{jp}} + h_{jp}\left(\frac{Q_{jp}}{2} + \sum_k\left(lt_{kp}\mu_{kp} + SS_{kp}\right)Y_{jk}\right) + wX_j\frac{Z}{T}\right] + \sum_{i\in I}\sum_{p\in P}\left[\frac{a_{ip}D_{ip}}{Q_{ip}} + h_{ip}\left(\frac{Q_{ip}}{2} + \left(\sum_j\sum_k\left((lt_{jp} + lt_{kp})\mu_{kp} + SS_{kp}\right)Y_{jk}\right)G_{ijp}\right) + wX_i\frac{1}{T}\right] \quad (7)$$

Subject to:

$$\sum_{v\in V}\sum_{l\in M} R_{klv} = 1, \forall k \in K \quad (8)$$

$$\sum_{l\in K}\sum_{k\in M} Q_l R_{klv} \le vc, \forall v \in V \quad (9)$$

$$M_{kv} - M_{lv} + (B \times R_{klv}) \le B - 1, \forall k, l \in K, \forall v \in V \quad (10)$$

$$\sum_{l\in M} R_{klv} - \sum_{l\in M} R_{lkv} = 0, \forall k \in M, \forall v \in V \quad (11)$$

$$\sum_{j\in J}\sum_{k\in K} R_{jkv} \le 1, \forall v \in V \quad (12)$$

$$\sum_{l\in M} R_{klv} + \sum_{l\in M} R_{jlv} - Y_{jk} \le 1, \forall j \in j, \forall k \in K, \forall v \in V \quad (13)$$

$$\sum_{n\in N_j} U_j^n \le 1, \forall j \in J \quad (14)$$

$$\sum_{k\in K}\sum_{p\in P} \mu_{kp} Y_{jk} \le \sum_{n\in N_j} b_j^n U_j^n, \forall j \in J \quad (15)$$

$$\sum_{k\in K} \mu_{kp} Y_{jk} = \sum_{n\in N_j} D_{jp} U_j^n, \forall p \in P, \forall j \in J \quad (16)$$

$$\sum_{j\in J} Y_{jk} = 1, \forall k \in K \quad (17)$$

$$\sum_{j\in J} G_{ijp} \ge 1, \forall p \in P, \forall i \in I \quad (18)$$

$$\sum_{n\in N_j} D_{jp} U_j^n = \sum_{i\in I} V_{ijp} G_{ijp}, \forall p \in P, \forall j \in J \quad (19)$$

$$\sum_{j\in J} V_{ijp} = D_{ip}, \forall p \in P, \forall i \in I \quad (20)$$

$$\sum_{j\in J} V_{ijp} \le b_{ip}, \forall i \in I \quad (21)$$

$$SS_{kp} = z_\alpha\sqrt{lt_{kp}\sigma_{kp}^2}, \forall p \in P, \forall k \in K \quad (22)$$

$$MK_{kp} = \sqrt{lt_{kp}\sigma_{kp}^2}[f(z_\alpha) - z_\alpha\psi(z_\alpha)], \forall p \in P, \forall k \in K \quad (23)$$

$$RK_{kp} = lt_{kp}\mu_{kp} + SS_{kp}, \forall p \in P, \forall k \in K \quad (24)$$

$$RK_{jp} = \left(\sum_k\left(lt_{jp} + lt_{kp}\right)\mu_{kp} + SS_{kp}\right)Y_{jk}, \forall p \in P, \forall j \in J \quad (25)$$

$$RK_{ip} = \left(\sum_k lt_{ip}\mu_{kp} + \left(\sum_j\sum_k\left(lt_{jp} + lt_{kp}\right)\mu_{kp} + SS_{kp}\right)Y_{jk}\right)Gijp, \forall p \in P, \forall i \in I \quad (26)$$

$$T = \frac{Q_{ip}}{D_{ip}} = \frac{NP_{jp}Q_{jp}}{D_{jp}} = \frac{NP_{jp}NP_{kp}Q_{kp}}{\mu_{kp}}, \forall p \in P, \forall k \in K, \forall j \in J \quad (27)$$

$$NP_{kp} = E, \forall p \in P, \forall k \in K \quad (28)$$

$$NP_{jp} = Z, \forall p \in P, \forall j \in J \quad (29)$$

$$\sum_{p\in P} Q_{kp} = Q_k, \forall k \in K \quad (30)$$

$$\sum_{p\in P} Q_{jp} = Q_j, \forall j \in J \quad (31)$$

$$\sum_{p\in P} Q_{ip} = Q_i, \forall i \in I \quad (32)$$

$$X_j = \left\lceil\frac{Q_j}{pp}\right\rceil, \forall j \in J \quad (33)$$

$$X_i = \left\lceil\frac{Q_i}{pp}\right\rceil, \forall i \in I \quad (34)$$

$$U_j^n \in \{0,1\}, \forall j \in J, \forall n \in N_j \quad (35)$$

$Y_{jk} \in \{0,1\}, \forall j \in J, \forall k \in J$ (36)
$R_{klv} \in \{0,1\}, \forall k, l \in M, \forall v \in V$ (37)
$G_{ijp} \in \{0,1\}, \forall p \in P, \forall j \in J, \forall i \in I$ (38)
$M_{kv} \geq 0, \forall k \in K, \forall v \in V$ (39)
$Q_{ip}, Q_{jp}, Q_{kp} \geq 0, \forall p \in P, \forall i \in I, \forall j \in J, \forall k \in K$ (40)
$T \geq 0$ (41)
$E, Z, NP_{jp}, NP_{kp} \geq 1, E, Z, NP_{jp}, NP_{kp} \in int, \forall j \in J, \forall k \in K, \forall p \in P$ (42)
$V_{ijp} \geq 0, \forall p \in P, \forall j \in J, \forall i \in I$ (43)

Equation Eq. (7) is the objective function that minimizes the total cost. The total cost consists of fixed cost for opening and operating UCC, routing cost, and expected inventory costs. Constraints Eq. (8) guarantee that each retail market is placed on exactly one vehicle route. Constraints Eq. (9) are the constraints for the vehicle capacity. Constraints Eq. (10) are the constraints of subtour elimination. Constraints Eq. (11) are the constraints of flow conservation. Constraints Eq. (12) guarantee that in each route there is only one UCC included. Constraints Eq. (13) relate the allocation and routing components of the model. Constraints Eq. (14) guarantee that each UCC can only be assigned to one capacity level. Constraints Eq. (15) are the constraints for capacity of UCC. Constraints Eq. (16) guarantee that UCC's demand for each product is the amount of retail markets' demand allocated to it. Constraints Eq. (17) guarantee that a retail market is allocated exactly once to a UCC. Constraints Eq. (18) allow supplier to supply more than one UCC for one product. Constraints Eq. (19) guarantee that UCC's demand for each product is met. Constraints Eq. (20) guarantee that supplier's demand for each product is the amount of product supplied from the supplier. Constraints Eq. (21) guarantee that the amount of product supplied from supplier does not exceed its capacity. Equations Eq. (22)-(23) are the formulas for calculating safety stock and the amount of shortage at retail market, respectively. Equations Eq. (24)-(26) are the formulas for calculating reorder points at retail market, UCC, and supplier, respectively. Constraints Eq. (27) are the constraints of single cycle time. Constraints Eq. (28)-(29) are the constraints of order frequency at retail market and UCC, respectively. Constraints Eq. (30)–(32) are the constraints for calculating the total lot size at retail market, UCC, and supplier, respectively. Equations Eq. (33)-(34) are formulas for calculating the number of trucks at UCC and supplier, respectively. Constraints Eq. (35)-(43) are the constraints of the decision variables.

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