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A Novel Mathematical Model for a Cloud-Based Drone Enabled Vehicle Routing Problem considering Multi-Echelon Supply Chain

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Abstract: In recent years, the product delivery system has faced a significant amount of changes with reducing cost and waiting time of last-mile delivery. Unmanned aerial vehicles, or drones, have the potential to deal with these issues effectively. This paper developed a novel mathematical formulation to investigate the optimum routing between various types of nodes in a multi-echelon supply chain, including third-party logistics companies (3PL), warehouses, and consumers. A conceptual model is represented in the paper to comprehend the readers better, and eventually, the novelty of the developed model is discussed further by explaining the concept of solving.

Keywords: Cloud service matching, drone parcel delivery, industry 4.0

1. INTRODUCTION

Unmanned aerial vehicles (UAVs), also known as drones, are new technological developments that attract a tremendous amount of attention from various sectors such as agriculture, civilian, commercial, mapping, shipping, and delivery. In recent years' drone goods delivery became a challenging problem. Especially since 2013, when Amazon prepared drones for transporting packages to the customers less than an hour (Amazon, 2016). Other companies like DHL, Google, UPS, and Domino's started designing a drone delivery system to send the packages with lower cost and lower last-mile delivery time. Generally, Drones are less expensive to maintain than traditional delivery vehicles. And they are not limited by some infrastructure such as roads. So, they are supposed to bring competitive advantages for the delivery companies and the E-retailing.

On the other side, from the operational point of view, drones as a promising technology required to be adaptive and responsive to the dynamic conditions in the intense global competition. Cloud manufacturing, as a new paradigm, satisfies these necessities in planning. In addition, cloud-based designing fulfills the industry 4.0 framework by enabling resource service sharing and improving company capability. This paper considers four kinds of resources in a cloud-based collaboration in a multi-echelon supply chain that is shared and allocated to satisfy their related customers. These companies are drone holders (third party logistics (3PL) based on this research assumption), warehouse holders like Amazon's warehouses, distributed in the city, Consumers, and charging stations. The purpose of this paper is to select the set of warehouses and 3PL companies to deliver the demand of consumers by drones in which all of these services shared in the cloud-based platform. As an illustration of the discussed problem to help readers better comprehend, see fig. 1.

According to fig. 1, after solving the optimization problem, the set of routes allotted to drones based on some practical constraints. Each drone commences its journey from a 3PL company then moves to a warehouse to pick up set of goods after that serves consumers and comes back to the 3PL company. Moreover, the drone may return to charging stations distributed in the city for refreshing energy to satisfy transportation requests during its journey.

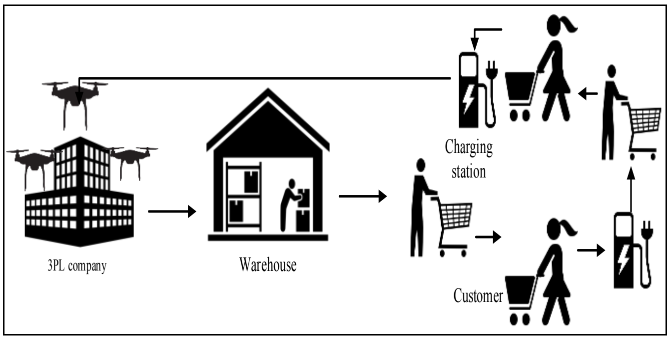

Fig. 1. Conceptual illustration of the defined problem

To reach the purpose of this research, the rest of this paper is organized as follows: Section 2 presents the literature review on cloud manufacturing, Vehicle routing problem (VRP), and drone routing problem. In Section 3, the optimization model is further discussed. In Section 4, an example is provided to clarify the developed approach. Finally, Section 5 entails conclusions and areas for further research.

2. LITERATURE REVIEW

2.1 Cloud Manufacturing

Cloud manufacturing (CMfg) is a service-oriented model developed from advanced manufacturing models under the support of cloud computing (CC), internet of things (IoT), virtual manufacturing, and service-oriented technologies. The concept of cloud manufacturing was initially presented by (Li *et al.*, 2010). Indeed, Cloud manufacturing enables various manufacturing resources and capabilities to be circulated through a cloud platform as a service by using the technologies mentioned earlier (Valilai and Houshmand 2013, Houshmand and Valilai 2013)..

Of late, cloud manufacturing as a new paradigm of advanced manufacturing has attracted many researchers to a variety of related issues. (Liu, Wang and Wang, 2018) classified 884 documents in the context of cloud manufacturing into interesting topics including integration and interoperability (Delaram and Valilai, 2017), sharing and collaboration (Liu *et al.*, 2015), big data (Zhong *et al.*, 2015), cloud-based supply chain (Akbaripour, Houshmand and Valilai, 2015), and service-task allocation (e.g., Task decomposition, matching network, service selection, resource allocation, planning and scheduling, resource classification (Assari, *et al.* 2018, Delaram and Valilai 2018), monitoring, and control). In this research, service selection and service-task allocation problems are going to be considered. Concretely, the aim of this paper is modifying aforementioned problems based on features and limitations which the drone delivery system may have.

2.2 Vehicle Routing Problem

Vehicle routing problem (VRP) is the developing concept of the traveling salesman problem (TSP), which dates back to the end of the fifties of the last century when Dantzig and Ramser formulated related mathematical programming (Dantzig and Ramser, 1959). VRP is the combinatorial optimization problem seeking to supply customer's demand subject to vehicle capacity constraints through designing the optimal routs. VRP and its variant problems are the most popular topics in which they are related to real-world applications such as delivery goods. UAVs as a last-mile and low-cost delivery vehicle, are pioneering transport technology for logistics service providers. Recently, adapting the two existing general classic problems namely VRP and TSP to the UAV context becomes a challenging issue. To show the differences between the multi-depot vehicle routing problem and drone routing problem, Table. 1 is gathered based on (Schermer and Moeini, 2018), (Pereira, Battarra and Fliege, 2018), and (Montoya-torres *et al.*, 2015).

The number of reviews on the operational challenges associated with leveraging drone technology is not limited as well. So, many researchers addressed the related problems by their individual contribution. Besides, some researchers formulate the drone-truck routing problem to increase the drone capability for visiting all the customers everywhere with different package size. For instance, (Murray and Chu, 2015) formulated the problem of truck-drone delivery to find the optimum solution. They limit the timing of the goods delivery by drones in an acceptable range contrary to trucks in which they only serve the customers with large parcels or those outside of the acceptable range. Furthermore, (Ham, 2018) proposed a constraint programming approach to distribute packages between drones, trucks and finally customers by considering the drop and pickup task for drones. A mathematical model is formulated by (Sacramento, Pisinger and Ropke, 2019), defining a problem for the capacitated multiple-truck case with time limit constraints and minimizing cost as an objective function. In this problem, the authors considered that drones could be launched and recovered at certain visits on the truck route. A robust optimization approach is proposed to find the optimal number of drones and flight path, besides developing a regression model to estimate battery usage duration as a function of air temperature (Kim, Lim and Cho, 2018). Two multi-trip VRPs are presented for planning drone deliveries parallel to consider the effect of battery and payload weight on energy consumption. The first objective function minimizes the overall delivery time and the second objective function investigates the best routes by presuming that drone might return to the depot to gain a fresh battery or set of packages (Dorling *et al.*, 2017). (Hong, Kuby and Murray, 2018) analyzed a different aspect of the drone delivery system and as a result, they proposed the drone delivery recharging location model to maximize the number of demands that could be satisfied when the number of charging stations is given. However, the location of charging stations are fixed in the current research and the purpose of this study is satisfying all the demands through optimizing the allocation of the multiple shared services and drones routing.

In the another paper, real-time routing problem is designed for different types of the drone to collect and deliver parcels by considering multiple charging stations (Coelho *et al.*, 2017). As it mentioned in the introduction, one of the shared services in the cloud-based supply chain is the charging stations which is the idea of a smart city, fig. 2. As a result, the issue of limited stored energy in the drone's battery would be solved. It is noteworthy to say that the aim of this paper is to incorporate the industry 4.0 concept into aerial transportation planning. So allocation of the shared services in the cloud-based platform and overcoming the limited stored energy in the drone's battery by considering charging stations is the matter of this research.

Fig. 2. Huge UAVs charging station in New York – Extracted from the eVolo Magazine 2016 Skyscraper Competition, (Mohammad, Zhao and Chengda, 2016)

Table. 1. Difference between the drone and traditional routing problem

problem	vehicle feature		objectives		constraints	solving methods
Multi-depot vehicle routing problem	Weight	heavy	Cost	80 percent of 147 research	pickup and delivery	meta-heuristics (GA, PSO, Tabu Search, and so on)
	Speed	low	Time		capacity	
	Service time	long	Distance		route continuity	
	Energy consumption	high	other	20 percent	timing	
Drone routing problem	Weight	light	Cost	energy consumption impress the time and distance, so energy function is an essential open issue	pickup and delivery	heuristics and exact
	Speed	high	Time		flight time and capacity	
	Service time	short	Distance		recharging stations	
	Energy consumption	low	Energy		environment conditions such as weather, temperature	

3. MATHEMATICAL FORMULATION

According to the defined problem shown in fig. 1, a new MILP mathematical model is developed and described in detail in this section. Significant assumptions of this optimization model are as follows.

1. Drones start their routes at a 3PL company and finish it at 3PL company which means this problem is closed drone routing problem;
2. Drones pick up demands from warehouses and visit each warehouse just once in each route;
3. The capacity of each drone is limited to a specific amount;
4. Third-party companies have a limited number of drones;
5. Each customer should be visited just once;
6. Drones are homogenous;
7. The cost of flying from each node to another is considered deterministic, and it is calculated based on some features such as distance and difficulty of the route;
8. Drones can leave each node and travel to another if and only if they have enough energy for that route;
9. Drones leave 3PL company and charging station with full energy capacity;
10. The demand of the customer is deterministic.

The following notations will be used for this formulation.

Indices

I, J   Set of all the nodes (i, j=1, 2, …, N)

K   Set of drones (k=1, 2, …, K)

3PL   Set of 3PL companies (3PL=1, 2, …, N_{3PL})

Wa   Set of warehouses (wa=1, 2, …, Wa)

C   Set of customers (c=1, 2, …, C)

CS   Set of charging stations (cs=1, 2, …, CS)

Parameters

dis_{ij} The flight distance between node i and j

$COST_{ij}$ The cost of traveling from i to j

DE_{ij} The amount of energy needed to travel from i to j

d_i The demand for node i

EI The maximum stored energy of drone's battery

V The maximum speed of drones

St Needed time for charging

θ, ρ Turning time to cost coefficient (calculated based on the operational cost)

M Big number

ε Small number

Decision variables

x_{ij}^{k} 1 if drone k flies from node i to j, 0 otherwise

w_{i}^{k} Weight of drone k in node i

ER_{i}^{k} Remained energy of drone k at node i

a_k 1 if drone k is used for delivery, 0 otherwise

b_k Weight of drone k at the beginning of its route

We can now formulate a mixed integer programming (MIP) model for drone routing and service allocation problem.

Minimizing

$$\sum_{k\in K}\left(\theta\sum_{i\in I}\sum_{j\in J}\left(\frac{dis_{ij}}{V}\right)x_{ij}^{k}+\sum_{i\in I}\sum_{j\in J}COST_{ij}x_{ij}^{k}+\rho\sum_{i\in C}\sum_{j\in CS}St\,x_{ij}^{k}\right) \quad (1)$$

Subject to:

$$\sum_{i\in Wa\cup C\cup CS}\sum_{k\in K}x_{ij}^{k}=1 \quad \forall j\in C \qquad (2)$$

$$\sum_{j \in Wa} x_{ij}^k \le 1 \quad \forall i \in 3pl, \forall k \in K \tag{3}$$

$$\sum_{i \in I} \sum_{j \in Wa} x_{ij}^k \le 1 \quad \forall k \in K \tag{4}$$

$$\sum_{i \in I} \sum_{j \in 3pl} x_{ij}^k \le 1 \quad \forall k \in K \tag{5}$$

$$Ma_k \ge \sum_{i \in Wa \cup C \cup CS} \sum_{j \in C} x_{ij}^k \quad \forall k \in K \tag{6}$$

$$\varepsilon a_k \le \sum_{i \in Wa \cup C \cup CS} \sum_{j \in C} x_{ij}^k \quad \forall k \in K \tag{7}$$

$$a_k \le \sum_{i \in 3pl} \sum_{j \in Wa} x_{ij}^k \quad \forall k \in K \tag{8}$$

$$\sum_{i \in 3pl} x_{ij}^k = \sum_{i \in C} x_{ji}^k \quad \forall j \in Wa, \forall k \in K \tag{9}$$

$$\sum_{i \in I} x_{ij}^k = \sum_{i \in I} x_{ji}^k \quad \forall j \in J, \forall k \in K \tag{10}$$

$$\sum_{i \in 3pl} \sum_{j \in Wa} x_{ij}^k = \sum_{i \in C \cup CS} \sum_{j \in 3pl} x_{ij}^k \quad \forall k \in K \tag{11}$$

$$\sum_{j \in Wa} \sum_{k \in K} x_{ij}^k \le \frac{K}{N_{3pl}} \quad \forall i \in 3pl \tag{12}$$

$$\sum_{i \in I} \sum_{j \in C} d_j x_{ij}^k \le Cap \quad \forall k \in K \tag{13}$$

$$\sum_{i \in Wa, C, CS} \sum_{j \in C} d_j x_{ij}^k = b_k \quad \forall k \in K \tag{14}$$

$$w_i^k \ge b_k - M(1 - \sum_{j \in C} x_{ij}^k) \quad \forall k \in K, \forall i \in Wa \tag{15}$$

$$w_i^k \le b_k + M(1 - \sum_{j \in C} x_{ij}^k) \quad \forall k \in K, \forall i \in Wa \tag{16}$$

$$w_j^k \ge w_i^k - d_j x_{ij}^k - M(1 - x_{ij}^k) \quad \forall k \in K, \forall i \in Wa \cup C \cup CS, \forall j \in C \cup CS \tag{17}$$

$$w_j^k \le w_i^k - d_j x_{ij}^k + M(1 - x_{ij}^k) \quad \forall k \in K, \forall i \in Wa \cup C \cup CS, \forall j \in C \cup CS \tag{18}$$

$$ER_i^k - \sum_{j \in J} DE_{ij} x_{ij}^k \ge 0 \quad \forall k \in K, \forall i \in I \tag{19}$$

$$ER_i^k = EI \sum_{j \in Wa} x_{ij}^k \quad \forall k \in K, \forall i \in 3pl \tag{20}$$

$$ER_i^k = EI \sum_{j \in C} x_{ji}^k \quad \forall k \in K, \forall i \in CS \tag{21}$$

$$ER_j^k \ge ER_i^k - DE_{ij} - M(1 - x_{ij}^k) \quad \forall j \in Wa \cup C, \forall i \in I, \forall k \in K \tag{22}$$

$$ER_j^k \le ER_i^k - DE_{ij} + M(1 - x_{ij}^k) \quad \forall j \in Wa \cup C, \forall i \in I, \forall k \in K \tag{23}$$

$$ER_i^k \le EI \sum_{j \in J} x_{ij}^k \quad \forall k \in K, \forall i \in I \tag{24}$$

$$x_{ij}^k = 0 \quad \forall i, j : i = j, \forall k \in K \tag{25}$$

$$u_i^k - u_j^k + N x_{ij}^k \le N - 1 \quad \forall i, j \in C \cup CS : i \ne j, \forall k \in K \tag{26}$$

$$x_{ij}^k \in \{0,1\} \quad \forall k \in K, \forall i, j \in I, J \tag{27}$$

$$u_i^k, ER_i^k, w_i^k \ge 0 \quad \forall k \in K, \forall i \in I \tag{28}$$

$$a_k, b_k \ge 0 \quad \forall k \in K \tag{29}$$

The objective function (1) minimizes the total cost of visiting customers to satisfy their demands includes the cost of delivery that is calculated based on the difficulty of the flight path (such as the height of buildings in the predefined transportation network), cost of energy consumption that is taken into the account based on the required delivery time between the nodes, and finally fixed cost of drones' recharging. It is noteworthy to mention that the delivery time between the nodes and charging time in the charging station are converted to costs by multiplying to a coefficient that will be calculated according to the drone characteristics. Constraint (2) ensures that each customer visited just once, and similarly each warehouse visited just by a drone in (3). Constrains (4) and (5) make sure that drones do not turn back to the warehouse or 3PL company; it only flies from these locations at the beginning of the route. Constraints (6) -(8) indicate that if the UAV is launched from a warehouse, then it could visit the customers and charging stations node. The flow conservation constraints for the drone are defined in (9)-(11). There is a limited number of UAVs that each 3PL company has, which is considered by (12). The capacity of drones is limited to a specific amount given in (13). The sum of customer’s demand weight, which carries by each drone is considered by constraint (14). Constraints (15)-(18) keep track of the demand weight that a drone arrives at location i. Hence, the drone's weight when it flies from the warehouse is obtained from (15) and (16), and it will be updated by (17) and (18). Constraint (19) is defined to avoid drone flying from a node to another without enough energy by keeping the differences between the remained energy and the required energy to continue its route positive. As previously described in the assumptions, UAV leaves the 3PL company and charging station with full battery energy, which is considered by (20) and (21). Moreover, constraints (22) and (23) keep track of remained energy of drone at the locations except charging stations and 3PL companies. The upper bound of remained energy at each node is provided by (24). The sub tour elimination constraints for the UAV are defined in (25) and (26). Finally, the domain of the variables is defined in (27)-(29).

4. DISCUSSION OF THE MATHEMATICAL MODEL

To better demonstrate our proposed model, a numerical example is developed through this section. The parameters of the optimization model are generated based on drone's practical features, for instance, the maximum weight that each drone can carry, maximum energy that drone's battery can store, and maximum flight range. Also, the linear distance of flying between nodes are gathered according to the google map. The study region covers an area shown in figure 3, from Clementi district to Bedok district. With reference to fig. 3, there are two 3PL companies (triangles, 3PL=1, 2), three warehouses (squares, wa=3, 4, 5), customers (circles, c=6, 7,…, 13), and charging stations (dark circles, cs=14, 15, 16). The optimization problem with the initial energy of 100 watts for two drones in each 3PL companies (k=1, 2 for 3PL=1 and k=3, 4 for 3PL=2) is solved by GAMS software on an Intel® Core™ i3 CPU M350 @ 2.27GHz, 4GB RAM system. Results are reported in fig. 4. The amount of remained energy (watts) and the drone's weight (kg) after leaving the location are expressed. The numbers presented on the arrows are the required energy for delivering packages between the locations. It is assumed that each drone can carry at most 3 kg set of goods. Equally, the demand of customers are between 0 kg and 3 kg, and for this specific example are 0.1, 1, 1.5, 1.6, 1.1, 0.2, 0.3, and 0.7, respectively.

Based on the best solution given in figure 4, three drones are requierd to answer the customers' demand at the lowest cost. And among these drones, only drone number 2 launched from 3PL number 1 meets a charging station in its journey. Visiting a charging station depends on the conditions of constraint (19). If we assume that drone 2 continues its flight without recharging its battery in node 15, then it faces a lack of energy since it needs 89 watts to pass nodes 10,12 and finally to land to node 1, but it has 64 watts in node 9. Furthermore, from the cost aspect, it is beneficial to travel 9-15-10-12-1 instead of 9-10-15-12-1 or 9-10-12-15-1. According to the input parameters, the total cost of the first route is far less than the later ones.

The distribution of charging stations plays a critical role as well. The reason is the existence of two types of cost for charging stations, including the cost of traveling to the charging station and the cost of spending time for recharging the battery in the objective function.

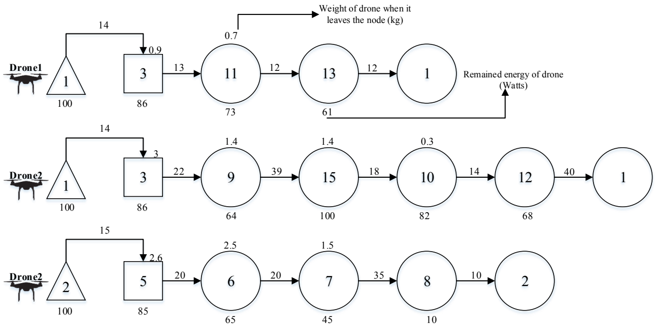

Fig. 4. Best routing and allocation of services after solving the optimization model

5. CONCLUSIONS AND FUTURE STUDY

This paper has presented a novel drone routing problem by presuming that all the logistics services are circulated through a cloud-based platform. In this research, four kinds of services, namely 3PL companies, warehouses, customers, and charging stations, are provided in the cloud to support a multi-echelon supply chain. The results show that the

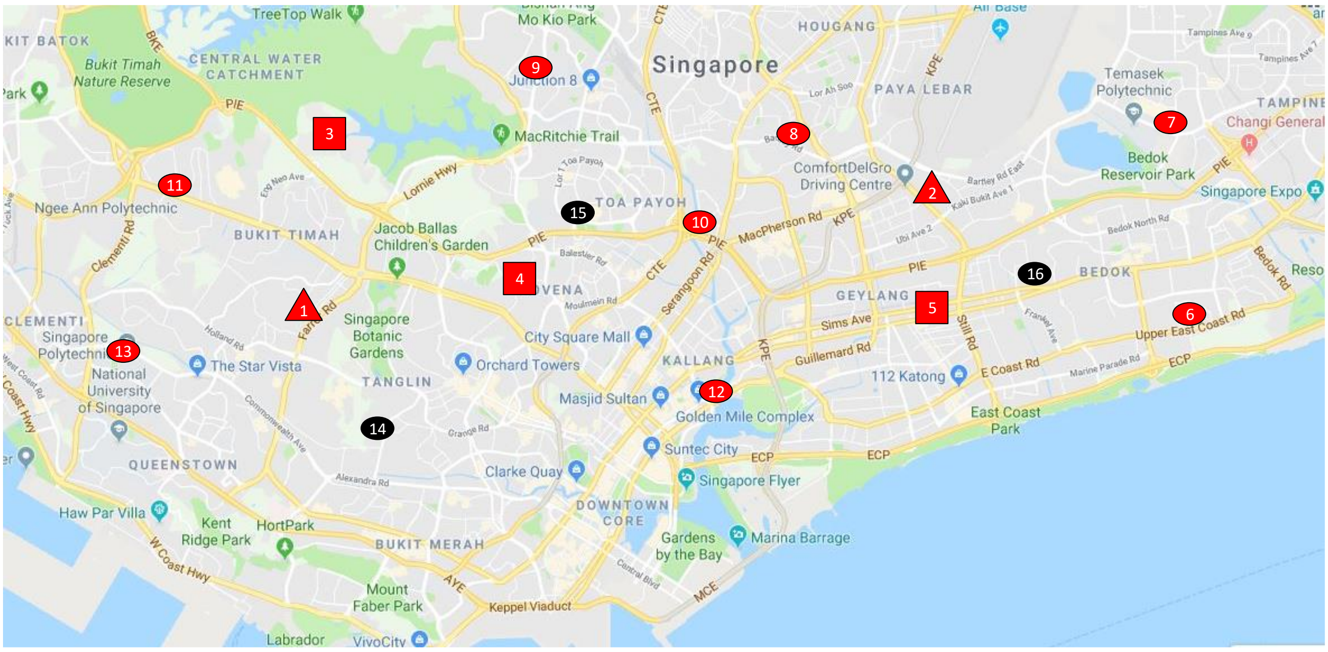

Fig. 3. Selected area for the proposed example

effective collaboration of these services is highly dependent on their distribution. The interesting area for future studies could be introducing another task for 3PL companies like maintenance and considering its cost in the model. Besides, taking into account the quality of service for each defined service in cloud-based platform could be another challenge. In this paper, the delivery network is designed based on assuming the fixed locations for charging stations, so considering the mobility feature for charging stations is a valuable subject for future research.

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