University of Hormozgan

International Journal of Industrial Engineering & Management Science

journal homepage: www.ijiems.com

Hybrid truck-drone delivery system with pickup and delivery Operations

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ARTICLE INFO

Article history:
Received: 2023-06-21
Received in revised form: -
Accepted: 2023-10-09

Keywords:
Last mile delivery
paired pickup and delivery
truck and drone routing
heuristic
Branch-and-Bound
mobile depot routing

ABSTRACT

In recent past years, drone delivery services gained tremendous attention from academia and logistic service providers, but it has some restrictions. For example, they have limited battery and payload capacities which reduce the efficiency of the delivery system. For that matter, coordination of ground vehicles and drones is proposed to take advantage of both trucks' large capacity and the drone's high speed, where the truck is used as a mobile depot and the drone is used to deliver parcels to customers. On the other hand, due to the increase in e-commerce popularity, customers' expectations for door-to-door services are increased. For this reason, we focused on the pickup and delivery problem in a truck and drone delivery system and proposed a mathematical model which aims to minimize the completion time. This work processes with a Branch-and-Bound and a heuristic Branch-and-Bound. To evaluate the performance of the proposed solution methods, numerous computational experiments are conducted, where the results show the efficiency of the proposed solution methods.

1. Introduction

Transportation systems are a crucial component of cities (Arvidsson and Pazirandeh 2017), which aids in economic and social activities, but it is responsible for reducing urban viability with so many negative impacts comprising dense traffic, reduction in road safety, noise, and pollution. As a new solution, two-echelon truck and drone delivery systems are proposed, which take advantage of both trucks' large capacity and the drone's high speed simultaneously.

In the classical VRP, capacitated vehicles depart and return to the warehouse in each tour, distributing goods to a set of customers, which has a known demand and needs to be visited by exactly one vehicle (Tavakkoli-Moghaddam, et al. 2005, Aghdaghi and Jolai, 2008, and Kir, et al. 2017), and its main ingredients are depots, vehicles, and network of road and customer location (Zibaei et al. 2016). In the two-echelon truck and drone routing problem, trucks act as mobile depots, and drones service the customers.

In this paper, we worked on the paired pickup and delivery problem in a two-echelon truck and drone system. Fig. 1 depicts pickup and delivery service in the two-echelon truck and drone delivery system. In this study, the truck departs from the depot and transports to the customers' vicinity. Then the drone takes off and pickups up from or delivers parcels to the customers.

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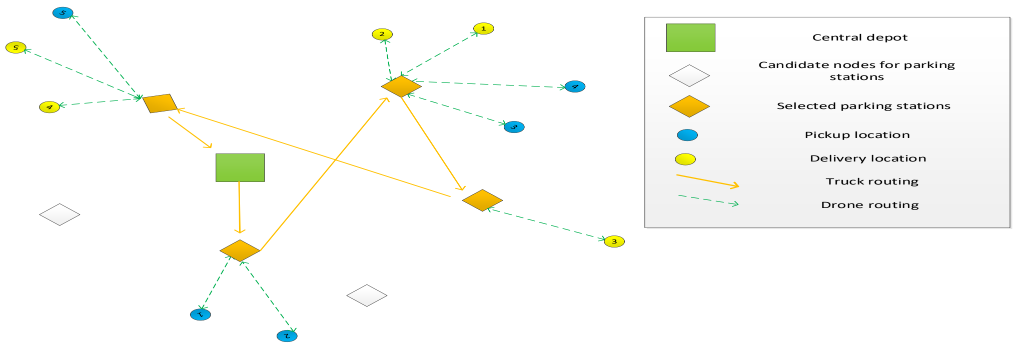

Figure 1. Pickup and delivery problem in a two-echelon truck and drone system

The main contributions of this paper can be summarized as follows:

- This is the first study to model the paired pickup and delivery problem in a two-echelon truck and drone delivery system.
- In this paper, we have proposed a Branch-and-Bound and an effective heuristic Branch-and-WBound for the problem.

The remainder of this paper is organized as follows. Section 2 represents an overview of related literature. Section 3 represents a mathematical model for the problem. We describe our proposed heuristic Branch-and-Bound in section 4. The computational results are provided in section 5, and section 6 outlines future research directions and concludes our study.

2. Related works

Truck and drone coordination

Coordination of a ground vehicle and a drone for delivery service is proposed by Murray and Chu (2015). They assumed a single depot and two types of customers, that the first type of customers gets service either by truck or drone, and the second type of customers just can get service by truck. They formulated the system in a way that the drone could travel independently or it can be transported by the ground vehicle. There are so many papers worked on this problem (Luo et al., 2021); some extended the problem formulation (Jeong et al., 2019) and some presented a new solution (Freitas et al., 2019). For example, Murray and Raj (2020) assumed that each truck is equipped with a fleet of heterogeneous drones and proposed multiple flying sidekicks traveling salesman problem (mFSTSP). Raj and Murray (2020) considered variable speed for drones and extended this problem into multiple flying sidekicks traveling salesman problem with variable drone speeds (mFSTSP-VDS).

Traveling salesman problem with drones (TSP-D) is an extension for truck and drone routing problem. In this problem drone routes are dependent on the truck route and the drone is not allowed to start a flight directly from/ to the depot (Bouman et al. 2018, Poikonen et al. 2019, Wang et al. 2019). Tu et al. (2018) considered multiple drones for each ground vehicle and proposed the traveling salesman problem with multiple drones (TSP-mD). As another extension for the truck-drone routing problem, Poikonen et al. (2017) considered multiple trucks which could be equipped with one or more drones and proposed the vehicle routing problem with drones.

To extend the literature on truck and drone coordination, researchers assumed various aspects of the problem. For an instance, some assumed that the drone can service more than one customer on each trip (Chen et al. 2021, Luo et al. 2021, Kitjacharoenchai et al. 2020). some researchers assumed that the drone must return to the node where it is dispatched and focused on the dispatch-wait-collect tactic (Li et al. 2020, Chen et al. 2021), and some considered no restriction for the drone to return its departure node (Wang et al. 2019, Sacramento et al. 2019, Schermer et al. 2019, Luo et al. 2021). For the truck stop locations, some studies assumed that customer locations do have not enough space for truck parking and drone operation and considered rendezvous locations for truck stop locations (Lu et al. 2017, and Karak and Abdelghany 2019).

Pickup and delivery

Parragh et al. (2008) categorized pickup and delivery routing problems into Vehicle Routing Problems with Backhauls (VRPB) and vehicle routing problem with Pickups and Deliveries (VRPPD). In the VRPB, parcels are transferred from the central depot to linehaul consumers and from backhaul consumers to the central depot. We refer to Nolz et al. (2022), Fontaine et al. (2021), and Park et al. (2021).

Contrary to the VRPB, in the VRPPD truck is not loaded while departing or returning to the depot, and parcels are transferred among pickup and delivery nodes. VRPPD is comprised of two major subclasses of unpaired and paired problems (Parragh et al. 2008). In the unpaired problem, there is no dependency among each pair of pickup nodes and delivery nodes, a homogeneous parcel type is considered and each picked-up parcel can be delivered to a delivery point. We refer to Martins et al. (2021), Casazza et al. (2021), and Abdi et al. (2019). In the paired type of VRPPD which is also called the Pickup and delivery problem (PDP), the origin and the destination of each parcel are determined, and a picked-up parcel must be delivered to a specific delivery point. We refer to Li et al. (2021), and Cherkesly and Gschwind (2021).

There are some studies focused on the truck and drone routing problem with unpaired pickup and delivery. For example, Karak and

Abdelghany (2019) considered a location routing problem for truck and drone coordination and studied unpaired pickup and delivery in a hybrid truck-drone delivery system. Studies on paired pickup and delivery problem in hybrid truck-drone delivery systems are scarce, for this reason, this paper focused on the paired pickup and delivery problem in a two-echelon truck and drone delivery system.

3. Formal Problem Description and

This section defines the pickup and delivery problem in a two-echelon truck and drone delivery system. At the first echelon, the truck which is equipped with a drone transfers to the customers' vicinity and stops in some parking locations which have enough space for parking the truck and operating the drone. Then the drone starts its trips in the second echelon for servicing the customers. To prepare a detailed description of the proposed delivery system, assumptions are listed as follows:

- The truck starts its route from the depot and it must turn back to the depot after servicing all of the customers.
- All of the customers can only be visited once.
- There is a sight radius for the drone operation.
- The drone can be operated only from rendezvous locations. Rendezvous locations are parking locations that have sufficient space for truck parking and drone operation.
- The drone delivers or picks up only one parcel per trip.
- The truck has enough capacity to serve all the demands.
- A paired pickup and delivery problem is considered, where each parcel has a specific origin and destination.

The problem is defined on G= (N, A) as a directed graph, where A is the set of arcs and N is the set of various locations including depot location, customer locations, and rendezvous locations.

3.1. Mathematical model formulation

In this section, we have proposed a MILP model, where the objective function calculates the completion time.
The relevant notation used in the model is listed as follows:

Sets:

S Set of locations containing customer locations and rendezvous locations.

S_1 Set of customer locations, including $S_1 = \{2, \ldots, N-1\}$

S_2 Set of rendezvous locations.

SP Set of all pick up locations including $SP = \{2, \ldots, \frac{N}{2}\}$

SD Set of delivery locations including $SD = \{\frac{N}{2} + 1, \ldots, N-1\}$

De Depot node $De = \{1, N\}$.

ST Set of all locations where the truck can stop including $ST = S_2 \cup DE$.

SN Sequences of depot and customers *i=1, …, N.*

Parameters:

td_{lf} Drone travel time between customer location *l* and rendezvous location *f*.

t_{kf} Truck travel time between nodes *k* and *f*.

SR Sight radius for operating the drone.

d_{lf} Distance between node *l* and *f*.

Variables:

h_{lf} A binary variable, which gets the value of 1 if customer *l* is assigned to rendezvous location *f*.

$U_{f,i}^{l}$ A binary variable, which gets the value of 1 if customer *l* is serviced with a drone flying from rendezvous location *f* at sequence *i*.

t_{kf}^{i} A positive variable to calculate truck transportation time between nodes *k* and *f*, where the customer with sequence *i* is assigned to rendezvous location *k*, and the customer with sequence *i+1* is assigned to rendezvous location *f*.

Objective function:

$$Min\ completion\ time = \sum_{k,f \in ST\ and\ (i \le N-1) \in SN} t_{kf}^{i} + \sum_{k \in S_2, l \in S_1} 2.\, td_{lk} . h_{lk} \quad (1)$$

Constraints:

$$\sum_{f \in S_2} h_{rf} = 1 \qquad \forall r \in S_1 \qquad (2)$$

$$\sum_{f \in S_2} h_{rf} . d_{rf} \le SR \qquad \forall r \in S_1 \qquad (3)$$

$$\sum_{i \in SN \ne (1\ and\ N)} U_{f,i}^{r} = h_{rf} \qquad \forall r \in S_1, f \in S_2 \qquad (4)$$

$$U_{1,1}^{1} = U_{N,N}^{N} = 1 \qquad (5)$$

$$\sum_{r \in (S_1 \cup DE), k \in ST} U_{k,i}^{r} = 1 \qquad \forall i \in SN \qquad (6)$$

$$\sum_{i \in SN, k \in S_2} i.(U_{k,i}^{r}) \le \sum_{i \in SN, k \in S_2} i.(U_{k,i}^{l}) \quad \forall r \in SP\ and\ l = (r + \frac{N}{2} - 1) \in SD \quad (7)$$

$$t_{kf}^{i} \ge t_{kf} - M.\left(1 - \sum_{r \in (S_1 \cup DE)} U_{k,i}^{r}\right) - M.\left(1 - \sum_{l \in (S_1 \cup DE)} U_{f,i+1}^{r}\right) \qquad (8)$$

t_{kf}^{i}: *positive variable*

$h_{lf}, U_{k,j}^{r}$: *Binary variables* $\forall k\ and\ f \in ST, and\ i,j \in SN$

The objective function aims to minimize the completion time. Constraint 2 ensures that all customers are assigned to rendezvous locations. Constraint 3 makes sure that customers are assigned in sight radius of rendezvous locations. Constraints (4, 5, and 6) assign a sequence for each customer and ensures that at most one customer is assigned for each sequence. Constraint (7) restricts the system to service the origin of parcels before servicing their destinations, and constraint (8) calculates the truck travel time after each sequence.

4. Solution method

In this section, we proposed a Branch-and-Bound algorithm (B&B) and a heuristic Branch-and-Bound algorithm (HB&B) for the paired pickup and delivery problem in a truck-drone delivery system.

4.1. Branch-and-Bound

Branching procedure:

In this algorithm, we have defined four rules for the branching procedure:

First rule: The next customer always is selected based on the minimum time required to service a customer after the last scheduled customer.

Second rule: If rendezvous location (f) is selected, for the next branches, all combinations of customers in sight radius of that must be checked for assigning to the rendezvous location f.

Third rule: If the last selected rendezvous location f has the minimum distance to the customer c, then; If c is a pickup node, or it is a delivery node while its related pickup node is serviced before the current stage, customer c must be serviced in the next sequence.

It is clear that if rendezvous location f is selected, there is no need for more truck travel time to service customer c and it has minimum drone travel time, so if it is not assigned to f, the final solution cannot be optimal.

Fourth rule: In the worst case of the optimal solution, a rendezvous location may be visited by the truck two times (once for pickup nodes and once for delivery nodes). So, if the truck leaves a rendezvous location, it can return that only once more.

When the truck visits rendezvous location f, all assigned pickup nodes could be serviced. If there is more than one delivery node assigned to f, where their related pickup nodes are not serviced, rendezvous location f can be visited after servicing all related pickup nodes. As depicted in Fig. 2, in the optimal solution, if pickup node f is serviced after pickup node k, c is always smaller than (a+b), so to evade excessive truck travel time, the rendezvous location h is going to be visited after servicing both nodes of k and f.

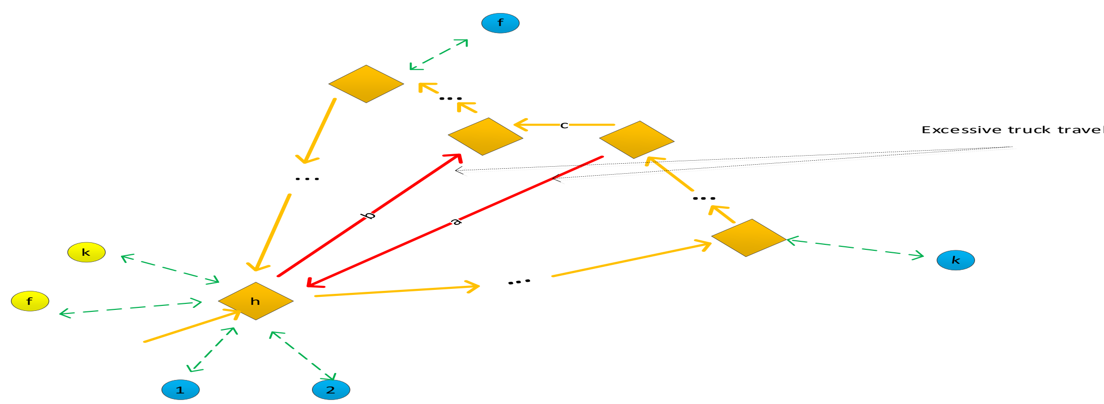

Figure 2. The paired pickup and delivery system when rendezvous location h needs to be visited more than once

Lower bound calculation:

At branching stage (*i*), Lower Bound (*LB*) is calculated as follows:

$$CT_i + \acute{CT}_i$$

Where CT_i is the completion time until stage *i*, which is computed as follows:

$$CT_i = CT_{i-1} + (td^i + t^i)$$

Where td^i and t^i are drone travel time and truck travel time at stage *i* from the scheduled customer at stage *i-1*.

$\acute{CT}_i$ is an estimation for the truck travel time and the drone travel time to service non-scheduled customers until stage *i* which can be calculated as follows:

$$\acute{CT}_i = \sum_{c \in \acute{S}_{1,i-1}} lst_c^i$$

Where, $\acute{S}_{1,i}$ is the set of non-selected customers until stage *i*, and lst_c^i is the minimum time required to service a customer exactly after customer c, which can be calculated as follows:

$$lst_c^i = \min\{td_{ck} + t_{kf} + td_{pf}, \forall p \in \{\acute{S}_{1,i}, N\}\ and\ k,l \in S_2\}$$

After servicing final customer, the truck and the drone must return back to the depot and if there are remained more than one customer, another customer must be serviced. So, if we consider the graph of problem with non-scheduled customers and depot, $\acute{CT}_i$ is always a lower bound for sum of minimum service times required to service all remaining customers and then return back to the depot.

4.2. heuristic Branch-and-Bound

For the heuristic branch-and-bound algorithm, it is assumed that if the rendezvous location of stage *i-1* is the f, the maximum number of branches at stage *i* with different rendezvous locations are limited to $\bar{k}$. It says that at most $\bar{k}$ various rendezvous locations can be selected for the next sequence. Fig. 3. demonstrates how this rule defines a neighborhood zone for a selected truck stop at stage *i*.

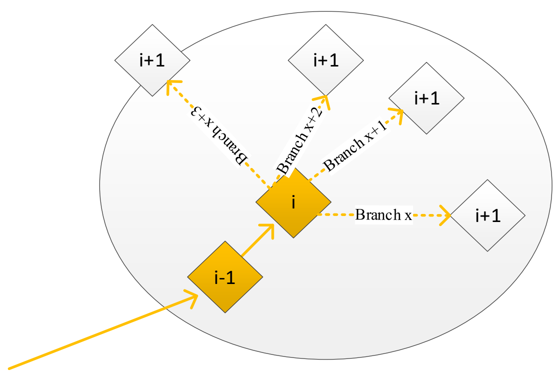

Figure 3. Neighborhood zone for a selected rendezvous location at stage i in the proposed HB&B, when $\bar{k}$=4

5. Computational study

We implemented our proposed algorithm in Python 3.9.12, and the CPLEX is used to solve the proposed MIP model. All computations are performed on a LENOVO Laptop with Intel(R) Core (TM) i7-9750HF CPU @ 2.60 GHz 2.59 GHz and 16 GB installed RAM running Windows 10.

5.1. Test instances

To evaluate the performance of B&B and HB&B, we generated 80 instances. We generated customer locations and rendezvous locations in a 1000*1000m2 square. Customers must be covered with the rendezvous locations, so we created them in a way that at least one rendezvous node is in sight radius of each second-class or third-class customer. The sight radius is considered to be 100 meters for this data generation. We have assumed that the depot is located at the vertex of the square (0,0). We assumed 10 meters per second for truck speed and 20 meters per second for drone speed.

5.2. performance of the proposed solution methods

In this section, the performance of the B&B and the HB&B are analyzed. The computational time is limited to 1800 seconds, and $\bar{k}$ is assumed to be equal to 3. As demonstrated in table 1, MILP cannot solve instances with sizes bigger than 12 customers and 3 rendezvous locations. The B&B showed better results, where it can solve instances with sizes of up to 24 customers and 6 rendezvous locations. In comparison to the exact methods, HB&B is more effective where it can solve most of the instances optimally, and among 80 instances the maximum CPU time is 0.13 seconds and the maximum average CPU time for the largest instance size (28 customers and 8 rendezvous locations) is 0.07 seconds.

Table 1. Performance of the MILP, B&B and HB&B

Number of customers	Number of rendezvous locations	Depot Position	Number of instances	*MILPs*			*B&B*			*HB&B* $\bar{k}=3$			
				Solved instances (%)	CPU time (sec)		Solved instances (%)	CPU time (sec)		Solved instances (%)	CPU time (sec)		Gap (%)
					Best	Average		Best	Average		Best	Average	
4	2	(0,0)	10	100	0.08	0.13	100	0	0.01	100	0	0	0
6	3	(0,0)	10	100	0.17	0.21	100	0.04	0.07	100	0	0	0
8	3	(0,0)	10	100	0.44	0.97	100	0.08	0.15	100	0	0	0
12	3	(0,0)	10	100	8.48	11.66	100	0.26	0.91	100	0	0	0
16	4	(0,0)	10	0	156.67	213.52	100	17.95	39.87	100	0	0	0
20	4	(0,0)	10	0	-	-	100	268.92	924.19	100	0	0.01	0
24	6	(0,0)	10	0	-	-	30	1308.70	-	100	0.02	0.02	-
28	8	(0,0)	10	0	-	-	0	-	-	100	0.03	0.07	-

To analyze the effects of $\bar{k}$ on the performance of the HB&B, we considered 30 instances in three sizes and depicted the average gap and CPU time of the HB&B for various values of $\bar{k}$ in Fig. 4. As it is depicted, at the beginning of the curve, the average gap is reduced significantly, but when $\bar{k}$ is increased to 4, the curve of the average gap becomes flat. It is also shown that for bigger values of $\bar{k}$, increasing that changes the CPU time significantly.

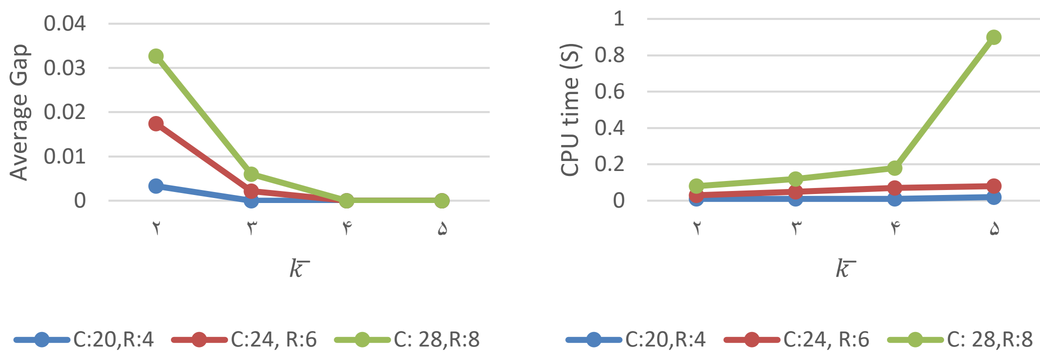

Figure 4. Average gap and CPU time of the performance of the HB&B for different values of $\bar{k}$

To analyze the effects of sight radius on the performance of the HB&B, we considered 10 instances with 24 customers and 6 rendezvous locations and depicted the average gap and CPU time of the HB&B for various values of sight radius in Fig. 5. For this analysis $\bar{k}$ is assumed to be 3. As it is demonstrated, in the beginning, the curve is flat but when the sight radius is increased to 1000, the CPU time is increased significantly.

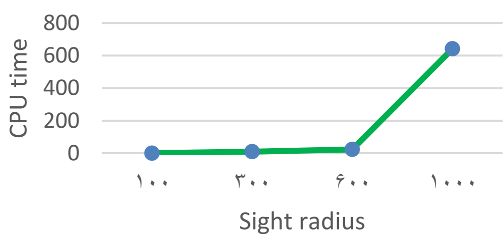

Figure 5. the performance of the HB&B for different values of sight radius

To analyze the effects of the drone speed on the completion time, we considered 10 instances with 28 customers and 8 rendezvous locations and demonstrated the average completion time of the delivery system for various values of drone speed in Fig. 6. at the beginning of the curve the completion time is reduced considerably, but for bigger values of drone speed, the curve becomes flat. One reason may be tuck travel times which cannot be ignored. If the drone speed is increased not only it reduces drone travel time but also it is impacting truck travel directions. But as there is a sight radius restriction for servicing customers, even if drone travel time is reduced to zero, truck travel time among selected rendezvous locations and the depot cannot be ignored.

As a comparison of the hybrid truck-drone delivery system and the truck-only delivery system, for drone speeds smaller than 14.1, the truck-only delivery system shows better performance, but when the drone speed is increased the hybrid truck-drone pickup and the delivery system shows better performance.

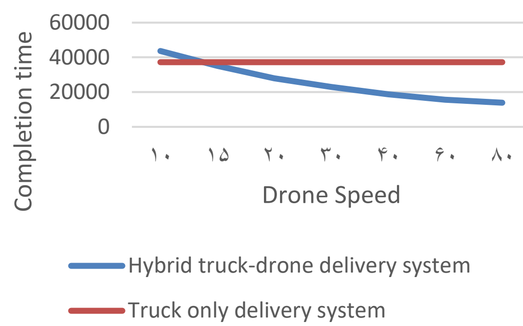

Figure 5 The performance of the hybrid truck-drone delivery system and the truck only delivery system for different values of drone speed

6. Conclusion

In this study, we have considered paired pickup and delivery system and proposed a hybrid truck and drone routing problem for paired pickup and delivery service. We have extended a MILP model for the proposed delivery system and developed a Branch-and-Bound and a heuristic Branch-and-Bound. We have designed a series of numerical experiments, where the proposed algorithms provided encouraging results.

Sensitivity analysis of the system shows that the completion time of the system is significantly dependent on the drone speed. For small drone speeds, the truck-only mode has better performance, but when the ratio of $(\frac{drone\ speed}{truck\ speed})$ is increased to 1.41, the hybrid truck-drone mode outperforms the truck-only pickup and delivery system.

This work can be extended by considering the uncertainty of the pickup and delivery services. To present more practical models, future research should consider multi trucks and multi drones. Finally, there are also opportunities to present more efficient solution methods.

Disclosure statement:

No potential conflict of interest was reported by the author(s).

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