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Drone airfield location determination method for parcel delivery by vehicle and drone

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Abstract— **While the e-commerce market has been expanding in recent years, some regions are facing a shortage of delivery drivers due to the declining birthrate and aging population, and so securing a delivery network is beginning to become a societal issue. For this reason, there are growing expectations for the use of drones to improve the efficiency of delivery. In this study, a method for determining drone airfields to realize efficient delivery through the coordination of a vehicle and a drone is proposed. In this method, road locations close to the average of the locations of residences belonging to each cluster calculated using the K-means method is selected as candidate locations for a drone airfield. Among the candidates, the location that minimizes the sum of travel time to the residences belonging to the cluster is selected as the location of the drone airfields. Through simulation evaluation, it was confirmed that the number of packages that can be delivered within the specified time slot increases, and the time required for delivery is reduced compared to the case where the location on the road closest to the average of the locations of residences belonging to each cluster calculated using the K-means method is used as the location of the drone airfields.**

I. Introduction

As the e-commerce market expands, the volume of parcel delivery services continues to increase. In Japan, in particular, the shortage of delivery drivers is becoming a serious problem, due to the declining birthrate and aging population. Therefore, there is a need to improve the delivery efficiency. Expectations are growing for drones to improve delivery efficiency, and demonstration experiments have been conducted in various regions[1][2][3].

Although drones can enable unmanned delivery, it is currently difficult to unmanned load packages, and basically human resources are required when loading packages. In addition, due to battery constraints, batteries may need to be replaced, which also often requires manual labor.

Although it is possible to assign a full-time person in charge of such loading and battery replacement, the advantages in terms of cost and human resources cannot be fully realized if a full-time person is assigned to this task. Therefore, instead of assigning a person in charge exclusively of drones, methods in which one driver uses both a vehicle and a drone to deliver packages by loading packages onto the drone and replacing batteries have been considered. In these methods, a drone is transported by a vehicle to the vicinity of delivery destinations, mixed with other cargo, which can shorten the drone's service distance, and further efficiency improvements can be expected.

In Japan, services that specify delivery time slot to reduce re-delivery have become widespread, and planning must take delivery time slot into account when using vehicles and drones to make deliveries.

In response to this problem, we proposed a look-ahead search method for parcel delivery planning in collaboration with a vehicle and a drone[4][5]. In this method, a delivery plan is created by calculating each delivery location's weight that takes into account the delivery time slot, looking ahead at the delivery route for multiple candidates of locations to be visited as determined by the weights, and sequentially selecting destinations that will yield good results. Although this method can obtain an efficient solution in a relatively short computation time, it is assumed that the location of drone airfields is given, and there may be a location of airfields that enables more efficient delivery.

Therefore, this study proposes a method for determining the location of drone airfields that enables efficient delivery. In the following, related work is first shown in chapter 2 and our proposed look-ahead search method is described in chapter 3. Then, a drone airfields' location determination method is explained in chapter 4. Lastly, simulation experiments are presented and discussed in chapter 5.

II. Related Work

One method for determining drone airfields when using drones for deliveries is to use the K-means method to minimize the total drone flight distance[6]. In Ref [7], locations of launch and refuel stations that minimize the total cost are calculated by using genetic algorithm. In Ref [8], a method for locating facility to maximize the area covered by drones is presented, taking into account the battery capacity of the drones. In Ref [9], a method for determining facility locations to streamline the delivery of first-aid products in the event of a disaster is presented. However, these studies assume delivery of packages by drones and do not consider delivery using both vehicles and drones.

In Ref [10], a method for determining the location of the delivery center is presented that allows for efficient operation when both vehicles and drones make deliveries. However, it is assumed here that the vehicles and drones deliver packages independently from the delivery center, and not that a single driver uses a vehicle and a drone to deliver packages.

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Therefore, this study proposes a method for determining the location of drone airfields that enables efficient package delivery when a single driver uses a vehicle and a drone to deliver packages and evaluates its effectiveness.

III. Look-ahead Search Method for Parcel Delivery Planning

A. Definition of Delivery Planning Problem

In the look-ahead search method[4][5], the combination of one vehicle and one drone is considered, and the delivery destination for one day is known at the start of the delivery. Some of the destinations have specified delivery time slot. The area to be delivered by the drone is assumed to be fixed in advance, because some facilities are required to receive package delivered by the drone.

The vehicle can carry the packages that the vehicle and the drone deliver in a day. On the other hand, the drone can carry only one package at a time. That is, each time a package is delivered by the drone, it is necessary to transship the next package from the vehicle to the drone. Note that the existence of package that cannot be delivered by the drone is not assumed. No range limitation is assumed. The battery of the drone is replaced by the driver of the vehicle when loading the package if necessary, and so it is assumed that the battery will not run out.

Since the drone requires a certain amount of space for takeoff and landing, it is assumed that the drone can take off and land only at predetermined airfields or delivery centers. It is assumed that the loading of a package onto the drone is done manually, and that the driver of the vehicle is present at the drone airfield when the drone takes off.

B. Algorithm

This method is divided into two phases: a phase to obtain an initial solution and a phase to improve the initial solution. In the first phase, the weights are computed using an extension of the nearest neighbor method[11], which is one of the methods for generating an initial solution to a time-constrained delivery planning problem for vehicles only.

First, the weights for determining the candidate destinations to visit are explained.

The weights of the vehicle delivery request locations are obtained as follows, where b_i^v is the start time of the specified time slot for delivery request i, e_i^v is its end time, r_i is the time required for the vehicle to travel to delivery request i, and t is the time at which the next destination is determined.

$$weight_i = \max(b_i^v - t, r_i) \cdot (e_i^v - t)$$

The weight can be understood as operating in such a way that requests that can be delivered sooner are given priority (corresponding to the first term of weight), and requests that have less time to spare before the delivery deadline are given priority (corresponding to the second term of weight).

When the vehicle is carrying the drone and when the vehicle is not at the drone airfields, the weights of the drone airfields are obtained as follows, where a_j is the time required for the vehicle to travel to the drone airfield j, b_i^d is the start time of the specified time slot for delivery request k by the drone, and e_k^d is its end time.

$$weight_j = \min_k \{ \max(b_k^d - t, a_j) \cdot (e_k^d - t) \}$$

When the vehicle is at the drone airfields, as when the vehicle retrieves the drone, the weights of the drone airfields are obtained as follows, where ε is a sufficiently small positive number and $r_{j\to k}^d$ is the time required for the drone to travel from the drone airfield j to the delivery request k because it is more efficient to have the drone take off from the same airfield.

$$weight_j = \min_k \{ \varepsilon (b_k^d - t)(e_k^d - t) r_{j\to k}^d \}$$

When the vehicle is not carrying the drone, the weights of the drone airfields are obtained as follows, where l_j is the time at which the drone can arrive at the airfield j.

$$weight_j = \max(l_j - t, a_j) \cdot \min_k (e_k^d - t)$$

In the original nearest neighbor method, some terms such as $(e_i - t)$ cannot be negative because vehicles are added if they cannot meet the specified delivery time slot. However, since the number of vehicles and drones is fixed in the present assumption and some terms may become negative, the weights are calculated with this value set to 1 in this case.

Next, the method of determining the route using these weights is described.

The method is illustrated using Fig. 1. It is assumed here that the vehicle and drone are at the initial location, the delivery center (s1). The width and depth of the look-ahead are set to N and 3, respectively.

First, the weights of all the candidates for the next destination are obtained, and the N candidate destinations with the smallest weights are selected. Here, N candidates are selected, including s3, s15, and s70.

Next, for each of the selected candidate destinations, the weights of the next candidate destinations are all calculated, and the N candidate destinations with the smallest weights are selected. For example, N candidates including s18, s31, and s61 are selected as the next destination candidates after s15. This results in N^2 route candidates being selected. The same process is performed again, and finally N^3 candidate routes are selected.

For each of the N^3 candidate routes, the location with the lowest weight is selected as the next destination. This process is continued until all the packages are delivered and return to the distribution center. Then, the evaluation value is calculated for each of the N^3 route candidates, and the location connected to the route with the maximum evaluation value is determined as the next destination.

Here, the number of packages that can be delivered within the specified delivery time slot is used as the evaluation value. If there are routes with equal evaluation values, the route with the shortest delivery time is selected. Here, the maximum evaluation value is 85, and s15, which is connected to this route, is determined as the next destination from s1.

In this way, the delivery route is determined by sequentially determining the next destination from the initial location.

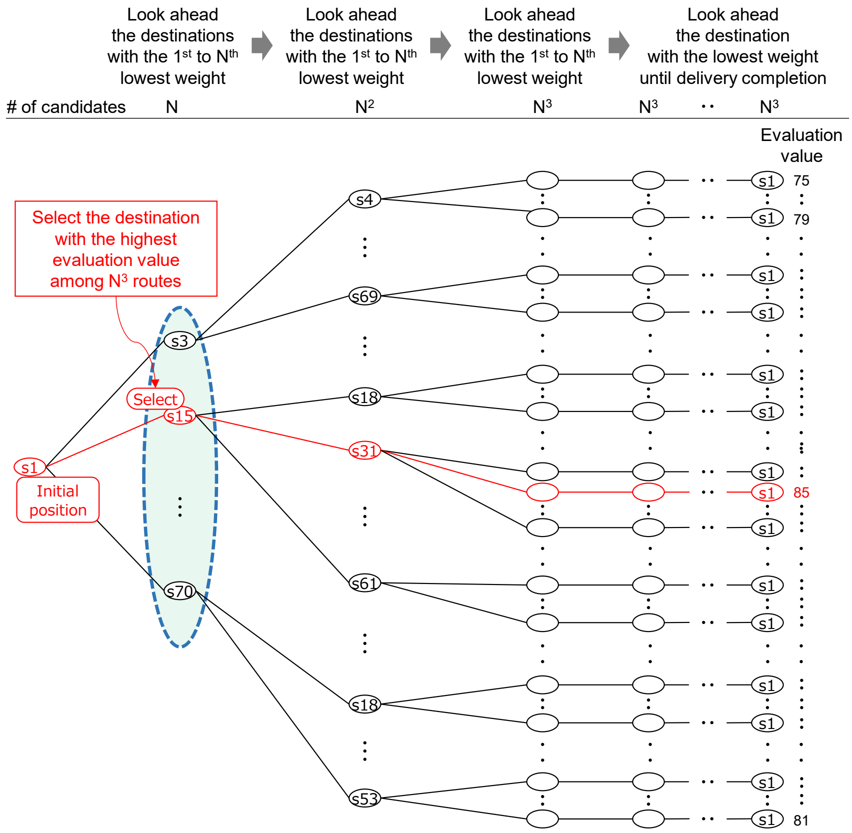

Figure 1. Look-ahead search method

For the improvement operations, firstly, intra-route relocation and intra-route exchange, two of the intra-route operations that have been used in many studies on time-constrained delivery planning problems, are performed[12].

Intra-route relocation is an operation to change the visiting order of a single point. In our method, the operation is to change the visiting order of delivery requests for which the vehicle is in charge and for which no delivery time slot is specified.

Intra-route exchange is an operation to exchange the visiting order of two points. In our method, the operation is to exchange the visiting order of two delivery requests for which the vehicle is in charge and for which no delivery time slot is specified.

The above operations are performed in this order, and the delivery plan is updated when the number of delivery requests that can be delivered within the specified delivery time slot increases, or when the number of delivery requests that can be delivered within the specified delivery time slot remains the same, but the total delivery time is reduced in each trial within each operation.

Next, an improvement operation is performed for the delivery requests for which the vehicle is in charge and for which a delivery time slot is specified. In this operation, among the delivery requests that cannot be delivered within the delivery time slot, the ten delivery requests with the earliest delivery time are inserted at an arbitrary position in order, and the subsequent plans are obtained in the same way as the generation of the initial solution. Then, the delivery plan is updated when the solution is improved in the same manner as above.

IV. Drone Airfield Location Determination Method

A. Premise

It is possible to place a drone airfield away from roads and have the driver walk from where the vehicle is parked to the airfield to load a parcel onto the drone. However, to improve delivery efficiency, it is considered better to shorten the time the driver spends walking, so the drone airfield is located adjacent to roads.

Roads are continuous, but candidate locations for drone airfields are discrete, not continuous. In other words, the number of candidate locations for drone airfield is assumed to be finite.

B. Approach

The K-means method of determining location of drone airfields in existing studies is effective when delivery is made solely by drones and when the location of the drone airfields is highly flexible.

However, in the case of delivery by a combination of a vehicle and a drone, drone airfields need to be located adjacent to roads as mentioned above. Therefore, the K-means method cannot be used as it is.

A simple way to transfer the location obtained by the K-means method to a location adjacent to roads would be to transfer the location obtained by the K-means method to the location on the nearest road. However, with this way, depending on the road geometry, drone airfields may be an area that is difficult for vehicles to visit. Therefore, the method of transferring to the location on the nearest road may not be able to achieve efficient delivery.

An example is shown in Fig. 2. In Fig. 2, the upper side of the river is sparsely populated with residences and roads. Conversely, the lower side of the river is densely populated with residences and roads. In this case, it would be efficient to set up a drone airfield on the lower side of the river, with a vehicle delivering to residences on the lower side of the river and a drone delivering to residences on the upper side of the river. However, depending on the layout of the residences, the center of gravity of the residences would be on the upper side of the river, and if the nearest location on the road is used as a drone airfield, this location would also be on the upper side of the river. If this occurs, when a vehicle is delivering residences on the lower side of the river, it will take a lot of time for a vehicle to visit the drone airfield.

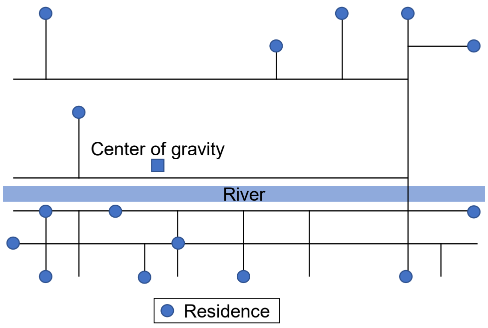

Figure 2. Example of a layout of residences

```
repeat 100 times:
 initialize locations of airfields with random value;
 repeat:
  repeat each residence:
   assign location of airfield that can be reached in the shortest
   time;
  end loop
  repeat each airfield:
   calculate average of assigned residence locations;
   extract the 50 nearest airfield candidate points from the
   average of assigned residence locations;
   repeat each candidate point:
    calculate the sum of travel time to assigned residences;
   end loop
   set location of airfield as the point where the sum of travel
   time is the smallest;
  end loop
  if no change in location of airfield:
   break;
 end loop
end loop
result with the smallest sum of travel time is determined as
locations of airfields;
```

Figure 3. Pseudo code of location determination method

Therefore, in the proposed method, multiple locations on roads are extracted as candidates for drone airfields, based on the locations obtained by the K-means method. Specifically, points that are close in distance from the locations obtained by the K-means method are extracted as candidates, and the point where the sum of the distances from the candidate points to the residences belonging to each cluster in the K-means method is the smallest is selected as the location of the drone airfields. This process is performed for each cycle of the K-means method to determine the location.

C. Algorithm

The specific process based on the approach in the previous section is described below.

Since the results obtained by the K-means method depend on initial values, initial values are randomly set multiple times, the same process is performed multiple times, and the final solution is selected from the multiple results obtained. Here, the point where the sum of the travel distances from the drone airfields to the residences belonging to each cluster is the smallest is selected as the location of the drone airfields. This time, the same process is performed 100 times using different initial values.

In the previous section, it was mentioned that multiple points close in distance from the location obtained by the K-means method were extracted as candidates. In this case, 50 points were extracted as candidates.

The process described so far is shown in pseudo code in Fig. 3.

V. EVALUATION BY SIMULATION

A. Evaluation Model

The road model is based on Japanese road geometry. OpenStreetMap data is used for road geometry, and roadways are extracted. The area size is 15 km square. The extracted roadways are approximated by a 50 m mesh road geometry as in Ref [5]. The vertices of the 50 m mesh road geometry are candidates for locations of drone airfields.

A delivery destination is a residence, but since it is difficult to know the actual location of residences, the location of residences is set based on the road geometry. In general, dwellings are more abundant near major roads and less abundant in mountainous areas. It is assumed that delivery requests also tend to exist in the same way. For this reason, roads (hereafter referred to as "arterial roads") are set manually as a basis for the placement of residences, and residences and delivery requests are placed based on the arterial roads.

Specifically, a weight is set for the vertices of the 50 m mesh road geometry according to the minimum distance from the arterial roads, and the vertices are randomly selected in consideration of the weights. The selected vertices are then used as the locations of residences and delivery locations are randomly selected from residences. The distance here is the shortest distance to be traveled on the roads. Assuming that there are 0.4 delivery requests per km^2 per day, and since an area of 15 km square is assumed in this case, the number of delivery locations is 90. For each road geometry, five cases of residences are assumed, and five cases of delivery locations are assumed for each case of residences.

The five possible delivery time slots are 9:00 to 12:00, 14:00 to 16:00, 16:00 to 18:00, 18:00 to 20:00, and 19:00 to 21:00, which is based on what is used by actual delivery services in Japan. The probability of specifying a delivery time slot is assumed to be 30 %, and the probability of selecting each delivery time slot is equal. That is, there is a 6 % probability of specifying each delivery time slot.

Basically, the closer an area is to the arterial roads with high road density, the more efficient it is to deliver by vehicle, and the farther an area is from the arterial roads with small road density, the more efficient it is to deliver by drone.

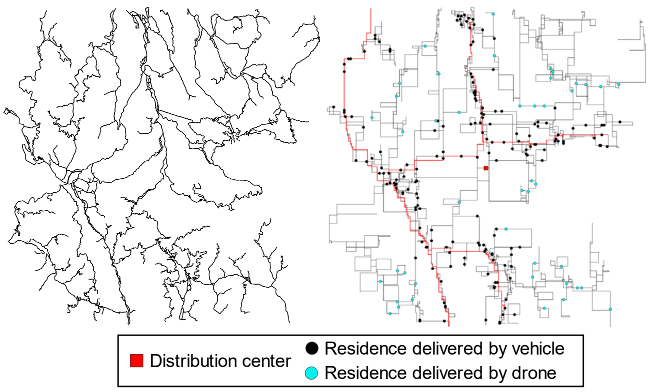

Figure 4. Example of the road model

For this reason, the area to be delivered by vehicle and the area to be delivered by drone are divided according to the distance from the arterial roads. The area where the minimum distance from the arterial roads is within 2.0 km are area to be delivered by vehicle, and the area where the distance from the arterial roads exceeds 2.0 km are area to be delivered by drone. As in the case of setting up residences, the distance here is the shortest distance to be traveled on the roads.

The delivery center is located in the center of the target area. Two road models are used in the evaluation. Fig. 4 shows the actual road geometry and 50 m mesh road geometry for road model 1. The left side shows the actual road geometry, and the right side shows the 50 m mesh road geometry. The roads drawn thick in the 50 m mesh road geometry are the defined arterial roads. The residences show one of the five cases. The road density in the 50 m mesh road geometry is 2201.1 m/km^2 for road model 1 and 1384.2 m/km^2 for road model 2.

The average speed of the vehicle is set to 25 km/h and the time required at delivery locations is set to 3 minutes. The departure time from the delivery center is set to 9:00 a.m.

The average speed of the drone is set to 50 km/h, and the time required at delivery locations is set to 3 minutes. The time required to load a package at an airfield is assumed to be 2 minutes. The departure time from the delivery center is set to 9:00 a.m., the same as for the vehicle.

TABLE I. RESULT OF PACKAGE DELIVERY SIMULATION

Road Model	# of drone airfields	Item	Proposed Method	Comparison Method 1	Comparison Method 2
1	4	# of packages that can be delivered within during the specified time slot	85.2	78.4	84.3
		Required time	821.9 min	897.6 min	822.5 min
		Vehicle’s travel distance	231.7 km	243.8 km	230.4 km
		Drone’s travel distance	202.2 km	161.1 km	200.1 km
	6	# of packages that can be delivered within during the specified time slot	86.1	78.7	85.5
		Required time	795.8 min	895.9 min	817.9 min
		Vehicle’s travel distance	221.5 km	244.4 km	229.3 km
		Drone’s travel distance	201.4 km	164.1 km	201.6 km
2	4	# of packages that can be delivered within during the specified time slot	86.5	83.0	86.4
		Required time	786.0 min	838.1 min	784.6 min
		Vehicle’s travel distance	218.0 km	228.4 km	217.5 km
		Drone’s travel distance	208.2 km	179.5 km	204.8 km
	6	# of packages that can be delivered within during the specified time slot	87.0	82.7	86.4
		Required time	773.6 min	844.6 min	788.9 min
		Vehicle’s travel distance	211.3 km	229.9 km	218.4 km
		Drone’s travel distance	201.9 km	184.4 km	202.3 km

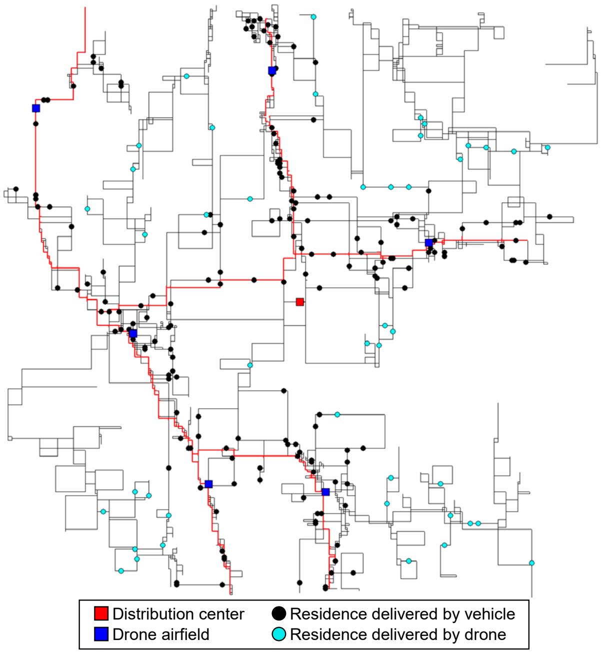

Figure 5. Example of drone airfield layout (Road model: 1, # of drone airfields: 6)

B. *Result*

For the model mentioned above, location of the drone airfields was determined using the proposed method. Then, simulation regarding package delivery was performed using the look-ahead search method. The simulation software was developed by the authors in Python. The number of drone airfields were assumed to be 4 and 6. The depth and width in the look-ahead search method were set to 3 and 5, respectively.

For comparison, a method in which only the residences to be delivered by a drone were used and the locations were determined by the K-means method was also evaluated (comparison method 1). However, since the obtained location may not be adjacent to roads, the location of the drone airfields was determined by transferring the obtained location to the nearest road at the end.

Also, a method in which the obtained locations were transferred to the nearest road at each iteration of the K-means method was also evaluated (comparison method 2).

Table 1 shows the number of packages that can be delivered within during the specified time slot and required time in each case. It also shows the vehicle's travel distance and the drone's flight distance.

For reference, Fig. 5 shows an example of the location of drone airfields obtained by the proposed method.

The proposed method achieves better results than either of the comparison methods. In comparison method 1, the drone's flight distance is shorter than the other methods, but on the contrary, the vehicle's travel distance is longer.

It is considered that this is because the drone airfields are located in places where it takes time for the vehicle to visit, since only the location of the residences to be delivered by the drone is used to determine the location of the drone airfields. This may result in inefficient delivery. The proposed method gives better results, although the results of comparison method 2 are improved compared to comparison method 1.

VI. Conclusion

A method for determining the location of airfields that enables efficient delivery by a vehicle and a drone was proposed and was confirmed to be effective through simulation.

In this paper, the effectiveness of the proposed method was confirmed when residences were placed based on the determined arterial roads, but the effectiveness of the method when the distribution of residences is different has not yet been confirmed. Therefore, it is important to confirm the effectiveness of the proposed method in a variety of situations, and to improve the method in the future. A drone flies the shortest routes in this study. In actual operation, drones may only be able to fly in a limited area. Future work is also needed to study methods for such situations.

References

[1] P. E. Ross, "Iceland's Consumers Try Drone Delivery: The Startup Aha Takes on Amazon with Basic Drones Bearing Burgers," IEEE Spectrum, Vol.55, No.10, pp.12–13, 2018.

[2] E. Frachtenberg, "Practical Drone Delivery," Computer, Vol.52, No.12, pp.53–57, 2019.

[3] D. Schneider, "The Delivery Drones Are Coming," IEEE Spectrum, Vol.57, No.1, pp.28–29, 2020.

[4] S. Hori, N. Komoda, and T. Ohkawa, "A parcel delivery method by combining vehicle and drone," IEEJ Transactions on Electronics, Information and Systems, Vol.141, No.11, pp.1175-1184, 2021. (in Japanese)

[5] S. Hori, N. Komoda, and T. Ohkawa, "A look-ahead search method for parcel delivery planning in collaboration with vehicle and drone," Proceedings of the 87th Technical Meeting on "Information Systems," IEE Japan, 2022. (in Japanese)

[6] J. Lynskey, K. Thar, T. Z. Oo, and C. S. Hong, "Facility Location Problem Approach for Distributed Drones," Symmetry, 11, 118, 2019.

[7] S. M. Shavarani, M. G. Nejad, F. Rismanchian, and G. Izbirak, "Application of hierarchical facility location problem for optimization of a drone delivery system: a case study of Amazon prime air in the city of San Francisco," The International Journal of Advanced Manufacturing Technology, Vol.95, pp.3141–3153, 2018.

[8] D. Chauhan, A. Unnikrishnan, and M. Figliozzi, "Maximum coverage capacitated facility location problem with range constrained drones," Transportation Research Part C: Emerging Technologies, Vol.99, pp.1-18, 2019.

[9] T. Zhu, S. D. Boyles, and A. Unnikrishnan, "Two-stage robust facility location problem with drones," Transportation Research Part C: Emerging Technologies, Vol.137, 2022.

[10] S. Chowdhurya, A. Emelogua, M. Marufuzzamana, S. G. Nurreb, and L. Biana, "Drones for disaster response and relief operations: A continuous approximation model," International Journal of Production Economics, Vol.188, pp.167-184, 2017.

[11] L. M. Gambardella, E. Taillard. and G. Agazzi, "MACS-VRPTW: A Multiple Ant Colony System for Vehicle Routing Problems with Time Windows," New Ideas in Optimization, McGraw-Hill, London, pp.63–76, 1999.

[12] O. Bräysy and M. Gendreau, "Vehicle Routing Problem with Time Windows, Part I: Route Construction and Local Search Algorithms," Transportation Science, Vol.39, No.1, pp.104–118, 2005.