POTENTIAL BENEFITS ASSESSMENT ON HOME DELIVERY SERVICE USING MULTIPLE DRONES

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Abstract

A tandem home delivery service combining a drone and a truck has attracted worldwide attention. We proposed a multi-objective path planning method for the tandem delivery problem in past research. In addition, we showed quantitatively how much the drone contributes to cost reduction of the delivery service by using this method. However, the proposed method has some drawbacks. For example, problem setting applicable to this method is very limited, and there may be cases where the optimization cannot be performed depending on the characteristics of the objective function. Therefore, we propose a new method to solve these problems in this paper. By using the improved method, it became possible to generate multiple delivery routes at the same time. Moreover, we also found that the effect of cost reduction by drone greatly varies depending on preset constraint conditions by evaluating the potential benefits of the drone again. For this reason, it can be said that additional analyses are necessary to maximize the benefits of the drone in the delivery service.

1 Introduction

In recent years, the sharp increase in the home delivery costs and the shortage of workers due to the expansion of the online mail order service have become major issues of the delivery industry. The drone is drawing attention as one means to solve these problems. It is said that the drone delivery can significantly reduce the delivery cost compared to the conventional truck delivery [1-3]. In addition, it is expected that the drone delivery can be utilized as a means of transporting rescue supplies in the event of a disaster [4,5]. However, due to the limited duration of flight time and the payload of the drone, it is not suitable for the independent operation. Therefore, the tandem delivery that is combining the drone and the truck is actively studied [6].

In past research, we proposed a method of generating the tandem delivery route [7]. This method formulates the delivery problem as a constrained multi-objective optimization problem and solves this by using a new method called "provisional ideal point method". We quantitatively evaluated how much the tandem delivery can reduce the delivery cost such as the travel distance or the delivery time than the truck delivery by using the proposed method. As a result, we found that the tandem delivery can reduce the travel distance by about 40%, and the delivery time by about 25%.

On the other hand, the provisional ideal point method had a drawback in that the objective function whose evaluation value of the feasible solution is 0 cannot be optimized. In addition, the route generation method has some restrictions such that only one pair of the tandem home delivery routes cannot be generated at one time. Therefore, we newly propose a method to solve these problems and aim to evaluate the usefulness of the drone once again.

The structure of this paper is as follows. In Chapter 2, the outline of the provisional ideal point method and its improvement method will be described. In Chapter 3, the details of the improved tandem delivery route generation method will be described. In Chapter 4, we formulate the delivery problem as a constrained multi-objective optimization problem based on our assumptions. In Chapter 5, we will show the simulation results. Then the discussions and the future works will be mentioned. In Chapter 6, we will conclude this research.

2 Provisional-Ideal-Point Based Method

2.1 Outline

The constrained multi-objective optimization problem is generally expressed by the following equation.

$$\begin{cases} \min_{\boldsymbol{x}} \boldsymbol{F}(\boldsymbol{x}) = \\ \quad \min_{\boldsymbol{x}} \ [F_1(\boldsymbol{x}), F_2(\boldsymbol{x}), \cdots, F_I(\boldsymbol{x}), \cdots, F_M(\boldsymbol{x})]^T \\ subject\ to\ g_J(\boldsymbol{x}) \leq 0, \\ \quad I = 1,2,\cdots,M,\ J = 1,2,\cdots,m \end{cases} \tag{1}$$

The above expression means searching for a solution $\boldsymbol{x}$ that optimizes all objective functions $\boldsymbol{F}(\boldsymbol{x})$ while satisfying all constraint conditions at the same time.

The outline of the provisional ideal point method to solve this problem is as follows. First, we define a new evaluation function called a penalty value $P(\boldsymbol{x})$ as shown below in order to search for a feasible solution satisfying all $g_J(\boldsymbol{x})$.

$$\min_{\boldsymbol{x}} P(\boldsymbol{x}) = \min_{\boldsymbol{x}} \sum_{J=1}^{m} P_J(\boldsymbol{x}) \tag{2}$$

$$s.t. \begin{cases} P_J(\boldsymbol{x}) = g_J(\boldsymbol{x}), & g_J(\boldsymbol{x}) > 0 \\ P_J(\boldsymbol{x}) = 0, & g_J(\boldsymbol{x}) \leq 0 \end{cases} \tag{3}$$

Generation of an executable solution is possible by searching for a solution that $P(\boldsymbol{x}) = 0$ using a genetic algorithm.

Next, we perform the multi-objective optimization for the generated feasible solutions. At this time, each evaluation value will be normalized in order to handle each $F_I(\boldsymbol{x})$ having different unit system in a unified manner. For that purpose, a value called "provisional optimum value $F_{I_{pro}} (\leq F_I(\boldsymbol{x}) | P(\boldsymbol{x}) = 0)$" is newly defined. This value is the minimum value of the objective function at that time point, and this value is updated to that value each time when a better evaluation value is generated in the search process. Using this value, coordinate points called "solution point $\boldsymbol{C}_{sol}(\boldsymbol{x})$" and "provisional ideal point $\boldsymbol{C}_{ideal}$" are defined as follows.

$$\begin{aligned} \boldsymbol{C}_{sol}(\boldsymbol{x}) &= \left[\frac{F_1(\boldsymbol{x})}{F_{1_{pro}}}, \frac{F_2(\boldsymbol{x})}{F_{2_{pro}}}, \dots, \frac{F_I(\boldsymbol{x})}{F_{I_{pro}}}, \dots, \frac{F_M(\boldsymbol{x})}{F_{M_{pro}}}\right]^T \\ &= [F'_1(\boldsymbol{x}), F'_2(\boldsymbol{x}), \dots, F'_I(\boldsymbol{x}), \dots, F'_M(\boldsymbol{x})]^T \end{aligned} \tag{4}$$

$$\begin{aligned} \boldsymbol{C}_{ideal} &= \left[\frac{F_{1_{pro}}}{F_{1_{pro}}}, \frac{F_{2_{pro}}}{F_{2_{pro}}}, \dots \frac{F_{I_{pro}}}{F_{I_{pro}}} \dots \frac{F_{M_{pro}}}{F_{M_{pro}}}\right]^T \\ &= [1,1,\dots,1,\dots 1]^T \end{aligned} \tag{5}$$

$\boldsymbol{C}_{sol}(\boldsymbol{x})$ is defined only by solutions that satisfy the condition $P(\boldsymbol{x}) = 0$. $\boldsymbol{C}_{ideal}$ is a virtual solution that can optimize all objective functions into each optimal value of $F_{I_{pro}}$. Here, the distance $D_{PS}(\boldsymbol{x})$ between $\boldsymbol{C}_{sol}(\boldsymbol{x})$ and $\boldsymbol{C}_{ideal}$ is defined as follows.

$$D_{PS}(\boldsymbol{x}) = \left|\boldsymbol{C}_{P_{ideal}} - \boldsymbol{C}_{sol}(\boldsymbol{x})\right| \tag{6}$$

This method can realize the multi-objective optimization by searching for a solution that minimizes the value of $D_{PS}(\boldsymbol{x})$.

2.2 Problems and Improvements

The problem with this approach is that the value of $F'_I(\boldsymbol{x})$ become indeterminate form when $F_{I_{pro}} = 0$, $\boldsymbol{C}_{sol}(\boldsymbol{x})$ cannot be defined. Therefore, an objective function that may have $F_{I_{pro}} = 0$ cannot be incorporated into the definition formula of $D_{PS}(\boldsymbol{x})$. Therefore, when this objective function is set to $F_{\hat{I}}(\boldsymbol{x})$, we will perform the optimization of $F_{\hat{I}}(\boldsymbol{x})$ independently after the multi-objective optimization is completed. Specifically, single-objective optimization of $F_{\hat{I}}(\boldsymbol{x})$ is performed under the following conditions.

$$\begin{cases} \min_{\boldsymbol{x}} F_{\hat{I}}(\boldsymbol{x}) \\ subject\ to\ P(\boldsymbol{x}) = 0, \\ F_I(\boldsymbol{x}) \leq F_I(\boldsymbol{x}^*),\ I = 1,2,\dots,M \end{cases} \tag{7}$$

Where $\boldsymbol{x}^*$ represents a multi-objective optimal solution obtained by the provisional ideal point method. The above equations mean searching for $\boldsymbol{x}$ that minimizes $F_{\hat{I}}(\boldsymbol{x})$ within a range that does not degrade each evaluation value of $\boldsymbol{x}^*$. If there are multiple $F_{\hat{I}}(\boldsymbol{x})$, decision-makers will optimize them sequentially by setting priorities. By doing this, optimization of $F_{\hat{I}}(\boldsymbol{x})$ can be realized while solving the problem that $F'_I(\boldsymbol{x})$ becomes indeterminate form.

3 Delivery Route Planning Method

3.1 Disadvantages of Existing Method

Problems related to the route generation method for the tandem home delivery proposed last time are listed below.

- Take-off place of the drone is limited only to the delivery place.
- The driver can deliver only one parcel within one usage of the drone.
- It is impossible to generate the multiple delivery routes at the same time.

The first one means that the driver cannot generate a delivery route that it makes halfway parking for usage or collection of the drone. This limitation severely hinders the diversity of the delivery route that can be generated. The second one means that the drone is restricted to only one place that can be delivered by one usage. In other words, if it becomes possible to obtain a route that can be delivered to multiple places in one flight, the expected benefit can be further increased. The third one means that the existing method cannot task allocation of the delivery service to multiple trucks. However, some drivers are engaged in actual delivery service at the same time. The route generation considering task allocation or assignment is called "multi-agent type". We propose a method to solve these drawbacks of the existing method as shown below.

3.2 Proposed Method

We propose a new expression of the tandem delivery route to solve some drawbacks of the existing method as follows.

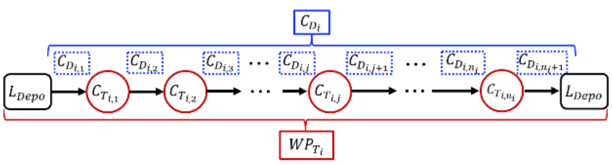

Fig. 1 Conceptual diagram of tandem delivery route

Where L_{Depo} is the coordinates at which the depot is located, C is the coordinates at which the customer's house is located, T_i is i-th truck, WP_{T_i} is the delivery route of the i-th truck, $C_{T_{i,j}}$ is the delivery WP where the i-th truck visits in j-th, n_i is the total number of the delivery WPs that i-th truck delivers, C_{D_i} is a set of $C_{D_{i,j}}$. $C_{D_{i,j}}$ is a set of the delivery WPs where the drone delivers while the i-th truck moves from $C_{T_{i,j-1}}$ to $C_{T_{i,j}}$. Then, we refer to $C_{T_{i,j}}$ as a truck WP, and $C_{D_{i,j,k}}$ as a drone WP which is included in $C_{D_{i,j}}$. The truck WP represents a place where the truck delivers, and the drone WP represents a place where the drone delivers. $n_{D_{i,j}}$ is the total number of the drone WPs in the $C_{D_{i,j}}$. The use and collection of the drone must be completed between the truck WP. For example, if one driver departed $C_{T_{i,j-1}}$, the usage of the drone between $C_{T_{i,j-1}}$ and $C_{T_{i,j}}$ must be finished at least before the driver departs $C_{T_{i,j}}$. Fig. 2 shows the general expression of the flight route for the drone.

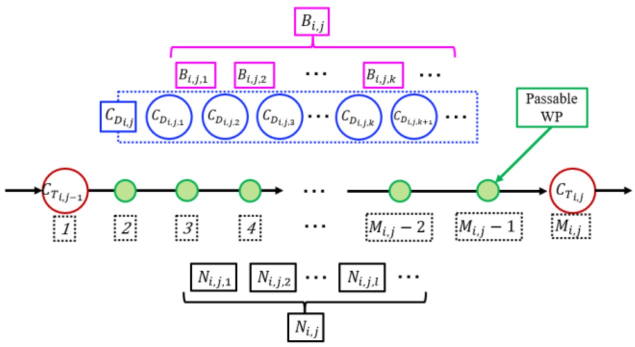

Fig. 2 Expression of flight route between $C_{T_{i,j-1}}$ and $C_{T_{i,j}}$

The green circle between the trucks WP is called "passable WP". These WPs are set in advance at an appropriate interval on the shortest path connecting the trucks WP. $B_{i,j}$ and $N_{i,j}$ determine the flight path of the drone. $B_{i,j}$ is the set of $B_{i,j,k}$ ($\in \{0,1\}$) and $B_{i,j,k}$ is placed between $C_{D_{i,j,k}}$ and $C_{D_{i,j,k+1}}$. If $B_{i,j,k}$ is 0, the drone flies towards $C_{D_{i,j,k+1}}$ after completing home delivery at $C_{D_{i,j,k}}$. If $B_{i,j,k}$ is 1, the drone is collected by the driver in one of the passable WP after completing home delivery at $C_{D_{i,j,k}}$. After that, the drone flies again toward $C_{D_{i,j,k+1}}$. $N_{i,j}$ determines the collection point or the takeoff point of the drone. $N_{i,j}$ is the set of $N_{i,j,l}\ (\in \{1,2,\dots,M_{i,j}\})$, and $M_{i,j}$ is the total number of WPs between $C_{T_{i,j-1}}$ and $C_{T_{i,j}}$. Let $n_{B_{i,j}}$ be the number of $B_{i,j,k}$ included in $B_{i,j}$, and $n_{N_{i,j}}$ be the number of $N_{i,j,l}$ included in $N_{i,j}$. $n_{B_{i,j}}$ and $n_{N_{i,j}}$ can be expressed by the following equations.

$$n_{B_{i,j}} = n_{D_{i,j}} - 1 \tag{8}$$

$$n_{N_{i,j}} = 2 + 2 \sum_{k=1}^{n_{B_{i,j}}} B_{i,j,k} \tag{9}$$

Each value of $N_{i,j,l}$ can be arbitrarily determined under the condition of $N_{i,j,l} \le N_{i,j,l+1}$. Whether the $N_{i,j,l}$ corresponds to the rendevzous point of the drone or the takeoff point of that is determined by the value of $B_{i,j}$. Fig. 1 is an example of the drone flight route between $C_{T_{i,j-1}}$ and $C_{T_{i,j}}$.

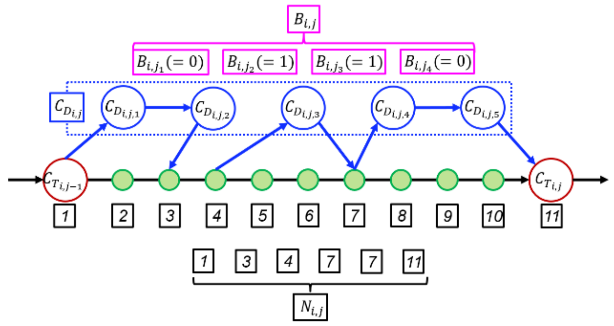

Fig. 3 Example of generated flight route between $C_{T_{i,j-1}}$ and $C_{T_{i,j}}$

We can extend this method into the multiagent system by generating WP_{T_i} as many as the number of trucks as shown below.

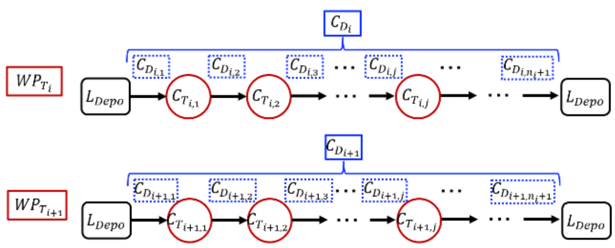

Fig. 4 Expression of multi-agent delivery routes

By applying the following 12 kinds of genetic operations to the above solution representation, a tandem delivery route using a genetic algorithm is generated.

- Select an arbitrary $C_{T_{i,j}}$ and insert it into an arbitrary $C_{D_{i,j}}$.
- Select an arbitrary $C_{T_{i,j}}$ and insert it into an arbitrary WP_{T_i}.
- Select an arbitrary $C_{D_{i,j,k}}$ and insert it into an arbitrary $C_{D_{i,j}}$.
- Select an arbitrary $C_{D_{i,j,k}}$ and insert it into an arbitrary WP_{T_i}.
- Select an arbitrary WP_{T_i} and invert a part of the route.
- Select an arbitrary WP_{T_i} and insert a part of the route into another arbitrary selected WP_{T_i}.
- Select an arbitrary WP_{T_i} and select one of the $B_{i,j,k}$. If $B_{i,j,k} = 0$, change the $B_{i,j,k}$ into 1. If $B_{i,j,k} = 1$, change the $B_{i,j,k}$ into 0.
- Select an arbitrary $N_{i,j,l}$ and change it to an arbitrary value within the range of the value between $N_{i,j,l-1}$ and $N_{i,j,l+1}$.
- Select an arbitrary $N_{i,j}$ and arbitrarily change the values of all $N_{i,j,l}$.
- Change arbitrary $C_{T_{i,j}}$ to $C_{D_{i,j}}$.
- Change arbitrary $C_{D_{i,j}}$ to $C_{T_{i,j}}$.
- Repeat the above genetic operations a certain number of times.

If all C_{D_i} are empty sets, it is possible to generate the conventional delivery routes.

4 Problem Statements

4.1 Assumption

The assumption of the drone delivery problem in this paper is shown below. However, the conditions overlapping with the contents described in Chapter 3 are omitted.

- All trucks leave the depot at the same time.
- Only one drone can be mounted in each truck.
- It needs to stop the truck once when taking off or collecting the drone.
- A drone that took off rises vertically until it reaches a certain altitude and then flies straight at a certain altitude.
- The drone descends vertically when it reaches above a delivery destination or a rendezvous WP.

- The driver needs to exchange the battery of the collected drone and reloading a parcel.
- If the drone arrives at rendezvous WP earlier than the truck, it must wait in the sky. However, it is limited within its duration time.
- During flight of the drone, the driver can move to another delivery WP.
- It takes a certain period of times for takeoff and landing of the drone, its battery exchange, temporary stop and departure of the truck, and action for the driver to deliver parcels at a delivery WP.
- The location of the depot and the delivery WPs, and the weight of the package can be set arbitrarily.
- Total number of the depot is set to only 1 place.
- Total number of delivery WPs is set to 50 places.
- The weight of the parcels will be not less than 1 kg and less than 3 kg.
- The total number of passable WPs is 1015, which is set in advance with appropriate spacing.
- The delivery area is shown below.

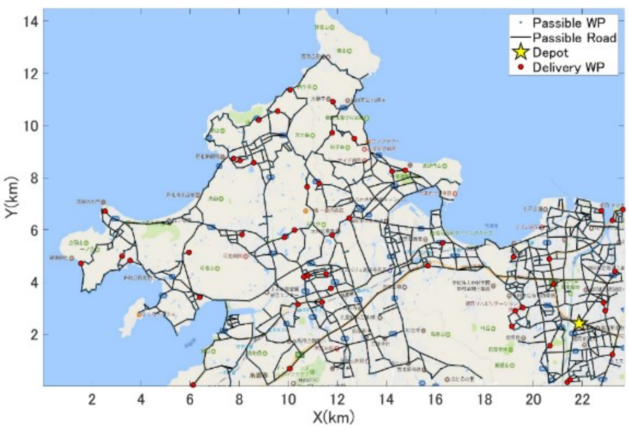

Fig. 5 Map of the delivery area

4.2 Definitions

The parameters for formulating the drone delivery problem are defined as follows.

$$P_{wp} = \left[w_1, \cdots, w_a, \cdots, w_{n_p}\right] \quad (a = 1,2,\ldots,n_p) \qquad (10)$$

$$C = [C_1, \cdots, C_b, \cdots, C_{n_c}] \qquad (11)$$

$$(\forall C_b \in P_{wp},\ b = 1,2,\ldots,n_c)$$

$$C_{path} = \begin{bmatrix} [\ ] & c_{12} & \cdots & c_{1n_p} \\ c_{21} & [\ ] & & c_{2n_p} \\ \vdots & & \ddots & \vdots \\ c_{n_p1} & c_{n_p2} & \cdots & [\ ] \end{bmatrix} \qquad (12)$$

$$\begin{cases} w_\alpha \text{ and } w_\beta \text{ are adjacent} \Rightarrow c_{\alpha\beta} = c_{\beta\alpha} = 1 \\ \text{Otherwise} \qquad \Rightarrow c_{\alpha\beta} = c_{\beta\alpha} = 0 \\ \alpha, \beta = 1,2,\ldots,n_p, \alpha \neq \beta \end{cases}$$

$$S_{path} = \begin{bmatrix} [\ ] & Path_{12} & \cdots & Path_{1n_p} \\ Path_{21} & [\ ] & & Path_{2n_p} \\ \vdots & & \ddots & \vdots \\ Path_{n_p1} & Path_{n_p2} & \cdots & [\ ] \end{bmatrix} \qquad (13)$$

$$Path_{\alpha\beta} = [wp_1, wp_2, \cdots, wp_\gamma, \cdots, wp_{\alpha\beta}] \qquad (14)$$

$$(\forall wp_\gamma \in P_{wp},\ wp_1 = w_\alpha,\ wp_{\alpha\beta} = w_\beta,\ \gamma = 1,2,\ldots,\alpha\beta)$$

$$P_{cost} = \begin{bmatrix} 0 & Cost_{12} & \cdots & Cost_{1n_p} \\ Cost_{21} & 0 & & Cost_{2n_p} \\ \vdots & & \ddots & \vdots \\ Cost_{n_p1} & Cost_{n_p2} & \cdots & 0 \end{bmatrix} \qquad (15)$$

$$F_{cost} = \begin{bmatrix} 0 & FCost_{12} & \cdots & FCost_{1n_p} \\ FCost_{21} & 0 & & FCost_{2n_p} \\ \vdots & & \ddots & \vdots \\ FCost_{n_p1} & FCost_{n_p2} & \cdots & 0 \end{bmatrix} \qquad (16)$$

Where P_{wp} is a set of all the WPs that can be passable, and C represents a set of whole delivery points. From the problem settings as shown in section 4.1, $n_p = 1015$ and $n_c = 50$. The C_{path} indicates whether adjacent WPs are adjacent to each other by a value of 0 or 1. S_{path} has all results of calculating the shortest route between the WPs. It can be calculated by using the A* algorithm [8]. P_{cost} is the distance cost of each route stored in the S_{path}, and F_{cost} is the distance costs in the case of directly connecting between the passable WPs. By referring to P_{cost} and F_{cost} to calculate the evaluation value of the generated delivery route, calculation load can be drastically reduced. In addition, the number of usable trucks is N_{truck}, the traveling speed is V_{truck}, the time required for temporary stop of the truck is t_{stop}, the time required for re-departure of the truck is t_{start}, the number of drones that can be used is N_{drone}, the flight speed of the drone is V_{drone}, loadable weight of the drone is W_{drone}, the duration time of the drone is $t_{duration}$, the takeoff time of the drone is t_{launch}, the landing time of the drone is $t_{landing}$, the time required the battery exchange of the collected drone is t_{load}, and the time required the driver delivers the parcel at the delivery point is denoted by $t_{parking}$.

4.3 Formulation

We set the following items as the objective functions in this paper.

$F_1(\boldsymbol{x})$: the total delivery distance of all the trucks
$F_2(\boldsymbol{x})$: the total delivery time of all the trucks
$F_3(\boldsymbol{x})$: the time required to complete the delivery service
$F_4(\boldsymbol{x})$: the total number of trucks used
$F_5(\boldsymbol{x})$: the total flight distance of all the drones

We also prepare two kinds of the constraint condition. In Case 1, the number of trucks to be used is limited to 1 without considering the constraint condition on the objective function. In case 2, increase the number of usable trucks to five while adding some constraint conditions related to the objective function.

The above contents can be formulated as the constrained multi-objective optimization problem as follows.

$$\min_{\boldsymbol{x}} \boldsymbol{F}(\boldsymbol{x}) = \min_{\boldsymbol{x}} [F_1(\boldsymbol{x}), F_2(\boldsymbol{x}), F_3(\boldsymbol{x}), F_4(\boldsymbol{x}), F_5(\boldsymbol{x})]^T \quad (17)$$

$$F_1(\boldsymbol{x}) = \sum_{i=1}^{N_{truck}} f_{1_i}(\boldsymbol{x}) \quad (18)$$

$$F_2(\boldsymbol{x}) = \sum_{i=1}^{N_{truck}} f_{2_i}(\boldsymbol{x}) \quad (19)$$

$$F_3(\boldsymbol{x}) = max\left\{f_{2_1}(\boldsymbol{x}), f_{2_2}(\boldsymbol{x}) \cdots, f_{2_i}(\boldsymbol{x}), \cdots, f_{2_{N_{truck}}}(\boldsymbol{x})\right\} \quad (20)$$

$$F_4(\boldsymbol{x}) = \sum_{i=1}^{N_{truck}} wp_{T_i}, \quad wp_{T_i} = \begin{cases} 1, & WP_{T_i} \neq \emptyset \\ 0, & WP_{T_i} = \emptyset \end{cases} \quad (21)$$

$$F_5(\boldsymbol{x}) = \sum_{i=1}^{N_{truck}} \sum_{j=1}^{n_i+1} FD_{i,j} \quad (22)$$

$$f1_i(\boldsymbol{x}) = Cost_{L_{depo}C_{T_{i,1}}} + \sum_{j=2}^{n_i} Cost_{C_{T_{i,j-1}}C_{T_{i,j}}} + Cost_{C_{T_{i,n_i}}L_{depo}} \quad (23)$$

$$f_{2_i}(\boldsymbol{x}) = f_{1_i}(\boldsymbol{x})/V_{truck} + n_i \times t_{parking} + (t_{start} + t_{stop}) \sum_{j=1}^{n_i+1} \left(1 + 2 \sum_{\substack{k=1 \\ B_{i,j,k} \neq 1 \\ B_{i,j,k} \neq M_{i,j}}}^{n_{B_{i,j}}} B_{i,j,k} \right) + \sum_{j=1}^{n_i+1} WT_{i,j} \quad (24)$$

Subject to Case 1 or Case 2

Case 1	*Case 2*
$V_{truck} - 10 = 0$	$V_{truck} - 10 = 0$
$V_{drone} - 15 = 0$	$V_{drone} - 15 = 0$
$t_{parking} - 90 = 0$	$t_{parking} - 90 = 0$
$t_{load} - 30 = 0$	$t_{load} - 30 = 0$
$W_{drone} - 2 = 0$	$W_{drone} - 2 = 0$
$t_{duration} - 900 = 0$	$t_{duration} - 900 = 0$
$t_{start} - 5 = 0$	$t_{start} - 5 = 0$
$t_{stop} - 5 = 0$	$t_{stop} - 5 = 0$
$N_{truck} - 1 = 0$	$N_{truck} - 5 = 0$
$N_{drone} - 1 = 0$	$N_{drone} - 5 = 0$
	$F_1(\boldsymbol{x}) - 100000 \leq 0$
	$F_3(\boldsymbol{x}) - 10800 \leq 0$
	$F_4(\boldsymbol{x}) - 5 \leq 0$

Where $WT_{i,j}$ represents the sum of the waiting time when the driver collects the drone between $C_{T_{i,j-1}}$ and $C_{T_{i,j}}$. The waiting time in a case where the drone arrives at the collection point earlier than the driver is 0. $FD_{i,j}$ means the total flight distance of drones between $C_{T_{i,j-1}}$ and $C_{T_{i,j}}$. Since there is a possibility that the value of $F_5(\boldsymbol{x})$ would become 0 in the solution search process, optimization with $F_5(\boldsymbol{x})$ alone is performed after multi-objective optimization of $F_1(\boldsymbol{x})$ to $F_4(\boldsymbol{x})$ is completed as previously mentioned.

5 Simulation Results

This chapter shows some diagrams of the delivery routes generated under the conditions of Case 1 and Case 2. We also show the transition of the evaluation values. Then, the analysis results of these routes and discussion will be described.

5.1 Case 1

Fig. 6 shows a truck delivery route obtained under Case 1 condition (note that one of the conditions is changed to $N_{drone} = 0$). On the other hand, Fig. 7 is a tandem delivery route obtained under Case 1. As a result of comparing the two, the tandem delivery route reduces $F_1(\boldsymbol{x})$ by about 52.5% and $F_2(\boldsymbol{x})$ by 25.8% (Since $F_2(\boldsymbol{x}) = F_3(\boldsymbol{x})$ in Case 1, we omitted $F_3(\boldsymbol{x})$) compared with that of the truck delivery route. However, it is necessary to fly the drone over 150 km in total.

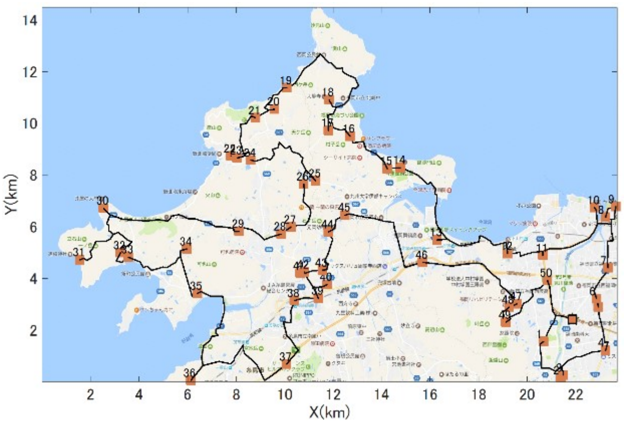

Fig. 6 Truck delivery route (Case 1)

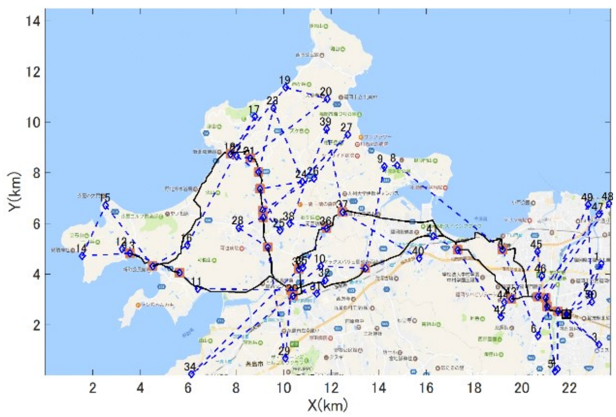

Fig. 7 Tandem delivery route (Case 1)

5.2 Case 2

Fig. 8 shows multiple truck delivery routes obtained under Case 1 condition (note that one of the conditions is changed to $N_{drone} = 0$). On the other hand, Fig. 9 is multiple tandem delivery routes obtained under Case 1. As a result of comparing the two, the multiple tandem delivery routes reduce $F_1(\boldsymbol{x})$ by about 14.1%, $F_2(\boldsymbol{x})$ by 26.0%, $F_3(\boldsymbol{x})$ by 31.8% compared with that of the multiple truck delivery routes. However, However, $F_4(\boldsymbol{x})$ increased by 1 unit, $F_5(\boldsymbol{x})$ increased by 207.5km.

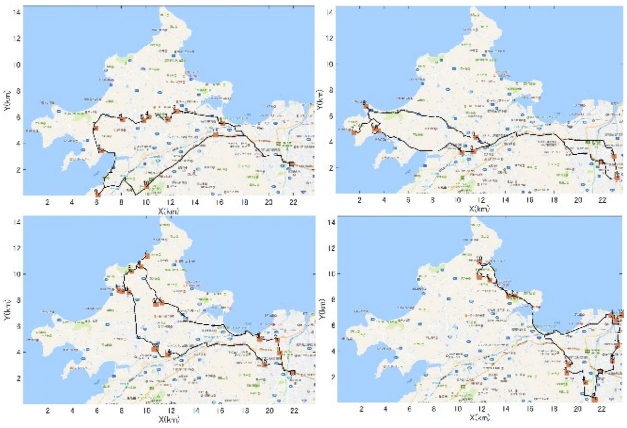

Fig. 8 Truck delivery route (Case 2)

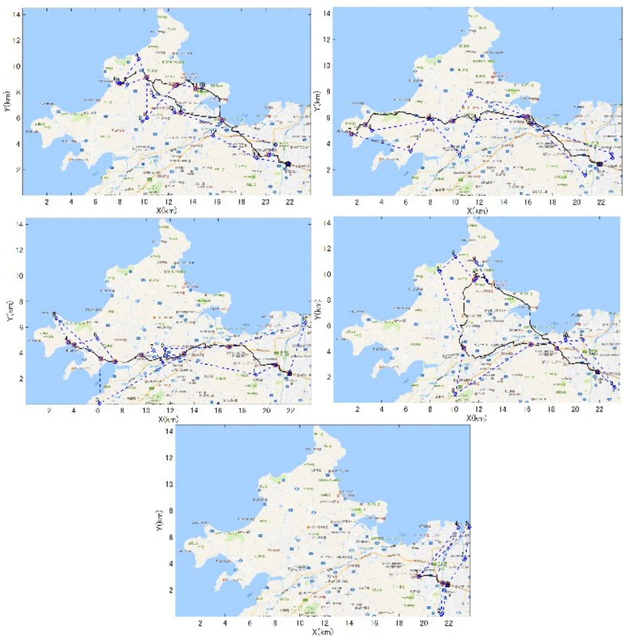

Fig. 9 Tandem delivery route (Case 2)

5.3 Transition of Evaluation Values

Figs. 10 to 13 show each transition of the evaluation values in the process of generating the delivery routes shown in Figs. 6 to 9. The horizontal axis represents the number of generations. The red line represents a region where $P(\boldsymbol{x}) > 0$, the blue line is a region where $P(\boldsymbol{x}) = 0$ and the green line is a region where $F_5(\boldsymbol{x})$ is optimizing independently after the multi-objective optimization is completed. In Case 1, the constraint conditions of the objective function are not given, so blue lines are displayed from the first generation in Fig. 10 and Fig. 11. Since Fig. 10 and Fig. 12 are evaluation values of the courier route using only the truck, the processing related to $F_5(\boldsymbol{x})$ can be omitted. What we can say in common with these figures is that the evaluation values of $F_1(\boldsymbol{x})$ to $F_4(\boldsymbol{x})$ are uniformly optimized. In addition, Fig. 12 and Fig. 13 in which the constraint conditions related to objective functions are imposed, since the blue line is shown in the region below the magenta color line representing the constraint conditions, it can be said that the multi-objective optimization process is being conducted within the feasible solutions as mention in Chapter 2. We also confirmed that a sharp increase in the evaluation value of $F_5(\boldsymbol{x})$ immediately after starting the search process in Fig. 11 and Fig. 13. The reason for that is that $F_5(\boldsymbol{x})$ is not considered as the evaluation value until the multi-objective optimization is completed. For the green line where optimization of $F_5(\boldsymbol{x})$ is being performed independently, almost no change can be confirmed in Fig. 11, but it is obviously improved in Fig. 13. Therefore, it can be said that the improved method works as expected.

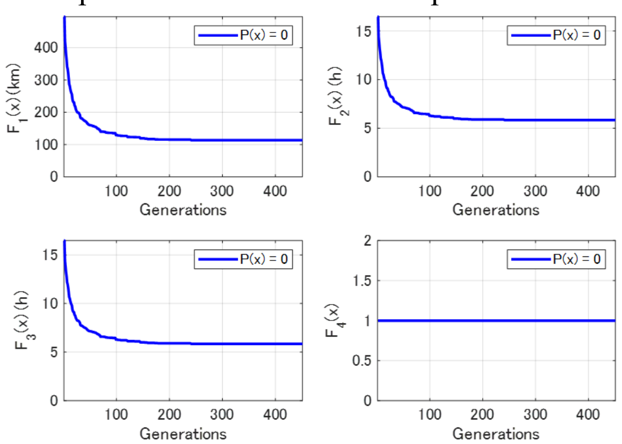

Fig. 10 Evaluation values of truck delivery route (Case 1)

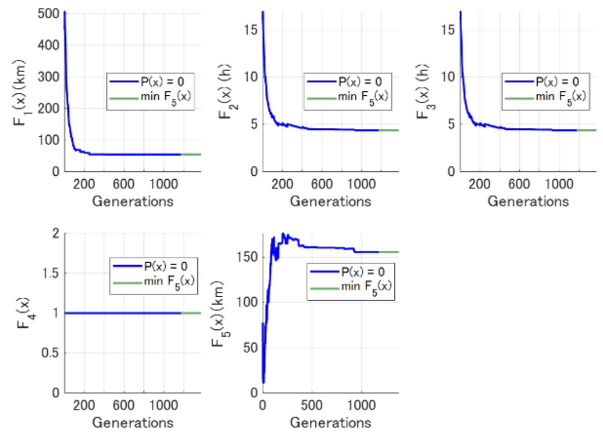

Fig. 11 Evaluation values of tandem delivery route (Case 1)

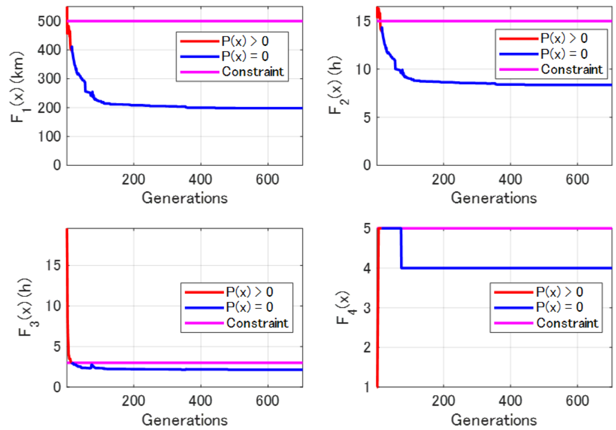

Fig. 12 Evaluation values of truck delivery route (Case 2)

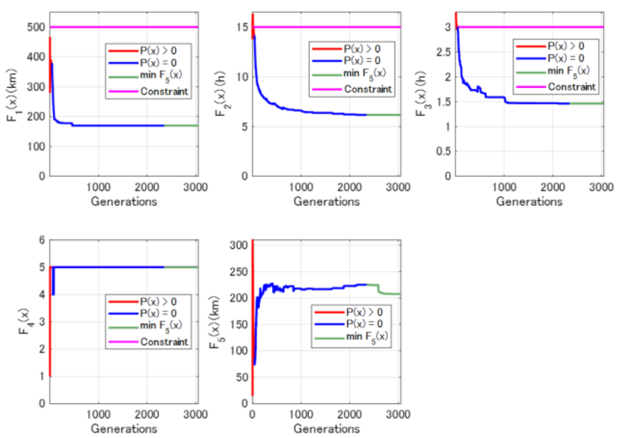

Fig. 13 Evaluation values of tandem delivery route (Case 2)

5.4 Monte Carlo Simulation

Fig. 14 and Fig. 15 show the result of comparing the truck delivery routes and the tandem delivery routes using Monte Carlo simulation for each case. The subjects to be randomly changed are the coordinates of the depot and the delivery place and the weight of the parcel for each delivery place. In addition, the number of iterations of the simulation is 100.

In the case of Fig. 14, it was found that the tandem delivery can be reduced by about 41.6% at $F_1(\boldsymbol{x})$ and by about 29.1% at $F_2(\boldsymbol{x})$ than the truck delivery. The proportion of all the baggage delivered by the drone is about 80.7% on average. On the other hand, $F_5(\boldsymbol{x})$ required on average about 133.6 km, and the average calculation time increased 4.7 times.

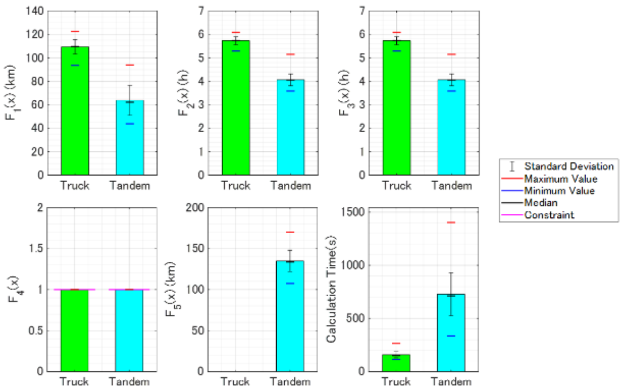

Fig. 14 Monte Carlo simulation (Case 1)

For the case in Fig. 15, we found that the tandem delivery can be reduced by about 14.7% at $F_1(\boldsymbol{x})$, about 25.0% at $F_2(\boldsymbol{x})$, and about 26.3% at $F_3(\boldsymbol{x})$ than the truck delivery. The average percentage of parcels delivered by drone was about 78.8%. On the other hand, $F_4(\boldsymbol{x})$ was increased to about 0.26 units, $F_5(\boldsymbol{x})$ was about 179.2 km, and the average calculation time was increased more than 2.8 times.

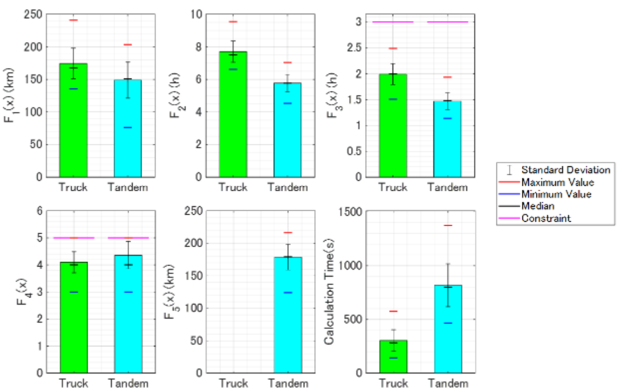

Fig. 15 Monte Carlo simulation (Case 2)

5.5 Discussion and Future Works

From the above results, the following can be said.

- The tandem delivery can significantly shorten the travel distance and the delivery time of the truck than the truck delivery. This tendency is the same even if changing the coordinates of the depot and the delivery point.
- There is a possibility that the tandem delivery generated using the proposed method may be more cost than the truck delivery depending on the constraint conditions.
- Benefits of the drone vary greatly depending on constraints.
- Calculation time required for generating a tandem delivery route increases from about 2 times to about 5 times than that of the truck delivery route.

Therefore, additional analysis on the relationship between the constraint conditions and the benefits of the drone is necessary. Moreover, it needs to shorten the calculation time in our future works.

6 Conclusion

We proposed an improved route planning method for the tandem delivery in this paper. This method makes it possible to generate such as multi-agent type routes which could not be expressed by conventional methods. It also became possible to incorporate some objective functions that could not be taken into account previously, such as the total flight distance of drone or the number of trucks used, into the evaluation value.

On the other hand, it became clear that the potential benefits obtained by utilizing the drone in the delivery service greatly depend on preset constraint conditions. In other words, it can be said that we would not be able to reduce the delivery costs depending on how to preset the constraint conditions.

Therefore, additional analysis to clarify the relationship between the potential benefits and constraint conditions will be necessary for our future works.

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