# Two-phase joint optimization of GSE routing and airport stand assignment under the consideration of ground handling time sequence

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**To better meet the demand of the growth of airport traffic, it is important to improve the operational efficiency of airports. This paper works on a two-phase joint optimization considering stand assignment and GSE routing. The time sequence between different ground handling services is considered during the optimization. A case study is performed with operational data of a Chinese hub airport with an improved NSGA-II algorithm. The results show that several key indicators can be improved under this optimization model. This study can help airports to better decide their operational strategies and to improve the decision logic of their CDM systems.**

## I. Introduction

The civil aviation industry is developing at a very high speed, leading to growing air traffic and challenging the whole industry[1]. Airports play a critical role in civil aviation operations and are facing more traffic and more passengers. The airport operators have made many efforts to improve operational performance and better service the flights and the passengers, such as introducing the Collaborative Decision Making (CDM) systems into operation[2]. The meaning of CDM has some differences between different regions as well as the decision-making objectives[3]. For some hub airports in China, one of the decision objectives of their CDM systems is to improve the operational efficiency of the apron. The main traffic elements included in the apron operations are aircraft, Ground Support Equipment (GSE) and stands[4]. The aircraft and GSE should operate under a proper logic and time sequence[5]. The airport operators have to assign every aircraft to a stand and dispatch GSE to service the aircraft during the ground handling with the help of their CDM systems. At the same time, several different stakeholders are involved in the process of stand assignment and GSE routing[6]. How to balance the interests of stakeholders is also an issue for airport operators to consider. Therefore, there is a need for some theoretical optimization studies to make the decision-making approach of the airport's CDM system more efficient and to take into account the interests of different stakeholders.

The stand assignment problem in airports, also known as the airport gate assignment problem (AGAP), is a typical problem in airport management[7]. AGAP research always considers the interests of multi-stakeholders, including passengers[8], airlines[9] and airport operators[10]. Several studies use passenger walking distance to describe passenger satisfaction[11] and the rate of aircraft using contact stands[12] is also popular in studies. The GSE routing problem can be considered a specific Vehicle Routing Problem(VRP)[13]. The GSE routing can influence the ground handling efficiency and the ground handling can influence the airport operational efficiency[14], wo it is important to research for

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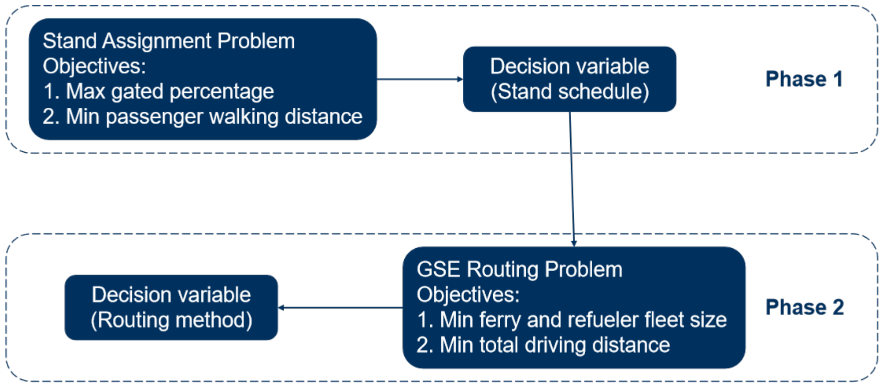



**Fig. 1 Logical relationship between two phases.**

a high-efficient GSE routing strategy. An aircraft always requires different ground handling services with different types of GSE[15] and different services need to be performed with different time windows[16].

Motivated by this perspective, we carry out this study. This study considers two typical ground handling operations: refueling and passenger ferry. These operations shall be performed in a proper time sequence[17]. This study works on a two-stage joint optimization of stand assignment and GSE routing to optimize key indicators of airport operational efficiency and A-CDM. The rest of this paper is organized as follows: Section II introduces the model in detail, Section III presents a case study and Section IV gives out the conclusions and outlooks.

## II. Methodology

This study develops a two-phase model for optimizing the stand assignment and the GSE routing problem. This study considers two types of GSE: refueller and passenger ferry bus. The problem consists of two sub-problems. The first is to assign each aircraft to a stand and the second is to dispatch the GSE to the flights requiring the service. The flight operation, like which stand the aircraft is using, will directly influence the GSE operation. Thus, we model this problem into two phases. The first phase will assign each flight to a stand, and the second phase will route the GSE considering the ground handling time sequence. The logical relationship between these phases is shown in Figure1.

### A. Time sequence of refueling and passenger ferry

The refueling and passenger ferry are typical ground handling operations that take place daily in airports worldwide. The time sequence between these two ground handling operations is shown as Figure2a. Following the regulations, the aircraft could only be refueled when no passengers are on board. That is, the refueling could only start after all passengers are deboarded and finish before the start of passenger boarding[17], as shown in Figure2b.

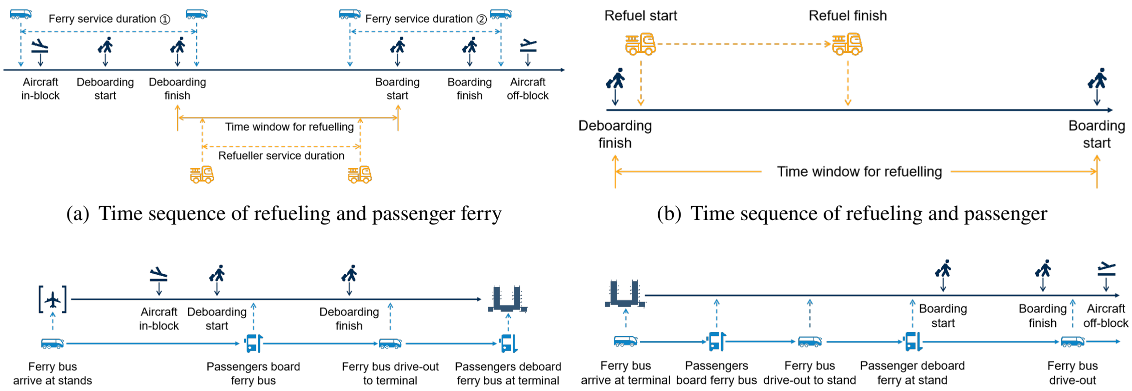
Define a flight assigned to a contact stand with a boarding bridge as gated, and assigned to a remote stand without a boarding bridge as ungated. The percentage of flights that are assigned to contact stands is called the gated percentage. A passenger ferry service will be mandatory for an ungated flight. The passenger ferry service can be sorted as deboarding ferry and boarding ferry. The procedure of deboarding ferry service is shown in Figure2c. The ferry bus should stand by before passengers start deboarding and drive to the terminal after all passengers deboarded. The procedure of boarding ferry service is shown in Figure2d. The ferry bus should stand by at the terminal, carry all the passengers and drive to the stand. The ferry bus will leave the stand after all passengers leave the ferry bus and are onboard.

### B. Basic assumptions and constraints

Before modeling, some basic assumptions and constraints should be discussed. The basic assumptions of the model include:

(1) At the beginning, there are no aircraft on the stands available, (2) all refuellers and ferry buses are parked at a one specialized parking, and (3) refuellers and ferry buses can be dispatched for service more than once.

For the stand assignment, the following constraints should be followed: (1) An aircraft can only use one stand, and one stand can not serve more than one aircraft at the same time, (2) the size of aircraft and stands must be matched, meaning large aircraft can only use large stands while small aircraft can use all, and (3) if two flights are using the same




(a) Time sequence of refueling and passenger ferry

(b) Time sequence of refueling and passenger

(c) Time sequence of arrival ferry

(d) Time sequence of departure ferry

**Fig. 2 Time sequence diagram.**

stand in sequence, there must be enough buffer time between those two flights due to safety reasons.

Before discussing the GSE routing, we first define a refueller or a ferry bus leaves the parking for service and goes back to the parking after several services is called a mission. For all GSE, there should be: (1) If two flights are serviced by the same refueller in sequence, there must be enough time for the refueller to drive between these two services, (2) the duration of each mission cannot exceed the limit, and sufficient rest time is required between two neighboring missions for safety reasons, and (3) every GSE must go back to the parking after a mission and all GSE must leave the stand once the service is finished. For the refueller, if refueling is required, one aircraft can only be serviced by one refueller, while one refueller can not service more than one aircraft at the same time. But for the ferry buses, if ferry service is required, one aircraft may be serviced by several ferry buses, depending on the size of the aircraft, while one ferry bus can not service more than one aircraft at the same time.

The optimization objectives of the stand assignment problem in this study are maximizing the gated percentage and minimizing the total passenger walking distance. The optimization objectives of the GSE routing problem are minimizing the fleet size of the refueller and ferry bus while minimizing the total vehicle driving distance.

### C. Modelling for Phase one

For modeling phase one as a stand assignment problem, we first define several mathematical elements as shown in Table1.

For the sets, $P_O = \{p_{o_1}, \dots, p_{o_p}\}$ is for all departure flights, $P_I = \{p_{o_1}, \dots, p_{o_p}\}$ is for all arrival flights corresponding to $P_O$ and $Q = \{q_1, \dots, q_q\}$ is the set of all stands available for this study in the airport. $P_O$ and $P_I$ are bijection of each other. For the parameters, $a_i^f$ and $d_i^f$ stand for the in-block and off-block time for flight $i \in P_O$, which is known in the dataset. $n_i$ stands for the number of passenger who take flight $i \in P_O$, which are also given in the dataset. $d_{ie}$ is the walking distance for each passenger when flight $i \in P_O$ using stand $e \in Q$. And $t_s$ is the safety interval time between two aircraft using a stand in sequence. For the variables, $g_i^e$ is a variable to identify the stand usage. If the flight $i \in P_O$ is using the stand $e \in Q$, then $g_i^e$ equals 1, else 0. $c_a^i$ is the variable to identify the size of flight. If the flight $i \in P_O$ is operated by a double-aisle aircraft then $c_a^i$ equals 2; if the flight is operated by a single-aisle aircraft then $c_a^i$ equals 1, and if the flight is operated by a regional aircraft then $c_a^i$ equals 0. $c_b^e$ is the variable to identify the size of a stand, if the stand $e \in Q$ is suitable for double-aisle aircraft then $c_b^e$ equals 2, else equals 1. $h_e$ is the boarding bridge identification variable. If stand $e \in Q$ is a gated stand, then $h_e$ equals 1, else 0. Finally, if flight $j \in W$ use stand $e \in Q$ just after flightt $i \in W$ use the same stand, then $y_{ij}^e$ equals 1, else 0.

For the logic reason, the relation between $y_{ij}^e$, $g_i^e$ and $g_j^e$ can be written as:

$$g_i^e \cdot g_j^e \geq y_{ij}^e, i, j \in P_O, e \in Q \tag{1}$$

And the stand assignment problem are also constrained by:

· One aircraft could only use one stand, while one stand can not serve more than one aircraft at the same time.

**Table 1 Definitions of mathematical elements for stand assignment.**

(a) Definition for sets

| Symbol | Definition |
|---|---|
| $P_O$ | All departure flights, $P_O = \{p_{o_1}, \dots, p_{o_p}\}$ |
| $P_I$ | All corresponding arrival flight of$P_I$, $P_I = \{p_{i_1}, \dots, p_{i_p}\}$ |
| $Q$ | Set of all available stands, $Q = \{q_1, \dots, q_q\}$ |

(b) Definition for parameters

| Symbol | Definition |
|---|---|
| $a_i^f$, $d_i^f$ | The start and ending time for flight $i \in P_O$ using a stand |
| $n_i$ | Number of passenger for flight $i \in P_O$ |
| $d_{ie}$ | Walking distance for each passenger when flight $i \in P_O$ using stand $e \in Q$ |
| $t_s$ | Safety interval time for all stands |

(c) Definition for variables

| Symbol | Definition |
|---|---|
| $g_i^e$ | $g_i^e = 1$ when the aircraft $i \in P_O$ is using the stand $e \in Q$, else 0 |
| $c_a^i$ | $c_a^i = 2$, if aircraft $i \in P_O$ is a double-aisle aircraft<br>$c_a^i = 1$, if aircraft $i \in P_O$ is a single-aisle aircraft<br>$c_a^i = 0$, if aircraft $i \in P_O$ is a regional aircraft |
| $c_b^e$ | $c_b^e = 2$, if stand $e \in Q$ can service double-aisle aircraft, else 1 |
| $h_e$ | $h_e = 1$ if stand $e \in Q$ is a stand with a boarding bridge, else 0 |
| $y_{ij}^e$ | $y_{ij}^e = 1$ if aircraft $j \in P_O$ use stand $e \in Q$ just after aircraft $i \in P_O$ use the same stand, else 0. |

$$\sum_{e \in Q} g_i^e = 1, i \in P_O, e \in Q \tag{2}$$

$$g_i^e \cdot g_j^e \cdot (d_j^f - a_i^f) \cdot (d_i^f - a_j^f) \leq 0, i, j \in P_O, e \in Q \tag{3}$$

· The size of aircraft and stands must be matched, which means large aircraft can only use large stands while small aircraft can use all stands.

$$c_b^e - c_a^i \geq 0, i \in P_O, e \in W \tag{4}$$

· If two flights use the same stand in sequence, there must be enough buffer time between those two flights due to safety reasons.

$$|(a_j^f - d_i^f) \cdot g_i^e \cdot g_j^e| \geq y_{ij}^e \cdot t_s, i, j \in P_O, e \in Q \tag{5}$$

As discussed before, the optimization objectives for phase one are maximizing the gated percentage while minimizing the total walking distance. Thus the objective functions can be written as:

$$\min \sum_{i \in P_O} \sum_{e \in Q} n_i \cdot d_{ie} \tag{6}$$

$$\max G_R = \frac{\sum_{i \in P_O} \sum_{e \in Q} g_i^e \cdot h_e}{\sum_{i \in P_O} \sum_{e \in Q} g_i^e} \tag{7}$$

**Table 2 Definition for sets for refueller and ferry bus.**

| Symbol | Definition |
|---|---|
| $R^G$ | All flights requesting refuelling, $R^G = \{r_1^G, \ldots, r_r^G\}$, $R^G \in P_O$ |
| $R^{B-}$ | All arrival flights requesting ferry bus, $R^{B-} \in P_I$ |
| $R^{B+}$ | All departure flights requesting ferry bus, $R^{B+} \in P_O$ |
| $R^B$ | All flights requesting ferry bus, $R^B = \{r_1^B, \ldots, r_b^B\}$, $R^B = R^{B+} \cup R^{B-}$ |
| $E^G$ | A surjection set of $R^G$, $E^G = \{e_1^G, \ldots, e_r^G\}$, $E^G \in Q$ |
| $E^B$ | A surjection set of $R^B$, $E^B = \{e_1^B, \ldots, e_b^B\}$, $E^B \in Q$ |
| $U^G$ | Set of refueller, $U^G = \{u_1^G, \ldots, u_g^G\}$ |
| $U^B$ | Set of ferry bus, $U^B = \{u_1^B, \ldots, u_u^B\}$ |
| $K_G^s$ | Mission set for refueller $s \in U^G$, $K_G^s = \{k_{G_1}^s, \ldots, k_{G_k}^s\}$ |
| $K_B^s$ | Mission set for ferry bus $s \in U^B$, $K_B^s = \{k_{B_1}^s, \ldots, k_{B_k}^s\}$ |
| $R_0^G$ | A set as $R_0^G = \{r_p\} \cup R^G$ |
| $E_0^G$ | A surjection set of $R_0^G$, $E_0^G = \{e_p\} \cup E^G$ |
| $R_0^B$ | A set as $R_0^B = \{r_p, r_t\} \cup R^B$ |
| $E_0^B$ | A surjection set of $R_0^B$, $E_0^B = \{e_p, e_t\} \cup E^B$ |

**D. Modelling for Phase two**

Similar to phase one, the definitions of several mathematical elements will also be given out before modeling.

The definitions of sets are shown in Table2. For the sets, $R^G$ indicates all departure flights that are requesting refueling. $R^G = \{r_1^G, \ldots, r_r^G\}$ and $R^G \in P_O$. The stand which are used for aircraft $i \in R^G$ is $E^G = \{e_1^G, \ldots, e_r^G\} \in Q$ and it is a surjection set of $R^G$. Similarly, we define $R^{B-}$, $R^{B+}$ and $R^B$, as well as $E^B$. Sets for all the refuellers and ferry buses are defined as $U^G = \{u_1^G, \ldots, u_g^G\}$ and $U^B = \{u_1^B, \ldots, u_u^B\}$. As defined in the problem description, a refueller $s \in U^G$ or a ferry bus $s \in U^B$ leaves the parking for service and back to the parking after several services is called a mission. A refueller or ferry bus can be dispatched for several missions, and the mission set for $s \in U^G$ is $K_G^s$, for $s \in U^B$ is $K_B^s$. For $i \in R_0^G = r_p$, it is a fiction flight representing the parking. And for $e \in E_0^G = e_p$, it means the efueller at the parking. The difinition of $R_0^B$ and $E_0^B$ are similarly defined and $r_t$ represents the terminal.

**Table 3 Definition for parameters for refueller and ferry bus.**

| Symbol | Definition |
|---|---|
| $a_i^g$, $d_i^g$ | Time for refueller arrive and leave the position for refueling the flight $i \in R^G$ |
| $a_i^{b-}$, $d_i^{b-}$ | Time for ferry bus arrive the stand and finish servicing flight $i \in R^{B-}$ |
| $a_i^{b+}$, $d_i^{b+}$ | Time for ferry bus arrive the terminal and finish servicing flight $i \in R^{B+}$ |
| $a_i^b$, $d_i^b$ | Time for ferry bus start and finish servicing flight $i \in R^B$ |
| $T_{s_k}^{g_o}$, $T_{s_k}^{g_i}$ | Time when refueller $s \in U^G$ leave and back to the parking |
| $T_{s_k}^{b_o}$, $T_{s_k}^{b_i}$ | Time when ferry bus $s \in U^B$ leave and back to the parking |
| $D_{e_i e_j}^G$ | The length of driving path between stands for $e_i, e_j \in E_0^G$ |
| $D_{e_i e_j}^B$ | The length of driving path between stands for $e_i, e_j \in E_0^B$ |
| $V$ | Average driving speed for all GSE |
| $t_t$, $t_t'$ | Mission duration and interval time for all GSE |
| $t_g$ | Time required for refueling |
| $t_b$ | Time required for single-aisle aircraft boarding and de-boarding |
| $t_b'$ | Time required for double-aisle aircraft boarding and de-boarding |
| $t_i^B$ | Boarding and de-boarding time required for flight $i \in R^B$ |

The definitions of parameters are shown in Table3. For the parameters, the refueling start time for aircraft $i \in R^G$ is $a_i^g$ and $d_i^g$ is the refueller leave the stand $i \in R^G$ in use. $a_i^{b-}$ and $d_i^{b-}$ is the time for ferry bus arrive the stand and finish servicing flight $i \in R^{B-}$, while $a_i^{b+}$ and $d_i^{b+}$ is the time for ferry bus arrive the terminal and finish servicing flight $i \in R^{B+}$. $T_{s_k}^{g_o}$ and $T_{s_k}^{g_i}$ mean the time when refueller $s \in U^G$ leave and back to the parking for mission $k \in K_G^s$, and $T_{s_k}^{b_o}$ and $T_{s_k}^{b_i}$ are defined similarly for ferry bus. Assume that there is only one specific driving path between $e_i, e_j \in E_0^G$ or $e_i, e_j \in E_0^B$ and define $D_{e_i e_j}^G$ and $D_{e_i e_j}^B$ as the length of the driving path. $V$ indicates the average driving speed for all GSE, and for all GSE, they should follow a mission duration and interval between missions. Those two time are defined as $t_t$ and $t_t^{'}$. $t_g$ indicates time required for refueling, and $t_b$ and $t_B$ are required boarding and de-boarding time for single-aisle and double-aisle aircraft.

**Table 4 Definition for variables for refueller and ferry bus.**

| Symbol | Definition |
|---|---|
| $x_i^{g_s}$ | $x_i^{g_s} = 1$ if flight $i \in R^G$ is serviced by refueller $s \in U^G$, else 0 |
| $z_{g_i}^{s_k}$ | $z_{g_i}^{s_k} = 1$ if flight $i \in R^G$ is serviced by refueller $s \in U$ at its mission $k \in K_G^s$, else 0. |
| $y_{ij}^{g_s}$ | $y_{ij}^{g_s} = 1$ if flight $j \in R^G$ and $i \in R^G$ are serviced by the same refueller $s \in U^G$ in sequence, else 0. |
| $c_A^i$ | $c_A^i = 2$, if flight $i \in P_I$ or $i \in P_O$ operated by a double-aisle aircraft<br>$c_A^i = 1$, if flight $i \in P_I$ or $i \in P_O$ operated by a single-aisle aircraft |
| $x_i^{b_s}$ | $x_i^{b_s} = 1$ if flight $i \in R^B$ is serviced by ferry bus $s \in U^B$, else 0 |
| $z_{b_i}^{s_k}$ | $z_{b_i}^{s_k} = 1$ if flight $i \in R^B$ is serviced by ferry bus $s \in U$ at its mission $k \in K_B^s$, else 0. |
| $y_{ij}^{b_s}$ | $y_{ij}^{b_s} = 1$ if flight $j \in R^B$ and $i \in R^B$ are serviced by the same ferry bus $s \in U^B$ in sequence, else 0. |

The definitions of variables are shown in Table4. For variables, $x_i^{g_s}$ is the variable to identify the refueller usage. If aircraft $i \in R^G$ is serviced by refueller $s \in U^G$ then $x_i^{g_s}$ equals 1, else 0. If flight $i \in R^G$ is serviced by refueller $s \in U^G$ at its mission $k \in K_G^s$, then refueller mission variable $z_{g_i}^{s_k}$ equals 1, else 0. If aircraft $j \in R^G$ serviced by refueller $s \in U^G$ just after aircraft $i \in R^G$ serviced by the same refueller, then $y_{ij}^{g_s}$ equals 1, else 0. The $x_i^{b_s}$, $z_{b_i}^{s_k}$ and $y_{ij}^{b_s}$ share similar difinitions for ferry buses. And $c_A^i$ defines the number of ferry requested for servicing a flight.

For the logical reason, the relations between $x_i^{g_s}$, $z_{g_i}^{s_k}$ and $y_{ij}^{g_s}$ should be:

$$x_i^{g_s} \geq z_{g_i}^{s_k}, i \in R^G, s \in U^G, k \in K_G^s \tag{8}$$

$$y_{ij}^{g_s} \leq z_{g_i}^{s_k} \cdot z_{g_j}^{s_k}, i, j \in R^G, s \in U^G, k \in K_G^s \tag{9}$$

Similarly, the relations between $x_i^{b_s}$, $z_{b_i}^{s_k}$ and $y_{ij}^{b_s}$ should also have:

$$x_i^{b_s} \geq z_{b_i}^{s_k}, i \in R^B, s \in U^B, k \in K_B^s \tag{10}$$

$$y_{ij}^{b_s} \leq z_{b_i}^{s_k} \cdot z_{b_j}^{s_k}, i, j \in R^B, s \in U^B, k \in K_B^s \tag{11}$$

The routing of the refueller is also constrained by:

· All flights require refueling.

$$|R^G| = |P_O| = |P_I| \tag{12}$$

· One aircraft could only be served by one refueller, while one refueller can not serve more than one aircraft at the same time.

$$\sum_{s \in U^G} x_i^s = 1, i \in R^G \tag{13}$$

$$x_i^{g_s} \cdot x_j^{g_s} \cdot (d_j^g - a_i^g) \cdot (d_i^g - a_j^g) \leq 0, i, j \in R^G, s \in U^G \tag{14}$$

· All refuellers must go back to the parking after a mission and the refuellers must leave the stand after the service finished.

$$\sum_{i \in R_0^G} y_{ir_p}^{g_s} = \sum_{i \in R_0^G} y_{r_p j}^{g_s}, s \in U^G \tag{15}$$

$$\sum_{i \in R_0^G} x_i^{g_s} \cdot y_{ij}^{g_s} = \sum_{j \in R_0^G} x_j^{g_s} \cdot y_{ij}^{g_s}, s \in U^G \tag{16}$$

· There must be enough time for the refuellers to drive between service points.

$$|(a_j^g - d_i^g) \cdot z_{g_i}^{s_k} \cdot z_{g_j}^{s_k}| \geq y_{ij}^{g_s} \frac{D_{e_i e_j}^G}{V}, i, j \in R_0^G, s \in U^G, e_i, e_j \in E_0^G, k \in K_G^s \tag{17}$$

· The routing strategy should follow the duration and interval limitations.

$$T_{s_k}^{g_i} - T_{s_k}^{g_o} \leq t_t, s \in U^G, k \in K_G^s \tag{18}$$

$$T_{s_{k+1}}^{g_o} - T_{s_k}^{g_i} \geq t_t^{'}, s \in U^G, k \in K_G^s \tag{19}$$

· The refueling must follow the time window limitations. The refueling should start after all arrival passengers leave the aircraft and all departure passengers board the aircraft. The refueller must leave the stand before the aircraft.

$$d_i^{b-} \leq a_i^g \tag{20}$$

$$a_i^g + t_g \leq a_i^{b+} \tag{21}$$

$$a_i^g + t_g \leq d_i^g \tag{22}$$

$$d_i^g \leq d_i^{b+} \tag{23}$$

Similarly, the routing of the ferry bus is also constrained by the following:

· All flights on stands which are not gated need ferry bus service.

$$|R^{B-}| = \sum_{i \in P_I} g_i^e \cdot (1 - h_e) = |R^{B+}| = \sum_{i \in P_O} g_i^e \cdot (1 - h_e) \tag{24}$$

$$g_i^e \cdot (1 - h_e) = 1, \forall i \in R^B \tag{25}$$

· Every ferry bus can only service one flight at a same time, while the number of ferry bus service the flight should follow the size of flight.

$$\sum_{s \in U^B} x_i^{b_s} = c_A^i, i \in R^{B-} \tag{26}$$

$$\sum_{s \in U^B} x_i^{b_s} = c_A^i, i \in R^{B+} \tag{27}$$

$$x_i^{b_s} \cdot x_j^{b_s} \cdot (d_j^b - a_i^b) \cdot (d_i^b - a_j^b) \leq 0, i, j \in R^B, s \in U^B \tag{28}$$

· All ferry buses must go back to the parking after a mission.

$$\sum_{i \in R_0^B} y_{ir_p}^{b_s} = \sum_{i \in R_0^B} y_{r_p j}^{b_s}, s \in U^B \tag{29}$$

· The ferry service is single-directed, which means there must be arcs from arrival flights to the terminal and from the terminal to departure flights.

$$\sum_{j=r_t} y_{ij}^{b_s} = 1, i \in R^{B-} \tag{30}$$

$$\sum_{i=r_t} y_{ij}^{b_s} = 1, j \in R^{B+} \tag{31}$$

· There must be enough time for the ferry buses to drive between service points.

$$|(a_j^b - d_i^b) \cdot z_{b_i}^{s_k} \cdot z_{b_j}^{s_k}| \geq y_{ij}^{b_s} \frac{D_{e_i e_j}^B}{V}, i, j \in R_0^B, s \in U^B, e_i, e_j \in E_0^B, k \in K_B^s \tag{32}$$

· The routing strategy should follow the duration and interval limitations.

$$T_{s_k}^{b_i} - T_{s_k}^{b_o} \leq t_t, s \in U^B, k \in K_B^s \tag{33}$$

$$T_{s_{k+1}}^{b_o} - T_{s_k}^{b_i} \geq t_t^{'}, s \in U^B, k \in K_B^s \tag{34}$$

· The ferry service must follow the time window, boarding and de-boarding duration limitations. The ferry bus should stand by at the stand before the arrival flight in-block, and the boarding should be finished at least ten minutes before off-block.

$$a_i^{b-} \leq a_i^f \tag{35}$$

$$d_i^{b-} \geq a_i^f + t_i^B + \frac{D_{e_i e_t}^B}{V} \tag{36}$$

$$d_i^{b+} \leq d_i^f - 10 \tag{37}$$

$$a_i^{b+} \leq d_i^{b+} - t_i^B + \frac{D_{e_t e_i}^B}{V} \tag{38}$$

The optimization objectives for this phase are minimizing the fleet size of the refueller and ferry bus while minimizing the total vehicle driving distance. The objective functions can be written as:

$$\min |U^G| \tag{39a}$$

$$and$$

$$\min |U^B| \tag{39b}$$

$$\min \sum_{k \in K_G^s} \sum_{i \in R_0^G} \sum_{j \in R_0^G} y_{ij}^{g_s} \cdot D_{e_i e_j}^G \tag{40a}$$

$$and$$

$$\min \sum_{k \in K_B^s} \sum_{i \in R_0^B} \sum_{j \in R_0^B} y_{ij}^{b_s} \cdot D_{e_i e_j}^B \tag{40b}$$

## III. Case study

A set of operational data of Beijing Capital Airport (ICAO:ZBAA, IATA:PEK), a hub airport in North China, in April 2023 is applied for this case study. In this case study, we consider there is only one specific route for GSE driving between different stands, and the distance is known. And all the passengers will choose the route with the shortest distance to board, and the distance for each boarding gate is also known.

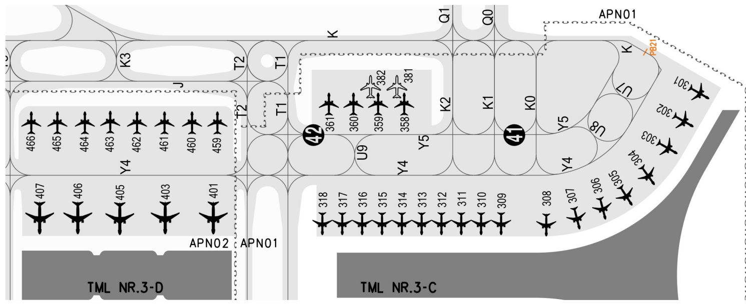



**Fig. 3 Layout of aprons.**

### A. Data and information

The dataset includes all flights operated on Apron 1 and 2 in one day. Aprons 1 and 2 service parts of domestic flights of Terminal 3. The layout of the aprons is shown in Figure3. There are 35 stands on these two aprons, 23 of them are contact stands. There are 99 flights in the dataset. The stand information includes the stand number, size, and if the stand is gated. The flight information includes flight number, the type of aircraft, which stand the flights are assigned in the real operation, and the start and ending time for an aircraft using a stand, corresponding to $a_i^f$ and $d_i^f$ mentioned in previous. The sample of stand and flight information are presented in Table5. The number of passengers on each flight is calculated by the seats of each flight and their occupancy, which are not presented here.

**Table 5 Data sample in case study.**

(a) Sample of stands information

| Stand | Size | Gated |
|---|---|---|
| 301 | Large | Yes |
| 311 | Medium | Yes |
| 401 | Large | Yes |
| ... | ... | ... |

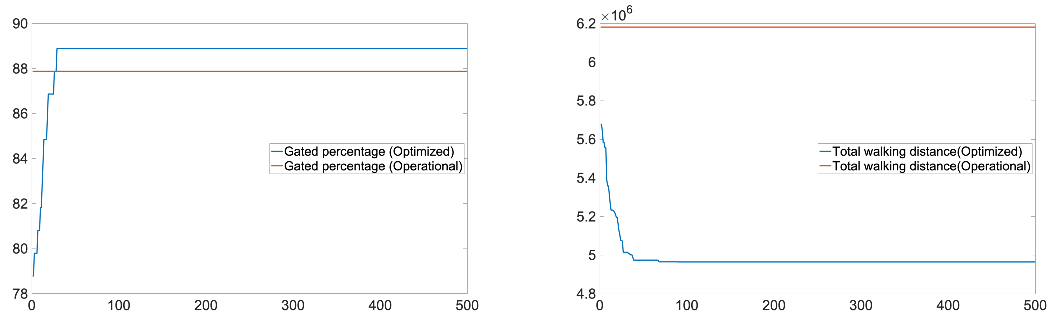
(b) Sample of flight information

| Flight No. | Aircraft | $a_i^f$ | $d_i^f$ | Stand |
|---|---|---|---|---|
| CA1425 | A330-200 | 14:45 | 17:30 | 301 |
| SC2126 | B737-800 | 12:05 | 13:25 | 306 |
| ZH9108 | A3330-300 | 17:40 | 19:00 | 361 |
| ... | ... | ... | ... | ... |

### B. Result and analysis

An improved NSGA-II algorithm is introduced in this study. The original NSGA-II algorithm runs randomly in the initialization and cross-variance, resulting in unsatisfactory solving speed, thus, this algorithm improves the initialization and cross-variance approaches for speeding up[4]. The algorithm is coded with Matlab 2020a and the results are shown as follows.

The first phase, as a stand assignment problem, is first performed. The population size is 100 and the maximum number of genetics is 500. There are a total of four Pareto optimal solutions, and here the process and the result of the solution with best gated percentage are presented in Figure4. The figure4a presents the gated percentage. In the real operation, there are 12 flights assigned to the remote stands, which indicates the gated percentage is 87.88%. The optimized gated percentage is 88.89%, with a slight improvement. This means it is difficult to improve the gated percentage in real operations. This is also in line with the current situation in which Chinese airports always prioritize gated percentage.

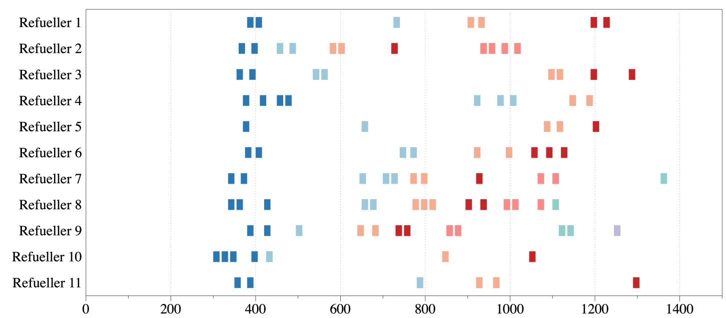



(a) Process of finding best gated percentage

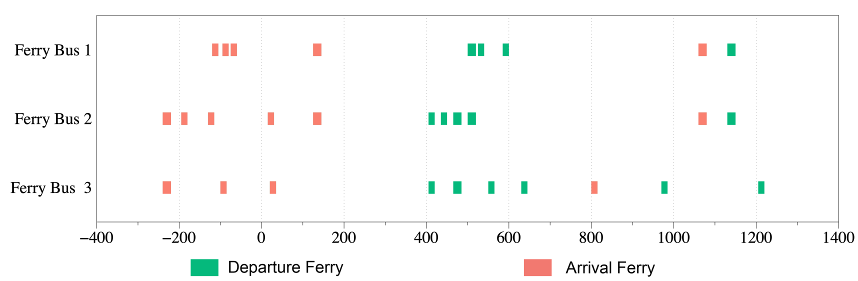
(b) Process of finding shortest walking distance

**Fig. 4 Result of stand assignment.**

As for the total passenger walking distance, this value is 6,182,000 meters according to the actually assigned stand. In comparison, the total passenger walking distance optimized under the best gated percentage is 5,004,210 meters. The total walking distance for passengers is reduced by 19.05%, meaning the passenger walking distance can be reduced while the gated percentage is considered. Therefore, airport operators should better design their stand assignment strategies to consider improving passenger satisfaction.




(a) Gantt chart for refuellers

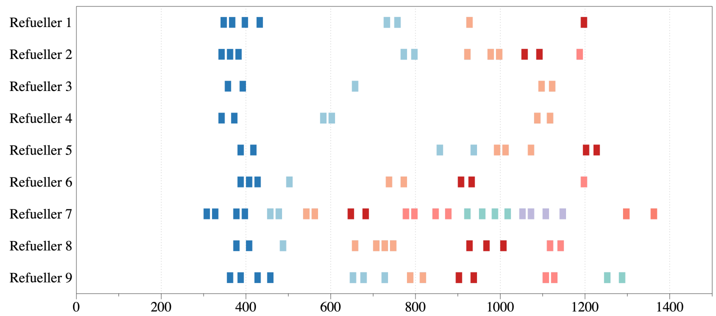



(b) Gantt chart for ferry buses

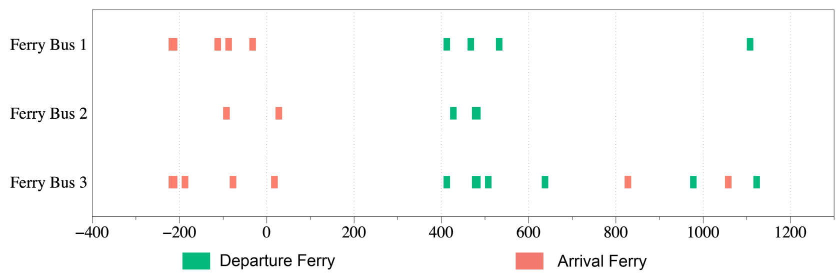
**Fig. 5 Result of GSE routing under operational stand assignment.**

Based on this stand assignment, the optimization result of the second phase is performed. The GSE operations follow these rules in this case study : (1) A mission for any GSE lasts no longer than 120 minutes, and the time between two missions cannot be less than 15 minutes, (2) all flights need refueling, and refueling last for 15 minutes, (3) the boarding and deboarding time for a double-aisle aircraft last for 20 minutes and the time for a single-aisle aircraft last for 15 minutes, and (4) a double-aisle aircraft needs 2 ferry buses and a single-aisle aircraft needs 1 ferry bus. The results are shown in Figure5 and Figure6.

Following the stand assignment in the real operation, at least 11 refuellers and 3 ferry buses are required to service all




(a) Gantt chart for Rrefuellers




(b) Gantt chart for ferry buses

**Fig. 6 Result of GSE routing under optimized stand assignment.**

the flights. The minimized driving distance for refuellers is 97,925 meters and for ferry buses the value is 56,840 meters. While following the optimized stand assignment, only 9 refuellers are required to service all the flights. However, the minimized driving distance for refuellers is 117,050 meters. For the ferry buses, there still needs 3 ferry buses but the minimized driving distance reduces to 46,600 meters. It can be seen that the ferry buses can perform better under the optimized stand assignment, but the performance of the refuellers is mixed. Whether to choose a smaller fleet size or a shorter travel distance needs to be further discussed based on the needs of the airport operator.

# IV. Conclusion and outlook

This study works on a two-phase joint optimization of GSE routing and airport stand assignment. The service time sequence of the refueling and passenger ferry service is considered. The results show that the stand assignment and the passenger ferry service can both have better performance, while the refueling optimization performs mixed. The result can help airports make operational decisions and improve the decision logic of their CDM systems.

Based on this research, we consider the further work can be carried out in several aspects. Since airports require efficient decision-making, the algorithm can be improved to obtain more accurate optimization results and faster solution speed. At the same time, two-level optimization can be considered to solve the problem of mixed optimization results. By feeding the results of GSE routing back to the results of stand assignment and iterating the results, a balance can be achieved between stand assignment and GSE routing.

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