Scheduling Strategy for Specialized Vehicles Based on Digital Twin in Airport

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Abstract. Flight schedule fluctuations are very common in many airports, which means the arrival of flights tend to be different from the plan. It has caused huge challenges for airports to real-time schedule the specialized vehicles to finish the ground-service operations. However, the existing scheduling methods, such as optimization algorithms and off-line simulations, rarely utilize the real-time information and could not adjust the specialized vehicles dispatching according to the flight schedule fluctuations. As a result, precise operation control for specialized vehicles couldn't be achieved. Therefore, this paper proposes a real-time scheduling strategy for specialized vehicles based on digital-twin, which is constructed by cloud-and-edge computing architecture. This method uses real-time arrival of flights and the current status of vehicles to generate and adjust the schedules of specialized vehicles. In this method, specialized vehicle priority and flight one are taken into account, and both of them are calculated based on the real-time information in the digital twin model. A number of experiments were processed and experimental results show that the proposed method have a better performance in shortening ground-service duration of three kinds of flights and improving the number of flights departed on time.

Keywords: Flight schedule fluctuation · Digital twin · Cloud-and-edge computing · Real-time scheduling

1 Introduction

Ground-service operations of turnaround flights, which are mainly undertaken by specialized vehicles, plays a pivotal role in determining level of flights departure on time. And it is also one of the most essential factors to reflect airport operating efficiency. So scheduling strategies of specialized vehicles in airports directly and positively influence both the efficiency of airports and flights' departure time. However, the phenomenon that flights' real arriving time fluctuates from its estimated arriving time are very common in many airports, increasing the pressure of scheduling specialized vehicles. In fact, once

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fluctuations in flight schedule happen, it means the previous plan of ground-service has to be adjusted. Therefore, in order to deal with the flight schedule fluctuations and improve the efficiency of ground-service process, it's very urgent for airport to dynamically adjust the schedule of specialized vehicles in real-time.

Actually, with modern communication and automatic driving technologies [1] applied in future smart airport [2], such as wireless sensor network, wireless local area network, the futuristic mobile communication network 5G, automated driven specialized vehicles and blockchain technology [4, 5], all of them provide a basis to achieve real-time information transmission and real-time control of specialized vehicles [6, 7]. However; there is still lack of a model that organizes them organically as a whole.

Recent years, the concept of digital twin has attracted many researchers' attention, which is a digital representation of physical system in cyber space, integrating multiple disciplines, scales and physical quantities [8]. The typical of digital twin are virtual and real-time integration and real-time interaction, iterative operation a characteristics and optimization, etc. [9]. Generally speaking, not only can digital twin compensate the deficiencies of traditional simulating method which cannot achieve online simulation based on real-time information, but achieve dynamical adjustment according to changes in the physical environment so as to accurately and precisely control [10]. Therefore, digital twin provides a new approach to build a model, which integrates specialized vehicle operations as a whole, offering the real-time information to formulate new scheduling schemes of specialized vehicles and achieve and precise control and real-time adjustment.

As a consequence, the contributions of this paper have been concluded as below:

1) This paper first proposed a digital twin model of specialized vehicles based on cloud-and-edge computing, which are responsible to provide a model as basis to achieve real-time control of four kinds of specialized vehicles.
2) And we also proposed a scheduling strategy about specialized vehicles, which can achieve self-adjustment in real-time according to flights schedule fluctuation in order to improve the level of turnaround flights departure on time.

This paper is organized as follows. First the related works review the past studies about specialized vehicle scheduling strategies in Sect. 2. Then the problem statement describes the ground-service process of turnaround flights in Sect. 3. The method has been divided into three parts in Sect. 4. Section 4.1 describes overall architecture of digital twin scheduling model based on edge-and-cloud computing. Section 4.2 illustrates the real-time scheduling strategy based-on digital twin model. Finally, the experiments and conclusions are shown up in the Sect. 5.

2 Related Works

At present, researches about how to allocate the ground-service resources are mainly divided into twofold aspects, which are optimization algorithms and off-line simulation respectively. And they have been illustrated as below.

2.1 Optimized Algorithms

The first one is optimization algorithm study based on the characteristics of specialized vehicles during working, which include genetic algorithm, heuristic algorithm, integer programming and time-window based algorithm. Angus Cheung et al. [11] took the total working time of vehicles as the goal, and designed separate scheduling models for different types of vehicles, using genetic algorithms to solve scheduling problem of water trucks, cleaning trucks and tractors. He Danni [12] used heuristic algorithm to establish an optimization model aiming at minimizing dispatched vehicles and the total distance of vehicles as well as balancing vehicle task allocation according to the service process's time window constraints of ferry vehicles. Kuhn [13] put forward simple integer programming model based on reducing shift delays and running costs to study the airport ground support service vehicles scheduling. Yin Long and Heng Hongjun [14] constructed a specialized vehicle scheduling model with time window, solved it with the nearest neighbor algorithm. However, all of them can hardly dynamically adjust the plan according to the change of flight plan, once the scheduling strategy has been made.

2.2 Off-Line Simulation

On the other hand, some researchers carried out simulation researches about the problem of scheduling specialized vehicles in airport. Huang Lishi [15] proposed a vehicle scheduling optimization model based on SIMIO, aiming at reasonably allocating equipment tasks and reducing flight delays, simulating ferry vehicles and refueling vehicles to optimize resources. Tao Jingjing [16] used the discrete-time simulation method to study the scheduling problem of ferry vehicles in remote positions, and simulated it on the platform of software SIMIO to reduce the flight delay caused by improper scheduling of aircraft ground support services. Although these methods have taken some uncertainties into account during simulation, they rarely considered the real-time information or fluctuations happening when the strategy was come into service. Therefore; these solutions might not achieve precise and accurate control of the ground-service process in real-time.

3 Problem Statement

Ground-service of turnaround flights is composed of a series of subunit task. And each task is mainly undertaken by one type of SV. Meanwhile since the duration of different flights tends to be different, meaning that ground-service operation have to be finished in different limited time window before flights departure. Meanwhile the duration of ground-service operation is determined by longest path of the whole process which is also called critical path as Fig. 1; as a result, we take the critical path as study object which contains passenger-stairs vehicles, passenger bus, fuel dispenser and tractor. Therefore, this paper intends to build a digital twin model based on cloud-and-edge computing to schedule specialized vehicles, which are passenger-stairs vehicles, fuel dispenser passenger bus and tractor, respectively.

4 Method

4.1 Digital Twin Scheduling System Based on Edge-Computing

The overall architecture of digital twin scheduling model, which is based on cloud-edge about specialized vehicles, designed to achieve dynamically scheduling [17] and precisely control to eliminate the fluctuations in real situation is illustrated as Fig. 1 which adopts a three-layer hierarchy, cloud center, edge layer, and end nodes of vehicles respectively [18]. In this section, the functions of each layer and the interaction among them will be introduced in detail.

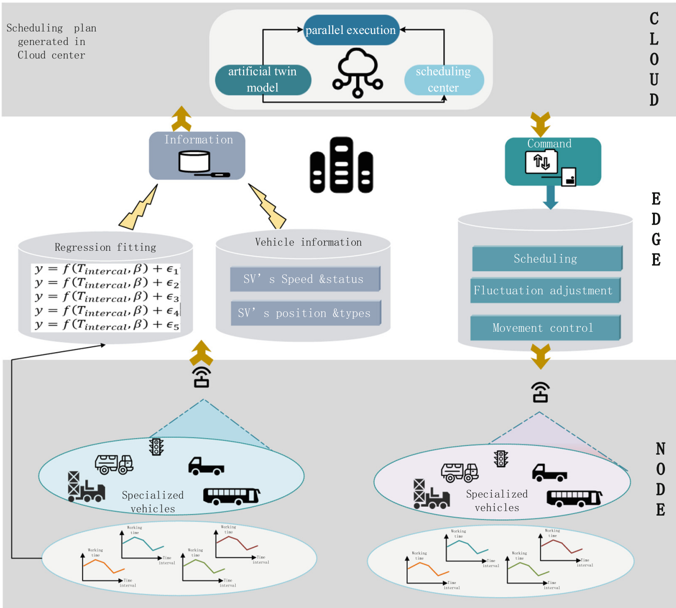

Fig. 1. Expanded model architecture and workflow of the proposed method

Firstly, as the most fundamental layer, end nodes are four different types of specialized automatic guided vehicles. These four kinds of specialized vehicles are directly connected with the edge layer, which can be regarded as executive agents of the model. There are two kinds of functions included in it. One is mainly responsible for collecting information and sending it to edge layer, such as the time duration of SV's operation to finish the ground-service task, the position and speed of SVs and the status of SVs. The other is to receive commands and guidance published by edge to control its operation in real-time, such as guiding route, speed control and scheduling commands. Along with other objects and such as roads, flights, stations and buildings, SVs of end nodes are composed of the physical entity of digital twin model.

Edge layer consists of a series of intelligent road-side units (RSD) which are distributed at different point of location on the ground to cover the whole area of SVs' operation. It is also combined with two function modulars, information modular and command modular respectively. The information modular is in charge of preliminarily processing of raw data gathered by SV, such as the uncomplicated computation about them, and then send them to the center cloud. Moreover, the information modular also conveys and transmits information, such as SV's position, status and speed etc., between the end nodes and cloud center. Secondly the command modular is to schedule and control the SV's operation in real time according to the scheduling plan generated in cloud center. Every road-side unit take responsibility of collecting and processing SV' information within its coverage which reduces the excessive or unbalanced computation burden greatly. Therefore, edge devices could not only polish distributed intelligence during real-time raw data gathering and processing but reduce the computing loads of the cloud center to achieve real-time control of SV. The edge layer is also the data layer of digital twin scheduling system.

Thirdly, the cloud center, can be divided into threefold function modulars, artificial twin model, computing and scheduling center, and parallel execution namely. Firstly, with the help of software-defined objects (SDOs), software-defined relationships (SDRs), and software-defined processes (SDPs), artificial elements and the relationship among them in real world, such as vehicle to vehicle and vehicle to infrastructure, are described and designed in artificial twin model. And it's achieved by using the bottom-up multiagent method. In this part, we build seven species of intelligent agents, artificial specialized vehicle, artificial road, artificial RSU, artificial base stations, artificial buildings, artificial time, and artificial flight, respectively as Fig. 2. Meantime; all of these agents are endowed with functions of simple calculation and interaction, through which we can improve the intelligent level of physical objectives without additional costs to update their hard-ware to finish some simple intelligent functions. Through the redefinition of the actions and interaction rules of the agents, various traffic scenarios can be simulated and assessed, and the knowledge of different situations can be acquired by means of AI, data mining, and machine learning. Additionally, on account of the fact that they are connected with physical entities in real-time through information layer of edge, it can inspect the evolvement of physical scene situation as well as provide real-time information to computing and scheduling center which can compute and make decision to formulate the scheduling plans of the specialized vehicles. Then the function of computing and scheduling center is to design the quantitative grouping strategy and sequential interaction rules for all kinds of intelligent vehicles with the help of the artificial twin model in order to generate specializes vehicles' scheduling plan. Finally, the modular of parallel execution will simulate and verify the scheduling and the outcome will send to the command layer of edge to schedule and control the specialized vehicles operation and moving. It also the virtual twin of digital twin model.

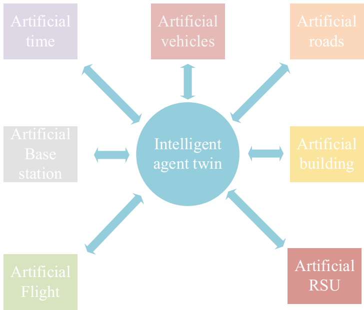

Fig. 2. Elements of the digital twin model

In a conclusion, the end nodes of vehicles are responsible for collecting and transmitting information to edge layer. Next edge layer processes and submit them to cloud center, and cloud center can make use of the real-time information to simulate and generate scheduling schemes. Then they will be conveyed to the command layer which can control the operation of specialized vehicles. Finally, a digital twin scheduling system based on edge-computing is constructed, which can achieve close-loop control [19, 20].

4.2 Real-Time Scheduling Strategy Based-On Digital Twin

After the digital twin model has been constructed, the process of scheduling strategy is completed in the cloud center of the digital twin. Next it will be described in details as follow.

At the moment when a flight arrives at random, the scheduling function in scheduling center in digital twin will be triggered in real time. There are twofold processes comprised scheduling function. The first is decompose ground-service task the into sequence of unit subtasks according to the characteristic of flight and get the priority of the ground-service task as a whole. The second is to compare the priorities of all flights in ground and make a list of them. The highest priority flight among all flights will get the privilege to schedule ground-service resources. Then the scheduling rights will be allocated to the rest flights in the light of flights priority list.

The concept of priority in this paper can be divided into two aspects, which are priority of specialized vehicles and priority of flights respectively. And they are introduced in detail as follow.

1) **Specialized vehicle priority**

The specialized vehicle priority is measured by two parts, which is the time that a SV spends to finish the task of target flight as well as the resource consumption.

First the $Priority_1$ has been shown as Eq. (1) and (2) below:

$$Priority_1 = -(T_1 + T_2) \tag{1}$$

$$T_1 = T_m + T_n \tag{2}$$

T_1 represents the rest of time that a SV finishes its current task. T_2 Represents the time to finish ground-service task of target flight. And it can be divided into two parts T_m and T_n as Eq. (2). T_m is the time that SV spends to reach the point of target flight. Because of the digital twin model based-on edge-cloud, it can be calculated by its near edge device and sent to cloud model to update model information in real-time. T_n is the time that SV finishes ground-service task when it arrives at the position of target flight. On account of that every single SV's operation time interval data has been recorded by the edge device, road-side unit, therefore in the cloud model, these time interval data can be fitted by machine learning algorithm such as interval-valued data regression algorithm [20]. In the end, the function of Tm can be provided as Eq. (3) below where X is time interval in a day, ε_i:

$$T_m = f(X, \varepsilon_i) + \theta_i \tag{3}$$

Then in the cloud digital twin model, intelligent twin SV will plus the $-T_1$ and $-T_2$. The higher the value is, the lower the priority is. Secondly, the priority2 can be calculated by Eq. (4).

$$Priority_2 = -P(v) * t(v) = -P(v) * \frac{s}{v} \tag{4}$$

$P(v)$ represents the power when SV's speed is average speed v; s denotes the path length. And $t(v)$ can be represented by the Tm. In the same case, the higher the consumption is the lower the priority2 is. Then a SV's priority can be calculated by Eq. (5) as below where the γ, ρ are indicator weights;

$$Priority_{vehicle} = \gamma \cdot Priority_1 + \rho \cdot Priority_2 \tag{5}$$

When all SV' priorities have been calculated by the intelligent twin SV in cloud model, they will be conveyed to the scheduling center where they will be compared and the highest priority SV will be chosen. Through calculating the specialized vehicle (SV) priority, it will help to match the highest priority vehicle to each subunit task of ground-service at the minimum time and resource consumption.

2) **Flight priority**

However, some flights will arrive in a same time interval and there are some other flights on ground waited to be served; meanwhile, their estimated taking-off time is different. So, their requirements for ground-service duration are different too. As a result, it's necessary to calculate flight priority to allocate the privilege of scheduling SVs. And it denotes as Eq. (6)

$$Priority_{flight} = -\beta * k * (t_{Eend} - t_{end}) + \varepsilon * (1 - k) * (t_{end} - t_{Eend}) \tag{6}$$

As mentioned above, when all the SVs with highest priority are chosen for the target flight, the whole time of ground-service operation can be obtained in the end. So t_{end} denotes the end time of flight's ground-service operation which can be obtained from

3). t_{Eend} is the expected ending time of the ground-service which is given by airport. β, ε are indicator weights. And the value of k has been set as Eq. (7).

$$k = \begin{cases} 1 & t_{EOBT} > t_{end} \\ 0 & t_{EOBT} < t_{end} \end{cases} \quad (7)$$

Therefore; when the priorities for all flights on ground are calculated, then the scheduling center will comparel them and the highest priority flight will be chosen and allocated the preferential privilege of SV resources. And other flights will enter the next round of SV scheduling. The whole process will be expressed in details as 3) and Fig. 3.

3) **Scheduling plan generation**

a) Scheduling center will decompose ground-service operations of arriving flights in a same time interval and send them to the intelligent twin SVs.
b) Intelligent SVs will compute vehicle priorities as described in 1) and feed back to scheduling center and the highest priority SV will be chosen for each ground-service operation of each flight.
c) Scheduling center will calculate the priorities of flights as described in 2) according to b) and Eq. 5 and compare their values.
d) Flight with highest priority will be chosen and the matched highest priority SV will be locked. Then the flight will withdraw the cycle.
e) Other flights will go on the cycle until all flights are allocated the SV for ground-service operation.

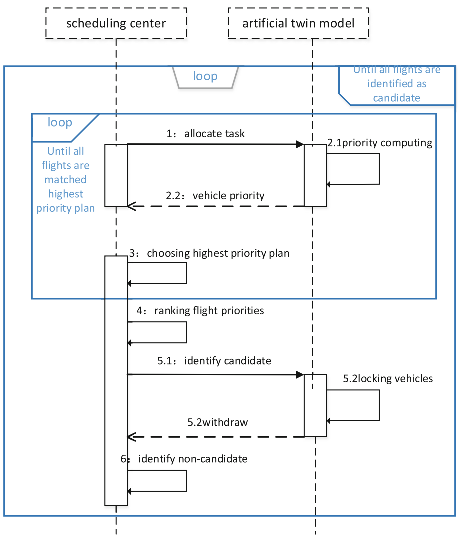

Fig. 3. Sequence diagram of the highest priority flights selection

5 Experiment

This section will provide a case to verify the effectiveness of the proposed approach on lowering the ground-service duration while improving the level of flight's taking-off on time when flight schedule fluctuates.

A simulation model has been constructed at the simulating platform of Anylogic 8.7.9 Professional as Fig. 4. To verify the real-time scheduling strategy based-on digital twin, three sets of comparative simulations has been implemented. And we take the 'First arrive, First serve' (FAFS) as the comparison. The relative parameter of the model has been shown as Table 1.

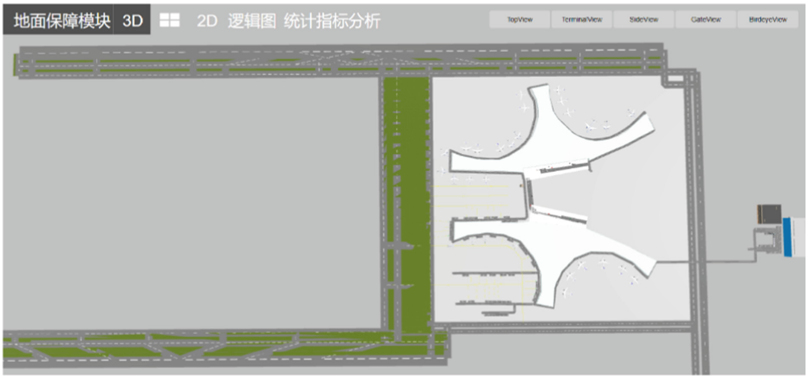

Fig. 4. A digital twin platform for ground-service process based on Anylogic

Table 1. Simulation parameters

Parameter	Number	Speed
Passenger-stair vehicle	10	In interval [1.39 8.3] m/s
Passenger bus	7	In interval [1.39 5.6] m/s
Fuel dispenser	10	In interval [1.39 8.3] m/s
Tractor	10	In interval [1.39 8.3] m/s

In the model, there are three types of flights which are A320 A300 A380 respectively as examples. They are typical representatives of small passenger planes, medium-sized passenger planes, and large passenger air bus and very common in airports. At mean time, each of them contains 15 flights which will arrive at random time. The outcomes of the experiment have been shown as Fig. 5 where the DT means the proposed method and FAFS means the mothed of First-Arrive-First-Serve.

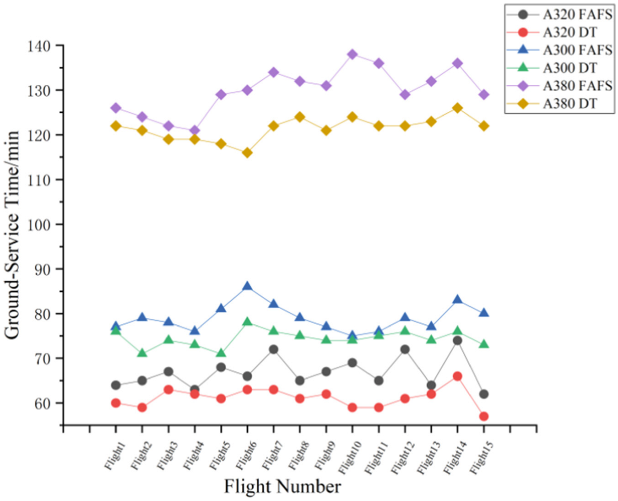

Fig. 5. Comparison of ground-service duration of three types of flights in DT and FAFS

We take the duration of ground-service as the metric to compare the effectiveness of the two kinds of method. The performance of proposed method is apparently better than the First-arrive-First-serve in all of these three kinds of flights. And the average time of these two methods have been shown as Table 2.

Table 2. Average time comparison of FAFS and DT

Flight types	FAFS	DT
A320	66.9 min	61.2 min
A300	79 min	74.4 min
A380	130 min	121.4 min

Then we compare the improvements of the proposed method on these three types of flights and the outcome has been shown as Fig. 6. As can be seen from Fig. 6. The improvement for large-sized air bus is the most obvious but the for medium-sized passenger planes the improvement is lower than that of other two kinds of flights. In a conclusion, the real-time scheduling strategy based-on digital twin has a better performance of scheduling specialized vehicles compared to FAFS such as the ground-service duration and the level of flights' taking-off on time when the flight schedule fluctuates.

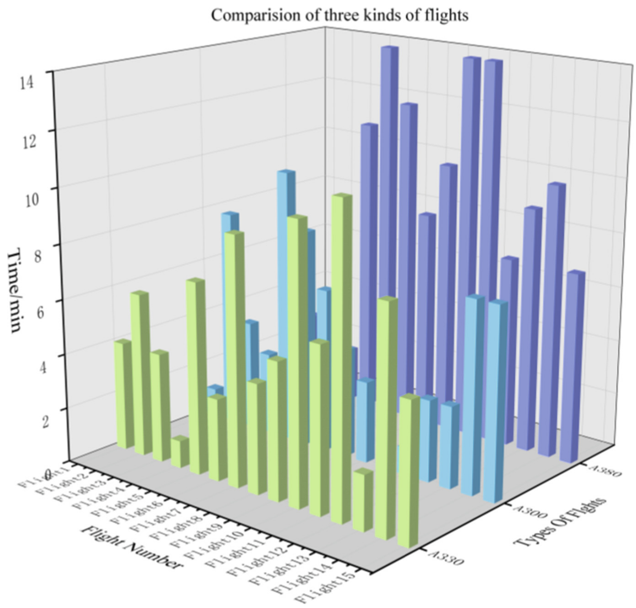

Fig. 6. Improvements of the proposed method on these three types of flights

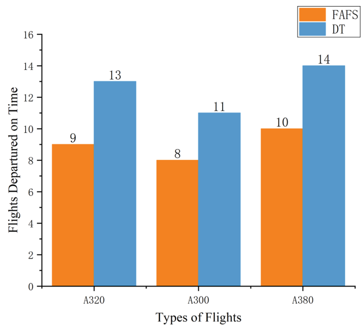

Fig. 7. Numbers of flights departure on time

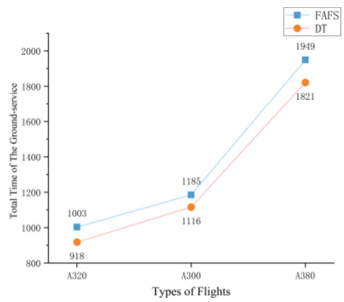

Fig. 8. Comparison of the total ground-service duration

And meanwhile according to Fig. 7 and Fig. 8 it shows the numbers of flights departed on time under the proposed scheduling strategy based on digital twin (DT) have achieved a significant raise compared to the traditional FAFS in all of these three kinds of flights; moreover, the total time of flights' ground-service process has also realized a moderate improvement. In a conclusion, the proposed real-time scheduling strategy based-on digital twin (DT) has a better performance in indicators such as efficiency of ground-service and level of flights departure on time in face of the arrival of flights in real time.

6 Conclusion

In this paper, we firstly proposed a real-time scheduling strategy of specialized vehicles based on digital twin in face of the real-time arrival of flights and the fluctuations happened in the actual implementations of the specialized vehicle operation. First, we adopt cloud-and-edge computing architecture to construct our digital twin model in order to achieve precise and real-time control of the specialized vehicles. Based on the digital twin model, we proposed a new scheduling strategy from the perspective of vehicle priority and flight priority by considering their real-time information. A lot of experiments have shown the proposed method achieves a satisfactory performance in shortening the duration of ground-service and improving the level of flights departed on time in face of the real-time arrival of flights.

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