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RESEARCH ARTICLE

Study on electric towing tractor quantity based on cellular automata

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Abstract
Aircraft ground taxiing contributes significantly to carbon emissions and engine wear. The electric towing tractor (ETT) addresses these issues by towing the aircraft to the runway end, thereby minimising ground taxiing. As the complexity of ETT towing operations increases, both the towing distance and time increase significantly, and the original method for estimating the number of ETTs is no longer applicable. Due to the substantial acquisition cost of ETT and the need to reduce waste while ensuring operational efficiency, this paper introduces for the first time an ETT quantity estimation model that combines simulation and vehicle scheduling models. The simulation model simulates the impact of ETT on apron operations, taxiing on taxiways and takeoffs and landings on runways. Key timing points for ETT usage by each aircraft are identified through simulation, forming the basis for determining the minimum number of vehicles required for airport operations using a hard-time window vehicle scheduling model. To ensure the validity of the model, simulation model verification is conducted. Furthermore, the study explores the influence of vehicle speed and airport scale on the required number of ETTs. The results demonstrate the effective representation of real-airport operations by the simulation model. ETT speed, airport runway and taxiway configurations, takeoff and landing frequencies and imbalances during peak periods all impact the required quantity of ETTs. A comprehensive approach considering these factors is necessary to determine the optimal number of ETTs.

Nomenclature

l_i	length of aircraft for flight i (i = 1,2,3. . . . . .)
d_i	distance of aircraft i to the next intersection
$d_{i,j}$	distance between aircraft i and j (i = 1,2,3. . .; j = 1,2,3. . .)
d_0	distance required for deceleration and coming to a complete stop at the stopping point
d_s	safety separation between aircraft
$V_i(t)$	taxiing speed of flight i at time t (i = 1,2,3. . . . . .)
a	aircraft acceleration
t_i^{gate}	threshold of waiting time for aircraft i at the parking position
t_i^{queue}	waiting time of flight i at the runway threshold
$Q(P^t)$	total number of queuing arrival and departure flights
V_{curve}	maximum speed during aircraft turns
$t_{i,plan}$	scheduled departure time of flight I
$t_{take\ off}$	interval time required to ensure separation between two consecutive takeoffs
t_{exit}	time it takes for an aircraft to taxi after landing to a rapid exit taxiway
$t_{interval}$	minimum time interval between takeoff and landing
n_{max}	permissible number of aircraft operating at the airport
$wait_i$	waiting time for flight i at the parking position

1.0 Introduction

International Air Transport Association (IATA) [1] and International Civil Aviation Organization (ICAO) [2] have set a target to reduce carbon emissions by 50% compared to 2005 levels by the year 2050. Emissions during the landing and takeoff are a significant component of flight emissions, with carbon emissions from ground taxiing accounting for 72% of landing and takeoff (LTO) emissions [3]. Additionally, aircraft engines operate less efficiently and experience greater wear during ground taxiing [4]. The electric towing tractor (ETT) addresses these challenges effectively by expanding the towing range and reducing aircraft ground taxiing distances [4, 5]. Given the increased towing range of ETTs, the towing distance and time have increased by several folds, rendering existing methods and empirical formulas for calculating the required number of towing vehicles inadequate. ETTs are crucial facilities for ensuring aircraft ground taxiing and an insufficient quantity could impact airport operational efficiency [5]. However, with ETT prices ranging from $500,000 to $1.5 m, excessive deployment could lead to wastage. Moreover, since the quantity of ETTs is closely related to their towing speed, distance and airport conditions, the determination of ETT quantity under different conditions is an urgent area for research.

Currently, there is limited research on the quantity of ETTs, often employing discrete event models to simulate airport operations and then discussing the minimum fleet size of ETTs considering their cost-benefit analysis [4, 5]. However, these studies primarily focus on the relationship between the number of towing vehicles and airport revenue, neglecting the impact of towing vehicle quantity due to taxiing speed and airport operational conditions. Meanwhile, research on vehicle scheduling models for other airport apron vehicles [6] can provide relevant insights for this study. Traditional vehicle scheduling models mainly emphasise meeting the demands of aircraft without considering the unevenness in vehicle demand over time. The vehicle routing problem with time windows (VRPTW) builds upon vehicle scheduling problems by incorporating time windows that specify the earliest time for visiting each demand point [7], thus addressing the issue of time imbalances. Time windows can be categorised as hard time windows and soft time windows based on their properties. Hard time windows mandate that vehicles access each demand node within the required time frame, while soft time windows allow for delays but with an associated penalty coefficient [8–12] previously researched the minimum ferry vehicles quantity required during peak hours to meet flight service and timing constraints using a multi-objective time window vehicle scheduling problem. Although time window models have achieved a relative level of maturity, most studies still estimate the ETT usage time for flights based on scheduled departure time and the distance between parking positions and runway ends. This approach doesn't account for the uncertainty in ETT usage time caused by factors like flight conflicts. Therefore, a single time window model fails to dynamically capture the changing ETT quantity requirements under the complex operational scenarios of an airport.

To define the dynamic nodes for ETT usage, this study employs a Cellular Automaton (CA) simulation model to replicate airport operations. Mori [13] developed a CA model for Tokyo International Airport that considers variations in taxiing speed due to interactions between aircraft. Yang [14] analysed the real-time status of aircraft on taxiways and apron networks at Baiyun International Airport, integrating conflict resolution strategies with aircraft priorities into the CA model. Simulation results demonstrated the effectiveness of conflict resolution strategies in alleviating taxiway congestion. Mazur [15] comprehensively considered route randomisation, aircraft acceleration and deceleration, constructing a flexible CA model for altering airport infrastructure. They compared airport operational efficiency before and after layout changes. Building upon previous research, Suwan [16] discussed aircraft apron pushback regulations, further refining airport simulation models. While the above studies replicate intricate airport traffic flow, they do not account for the impact of ETTs, particularly the departure sequence (i.e., priority rules) of ETTs. This aspect is also crucial [17].

To address these limitations, this paper addresses the uncertainty in aircraft takeoff time, taxiing time, and pushback time by proposing a real-time airport simulation model based on Cellular Automata. This model simulates the real-time positions of aircraft at the airport, determining various required time nodes from ETT application to aircraft being towed to the runway end. Subsequently, the operational characteristics and service sequence of ETTs are analysed. Based on the real-time airport simulation model and various constraints, a hard time window vehicle scheduling model is established to determine the minimum number of ETTs required while minimising airport delays. Differing from prior research, this paper also discusses the relationship between speed and the minimum number of ETTs required in airports of varying scales.

2.0 Methods

This section analyses the changes in airport operation rules after introducing ETTs and establishes an airport real-time simulation model based on the CA model. Then, it establishes a hard-time window vehicle scheduling model to solve the number of ETTs by analysing the service process of ETTs.

2.1 Airport real-time simulation model based on CA model

The airport cellular automaton (CA) model is an adaptation and enhancement of the Nagel-Schreckenberg (NS) model for road traffic [18]. In the NS model, roads are divided into several cells. An empty cell indicates that the road position is not occupied by a vehicle. On the other hand, a cell in the occupied state is assigned information such as vehicle velocity, vehicle acceleration and vehicle position. The CA model iterates in discrete time steps, during which non-empty cells are updated according to velocity change rules and position change rules. By progressing through time steps, the CA simulates the traffic state of the road. The CA model is an extension of the NS model that introduces aircraft-specific constraints and regulations, modifying velocity change rules and position change rules to simulate the operational state of an airport. However, aircraft operations on aprons, taxiways and runways during takeoff and landing are not completely uniform. Existing CA models have not taken into consideration aircraft apron activities and the intervals for runway departure and landing [13]. Therefore, to better reflect real airport operations, this paper establishes a new CA model to describe aircraft movements in the taxiway network. The model simulates the entire process, including the pushback of departing aircraft from gates, taxiing to the runway, takeoff, landing and taxiing to the parking positions. The real-time airport simulation model is divided into three modules: apron, taxiway and runway. This section will provide a detailed introduction to each module.

2.1.1 Assumptions

The following is a summary of the assumptions used for the simulation:

(1) All aircraft taxi along the prescribed taxiing paths.

(2) The taxiing route of ETT-towed aircraft is the same as that of conventional self-taxiing aircraft. Due to the slow initial speed of ETT, to ensure operational efficiency and safety, it is set that ETT-towed flights have lower priority than conventional self-taxiing flights.

(3) Aircraft are divided into three categories according to their weight [5]: small aircraft below 7t, medium aircraft between 7t and 150t and large aircraft above 150t. The aircraft lengths of the three types of aircraft are set as 30m for small, 50m for medium and 70m for large.

(4) The model discretisation step is set to 1s, and the real-time position of the aircraft is updated every second based on the real-time speed of the aircraft.

2.1.2 Apron model

The apron model simulates the activities of departing aircraft being pushed back from gates and arriving aircraft taxiing into parking positions. The model records the actual pushback and taxi-in time of flights. Traditional CA models have not accounted for aircraft activities on the apron [13]. Florian was the first

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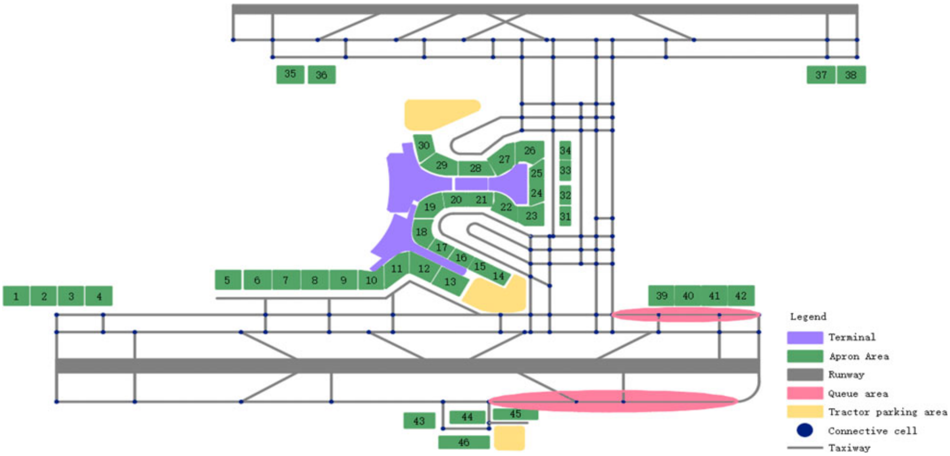

Figure 1. *Illustration of aircraft stand area.*

to consider the pushback time of aircraft on the apron [15]. Suwan used aggregated time functions to simulate aircraft dwell time on the apron [16]. However, neither of these approaches addressed the determination of the sequence in which neighboring aircraft are pushed back or taxi into the apron. In this section, the actual sequence of aircraft pushback and taxi-in at the airport is considered, and the apron model is established as follows.

(1) Figure 1 depicts a schematic representation of different areas within the airport. The purple colour represents the terminal area, the green colour signifies the aircraft parking area (apron), the grey colour represents the runway, the pink shade illustrates the queueing area for aircraft awaiting takeoff at the runway threshold, the yellow area indicates the ETT docking zone, blue circles denote connective cells and the lines represent taxiways. Notably, the green area (apron zone) is divided into 42 blocks based on the principle of grouping adjacent aircraft stands. When there are two or more flights departing or arriving in the same block, due to the proximity of the stands, there is significant mutual influence among the flights, leading to potential operational obstructions. Consequently, aircraft priorities are assigned as outlined in Table 1.

As shown in Table 1, landing flights have higher priority than take-off flights. Large aircraft have higher priority than small aircraft. In special cases, the flight priority is raised to the highest level.

(2) To avoid airport surface congestion, the number of aircraft operating on the surface is controlled by limiting [19]. The indicator is used to measure the degree of airport surface congestion. When the airport surface operation is highly congested, all flights with priority lower than III are not allowed to push out. The planned push-out time of the delayed flights is set as follows: if

$$Q\left(P^{t}\right) > n_{max}, t_{i,plan} = t_{i,plan} + 1 \tag{1}$$

(3) Considering that the long waiting time ($wait_t$) at the stand will affect the aircraft arrival at the airport and the passenger status, a waiting threshold (t^{gate}) is set: if

$$wait_i > t^{gate}\ priority_i = III \tag{2}$$

Aircraft with priority III are not affected by the degree of surface congestion and can be arranged to push out first.

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***Table 1.** The amount of fuel saved by airports*

Priority	I			II			III
	I-1	I-2	I-3	II-1	II-2	II-3	
Take off	small, ETT	medium	large	–	–	–	$t_i^{gate} > 15\text{min}$
Landing	–	–	–	small	medium	large	$t_i^{queue} > 120\text{s}$

2.1.3 Taxiway model

The taxiway model is a model that simulates the acceleration, deceleration and waiting activities of aircraft on the taxiway, which is divided into two parts: position change and conflict resolution.

Position change

The real-time position and speed of aircraft are closely related. Mori set the aircraft acceleration and deceleration rules in the CA model [13], and several studies set the random slow-down rules in the CA based on the aircraft operation characteristics [15, 16]. This section refers to the literature [13, 15, 16] and divides the taxiway into multiple cells, with the cell length set to 1m. The acceleration and deceleration rules are as follows.

(1) To avoid rear-end collisions when the trajectories of two aircraft overlap, if the distance between aircraft i and the preceding aircraft j ($d_{i,j}$) is greater than the safe distance (d_s),

$$V_it + 1 = min\{V_it + a, V_{max}\} \tag{3}$$

else

$$V_it + 1 = max\left\{V_it - a, V_j(t)\right\} \tag{4}$$

According to IATA, the maximum taxiing speed of aircraft should not exceed 10m/s [16]. There is research that shows that an acceleration of 0.2m/s^2 is applicable to various acceleration and deceleration situations of aircraft [13].

(2) To avoid aircraft overturning due to excessive turning speed, aircraft need to decelerate in advance when turning, so as not to exceed the prescribed maximumn V_{curve}, that is:

$$d_{curve} = \left(V_t^2 - V_{curve}^2\right)/2a \tag{5}$$

If

$$d_i \le d_{curve}, V_it + 1 = max\,\{V_i(t) - a, V_{curve}\} \tag{6}$$

Conflict resolution

Although we try to avoid aircraft taxiing paths crossing at the same time, such conflicts cannot be completely avoided at large airports. In actual airport operations, to resolve conflicts, the controller will order one of the aircraft to decelerate and wait. Mori [13] set the order of aircraft passing through the intersection in advance in the CA model to avoid conflicts. Suwan Yin [16] set the aircraft priority to determine the order of aircraft passing through the intersection. However, he did not consider the use of ETT priority rules for aircraft. Based on Suwan Yin's [16] priority rule, this paper considers the impact of ETV introduction on the priority rule, and establishes a taxiway conflict resolution model as follows.

Within the model, taxiway intersections are designated as a distinct type of cell referred to as 'connective cells'. These connective cells store various information about aircraft approaching the intersection, allowing the model to determine the sequence in which aircraft are given priority to pass through. This prioritisation enables aircraft to undertake appropriate actions for conflict resolution when approaching intersections, as illustrated in Fig. 2.

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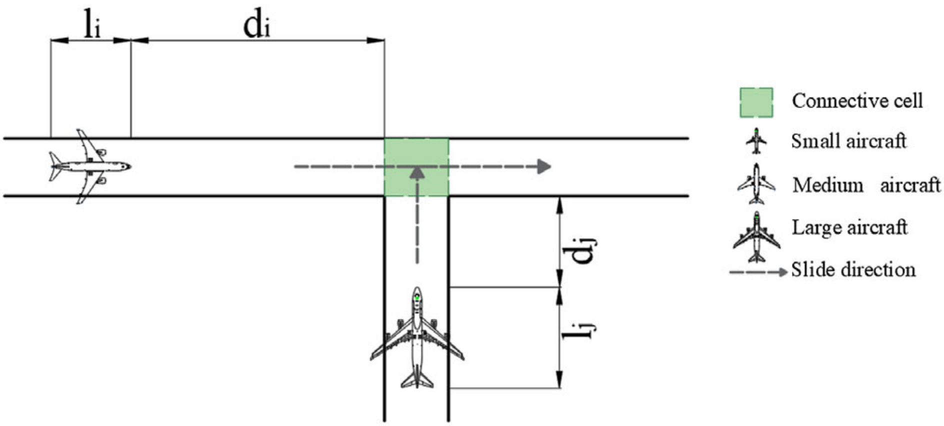

Figure 2. *Lict resolution rules.*

If $d_i < 360$m, $d_j < 360$m, the specific conflict resolution rules are as follows.

1. When aircraft i and j arrive at the connective cell at the same time, the aircraft with higher priority passes through the intersection first, and the aircraft with lower priority decelerates to avoid collision.
2. When aircraft i and j pass through the connective cell one after another, to avoid rear-end collision, the first-come first-served principle is implemented. The subsequent aircraft decelerates until it maintains a safe distance (d_s) from the aircraft ahead.

2.1.4 Runway model

The runway model is a model that simulates the take-off and landing activities of aircraft on the runway. Although the runway model records the real-time landing and take-off time of flights, which have no direct impact on the number of ETTs, the runway model simulates the runway usage situation, which indirectly affects the pushback and taxiing speed of flights on the taxiway.

In actual airport operations, aircraft usually need to stop at the runway entrance and wait for the controller's instructions. The controller decides the order of aircraft using the runway. When there is already an aircraft waiting for take-off, the aircraft needs to maintain a safe distance from the waiting aircraft. Suwan Yin [13] set the runway take-off and landing interval time in the model. This section refers to Suwan Yin's [16] runway interval time, considering the take-off and landing order of flights using the runway, and establishes the runway take-off and landing model as follows.

In the model, the controller's instructions are simulated by defining the flight priority. The take-off aircraft queue up in the order of arrival at the runway, and the landing aircraft also queue up in the order of planned landing time. When there is already an aircraft waiting at the runway end, the aircraft needs to maintain a minimum distance (50m) [14] from the other aircraft in the queue. Due to the influence of aircraft wake and safety issues, an interval time needs to be guaranteed between two consecutive take-offs ($t_{take\ off}$), and the minimum time interval between take-off and landing ($t_{interval}$), the time for taxiing out of the fast exit after landing is recorded as t_{exit}, and the runway take-off and landing interval time is shown in Table 2.

That is, at t time, the aircraft using the runway need to satisfy the formula:

$$t > t_{take\ off} + t_{previous\ take\ off} \tag{7}$$

$$t > t_{exit} + t_{previous\ land} + t_{interval} \tag{8}$$

Table 2. *The runway take-off and landing interval time [15, 16] 0*

$t_{takeoff}$	Small or medium aircraft take off after large aircraft	120s
	Small aircraft take off after medium aircraft	120s
$t_{interval}$	Medium aircraft land after large aircraft	120s
	Small aircraft land after medium or large aircraft	180s
	t_{exit}	110s

In addition, for departing aircraft, engine preheating time needs to be taken into consideration. Assume the engine preheating time is $t_{prepare}$, meaning that aircraft taking off at time t need to satisfy the following formula:

$$t > max\left\{t_{take\ off} + t_{previous\ take\ off}, t_{arrival} + t_{prepare}\right\} \tag{9}$$

$$t > t_{exit} + t_{previous\ land} + t_{interval} \tag{10}$$

Where $t_{arrival}$ is the time for the departing aircraft to reach the end of the runway.

$t_{prepare}$ is the engine preheating time. According to the regulations of the Civil Aviation Administration, the engine preheating requires a speed of 60%. This value varies for different engines. The Civil Aviation Administration of China stipulates that the preheating time should not be less than 3min.

For take-off aircraft, since the airport prioritises serving landing aircraft, the take-off aircraft need to additionally satisfy the formula:

$$t + t_{interval} < t_{next\ land} \tag{11}$$

2.2 Hard time window vehicle scheduling model

In this section, through the analysis of the ETT service process, the time points for aircraft to use ETT are determined. Based on the Jia [20] time window scheduling model, a hard time window vehicle scheduling model is established, and the four steps of model solving are explained.

2.2.1 ETT service process

ETT scheduling is mainly based on the estimated take-off time of flights, to determine the service path and timetable of vehicles, to meet the demand of aircraft. By considering time constraints, this problem can be abstracted as a vehicle routing optimisation problem with time windows. The ETT service process is shown in Fig. 3.

Figure 3 shows the ETT service process, different colours indicate different airport areas, [] indicates the different time points of ETT operation, and arrows indicate the direction and path of ETT operation. The service time required by each flight constitutes the time window of the corresponding node to be visited.

At time t_0, ETT leaves the parking area and heads to the stand;

At time t_1, ETT arrives at the stand and waits for the aircraft to push back. To prevent delays caused by ETT not arriving, it is required that the aircraft arrives at the stand 1min before the planned take-off time. This time can be obtained from the apron operation model in the airport real-time simulation model;

At time t_2, ETT actually pushes the aircraft out to the taxiway, which usually takes 2min;

At time t_3, ETT pulls the aircraft to the runway end. The aircraft can obtain each node on the taxiway from the taxiway taxiing model in the airport real-time simulation model;

At time t_4, ETT detaches from the aircraft. The detachment time is usually 2min;

At time t_5, ETT returns to the parking area.

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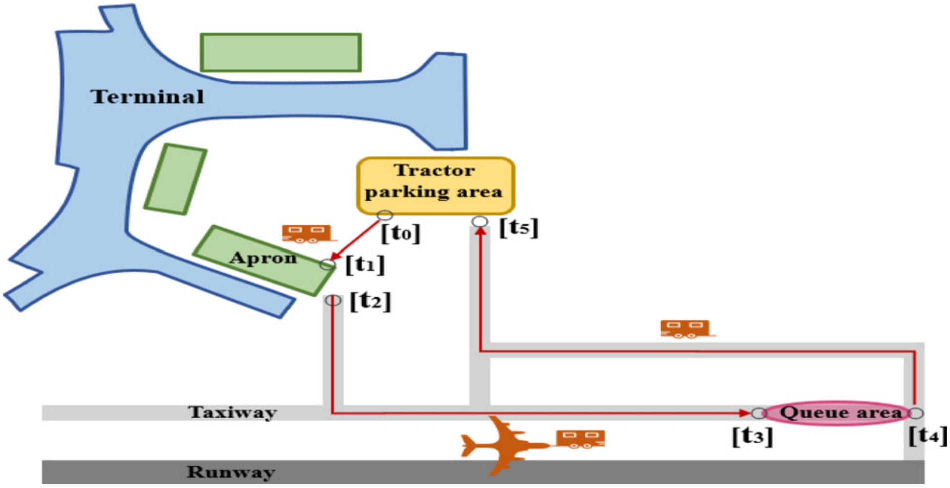

Figure 3. *ETT service process.*

2.2.2 The hard time window model

The hard time window model necessitates that the ETT can fulfil the aircraft requirements at any given moment. The model's solution process consists of four steps:

Step 1: The airport real-time simulation model generates the actual pushback time for each aircraft and, based on the time taken by ETT to reach the corresponding gate, deduces the starting node for each task's time window. Subsequently, the time windows are sorted in order of their start time.

Step 2: Set the aircraft's 'zero waiting' policy for ETT, and set the initial number set of ETT to infinity, to avoid aircraft delays due to insufficient ETT. When ETT receives the tug task issued by the aircraft, the nearest ETT will be assigned. The ETT that completes the tug task will automatically return to the ETT docking area and wait for a new round of task allocation. And compared with the same ETT docking area, the ETT that has not completed the tug task in the current period will be preferentially allocated.

Step 3: Loop through each time window and assign ETT to each time window in turn until all time windows are assigned.

Step 4: Calculate the ETT occupancy time window for each tug operation on the selected day: The occupancy time includes traveling time, waiting time, towing time, disengaging time and returning time.

Figure 4 shows the visualisation result of the time window model. The horizontal axis represents the time of the day, and the vertical axis represents the tug operations of different flights. Red, blue, green, grey and yellow represent the traveling time, waiting time, towing time, disengaging time and returning time of ETT respectively. This figure can reflect the number of ETTs required in each time period, and find the maximum value of ETT demand for the day.

3.0 Case Study

This section first compares the simulation data with the actual airport data to verify the accuracy of the airport real-time simulation model. The verified model is used to simulate the airport operation situation under different ETT usage scenarios. Then, this section analyses the simulation results and discusses the impact of ETT speed and different airports on the number of ETTs.

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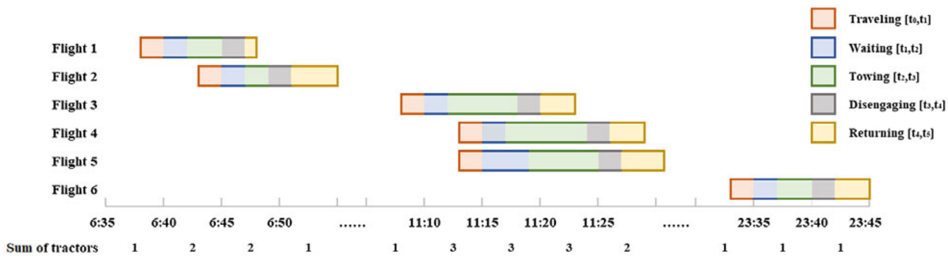

Figure 4. *The hard time window model.*

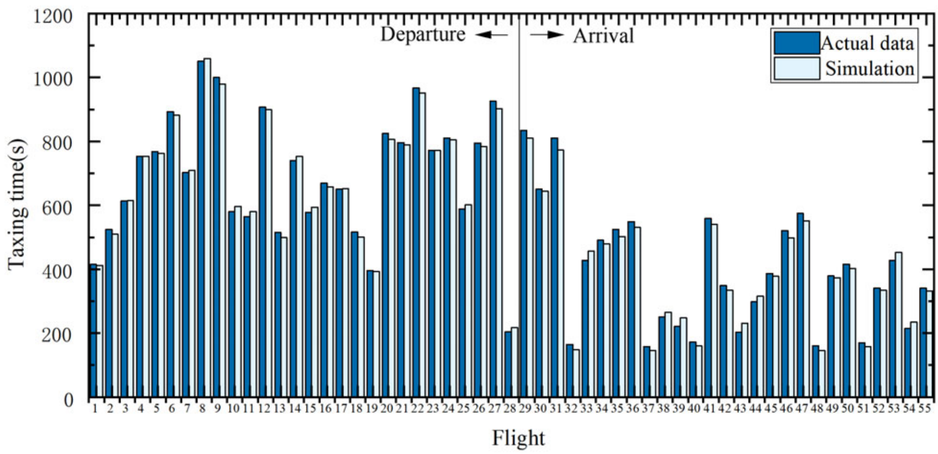

Figure 5. *Comparison of taxiing time.*

3.1 Validation of airport real-time simulation

The real-time airport simulation model serves as the fundamental basis of this study, and its accuracy significantly impacts the determination of the number of ETTs. In this section, the model is validated using peak-hour data from Shenzhen Airport. A comparison is made between the actual taxiing time of various flights during the peak hour and the simulated taxiing time, as illustrated in Fig. 5. It is important to note that the model assumes conventional self-taxiing for aircraft take-off and landing.

Figure 5 shows the comparison of the actual taxiing time and simulated taxiing time of each flight during the peak hour at Shenzhen Airport. The real data comes from the actual operation data of flights during the peak day and peak hour at Shenzhen Airport. The horizontal axis represents the flight sequence, the vertical axis represents the taxiing time, the left side of the dashed line represents the take-off flights, the right side of the dashed line represents the landing flights, the dark colour represents the actual taxiing time of each flight, and the light colour represents the simulated taxiing time of each flight.

From Fig. 5, it can be seen that the maximum difference between the actual taxiing time and simulated taxiing time of flights during the peak hour is 34s. To further analyse the magnitude of errors, plot the cumulative distribution function of relative errors (absolute error/actual data), as shown in Fig. 6.

From Fig. 6, all flights have errors less than 9%. The majority of departure flights have error values largely below 3%, and the majority of arrival flights have error values largely below 7%. Therefore, the established airport real-time simulation model can simulate the aircraft operation at the airport well, and can obtain more accurate demand time points for aircraft using ETT.

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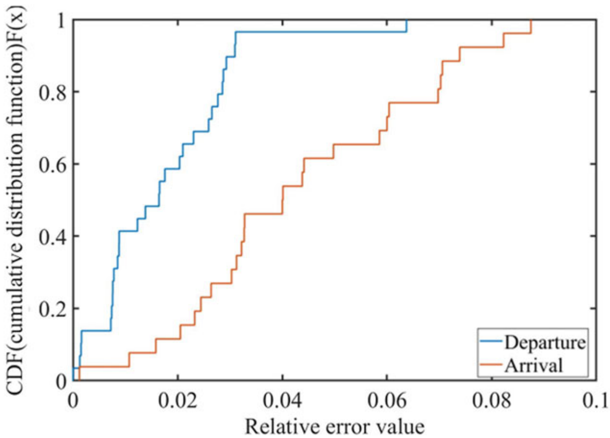

Figure 6. *The cumulative distribution function of relative errors.*

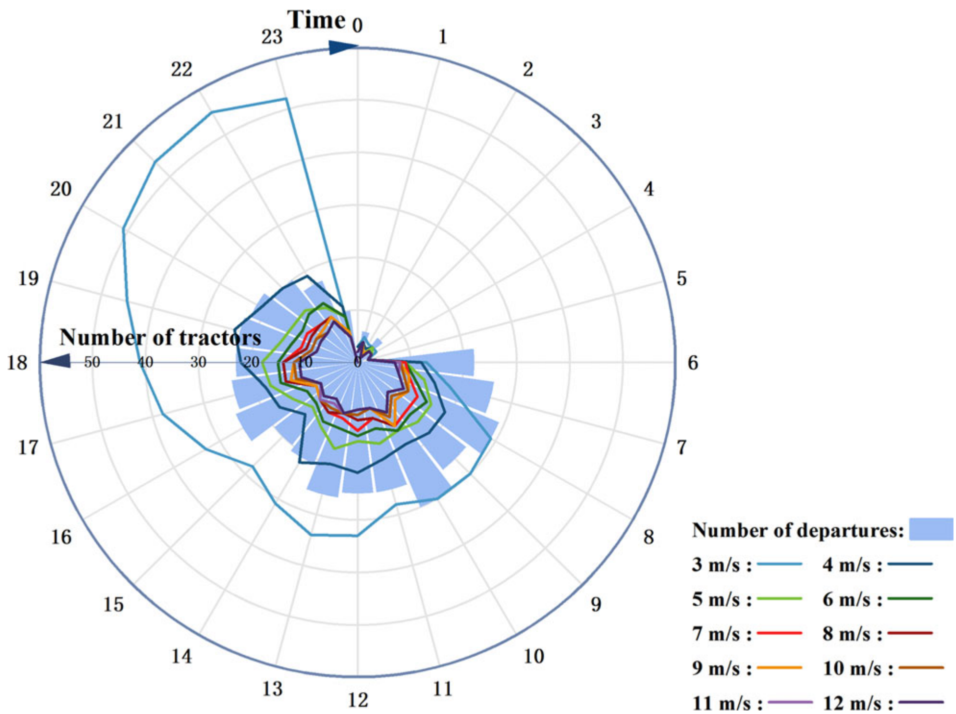

Figure 7. *Variation of ETT quantity with time.*

3.2 The impact of ETT speed on the number of ETTs

To analyse the impact of ETT speed on the ETT demand, this section simulates the 24-hour operation of the Diwopu Airport (one runway, 23,963,167 passenger throughput in 2019), assuming that all take-off flights use ETT and all landing flights use traditional self-taxiing. The initial speed of take-off flights is set to 3m/s, and the maximum taxiing speed is V_{max}. This section sets $V_{max} = 3, 4 \ldots\ldots 12$m/s (it has been proven by previous studies [21, 22] that ETT speed can reach 12m/s) for a total of 10 scenarios. All other parameters are the same for each scenario, except for V_{max}. This section simulates the 10 scenarios and analyses the simulation results to determine the number of ETTs required for each scenario. The simulation results are shown in Fig. 7.

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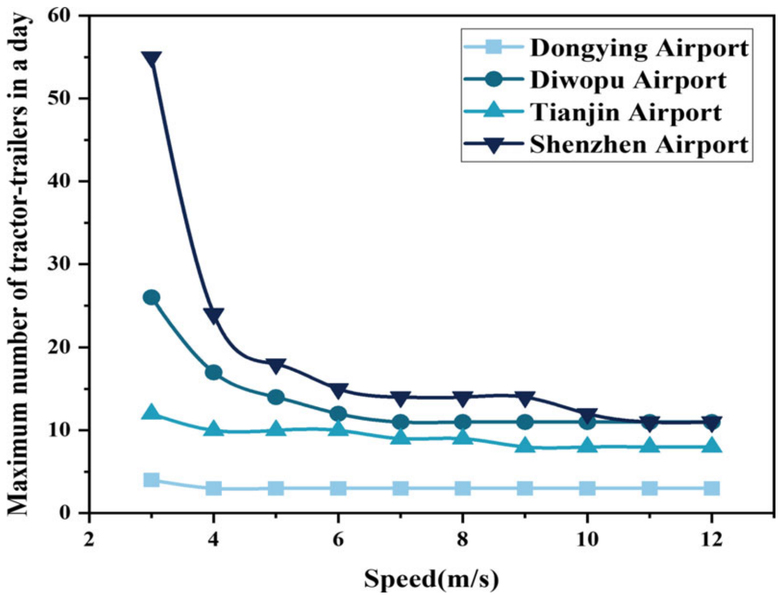

Figure 8. *Variation of ETT quantity with speed for different airports.*

Figure 7 shows the relationship between the number of ETTs and time at different speeds. The circular arrow indicates 24 hours a day, the blue bar indicates the number of take-off flights per hour, different colours indicate different ETT speeds, and different circle sizes indicate different numbers of ETTs. From Fig. 7, it can be seen that:

(1) The ETT demand decreases as the ETT speed increases.
(2) When the ETT speed is less than 4m/s, the peak hour is likely to cause large-scale congestion of airport flights, resulting in a surge in ETT demand.
(3) When the ETT speed is greater than 6m/s, the sensitivity of the number of ETTs to the speed decreases, and the change in ETT demand is less affected by the change in speed.
(4) In the peak time period, there is a certain lag in the ETT demand. That is, after the peak period, the ETT demand will not decrease immediately, but will remain for a period of time, and then continue to change with the change in flight volume.

3.3 Analysis of ett numbers for different airports

Speed is an important factor that affects the number of ETTs, but for different airports, the degree of impact of speed on the number of ETTs is still worth exploring. To analyse the impact of different airports on the number of ETTs, this section selects four airports as four simulation scenarios, namely Dongying Airport (one runway and half taxiway, 880,145 passenger throughput in 2019, peak hour flight volume is 5 flights), Diwopu Airport (one runway and two taxiways, 23,963,167 passenger throughput in 2019, peak hour flight volume is 30 flights), Tianjin Airport (two runways and three taxiways, 23,813,318 passenger throughput in 2019, peak hour flight volume is 29 flights), and Shenzhen Airport (two runways and five taxiways, 52,931,925 passenger throughput in 2019, peak hour flight volume is 55 flights). This section sets $V_{max} = 3, 4 \ldots\ldots 12$m/s, and simulates the four airports respectively, and analyses the simulation results. The results are shown in Fig. 8.

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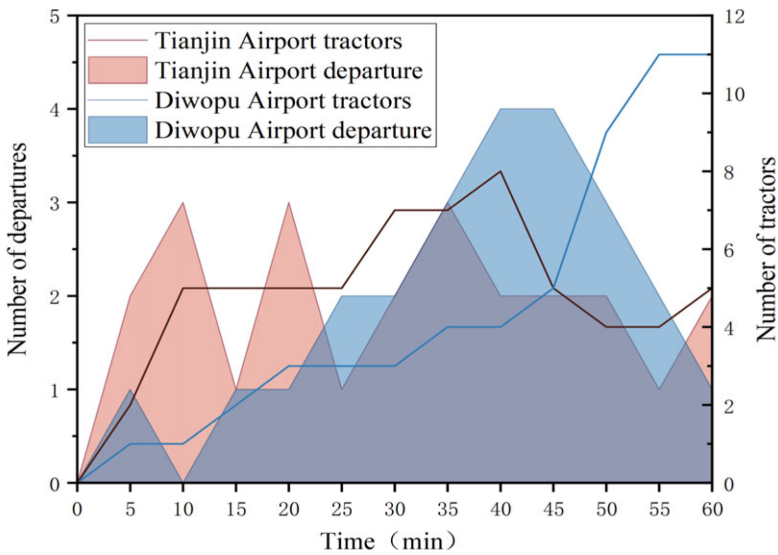

Figure 9. *Relationship between ETT quantity variation and departure flight distribution.*

Figure 8 shows the relationship between the ETT demand and the speed for different scale airports. The horizontal axis represents the speed, the vertical axis represents the maximum number of tugs in a day, and different colour lines represent different scale airports. From Fig. 8, it can be seen that:

(1) Under the same ETT speed, the larger the throughput of the airport, the greater the ETT demand.
(2) The higher the saturation level of airport facilities, such as Shenzhen Airport and Diwopu Airport, the greater the impact of speed variation on the required number of ETTs. It is recommended that when the airport capacity is close to its design capacity, the ETT operating speed can be increased appropriately.
(3) For all scales of airports, after the ETT speed exceeds a certain critical speed, the speed will have almost no impact on the required number of ETTs. But the larger the airport scale, the larger the critical speed.

3.4 The impact of peak hour imbalance on the number of ETTs

The required number of ETTs for airports with similar throughput, such as Diwopu Airport and Tianjin Airport, shows a similar trend, while their vehicle fleet sizes have significant differences. During peak hours, Tianjin Airport handles 29 flight movements, while Diwopu Airport handles 30 flight movements. As shown in Fig. 8, the maximum required ETT quantity at Tianjin Airport is only half of its peak-hour flight movements, whereas for Diwopu Airport, in the scenario with a speed of 3m/s, the relationship between peak-hour flight movements and the maximum ETT quantity is approximately 1:1. To explore the reasons for this difference in vehicle fleet size, this section compares the distribution of flight movements at both airports during peak hours and the required towing vehicle quantities for every 5-minute interval when ETT speed is 10m/s, as illustrated in Fig. 9.

Figure 9 shows the relationship between the changes in ETT quantity and the distribution of departing flights. The horizontal axis represents time, the left vertical axis represents the number of departing flights, the red and blue areas indicate the number of departing flights from Tianjin Airport and Diwopu Airport respectively, the right vertical axis represents the ETT quantity, and the red and blue lines indicate the ETT demand from Tianjin Airport and Diwopu Airport, respectively.

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Table 3. *The amount of fuel saved by airports*

	Dongying	Diwopu	Tianjin	Shenzhen
Total taxiing time(s)	4,599	72,695	52,361	152,798
Total fuel consumption(kg)	938.196	14,829.78	10,681.64	31,170.79
Average fuel savings per operation per aircraft(kg)	46.9098	58.156	44.88	71.99

From Fig. 9, it can be inferred that the number of ETTs required is correlated with the distribution of departing flight movements. Airports with a more concentrated distribution of departing flights tend to have a higher demand for ETTs, while airports with a more balanced distribution experience a lower ETT demand. At Tianjin Airport, where the departing flight movements are relatively evenly distributed across each 5-minute interval during peak hours, the demand for ETTs remains comparatively balanced. Conversely, at Diwopu Airport, the flight movements are concentrated after the initial 30min. Due to the lag in ETT demand, the ETT quantity reaches its highest point at the 55th minute.

It is suggested that when the airport capacity is close to the design capacity, it is appropriate to increase the ETT operation speed, balance the peak hour flight plan to ensure efficient airport operation and reduce tractor quantity.

4.0 Discussion

Due to the ability to shut down the main engines during taxiing, the fuel savings from the auxiliary taxiing system are undeniable [23]. Khadilkar and Balakrishnan [24] concluded, after considering the marginal effects of parking and turning, that fuel consumption is almost entirely determined by the total taxiing time. To investigate the fuel savings from using ETT at airports of different scales, this section simulates four airports to calculate the total taxiing time for aircraft. Considering that taxiing fuel consumption is influenced by factors such as aircraft type, aircraft weight and aircraft speed, it is difficult to obtain accurate fuel consumption. This study, based on ICAO's empirical data on the CFM56 engine [25], conservatively estimates taxiing fuel consumption as the consumption when the engines are at 7% thrust. The fuel consumption at 7% thrust for two engines is 0.204kg/s. The fuel savings for the four airports can be calculated as shown in the Table 3.

In Table 3, Dongying, Diwopu, Tianjin and Shenzhen respectively represent the local airports. And based on the Table 3, larger airports can save more fuel consumption compared to smaller airports. Meanwhile, the amount of fuel saved is related to taxiing distance, for example, the layout of Tianjin Airport's gates is close to the runway ends, resulting in relatively small fuel savings per flight.

5.0 Conclusion

This paper integrates the airport simulation model with the time window model to simulate the precise arrival time of aircraft at each node through the simulation model and calculate the minimum required number of ETTs using the time window model. The main conclusions are as follows.

(1) For the same airport, the ETT speed has a significant impact on the required ETT quantity. A lower speed corresponds to a higher demand for towing vehicles, while a higher speed leads to a reduced ETT demand.

(2) For different airports, the variation trend of ETT demand quantity with ETT speed becomes more significant. Airports with lower throughput exhibit lower ETT demand for the same speed, while those with higher throughput show higher ETT demand for the same speed. In practical airport operations with lower throughput, the ETT speed should not be lower than 4 m/s.

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In cases of higher throughput, the ETT speed should not be lower than 6 m/s to avoid excessive ETT demand and increased airport costs.

(3) The balance of departing flights greatly affects ETT demand. When the peak-hour flight volume is similar, a more balanced distribution of departing flights leads to lower ETT demand. During airport operations, enhancing the even distribution of departing flights can effectively reduce the demand for ETTs and subsequently minimise airport costs.

(4) When the airport capacity is close to the design capacity, there is a higher demand for ETT. In cases where the airport capacity is similar to the design capacity, airport operators can consider increasing the ETT operating speed, balancing peak-hour flight schedules and ensuring efficient airport operations to reduce ETT demand and mitigate airport costs.

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