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RESEARCH ARTICLE

Modeling and simulation study of end around taxiway operation of Shanghai Hongqiao Airport

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Abstract
With the rapid expansion of the aviation industry, an increasing number of Close Spaced Parallel Runway (CSPR) airports are either planning or constructing End Around Taxiways (EAT) to alleviate field operation pressures and enhance safety. Taking Shanghai Hongqiao Airport's typical CSPR EAT configuration as a case study, this research integrates the airport's current operational status with the anticipated requirements for future structural renovations and increased flight volumes. Various operational scenarios are established, and simulation research on optimising EAT operations is conducted in advance. The simulation study proceeds as follows: first, an AirTOP simulation model is constructed based on Hongqiao Airport's actual operational construction. Subsequently, leveraging existing operational scenarios, five simulation scenarios are devised by activating EATs at the departure and approach ends of the eastern zone. The merits and drawbacks of these scenarios are thoroughly analysed. The findings indicate that, with escalating flight volumes, the utilisation of EAT for larger aircraft can curtail their holding duration by nearly 8 min, consequently reducing overall arrival holding duration by 6 min. Departures from gates proximate to T1 experience a 3-min reduction in holding duration through the adoption of EAT at the approach end. Despite an increase in taxi distance due to a higher proportion of aircraft taxiing around, the overall taxi time is diminished. Activating EATs at the departure and approach ends of the eastern zone effectively mitigates the adverse effects of heightened flight volumes on field operational efficiency.

Nomenclature

AIBT	actual in block time
ALDT	actual landing time
AOBT	actual off-block time
ATOT	actual take-off time
ASDE-X	airport surface detection equipment, Model X
CSPR	closely spaced parallel runway
EAT	end-around taxiway
FAA	Federal Aviation Administration
OLS	obstacle limitation surface
RIM	runway incursion mitigation
RMSE	root mean square error
TERPS	terminal instrument procedures

1.0 Introduction

To address the burgeoning demands of the rapidly expanding aviation industry, airports have predominantly embraced runway expansion as a key strategy to augment overall airport capacity. Limited by land area and airport dimensions, many airports have opted for the construction of closely spaced parallel runways (CSPR). Traditional CSPR operations typically adhere to the "inside departure, outside arrival" model, necessitating arriving aircraft to cross the inner runway for access to parking positions. This practice elevates the risk of runway incursions, leading to safety incidents and concerns [1]. In a bid to mitigate these risks and enhance operational safety, airports often implement end- around taxiway (EAT), allowing aircraft to access aprons without runway crossings. Hongqiao Airport successfully commissioned its EAT at the end of 2021, effectively reducing runway incursion risks and enhancing overall operational safety, aligning with design expectations. Anticipating the growing need for aircraft types available for EAT, the possibility of an increased proportion of large aircraft, and a surge in flight numbers, a preliminary simulation study on optimising EAT operations was conducted. This lays the groundwork for the gradual optimisation of EAT operational protocols and the modification of associated infrastructure.

Research on strategies for adopting EATs and evaluation of operational benefits has been conducted from different aspects. On the EAT strategy, Uday found that although EAT shows great promise in emission reduction, this benefit depends on the operation of the taxiway [2]. Huimin et al. modelled the taxi time of approaching aircraft as the optimisation objective [3–8]. They discovered that the dependence on EAT becomes greater when there is a high volume of inbound and outbound flights and that skidding can greatly impact the effectiveness of airport activities. Fala et al. developed decision rules with fuel consumption as the optimisation objective [9–11]. They found that having some decision rules for using EAT helped reduce fuel consumption more than using all crossing or EAT. In addition, in 2015, the FAA launched the Runway Incursion Mitigation Program (RIM Program) to further improve runway safety at U.S. airports over the next 10 to 15 years by focusing on the planning and design of taxiways, including EATs and other taxiways [12]. The program focuses on identifying airport risk factors that may contribute to runway incursions and developing strategies to help mitigate the risks.

Current research on relative operational efficiency gains before and after the use of EAT is based on the taxi time of incoming aircraft. Engelland & Ruszkowski analysed the actual operation of Dallas (DFW) airport for 16 months based on the overall taxi time of aircraft using and not using EAT [13]. Feng explored the impact of different scenarios of constructing EAT on taxi time, fuel consumption, and the ability to cope with increased load levels during peak hours [14].

Other researchers have also studied aspects such as runway capacity before and after the use of EATs. For example, Satyamurti simulated and statistically analysed the actual flight data and predicted the data of DFW with and without the use of EATs at the airport. It was found that EATs are important for improving runway safety as well as departure rate [15]. Xiong et al. used SIMMOD to simulate the ultimate runway capacity at four different distances from the parallel runway centerline using four different operation modes to compare the two cases of no EAT and no runway crossing [16]. And found that in the condition of non-runway crossing, the capacity of the parallel runway system would increase by 13%. Youchao & Xiaowei used Flexsim to perform a field simulation of Pudong Airport and found that the installation of EAT increases the runway capacity of Pudong Airport by 7.4% [17]. Ting et al. found the average taxi time, airport ground capacity, number of conflict detections and releases during field operations, and delay times all improved after the activation of the EAT by simulating the northward operation of Shanghai Hongqiao Airport [18]. Using ASDE-X data, Massidda et al. empirically evaluated the operational benefits of taxiway operations at Dallas/Fort Worth International Airport, with a 40% and 25% increase in average maximum daily traffic inbound and outbound, respectively, and a 38% reduction in average daily outbound delays with the use of EATs [19]. The Airport Capacity Enhancement Plan (ACEP) adopted by Charlotte Douglas Airport to meet the future surge in aviation demand included the expansion of a fourth parallel runway and associated terminal building, including a partial north EAT and south EAT [20].

Other studies have considered human factors and environmental benefits, e.g., the FAA, to refine standards for the use of EATs and collected information on the impact of EAT procedures on the mental and physical workload of aircrews to assess the impact of aircraft on approaching aircrews [21, 22]. Jame, in "The Perimeter Push," notes that the use of EAT has significantly reduced runway incursions and

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frequent aircraft starts and stops during taxiing, saving Dallas-Fort Worth Airport (D/FW) an estimated $2.6 to $3 million annually [20]. Uday et al. analysed ASDE-X ground data from Dallas/Fort Worth International Airport and concluded that factors such as traffic conditions on adjacent runways, traffic flow direction, aircraft arrival time, and aircraft type play a major role in the environmental benefits of EATs [23]. Heinold concluded that the construction of EAT at George Bush Intercontinental Airport would reduce flight delays and fuel consumption and improve air quality by analysing a master plan for the construction of a dual runway with EAT [24]. Fala et al. used ASDE-X ground data to analyse the use of EATs at three airports in Atlanta (ATL), Dallas (DFW) and Detroit (DTW) to assess the environmental benefits of EATs and develop fuel-saving decision rules [9, 11].

Current research predominantly concentrates on taxi-around decision rules and the comparison of operational efficiency between runway crossing and taxiing around. However, it often neglects the consideration of real-world operational scenarios due to constraints related to airport size and operational rules. This limitation impedes the development of decision rules that align with the requirements of End Around Taxiway (EAT) operations.

For instance, at Shanghai Hongqiao Airport, due to the constraints imposed by the Obstacle Limitation Surface (OLS), aircraft of category D and above are restricted from crossing the takeoff runway to access the apron. Despite this, considerations of operational safety and controller workload often lead the airport and controllers to prefer arrivals using the taxi around mode. Without contemplating the expansion of aircraft types eligible for EAT to accommodate the increased demand from larger aircraft, the airport could face elevated operational risks in the future.

Therefore, recognising the evolving operational restrictions and the growing demand for flight volume, it becomes imperative to proactively investigate potential EAT scenarios. This involves a thorough comparison of field operational efficiency under various EAT scenarios and an analysis of the optimisation of EAT operation rules, along with the necessity for modifications to hardware facilities. Such an examination aims to offer valuable insights for alleviating the operational burden on airports.

2.0 Airport simulation model and flight data analysis

2.1 Airport simulation model

The Shanghai Hongqiao Airport, selected as the subject of this study, is equipped with two closely spaced parallel runways and features a highly typical End Around Taxiway (EAT) configuration. This layout bears a striking resemblance to the runway structure observed at DFW, particularly runways 17R and 17C, which were among the earliest to implement EATs. The inclusion of Hongqiao Airport is crucial for an in-depth exploration of EAT utilisation. Hongqiao Airport operates under curfew regulations, limiting its flight activities to the period between 6:00 and 24:00. With a daily average of over 750 flights and an hourly published capacity of 51, it is a bustling and sizable airport.

The primary focus of this study is on the strategic planning and application scenarios of End Around Taxiway (EAT). Given the complexity of testing in real-world scenarios, the research employs AirTOP as a simulation tool. AirTOP was developed by TransSoft, a Canadian company. AirTOP, the leading airport and airspace simulation software, is a comprehensive suite of tools to model, simulate, and visualise airport and air traffic operations in fast time. It can be used for enroute, approach and departure simulations as well as airport ground movement research. It is capable of setting up operational scenarios to analyse complex concepts in a single simulation scenario [25]. Therefore, we can set up different simulation scenarios of EAT applications for analysis through AirTOP.

Runway and gate assignments emerge as pivotal factors influencing the frequency of runway crossings. The spacing between the two runways at Hongqiao Airport is 365 m. In principle, the 18R/36L (west runway) is mainly used for take-off and the 18L/36R (east runway) for landing. The airport is divided into northward operation and southward operation. Runway 18L is used as the landing runway, and Runway 18R is used as the take-off runway when operating southward. Runway 36L is used as the take-off runway, and Runway 36R is used as the landing runway when operating northward. Gate

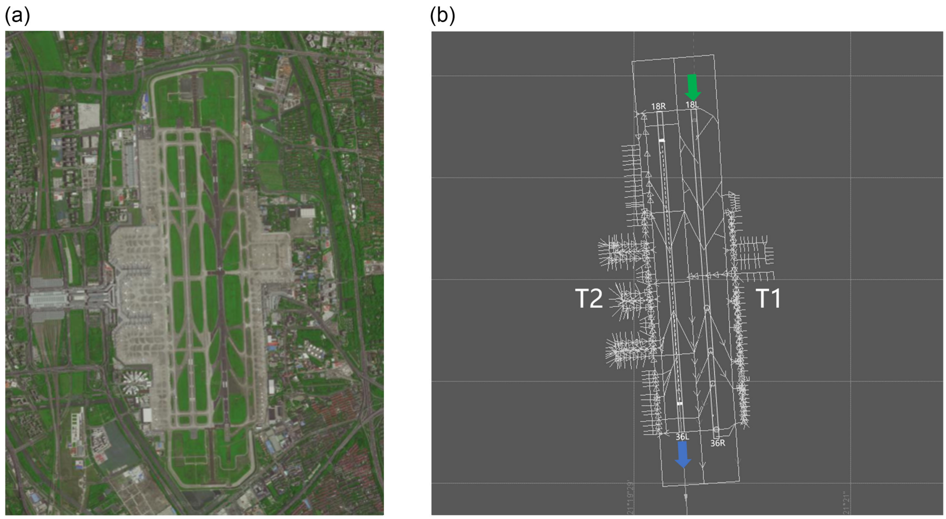

Figure 1. *Hongqiao Airport diagram with AirTOP simulation configuration.*

allocation rules at Hongqiao Airport predominantly hinge on the affiliations of different airlines, directing them to distinct apron areas. In this paper, the southward operation of the airport is used as the study scenario.

Figure 1(b) shows the AirTOP simulation model of Hongqiao Airport, in which runway 18R is used as the takeoff runway and runway 18L is the landing runway.

Operational parameter settings

The airport field-related setup parameters are shown in Tables 1, 2 and 3. Due to the high attack angle during take-off and landing, wake turbulence becomes significant and extremely hazardous, so wake vortex separations on aircraft are necessary [26]. As such, ICAO has set minimum separation standards for departure and arrival flights [27]. The wake turbulence separation between departures is judged by time intervals, while arrivals are judged by distance [28]. In addition, there are separation requirements between approaching and departing aircraft, which are judged by distance.

2.2 Flight data analysis

To conduct a precise analysis of Hongqiao Airport's operations, we utilised flight data from May 2023, a month during which the average daily flights at Hongqiao Airport amounted to 744. The decision to construct and operationalise the End Around Taxiway in the eastern section of the airport hinges on its potential impact on operational efficiency. Consequently, to simulate the airport's future incremental flight demand, we integrated both actual flight data provided by the airport and anticipated future flight demands. In addition to addressing the existing flight volume scenario, we conducted incremental increases based on the current flight data to meet future flight demands. Our study delves into the ramifications of different scenarios, both pre- and post-flight volume increases, on the operational efficiency of the airfield.

The average daily hourly traffic distribution and the percentage of arrivals and departures at Hongqiao Airport in May 2023 are shown in Fig. 2. Hongqiao Airport is an airport with a curfew and its flight activities are mainly concentrated from 6:00 to 24:00 h.

In various scenarios of EAT utilisation, EAT positioned at the approach and departure ends of the runway exerts influence on departing aircraft from Terminal 1 (T1) and approaching aircraft with gates at Terminal 2 (T2), respectively. Currently, EAT imposes restrictions on the use of aircraft classified as

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Table 1. *Taxi speed limit*

Ramp speed	Taxiway speed	Vacate speed
10 kt	15 kt	22 kt

Table 2. *Operation parameters setting*

	Parameter value
Runway occupancy time	Self-determination based on aircraft performance
DD separation	Meet the 2-min interval
AA separation	Continuous landing 6–7 km while meeting aircraft wake turbulence separation
DA separation	The landing aircraft is more than 5 km away from the entrance of the runway and the former aircraft can take off.

Table 3. *RECAT-CN wake turbulence separation (km)*

			Succeeding aircraft				
			Super	Heavy		Medium	Light
			J	B	C	M	L
Proceeding Aircraft	Super	J		9.3	11.1	13.0	14.8
	Heavy	B		5.6	7.4	9.3	13.0
		C				6.5	11.1
	Medium	M					9.3
	Light	L					

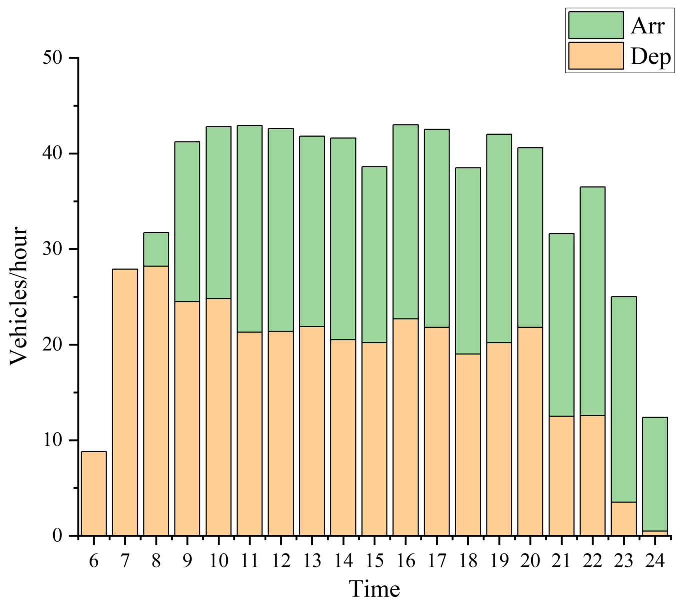

Figure 2. *Traffic flow distribution.*

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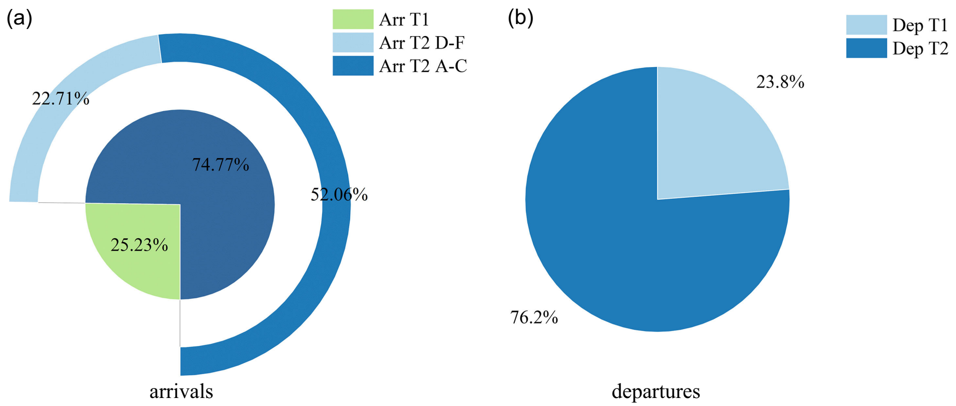

Figure 3. *Percentage of aircraft type and slot distribution.*

Class C and lower. Examining the structural layout of Hongqiao Airport, the terminals are dispersed on both sides of the runway. However, the west terminal (T2) boasts a significantly higher number of gates and passengers compared to the east terminal (T1). Hongqiao Airport designates the west runway for takeoffs and the east runway for landings. Consequently, there is a pronounced demand for arrivals to cross the departure runway to access the gates at T2, representing the primary terminal (as depicted in statistical data illustrating the terminals where arrivals and departures parking gates are located and the percentage of aircraft types, as shown in Fig. 3). As shown in Fig. 3, about 75% of the aircraft stands are close to the west terminal T2, with about 30% of the aircraft in category D and above.

We simulated the operation of Hongqiao Airport in May 2023, and to verify the validity of the simulation model, we compared the simulated runway throughput and taxiing time with the actual runway throughput and taxiing time obtained from ALDT, AIBT, AOBT and ATOT.

Figure 4 shows the empirical and simulated total throughput (departures and arrivals) for the average daily hourly flights. It can be seen that the empirical curves match the simulated curves with root mean square error (RMSE) of 2.63 and 3.67 (number of aircraft), respectively.

Figure 5 shows the comparison of taxi-in and taxi-out times based on empirical and simulation data. The average taxi-in times at Hongqiao Airport are 8.9 min (simulation) and 10.0 min (empirical), with a difference of 1.1 min, and the average taxi-out times are 13.8 min (simulation) and 16.7 min (empirical), with a difference of 2.9 min. The difference can be explained by the statistical range of the data and the difference in the operation rules. Firstly, there is a difference in the statistical range of taxiing time between simulation and empirical data; ALDT refers to the touchdown moment of the aircraft, and the simulation taxiing-in time starts at the moment when the aircraft vacates from the runway. The simulation does not take into account the effect of controlled airspace (flow control) for departing flights, so there is a discrepancy between the situation for take-off queues and the actual operation. In addition, the simulation taxi-out time starts with the moment of leaving the stand, and the simulation leaves the stand later than the AOBT. Hence, the difference between the simulation and empirical taxi time is within an acceptable range.

The simulation model can produce reasonable estimates that match empirical data in terms of taxi time and runway throughput. In addition, the simulation can set up scenarios outside of actual operations to analyse complex concepts in individual simulation scenarios, such as the expansion and activation of EATs, as described in Section 3.

2.3 Operational efficiency evaluation indicators

The main objective of constructing EAT is to provide a taxiing route for aircraft without crossing the runway, so that arrivals can complete "runway crossing" without affecting departing flights, hence

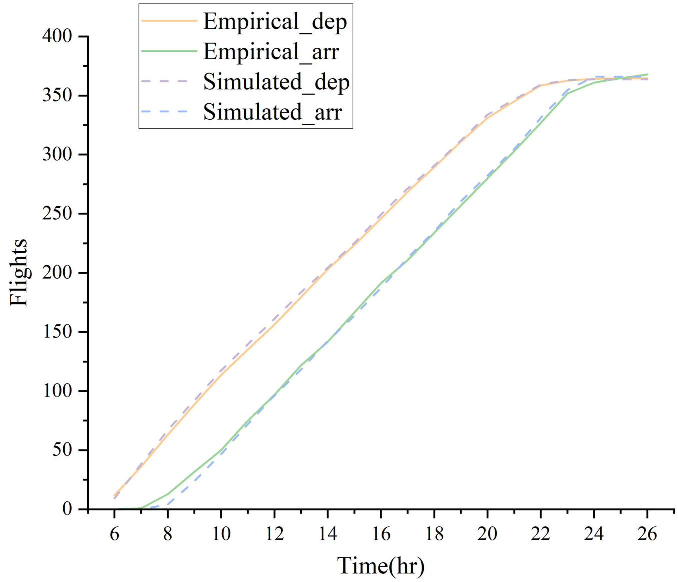

Figure 4. *Comparison of arrival and departure cumulative flights based on empirical and simulated data.*

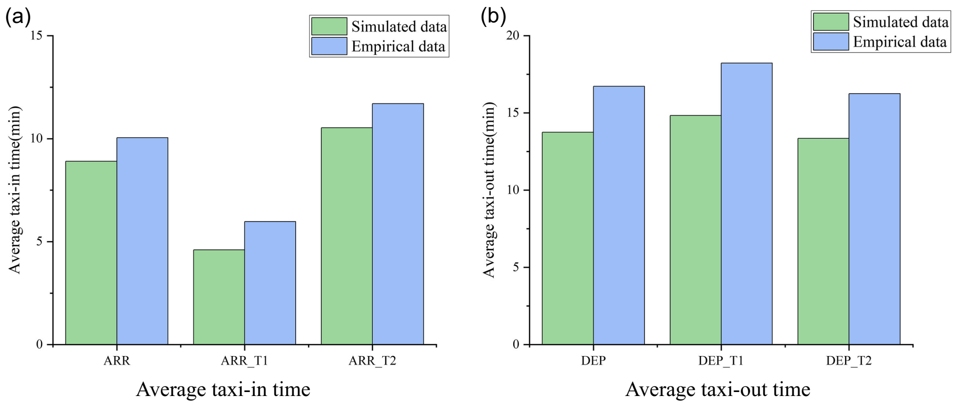

Figure 5. *Comparison of taxi-in and taxi-out times based on empirical and simulation data for terminal distinction.*

significantly reducing the possibility of runway incursion. In addition to the above, the use of EAT reduces holding for inbound flights and eliminates the need for frequent start/stop of aircraft during taxiing. While the adoption of EAT diminishes the holding duration, it substantially increases the taxi distance compared to runway crossing. Consequently, the use of EAT may lead to prolonged taxi times for aircraft, resulting in elevated time and fuel costs.

Based on the advantages and disadvantages of EAT mentioned above, we choose holding duration, taxi time and taxi distance as the evaluation indexes of field operation efficiency under different EAT operation scenarios.

Holding duration signifies the waiting time—an aircraft's taxi time minus its unimpeded taxi time based on the planned route—attributable to taxiing separation, conflicts or runway occupancy [29]. It serves as a metric reflecting the field's congestion level. Unimpeded taxi time in simulations represents

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an aircraft's necessary operating time within the simulation system, covering the distance from the parking position to the runway without any interference. This excludes time spent on taxiing stops, waiting, etc., prompted by potential operational conflicts. While the calculation methods for holding duration and additional taxi time are similar, this study introduces changes to aircraft taxi routes through distinct simulation configurations. Consequently, the unimpeded taxi time for the same combination of runway and stand varies across scenarios, influencing the calculation of additional taxi time. Hence, the additional taxi time of aircraft in different scenarios is collectively referred to as holding duration.

$$\text{Holding duration} = \text{Taxi-in/out time} - \text{Unimpeded taxi-in/out time}$$

Simulation taxi time encompasses the operational time of a flight within the simulation, spanning from the parking position to the runway. This duration comprises both taxi-in time and taxi-out time. Taxi-in time denotes the duration from runway exit to reaching the on-block position, while taxi-out time indicates the duration from leaving the stand to departing the take-off waiting queue. Statistics about taxi distance align with those of taxi time.

3.0 Operation scenario setup and simulation

Based on the actual field structure and operational requirements of Hongqiao Airport, the impact of enabling EAT at the approach end and the East zone EAT at the departure end on the operational efficiency of the field is investigated. Based on the existing operation scenarios, the following five simulation scenarios are set up to increase the use of EAT at the departure end and the approach end, respectively:

Baseline scenario: Only category C and lower arrivals use EAT at the departure end.

Scenario 2: Add the use of EAT for category D and above arrival aircraft to the baseline scenario, i.e., use of EAT for all arrivals.

Scenario 3: Add to the baseline scenario the use of the East zone EAT at departure end for Category D and above arrivals.

Scenario 4: Add the use of approach end EAT by departures to the baseline scenario.

Scenario 5: EAT at approach end and EAT at departure end of East zone both enabled.

These five scenarios can reflect the impact of EAT at the departure end and approach end on the field operation, and cover the possible field operation configurations of Hongqiao Airport in the future.

3.1 Scenario 1: Baseline scenario

The baseline scenario is simulated based on the existing operation mode of Hongqiao Airport, as shown in Fig. 6. Currently, the EAT operation procedure at the departure end of Hongqiao Airport is: provided for arrivals whose parking positions are on the west apron (T2); aircraft of category C and below can use EAT without restriction; aircraft of category D and above need to cross the runway, and need to pause the use of runway 18R/36L for takeoff if they enter EAT by mistake.

Since aircraft in category D and above need to cross the take-off runway, their waiting at the holding point will obstruct the taxiing of subsequent arrivals. Therefore, the proportion of aircraft in category D and above will affect the holding duration of arrivals, and the higher the proportion, the longer the holding duration.

3.2 Scenario 2: Unrestricted taxi around for category D and above arrivals

The OLS of Annex 14-Airports to the Convention on International Civil Aviation restricts the use of EAT at Hongqiao Airport to aircraft in category D and above. The use of EAT at DFW Airport is subject to the terminal instrument procedures (TERPS) standard.

For Hongqiao Airport, if it follows the FAA standards, aircraft of category D and above types can also operate on the EAT without restriction, as shown in Fig. 7. Therefore, the study of different operation

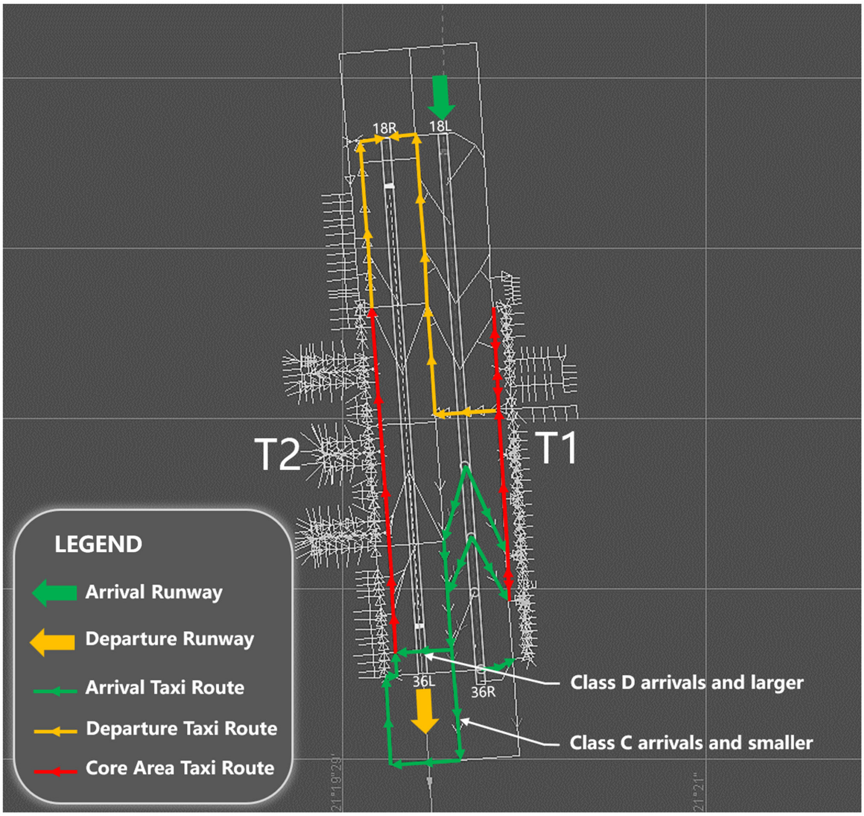

Figure 6. *Scenario 1 operation configuration (southward operation).*

scenarios of EAT at the airport is carried out in advance for the possible future increase of the slope of the takeoff-restricted surface.

All arrivals with parking positions on the west apron choose EAT so that approaching aircraft will not have crossing waiting time due to takeoff runway occupation. This approach diminishes the likelihood of congestion, markedly mitigating the influence of the aircraft type ratio on holding duration.

3.3 Scenario 3: Category D and above arrivals using EAT at the departure end of the East zone

In line with the current operational practices at DFW Airport, arrivals requiring the use of EAT will diverge from both sides of the landing runway and access the EAT via distinct entrances based on their aircraft type [30]. As illustrated in Fig. 8, Hongqiao Airport has similarly implemented EATs on both its east and west sides. To enhance EAT utilisation, arrivals of category D and above can leverage the east EAT.

An approaching aircraft using the East zone EAT will result in an increased taxi distance, and thus a longer taxi time, compared to an aircraft vacating from the west side of the runway to enter the EAT.

3.4 Scenario 4: Departures using approach end EAT

Currently, according to the FAA's study on the implementation of approach end EAT, aircraft operating on approach end EAT will have a psychological impact on the pilot who is landing, which is not conducive to the safety of flight [21, 22]. The EAT at the departure end adopts the measure of setting up a

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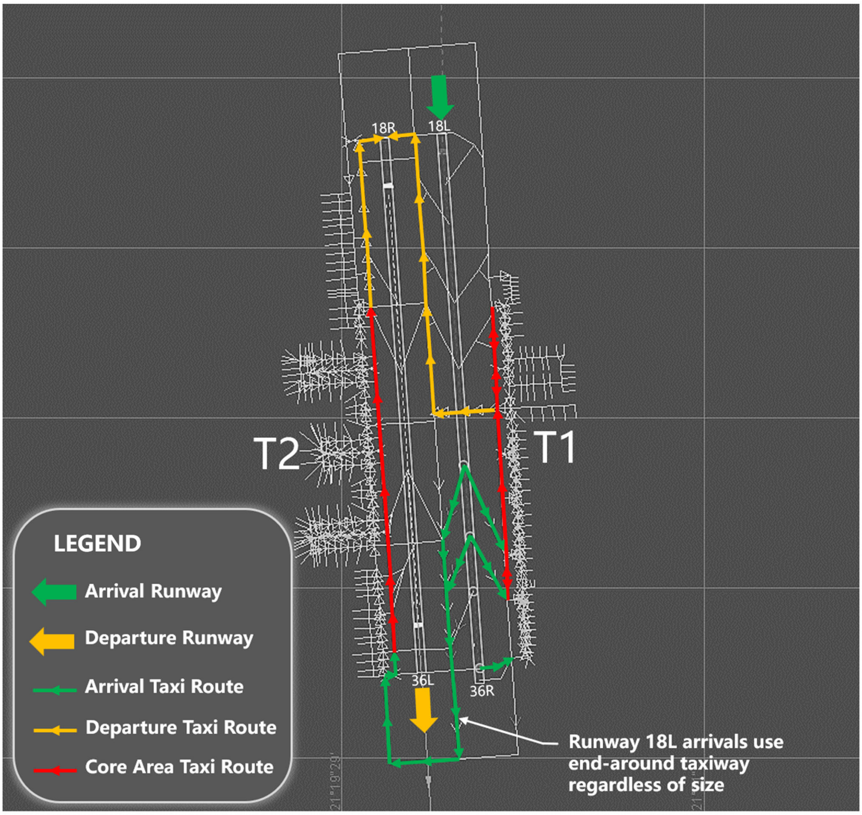

Figure 7. *Scenario 2 operation configuration.*

shelter to avoid the psychological impact on the pilot taking off on the runway. Since there is no effective measure to avoid the psychological impact on the landing pilots, the approach end EAT is still in the research and demonstration stage. However, approach EAT is important for reducing the risk of runway incursion, decreasing the holding duration of departing aircraft, and easing the congestion of the field, so it is possible to analyse the impact of the feasibility of approach EAT on the operational efficiency of the field in the future through the simulation study on the use of approach EAT by the departing aircraft, and to reflect the necessity of realising the approach end EAT in this way.

Given the operational mode at Hongqiao Airport, departing aircraft with gates at T1 are required to cross the landing runway, heightening the risk of runway incursion. Additionally, the priority given to arriving aircraft over ground-waiting aircraft increases the holding duration for departing flights awaiting clearance to cross the runway. Consequently, an exploratory study on the feasibility of enabling approach end EAT is initiated. This study, conducted within the framework of the baseline scenario that augments the use of approach end EAT by departing aircraft, aims to analyse its potential impacts on field operation efficiency and safety. Figure 9 shows the taxiing route of the departures using the approach end EAT.

3.5 Scenario 5: Category D and above arrivals using EAT on the departure end of the East zone and departures using EAT on the approach end

Building upon the four aforementioned scenarios, this particular case contemplates the concurrent activation of EAT at the East zone's departure end and the approach end, as shown in Fig. 10. The activation of EAT at both the east departure end and approach end serves to eliminate the need for runway crossings,

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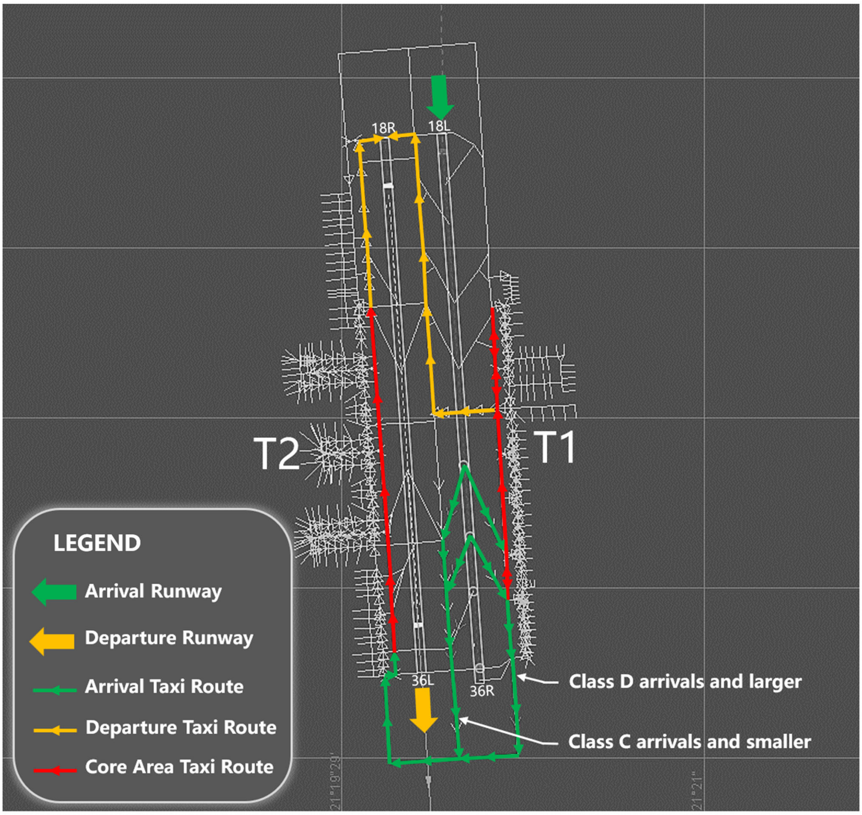

Figure 8. *Scenario 3 operation configuration.*

thereby significantly diminishing the risk of runway incursion. This strategic approach not only enhances the safety of airport operations but also alleviates the workload on controllers.

4.0 Results and discussion

Table 4 provides a summary of the simulation results for the five scenarios outlined in Sections 3.1–3.5. By comparing the average holding duration, average taxi time, and average taxi distance of arriving aircraft positioned at stands T2 in Scenarios 1, 2, and 3, we can discern the impacts of different utilisation modes of EAT at the departure end on field operations.

In the current flight volume, the waiting time for arrivals is minimal across all three scenarios. Nevertheless, the introduction of EAT for Category D and above aircraft leads to a notable extension in taxi distance, consequently elevating the overall taxi time. Specifically, in Scenario 3, the utilisation of EAT in the eastern region by Category D and above aircraft results in a further augmentation of both taxi distance and taxi time, in contrast to Scenario 2, where aircraft detach from the runway to the right before joining EAT.

With the existing flight volumes, the holding durations for arrivals are low in all three scenarios. However, after the aircraft of category D and above also use EAT, the taxiing distance increases significantly resulting in an increase in their taxiing time. In Scenario 3, the use of eastern EAT by aircraft in category D and above further increases the taxiing distance compared to Scenario 2, where the aircraft vacate from the runway on the right and join the EAT, resulting in a further increase in the taxiing time.

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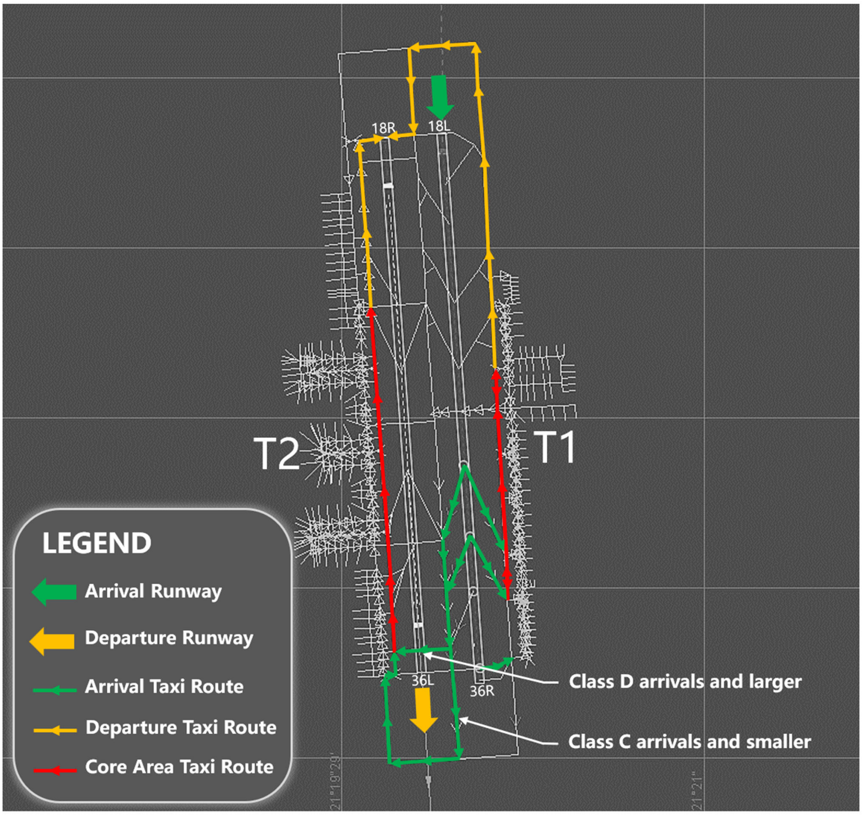

Figure 9. *Scenario 4 operation configuration.*

Based on the actual operational demand at Hongqiao Airport, the average daily flights increased to 827 (an 11% increase compared to the May 2023 average daily flights of 744). Flight schedules can be randomly cloned using AirTOP.

The comparison of the indicators changed when the number of flights increased. After the increase in flight volume, the holding duration and taxi time of arrivals in Scenario 1 increase significantly, especially the aircraft of category D and above need to wait to cross the takeoff runway, and their holding duration and taxi time increase by nearly 8 min. The aircraft of category C and below are hindered by the waiting to cross the runway and their holding duration increases by nearly 5 min. With the addition of EAT for aircraft in category D and above, there is no need to wait for crossing, the holding duration is greatly reduced, and the taxi time is almost unaffected by the increase in the number of flights. The increase in taxi distance by adopting EAT in category D and above aircraft does not have much effect on their taxi time. It can be seen that the use of EAT for aircraft of category D and above can effectively reduce the negative impact of the increase in flight volume on the operation of the field. The comparison of the operational efficiency of arrivals in Scenario 4 and Scenario 5 in Table 5 can also confirm this point.

The activation of the EAT at the approach end of the east area mainly affects the departures in T1. Comparing the operational efficiency of departures in Scenario 1 and Scenario 4 under the existing flight capacity, it can be seen that the holding duration of departures in T1 is reduced by nearly 1.5 min after taxi around, but the taxi-out time increases by nearly 2 min due to a significant increase in the taxi distance. After the increase in flight volume, the situation is the opposite, the average taxi-out time in Scenario 1 increases by nearly 7 min compared to that before the increase, but the average taxi-out time

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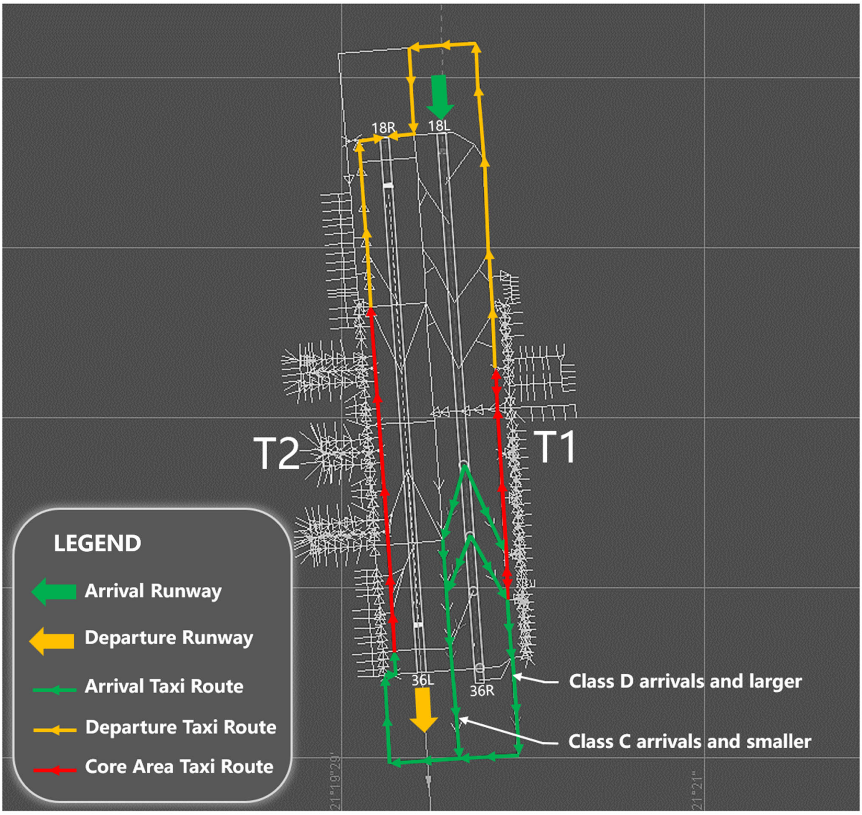

Figure 10. *Scenario 5 operation configuration.*

Table 4. *Comparison of operational efficiency for scenarios 1, 2 and 3*

Scenario	Category		Available flights: Holding duration	Available flights: Taxi time	Available flights: Taxi distance	After the increase in flights: Holding duration	After the increase in flights: Taxi time	After the increase in flights: Taxi distance
1	Arr	T2	0:00:21	0:10:32	3993.472	0:06:25	0:16:49	4040.078
		C and below	0:00:09	0:11:21	4562	0:05:37	0:16:57	4568.014
		D and above	0:00:44	0:08:55	2866.677	0:08:07	0:16:34	2928.965
	Dep	All	0:04:04	0:13:45	2786.168	0:13:26	0:20:04	2798.701
2	Arr	T2	0:00:04	0:11:16	4509.991	0:00:40	0:11:54	4515.018
		C and below	0:00:04	0:11:17	4571.701	0:00:37	0:11:49	4558.471
		D and above	0:00:04	0:11:14	4390.127	0:00:48	0:12:04	4421.944
	Dep	All	0:04:04	0:13:48	2788.336	0:14:04	0:20:02	2806.602
3	Arr	T2	0:00:04	0:11:27	4611.956	0:00:06	0:11:29	4610.122
		C and below	0:00:05	0:11:19	4573.761	0:00:05	0:11:21	4578.094
		D and above	0:00:03	0:11:45	4696.302	0:00:08	0:11:49	4687.794
	Dep	All	0:03:46	0:13:30	2774.485	0:13:32	0:20:03	2809.164

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Table 5. *Comparison of operational efficiency for scenarios 1, 4 and 5*

			Available flights			After the increase in flights		
Scenario	Category		Holding duration	Taxi time	Taxi distance	Holding duration	Taxi time	Taxi distance
1	Arr	T2	0:00:21	0:10:32	3993.472	0:06:25	0:16:49	4040.078
		C and below	0:00:09	0:11:21	4562	0:05:37	0:16:57	4568.014
		D and above	0:00:44	0:08:55	2866.677	0:08:07	0:16:34	2928.965
	Dep	All	0:04:04	0:13:45	2786.168	0:13:26	0:20:04	2798.701
		T1	0:04:19	0:14:50	3157.231	0:16:31	0:24:13	3169.962
		T2	0:03:59	0:13:21	2654.032	0:12:10	0:18:21	2645.416
4	Arr	T2	0:00:21	0:10:31	3976.946	0:06:03	0:16:25	4018.302
		C and below	0:00:09	0:11:20	4546.223	0:04:55	0:16:14	4552.946
		D and above	0:00:44	0:08:54	2860.678	0:08:25	0:16:48	2903.78
	Dep	All	0:03:47	0:14:08	3078.137	0:12:01	0:19:42	3108.302
		T1	0:03:39	0:16:36	4266.709	0:12:40	0:23:17	4268.003
		T2	0:03:50	0:13:16	2659.818	0:11:46	0:18:16	2648.183
5	Arr	T2	0:00:04	0:11:25	4595.335	0:00:07	0:11:30	4613.444
		C and below	0:00:04	0:11:15	4553.985	0:00:07	0:11:23	4584.324
		D and above	0:00:04	0:11:45	4690.121	0:00:07	0:11:47	4687.263
	Dep	All	0:03:49	0:14:04	3045.091	0:13:36	0:20:27	3091.521
		T1	0:03:34	0:16:28	4260.383	0:13:42	0:23:54	4292.746
		T2	0:03:53	0:13:19	2665.96	0:13:34	0:19:11	2647.972

in Scenario 4 increases by about 5.5 min, which is lower than that in Scenario 1, and the average taxi time also decreases. This is because the T1 departure aircraft does not need to wait to cross the landing runway, and the holding duration is reduced by about 4 min compared to Scenario 1. It can be seen that after the increase in flight volume, the activation of EAT at the approach end has a positive effect on reducing the taxi-out time and easing the congestion on the field.

Comparing the statistical results of Scenario 1 and Scenario 5, it can be found that after the increase in flight volume, enabling the EAT of the approach end and departure end of the East zone can effectively reduce the holding duration and ease the congestion of the field, and at the same time it has a positive effect on the reduction of the taxi time.

A discussion of the limitations and implications of this study.

1. The effects of weather are not taken into account. According to previous studies on the operation of EATs at DFW, the use of EATs increases significantly in low-visibility weather conditions [13]. EAT are important for controllers to resolve conflicts to improve field safety.
2. This study did not quantitatively analyse controller workload, capacity and fuel consumption, and we supplemented previous studies to illustrate the impact of increasing the use of EAT scenarios on each indicator.

FAA simulated and analysed the impact of KATL's and DFW's EAT procedures on crew mental or physical workloads from a human factors perspective, as well as analysing the TERPS and collision risk models (CRMs), and found that there was little to no impediment to runway takeoffs by the departing end of the EAT procedure [21, 22]. Since there is no impediment, the use of EATs compared to waiting for a crossing, both for arriving and departing aircraft, allows controllers to reduce the number of commands sent, reduces the focus on runway crossing risk, reduces the workload of both controllers and aircraft pilots, reduces the impact of the human factor and improves the safety of the operation.

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According to previous studies on EAT operations at DFW, enabling EAT is important for improving runway safety as well as departure rates [15]. From the results of this study, the increase in EAT usage scenarios can keep the taxiing time and additional taxi time of arriving aircraft at the same level as before the flight volume increment, and the increase of taxiing time and additional taxi time of departing aircraft is also reduced. In other words, considering that in practice runway crossing does not perfectly intersperse takeoff gaps for departing aircraft (i.e., it causes takeoff queues for departing aircraft to wait), an increase in EAT usage scenarios can lead to an increase in airport capacity for the same level of delay. This is one of the issues that our study is trying to illustrate.

The number of aircraft starts and stops is also one of the important factors affecting fuel consumption and pollutant emissions, and the taxiing time, fuel consumption and pollutant emissions are differently higher when the aircraft is in conflict than when it is in unimpeded taxiing [31, 32]. From the results after the incremental flight volume, increasing EAT usage scenarios can reduce the number of aircraft starts and stops, additional taxi time and taxiing time, which has some environmental benefits.

5.0 Conclusions

AirTOP served as our chosen simulation tool for the comprehensive examination and analysis of various EAT operational scenarios at Shanghai Hongqiao Airport. The airport's configuration embodies one of the most representative Close Spaced Parallel Runway EAT setups, making it a crucial focal point for the investigation into EAT operation modes. This paper analyses the impact of different taxiing scenarios for arrival and departure aircraft on the operational efficiency of the field, taking into account the need for further construction of taxiways and the increase in the number of flights at the airport in the future.

To this discovery:

(1) In situations where the airport EAT is not universally accessible to all aircraft types, the presence of arrivals awaiting a crossing can impede subsequent aircraft, leading to congestion at the runway crossing holding point. This congestion is notably exacerbated following an escalation in flight volume, resulting in a substantial increase in arrival holding duration.

(2) As airport infrastructure evolves and operational constraints undergo modifications, a broader range of aircraft types becomes eligible for EAT utilisation. However, within the current flight volume context at Hongqiao Airport, augmented use of EAT by arrivals contributes to an extended taxi-in distance without a commensurate reduction in holding duration, consequently resulting in increased taxi-in time. In the anticipated scenario where more aircraft types gain access to EAT in the future, the accompanying rise in flight volume exerts a more substantial impact on arrival holding duration compared to the impact on taxi-in distance, as indicated by the findings in this paper. The implementation of EAT significantly ameliorates the taxi-in holding situation, leading to reduced taxi-in time and alleviation of field congestion.

(3) The impact of employing East zone EAT for arrivals aligns with the aforementioned conclusion; however, the utilisation of East zone EAT introduces an additional increment in the taxi-in distance.

(4) The study omits the consideration of the psychological impact on landing pilots caused by aircraft using approach end EAT and increases the application of approach end EAT for departures originating from gates in the east terminal. In Scenario 1, the departure holding duration primarily comprises the waiting time for takeoff queuing and runway crossing. The escalated use of approach end EAT mitigates the waiting time for departures to cross the landing runway, thereby diminishing the departure holding duration from the east terminal.

(5) To enhance operational efficiency, the activation of both departure end EAT and approach end EAT necessitates a comprehensive assessment of the combined effects of increased taxiing distance and flight volume on taxi time.

In conclusion, through a comparative analysis of evaluation indices for operational efficiency of arrival and departure aircraft before and after the increment in flight volume across different scenarios,

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it is evident that the enhanced utilisation of EAT, as observed in scenarios other than Scenario 1, significantly mitigates the adverse effects of heightened flight volume on field operational efficiency. As flight volume demands escalate, the utilisation of EAT emerges as a crucial factor in ameliorating aircraft holding duration and enhancing overall field operation efficiency at CSPR airports.

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References

[1] Haibin, P. Runway incursion at Hongqiao Airport: two planes with wingtips 13m apart in near disaster, *YiMagazine*, 2016. https://www.yicai.com/news/5135361.html

[2] Uday, P. *Mitigating Environmental Impacts using Aircraft Operations: A Systematic Overview and a Focus on End-Around Taxiways.* (M.S.E.), Purdue University, United States – Indiana, 2011. https://www.proquest.com/dissertations-theses/mitigating-environmental-impacts-using-aircraft/docview/905306791/se-2?accountid=16605; http://www.yidu.edu.cn/educhina/educhina.do?artifact=&svalue=Simulation+Analysis+of+End-Around+Taxiway+Operations&stype=2&s=on ProQuest Dissertations & Theses Global database (1501884).

[3] Huimin, Z. *Application Research of End-Around Taxiway in Multi-Runway Airport.* (Master), Civil Aviation Flight University of China, 2020, Available from Cnki.

[4] Jiakai, G. *Research of Taxiing Route Optimization for Aircraft Based on the Parallel Runway of Guangzhou Baiyun Airport,* (Master), Civil Aviation Flight University of China, 2017. Available from Cnki.

[5] Long, L. *Research on the Design of End-Around Taxiway of Civil Airport.* (Master), Civil Aviation University of China, 2015. Available from Cnki.

[6] Tong, W. *Research of Taxiing Route Optimization for Airport Based on the Parallel Runway.* (Master), Civil Aviation University of China, 2019. Available from Cnki.

[7] Wei, W. and Long, L. Study on operation strategy of end-around taxiway and its application, *J. Highw. Transport. Res. Develop.*, 2016, **33**, (06), pp 119–122.

[8] Wenjuan, X. *The Planning and Operation of End-Around Taxiway for Civil Aerodrome.* (Master), Civil Aviation University of China, 2014, Available from Cnki.

[9] Fala, N., Le, T.T., Marais, K. and Uday, P. Surface performance of end-around taxiways. *Air Traffic Contr. Q*, 2014, **22**, (4), pp 327–351. doi: 10.2514/atcq.22.4.327

[10] Guanghong, F. *Study on Taxiing System Optimization of Multi-Runway Airport.* (master), Civil Aviation University of China, 2020, Available from Cnki.

[11] Le, T.T. and Marais, K. Optimization of end-around taxiway for efficient operations and environmental benefits, In *2013 Aviation Technology, Integration, and Operations Conference*, 2013.

[12] FAA. Runway Incursion Mitigation (RIM) Program, 2015. https://www.faa.gov/airports/special_programs/rim/

[13] Engelland, S. and Ruszkowski, L.M. Analysis of DFW perimeter taxiway operations, In *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, 2010.

[14] Feng, Y. *Simulation Analysis of End-Around Taxiway Operations.* (Ph.D.), Purdue University, United States – Indiana, 2020. https://www.proquest.com/dissertations-theses/simulation-analysis-end-around-taxiway-operations/docview/2827706619/se-2?accountid=16605; http://www.yidu.edu.cn/educhina/educhina.do?artifact=&svalue=Simulation+Analysis+of+End-Around+Taxiway+Operations&stype=2&s=on; http://159.226.100.141/Reader/union_result.jsp?title=1&word=Simulation+Analysis+of+End-Around+Taxiway+Operations; https://figshare.com/articles/thesis/SIMULATION_ANALYSIS_OF_END-AROUND_TAXIWAY_OPERATIONS/12698597 ProQuest Dissertations & Theses Global database (30503700).

[15] Satyamurti, S.D. *Runway Incursion Mitigation, Capacity Enhancement, and Safety Improvements with Perimeter Taxiway Operations at Dallas Fort Worth International Airport.* (Ph.D.). The University of Texas at Arlington, United States – Texas, 2007. https://www.proquest.com/dissertations-theses/runway-incursion-mitigation-capacity-enhancement/docview/304708529/se-2?accountid=16605; http://www.yidu.edu.cn/educhina/educhina.do?artifact=&svalue=Runway+incursion+mitigation%2C+capacity+enhancement%2C+and+safety+improvements+with+perimeter+taxiway+operations+at+Dallas+Fort+Worth+International+Airport&stype=2&s=on; http://159.226.100.141/Reader/union_result.jsp?title=1&word=Runway+incursion+mitigation%2C+capacity+enhancement%2C+and+safety+improvements+with+perimeter+taxiway+operations+at+Dallas+Fort+Worth+International+Airport ProQuest Dissertations & Theses Global database (3264607).

[16] Xiong, L., Dongbin, L. and Dongxuan, W. Airport capacity analysis for typical parallel runways based on simulation method, *J. Comput. Appl.*, 2012, **32**, (09), pp 2648–2651.

[17] Youchao, L. and Xiaowei, T. Influence of end-around taxiway on airport operation: take PVG for instance, *J. Civil Aviat. Univ. China*, 2019, **37**, (06), pp 29–33.

[18] Ting, X., Minghua, H. and Zheng, Z. Analysis of end- around taxiway's operational benefits, *Aeronaut. Comput. Techniq.*, 2015, **45**, (04), pp 112–115.

[19] Massidda, A., Mattingly, S.P. and Transportation Research Board *Empirical Assessment of the End-Around Taxiway's Operational Benefits at Dallas/Fort Worth International Airport Using ASDE-X Data*, Paper presented at the Transportation Research Board 92nd Annual Meeting, Washington DC, United States. 2013, Digital: https://trid.trb.org/view/1243064

[20] Jame, C. The perimeter push. *Air Transport World*, 2009, **6**, p 69.

[21] Reisweber, M.A. *Proof-of-Concept Demonstration for the Proposed 8R End Around Taxiway (EAT) at Hartsfield-Jackson Atlanta International Airport (KATL)* (DOT-FAA-AFS-440-5). P.O. Box 25082, Oklahoma City, OK 73125, 2004.

[22] Skiver, M.A.R.J.H.J.H.S.S.A.E. *End-Around Taxiway (EAT) Analysis—East Traffic Arrivals (Runways 17C and 17R) at Dallas/Fort Worth International Airport (DFW)* (DOT-FAA-AFS-440-38). Oklahoma City, Oklahoma 73169, 2008.

[23] Uday, P., Marais, K. and Burder, D. Environmental benefits of end-around taxiway operations, In *11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, 2011.

[24] Heinold, M.T.M.D. The case to build end-around taxiways at George Bush Intercontinental Airport for air quality benefit. In *T&DI Congress 2011*, pp. 339–352, 2011.

[25] Tee YY, Z.Z. Modelling and simulation studies of the runway capacity of Changi Airport, *Aeronaut. J.*, 2018, **122**, (1253), pp 1022–1037. doi: 10.1017/aer.2018.48

[26] EUROCONTROL. *Wake vortex turbulence*, 2012. https://www.eurocontrol.int/articles/wake-vortex

[27] ICAO. *Procedures for Air Liathc Navigation Services*, 2007. http:/dcaa.trafikstyrelsen.dk:8000/icaodocs/Doc%204444%20-%20Air%20Trafc%20Management/ATM%20%2015%20ed.pdf

[28] SKYbrary. *Mitigation of Wake Turbulence Hazard*, 2014. http://www.skybrary.aero/index.php/Mitigation_of_Wake_Turbulence_Hazard

[29] ICAO. *2016–2030 Global Air Navigation Plan*. Montréal, Canada: International Civil Aviation Organization, 2016, pp. 29–31.

[30] DFW. *Benefit-Cost Analysis*. Dallas/Fort Worth, TX, USA, 2017.

[31] Khadilkar, H. and Balakrishnan, H. Estimation of aircraft taxi fuel burn using flight data recorder archives, *Transport. Res. D: Transp Environ*, 2012, **17**, (7), pp 532–537. doi: 10.1016/j.trd.2012.06.005

[32] Zhang, M., Liu, S. and Li, H. Multi-objective route planning for aircraft taxiing under different traffic conflict types, *J. Aerosp. Inform. Syst.*, 2022, **19**, (2), pp 124–142. doi: 10.2514/1.I010982

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