SIMULATION ANALYSIS OF END-AROUND TAXIWAY OPERATIONS

by

Yilin Feng

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STATEMENT OF COMMITTEE APPROVAL

Dr. Mary E. Johnson, Chair

School of Aviation and Transportation Technology

Dr. John H. Mott

School of Aviation and Transportation Technology

Dr. Stewart W. Schreckengast

School of Aviation and Transportation Technology

Dr. Brandon J. Pitts

School of Industrial Engineering

Approved by:

Dr. Kathryne A. Newton

Dedicated to my parents and Huayi Chen

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AEDT	Aviation Environmental Design Tool
AER	Arrival Efficiency Rate
ASDE-X	Airport Surface Detection Equipment, Model X
ASPM	FAA Aviation System Performance Metrics
ATC	Air Traffic Control
ATCs	Air Traffic Controllers
ATL	Hartsfield-Jackson International Airport
CI	Confidence Interval
CLT	Charlotte Douglas International Airport
DER	Departure Efficiency Rate
DFW	Dallas/Fort Worth International Airport
DMTR	Daily Maximum Throughput Rate
DTW	Detroit Metro Airport
EAT	End-Around Taxiway
EAD	DFW Environmental Affairs Department
EASA	European Union Aviation Safety Agency
EHAM	Amsterdam Schiphol Airport
EWR	Newark Liberty International Airport
FAA	Federal Aviation Administration
HND	Tokyo International Airport
IAH	Houston George Bush Intercontinental Airport
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
IFR	Instrument Flight Rules
LTBA	Istanbul Ataturk Airport
MIA	Miami International Airport
NOAA	National Oceanic and Atmospheric Administration
NTSB	National Transportation Safety Board
NTX	NASA’s North Texas Research Station

ORD	Chicago O'Hare Airport
UHF	Ultra High Frequency
VFR	Visual Flight Rules
VHF	Very High Frequency
VMC	Visual Meteorological Conditions

ABSTRACT

Runway and taxiway configuration could affect airport capacity and safety, and airline taxiing time and fuel consumption. In this study, a discrete-event stochastic simulation model is created to explore the impact of four different runway and taxiway choices on a fictional airport with parallel runways that have End-Around Taxiways (EAT) at each end. Scenario 1 represent the conventional runway and taxiway choices used in parallel runway systems, while Scenarios 2, 3, and 4 mimic three new choices that become possible because of the usage of the EAT. Three designed experiments are used to explore the influence of the four scenarios in terms of taxi time, fuel consumption, and number of runway crossings during high traffic periods, as well as the ability to cope with increases in the load level.

Some main findings are: 1) using the outboard runway to land and the EAT as the taxi-in path would yield the shortest average taxi-out time, while the average taxi-in time is similar or longer than that in the conventional choice; 2) if arrival aircraft are allowed to land over an active EAT, using the outboard runway to take off and the EAT as the taxi-out path would show advantages in both the average taxi-in time and the average taxi-out time; 3) if the EAT is operated under current FAA regulation, using the outboard runway to take off and the EAT as the taxi-out path could still show advantages in the average taxi-in time, while the average taxi-out time is the longest during high arrival period; 4) the results of the average fuel consumption indicate similar trends with the results of the average taxi time; 5) using the EATs could either eliminate the number of runway crossings or reduce it significantly; 6) the taxi times with the use of EATs are more stable against the increases in the load level in comparison with the conventional choice.

Safety and human factor issues related to allowing arrival aircraft to land over an active EAT are discussed, as well as some future research topics. This study may encourage airport operators and researchers to explore how to make full use of existing EATs. This study, along with future cost-benefit analyses based on the results of this research, would be a valuable reference for airports that consider constructing EATs in the future.

1. INTRODUCTION

In parallel runway systems, aircraft are usually assigned to use the inboard runways to take off and the outboard runways to land (Hoover, 2007). Arrival aircraft landing on the outboard runway, then, have to cross the active inboard runway to approach the terminal area (Satyamurti, 2007). This type of runway crossing not only increases the probability of runway incursion (FAA, 2001), but also undermines airport capacity (Satyamurti, 2007). For example, on April 7, 2016, a Boeing 737-800 operated by American Airlines as a regularly scheduled passenger flight was on takeoff roll on runway 35L at Dallas-Fort Worth International Airport (DFW) while an Embraer 505 operated as a fractional ownership flight crossed the runway downfield. Fortunately, there were no injuries in this incident (NTSB, 2016).

End-Around Taxiway (EAT) is proposed to reduce the number of runway crossings. The Federal Aviation Administration (FAA) defines the EAT as a taxiway that goes around the extended centerline of a runway and operations on the EAT would not conflict with the operation on that runway. (FAA, 2014). Previous studies show that the EAT could improve airport safety by eliminating runway crossings (Massidda & Mattingly, 2013), yield environmental benefits by reducing fuel burned (Uday, Burder, & Marais, 2011; Le & Marais, 2013) and improve airport operational efficiency and capacity (Ozdemir, Cetek, & Usanmaz, 2018; Massidda & Mattingly, 2013).

In the U.S., the EAT has already been implemented at Dallas/Fort Worth International Airport (DFW), Hartsfield-Jackson International Airport (ATL), Detroit Metro Airport (DTW), and Miami International Airport (MIA) (Le, 2014). In Europe, Amsterdam Schiphol Airport (EHAM) built two EATs in 2003 (Uday, 2011). DFW plans to construct three more EATs in the northeast, southwest, and northwest quadrants of the airport (Lancaster, 2017) and has received a $180 million grant from the Department of Transportation (Nichelson, 2018). ATL plans to build a new EAT in the south side of the airport and has received a $15.8 million grant from the FAA (Yamanouchi, 2017). Figure 1 is an illustration of the current EAT at DFW.

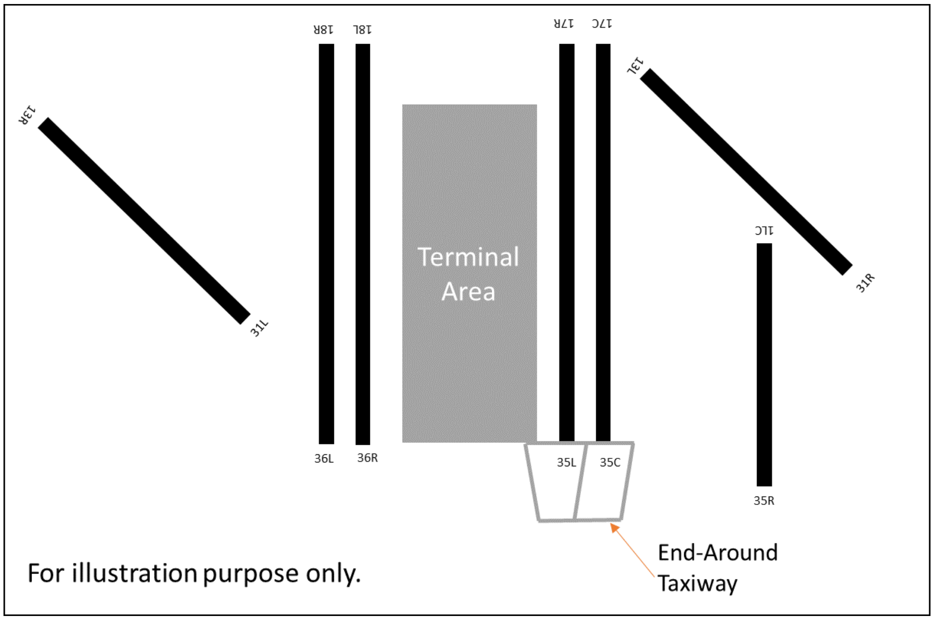

Figure 1. The EAT at the southeast airfield of Dallas/Fort Worth International Airport. Adapted from "Dallas/Fort Worth International Airport Map", by FAA, 2018, retrieved from https://www.faa.gov/nextgen/snapshots/airport/?locationId=27.

Other U.S. airports, such as Charlotte Douglas International Airport (CLT), Houston George Bush Intercontinental Airport (IAH), and Newark Liberty International Airport (EWR), are considering adding EATs to their future construction plan. CLT is planning to build two EATs with a new runway at the west of runway 18C/26C. The construction of the new runway and EATs will start in 2020 (CLT, 2015). IAH is considering building an EAT when the airfield demand exceeds 820,000 annual operations (Leighfisher, 2015). The construction outlook of EWR lists two EATs, but neither of the two new EATs is in the Capital Plan currently (FAA, 2018b).

Statement of Problem

An End-Around Taxiway (EAT), which connects the outboard runway with the terminal area by going around the inboard runway, is proposed to reduce the number of runway crossings. Previous studies about the EAT operations usually assumed that the inboard runways were used to take off and outboard runways were used to land with the EAT used as a taxi-in path. This kind of runway and taxiway choice is selected because it is widely used at major airports currently. There are two potential reasons that air traffic controllers prefer this kind of runway and taxiway choice at a parallel runway system in daily operations. One reason may be to reduce noise impacts on the communities surrounding the airports (LAWA, 2014). Another reason may be that the air traffic controllers believe that this kind of runway and taxiway choice would provide the most capacity (McNerney & Heinold, 2011).

However, for a parallel runway system with EATs at both ends, the thought that using the inboard runway to take off and the outboard runway to land could provide the most capacity may no longer be true. In a study about the potential impact of adding two EATs to the taxiway system at CLT, McNerney and Heinold (2011) assigned some departure aircraft to the outboard runway and used the EAT as the queueing route to approach the outboard runway. They found that departure and overall delay were reduced significantly while arrival delay decreased (McNerney & Heinold, 2011). The results of McNerney and Heinold (2011) indicated that the traditional runway choice (using the inboard runway to take off and the outboard runway to land) may not be the best option for a parallel runway system with EATs at both ends. However, no further research is found that comprehensively explores the potential benefits of using the inboard runway to land and outboard runway to take off at a parallel runway system with EATs at both ends. To address this gap, this dissertation research aims to explore the performance of four available runway and taxiway choices at a parallel runway system with EATs at both ends in terms of taxi time, fuel consumption, runway crossing, and the ability to cope with the increase in the traffic load level.

Research Question

The dissertation aims to answer the research question:

"What is the impact of different take-off and landing runway and taxiway choices on airport performance in terms of taxi time, fuel consumption, and runway crossing during high traffic periods, as well as the ability to cope with increases in the traffic load level?"

There are six sub-questions:

1. What is the impact of different runway and taxiway choices on airport performance in terms of taxi-in time during high traffic periods?
2. What is the impact of different runway and taxiway choices on airport performance in terms of taxi-out time during high traffic periods?
3. What is the impact of different runway and taxiway choices on airport performance in terms of fuel consumption per taxi-in during high traffic periods?

4. What is the impact of different runway and taxiway choices on airport performance in terms of fuel consumption per taxi-out during high traffic periods?
5. What is the impact of different runway and taxiway choices on airport performance in terms of runway crossings during high traffic periods?
6. What is the impact of different runway and taxiway choices on airport performance in terms of the ability to cope with increases in the traffic load level?

Significance of Problem

Previous studies found during this research (Satyamurti, 2007; Massidda & Mattingly, 2013; Uday, Burder, & Marais, 2011; Le & Marais, 2013; Ozdemir, Cetek, & Usanmaz, 2018) are based on the traditional runway choice, which uses the inboard runways to take off and outboard runways to land. The traditional runway choice may limit the potential benefit of the introduction of the EAT on airport performance. No research is found that comprehensively explored the potential benefits of using the in-board runway to land and out-board runway to take off at a parallel runway system with EATs. To address this gap, this research explores the impact of four different landing and take-off runway choices in terms of taxi-time, number of runway crossing, number of operations per time period, and fuel consumption at a commercial service airport during high traffic period.

The results of this research project may inspire further research about how to use the EAT more efficiently. The results of this research project may be a valuable reference to researchers who are interested in airport operations, and to the airport operators who consider building EATs in the future.

Statement of Scope

In this research, a simulation of runway-taxiway system of a fictional airport is built using ARENA®, a commercially available simulation software package from Rockwell Automation. The runway-taxiway system has a parallel runway system with EATs at both ends. The performances of different landing and take-off runway choices are investigated in terms of taxi-time, number of runway crossing, and fuel consumption. The scope of this research is limited to explore parallel runway systems which have EATs at both end at commercial service airports during high traffic period. As for the arrival aircraft, the model only simulates procedures of 1) arriving at the final approach fix (FAF), 2) landing on the designated runway, and 3) taxiing in to the designated near apron area. For the departure aircraft, the model only simulates procedures of 1) taxiing from the taxiway out to the designated runway, 2) taking off from the designated runway, and 3) climbing to 3000 feet. Other operations, such as terminal and apron operations, are not included in this research.

Assumptions

This research is conducted based on these assumptions:

1) The simulation provides a reasonable representation of the real word.
2) The data used is sufficient to reflect the traffic pattern during the peak traffic time at commercial service airports.
3) The model of a fictional parallel runway system with two EATs is useful to understand the usage of EATs at other airports.
4) Fuel consumption estimated by ICAO engine emission databank is sufficient to compare the real consumption differences.

Limitations

This research is conducted based on these limitations:

1) Models are abstract representations of the real world; therefore, there are differences between the real world and simulations.
2) Models do not simulate the whole system.
3) Human factors, such as the workload of air traffic controllers, the communication between the pilots and the tower, and the experience and skills of pilots, are not included in this simulation model.
4) The input traffic data of the simulation model are determined based on a sample of the real traffic data at DFW.
5) This research only investigates one fictional example of a dual parallel runway system with End-Around Taxiways at primary airports.
6) This research only simulates the normal airport operations at peak traffic times.

7) The configuration of the fictional parallel runway system is inspired by the configuration at DFW.
8) The model only considers aircraft operations under Visual Meteorological Conditions (VMC).
9) This model considers the minimum separation requirements for departures and landings due to wake turbulence. Only Boeing 737-800 aircraft are used in the experiment.
10) The taxiing speed, approach and landing speed, and takeoff speed are estimated based on historical data and previous studies.
11) Fuel flow rates obtained from the ICAO engine databank are used to estimate fuel consumption.

Delimitations

This research is conducted based on these delimitations:

1) This research does not explore the impact of the End-Around Taxiways on triple parallel runway systems or runway systems with other configurations or at any real airports.
2) The model only simulates aircraft's operations on runways, taxiways, and the End-Around Taxiways.
3) This research does not simulate the whole day's operations at an airport.
4) Other operations at an airport, such as the gate turnaround, the baggage delivery, and fuel refilling, are not considered in the model.
5) Any disruptive events, such as adverse weather, are not considered in this research.

2. REVIEW OF LITERATURE

This chapter provides a brief review of the regulations and literature that are related to the research question. The first section introduces regulation and suggestions from the ICAO and the FAA about the EAT. The second section discusses the strategies for runway selection specified by the FAA. The third section explores airports that have constructed or plan to build EATs in the U.S. The fourth section presents previous studies about the EAT. The last section explores previous studies that use simulation to study runway operations.

Regulations

ICAO

Working with 193 member states and industry groups, ICAO publishes the international civil aviation Standards and Recommended Practices (SARPs) and additional documents to enhance the safety, security, cooperation, efficiency, and sustainability of the international civil aviation. Those SARPs are generalized and categorized into 19 Annexes. The SARPs of Annex 10 contain the requirements and recommendations about the equipment and systems used for aeronautical telecommunications (ICAO, 2018a). The SARPs of Annex 14 prescribe the design requirements of airports (ICAO, 2018b). The *Doc 4444 – Procedures for Air Navigation Services – Air Traffic Management* (PANS-ATC) is a complement to *Annex 2 – Rules of the Air and Annex 11 – Air Traffic Services* (ICAO, 2016).

The SARP of Annex 14 Volume 1 prescribes the requirements about the physical characteristics at airports. ICAO (2018b) refers to an EAT as a perimeter taxiway and defines it as "a taxi route that goes around the end of a runway, enabling arrival aircraft (when landings are on outer runway of a pair) to go to the terminal, or departure aircraft (when departures are on outer runway of a pair) to get to the runway, without either crossing a runway or conflicting with a departing or approaching aircraft" (p. 344). ICAO (2018b) provides several criteria about the design of the perimeter taxiways:

1) The distance between the perimeter taxiway centerline and the end of the runway must ensure that the tails of the taxiing aircraft operating on the perimeter taxiways would not penetrate any approach surface.
2) The jet blast of departure aircraft should not impact the taxiing aircraft on the perimeter taxiway.
3) The design of the perimeter taxiway should follow the requirements for a runway end safety area. The potential interference with the ILS or other navigation aids should be considered. For example, the perimeter taxiway should be located behind the localizer antenna in order to reduce the possible interference with the ILS.
4) Appropriate measures and equipment should be added to assist pilots on the departure aircraft to distinguish between aircraft that are taxiing on the perimeter taxiway and those that are crossing the departure runway (ICAO, 2018b).

The SARPs of Annex 10 Volume 1 prescribe the equipment and systems used for aeronautical telecommunications (ICAO, 2018a). According to Annex 10 (ICAO, 2018a), the Instrument Landing System (ILS) shall comprise three basic components: 1) VHF localizer equipment and associated equipment (such as monitor, remote control, and indicator); 2) UHF glide path equipment and associated equipment; and 3) an appropriate means to enable glide path verification checks. The ILS critical and sensitive areas, which are areas around the localizer and glide path antennas, are used to protect the ILS signal from any potential interference. Any vehicles and aircraft are forbidden to operate in the ILS critical area during all ILS operations. In the ILS sensitive area, the movements of large objects should be controlled during the ILS operations. Six factors could influence the dimensions of the critical are: a) the radiation patterns of the localizer and glide path antennas, b) the category of approach and landing operations to be supported, c) the amount of static disturbance, d) locations, sizes and orientations of aircraft and other vehicles, e) runway and taxiway layout, and f)antenna locations (ICAO, 2018a).

Doc. 4444 Procedure for Air Navigation Services – Air Traffic Management (PANS-ATC) (ICAO, 2016) is a complement to *Annex 2 – Rules of the Air and Annex 11 – Air Traffic Services*. It specifies in detail the air traffic services such as the procedures of runway-in-use selection and separation minima for aircraft in the arrival and departure phase. Runway-in-use is defined as "the runway or runways that, at a particular time, are considered by the aerodrome control tower to be the most suitable for use by the types of aircraft expected to land or take off at the aerodrome"

(ICAO, 2016, p. 142). The air traffic controller should consider the surface wind and direction, the taxiway layout, the length of runways, the available approach and landing aids, and the requirements of noise abatement. However, the noise abatement should not be the determining factor in the runway selection when the weather condition is severe at the aerodrome (ICAO, 2016).

PANS-ATC (ICAO, 2016) specifies wake turbulence separation minima for three aircraft types. Each aircraft is classified to one of these three different aircraft types (HEAVY (H), MEDIUM (M), and LIGHT (T)) based on the certified maximum takeoff weight. As for separation minima, the controllers shall not need to consider the wake turbulence separation minima,

"a) for arriving VFR flights landing on the same runway as a preceding landing HEAVY or

b) MEDIUM aircraft; and between arriving IFR flights executing visual approach when the aircraft has reported the preceding aircraft in sight and has instructed to follow and maintain own separation from the aircraft (ICAO, 2016, p. 113)."

Under situation a) and b), the minimum separation between two departing aircraft is one minute if the takeoff paths of the aircraft diverge at least 45 degrees immediately after takeoff; otherwise, the following aircraft has to wait at least two minutes (ICAO, 2016).

As for wake turbulence separation, MEDIUM aircraft should wait at least 2 minutes to land behind HEAVY aircraft, and LIGHT aircraft should wait at least 3 minutes to land behind HEAVY and MEDIUM aircraft. The separation between a departure LIGHT aircraft and the preceding departure HEAVY or MEDIUM aircraft and between a departure MEDIUM aircraft and the preceding departure HEAVY aircraft should be at least 2 minutes (ICAO, 2016).

FAA

According to the FAA *AC No. 150/5300 – 13A:* Airport Design (2014), the End-Around Taxiway is "a taxiway crossing the extended centerline of a runway, which does not require specific clearance from air traffic control (ATC) to cross the extended centerline of the runway" (p. 5). The FAA *AC No. 150/5300 – 13A* (2014) provides specific design requirements for the EAT and the EAT visual screen.

To ensure that the tail height of any aircraft that are taxiing on the EAT would not penetrate the 40:1 departure surface, the distance between the centerline of an EAT and the stop end of the runway must be greater than 1,500 feet. An airspace study is required to verify the compliance with the takeoff regulation and limitations in Order 8260.3 and Part 121, §121.189. To avoid any potential interference with the ILS, the EAT must be located entirely outside of any ILS area (FAA, 2014). The FAA also suggest that the EAT could be constructed at a surface that is lower than the end of the inboard runway so that the EAT would not be too far away from the runway and terminal area (FAA, 2014). An EAT visual screen is recommended by the FAA (2014) to avoid potential issues where pilots on the departure aircraft confuse an aircraft taxiing on the EAT with one crossing the departure runway near the stop end of it.

The FAA *Order JO 7110.65X, Air Traffic Control* (FAA, 2017a) provide to air traffic controllers phraseology and practices, which they should be familiar with when providing air traffic control services. According to *Order JO 7110.65X* (FAA, 2017a), one runway crossing clearance normally could only allow an aircraft to cross one active runway. Another runway clearance must be issued if the aircraft need to cross a second active runway. For airports at which the taxi distance between two active runways is less than 1,300 feet, multiple runway crossing may be allowed if the air traffic manager submit a request to the Director of Air Traffic Operations. After receiving such approvals, controllers at those airports could allow aircraft to cross multiply active runways with one clearance (FAA, 2017a).

Order JO 7110.65X (FAA, 2017a) also clarifies the procedures to issue a runway crossing clearance. As for departure operations, the controller must visually observe that the departure aircraft is in a turn or has passed the location of the crossing aircraft before issuing a crossing clearance to the crossing aircraft. For arrival operations, the controllers could only issue a crossing clearance under one of the following conditions:

1) the crossing aircraft would complete the crossing before the arrival aircraft fly over the landing threshold；
2) the controller has verbally confirmed with the pilot on the arrival aircraft that has landed that the arrival aircraft would exit the runway before the location of the crossing aircraft;
3) the controller visually confirms that the arrival aircraft has exited the runway before the location of the crossing aircraft; or
4) the controller visually observes that the arrival aircraft has passed the location of the crossing aircraft (FAA, 2017a).

As for the simultaneous operations on parallel runways, the FAA (2017a) specifies two operation models: simultaneous, same direction operation and simultaneous, opposite direction operation. Both operation models could only be authorized under Visual Flight Rules (VFR) conditions. The controllers must ensure a two-way radio communication with the involved pilots. Moreover, the distance between the parallel runways must be larger than the same direction distance minima or the opposite direction operation minima if a simultaneous, same direction operation or a simultaneous, opposite direction is approved (FAA, 2017a). *Order JO 7110.65X* (FAA, 2017a) also specifies the aircraft separation requirements for takeoffs on the same runway, takeoffs on parallel runways, landings on the same runway, and landings behind takeoffs.

Discussion

Both ICAO and the FAA define the End-Around Taxiway as a taxiway that crosses the extended centerline of a runway and the operations of which would not conflict the operations on the runway. ICAO prescribes general requirements for the design of the EAT to ensure the safety of the departure and landing operations on the runway. The FAA provides more detailed information about the construction of the EAT to ensure that the operations on the EAT and the inboard runway would not conflict with each other. For example, in order to avoid potential interference with the ILS, ICAO requires that the EAT should be constructed behind the localizer antenna, while the FAA's regulation is clear and strict: the EAT should be entirely outside of the ILS critical area. The FAA also provides guidelines to build an EAT screen at the end of the runway. Currently, the FAA only allows the departure aircraft to fly over an active EAT. Landing aircraft passing over the active EAT is still under analyses (Hoover, 2007). No explicit regulatory information about the operations of the EAT was found in ICAO documents, SARPs, and FAA regulations.

As for airport ground operations, ICAO provides general guidelines and standards for runway-in-use and separation minima, while the FAA's regulations contain comprehensive information about the procedures of runway selection and separation minima determination. The FAA also presents procedures and standards to issue runway-crossing clearances. Such information could be used to build the logic modules in the simulation model so that the model could simulate the operations at airports more accurately.

Strategies for Runway Selection

According to *JO 7210.3AA: Facility operation and administration* (FAA, 2017b), the airport traffic control tower (ATCT) supervisor/ Controller-in-charge (CIC) is responsible for deciding active runways based on many factors, such as “surface wind direction and velocity, wind shear/microburst alerts/reports, adjacent airport traffic flows, severe weather activity, IFR departure restrictions, environmental factors” (p. 230), that may affect the safety of aircraft takeoffs and landing. If an airport does not establish a runway use program, the ATCT supervisor/CIC at that airport would decide may decide active runways based on wind speed. When the wind speed is less than 5 knots, the “calm wind” runways could be used. When the wind speed exceeds 5 knots, runways that are mostly aligned with the wind direction should be used. If there is an established runway use program, the air traffic control (ATC) would assign the runways that have the least noise impact according to the program unless there are some safety concerns (FAA, 2017a).

No regulations have been found during this research that explicitly state that the inboard runway is to be used for taking-off and the outboard runway is to be used for landing. One reason that many airports choose such “inboard taking-off, outboard landing” runway operation model is to reduce noise impacts on the communities surrounding the airports (LAWA, 2014; McNerney and Heinold, 2011). Another reason may be that the air traffic controllers believe that using the inboard runway to take off and the outboard runway to land could provide the most capacity (McNerney & Heinold, 2011).

For example, the runway usage strategy for DFW is to primarily use the inboard parallel runway for take-offs and the outboard parallel runway for landings. Wind direction and speed is the primary factor that decides aircraft operation direction and runway use at DFW (Lancaster, 2017). The winds at DFW are mainly from the south (about 70%) and the north (30%). Therefore, the airport typically uses the north/south runways (DFW, 2019). Table 1 shows the primary departure runways and the primary arrival runways at DFW, as well as the secondary departure and arrival runways. Under both wind flows, the inboard runways are the primary departure runway and the outboard runways are the primary arrival runways. Because of noise considerations, Runways 17L/35R and 13R/31L, which are close to the surrounding communities, would not typically be used for departures (Lancaster, 2017).

Table 1.

The Primary and Secondary Departure or Arrival Runways at DFW for South and North Flow.

	Departure		Arrival	
	Primary	Secondary	Primary	Secondary
South flow	35L, 35R	36L, 34C	18R, 17C	17R, 18L, 17L, 13R
North flow	18L, 17R	18R, 17C	36L, 35C	36R, 35L, 35R, 31R

Note. Adapted from "DFW Airport Noise Program: A Briefing for the City of Coppell" by S. Lancaster. Retrieved from http://www.coppelltx.gov/Documents/2017-DFW-Airport-Update.pdf.

However, the belief that using inboard runways to take off and outboard runways to land could provide airports the most capacity may not be true after implementing the EATs. In an EAT simulation study, McNerney & Heinold (2011) assigned some departure aircraft to the outboard runway and used the proposed EAT as the departure queue. The results showed that both of the average taxi-out time and the overall taxi time were reduced greatly. No research was found, however, that comprehensively explore the impact of different runway choices on airports with EATs at both ends. To address this gap, the author proposed a research study about focusing on the impact of different inboard and outboard runways choices in terms of airport operational and environmental performance.

Current EATs Usage

In U.S., the EAT has already been implemented at Dallas/Fort Worth International Airport (DFW), Hartsfield-Jackson International Airport (ATL), Detroit Metro Airport (DTW), and Miami International Airport (MIA) (Le, 2014). In Europe, Amsterdam Schiphol Airport (EHAM) have built two EATs in 2003 (Uday, Burder, & Marais, 2011).

DFW plans to construct three more EATs in the northeast, southwest, and northwest quadrants of the airport (Lancaster, 2017) and has received $180 million grant from the Department of Transportation on July 27, 2018 (Nichelson, 2018). ATL plans to build a new EAT in the south side of the airport and has received $15.8 million grant from the FAA (Yamanouchi, 2017).

Charlotte Douglas International Airport (CLT) is planning to build two EATs with a new runway that locates at the west of runway 18C/26C. The construction of the new runway and EATs will start in 2020 (CLT, 2015). Houston George Bush Intercontinental Airport (IAH) considers building an EAT when the airfield demand exceeds 820,000 annual operations (Leighfisher, 2015).

The construction outlook of Newark Liberty International Airport (EWR) lists two EATs, but neither of the two new EATs is in the Capital Plan currently (FAA, 2018b).

DFW

The first EAT at the southeast quadrant of DFW began operations in December 2008 (Le, 2014). Arrival aircraft that land on runway 17L could taxi around the inboard runways 17C and 17R via the EAT instead of crossing them. Arrival aircraft that land on runway 17C could also use the EAT to avoid crossing runway 17R. Aircraft with tail heights less than 46 feet could use the whole EAT, while aircraft with tail heights between 46 feet and 66 feet could only use the exterior segments of the EAT. Airbus 380 of which the tail height is 80 feet is not allowed to use the EAT under any conditions (Uday, 2011).

DFW plans to build three more EATs at the northeast, southwest, and northwest quadrants of the airport (Lancaster, 2017). The EAT at the northeast quadrant of the airport is already under construction and is expected to be completed by 2021, and the construction of the southwest EAT is expected to be done by 2023 (Nichelson, 2018). Figure 2 is the illustration of the three proposed EATs at DFW.

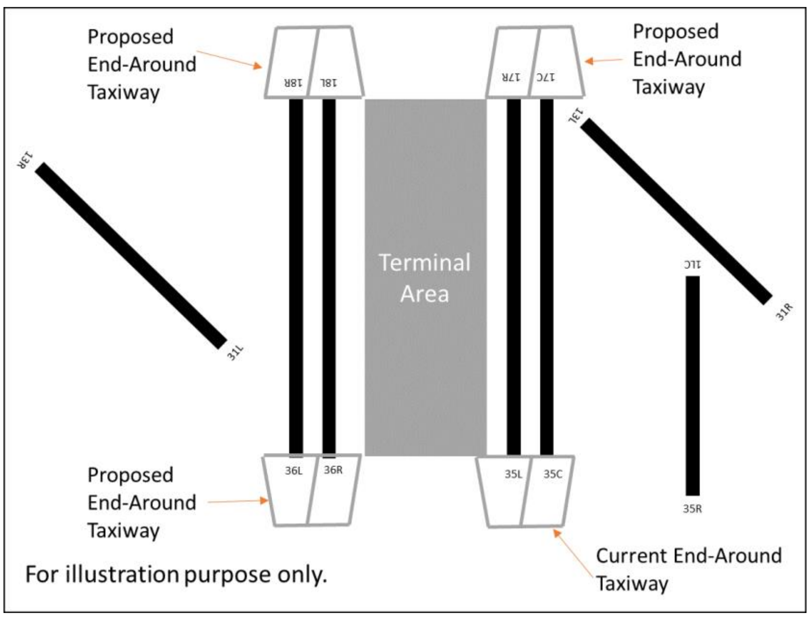

Figure 2. Dallas/Fort Worth International Airport map with the three proposed EATs. Adapted from “Dallas/Fort Worth International Airport Map”, by FAA, 2018c, Retrieved from https://www.faa.gov/nextgen/snapshots/airport/?locationId=27

ATL

The EAT at the northwest quadrant of ATL came into service in April 2007 (Le, 2014). Figure 3 is the illustration of the current EAT at ATL. The surface of the EAT is about 30 feet below the surface of runway 8R (Scott, 2015). The arrivals on runway 8L could use the EAT to taxi across the inboard runway 8R to approach the terminal area.

As a part of the short-range development plan, ATL plans to build a new EAT around the end of runway 27R. The proposed EAT will allow arrivals by Airplane Design Group (ADG) IV and smaller aircraft on runways 27L and 28 to taxi around runway 9L/27R during runway 27R departures (City of Atlanta, 2015). In 2017, ATL received a $15.8 million funding from the FAA to support the first phase of the construction (Yamanouchi, 2017).

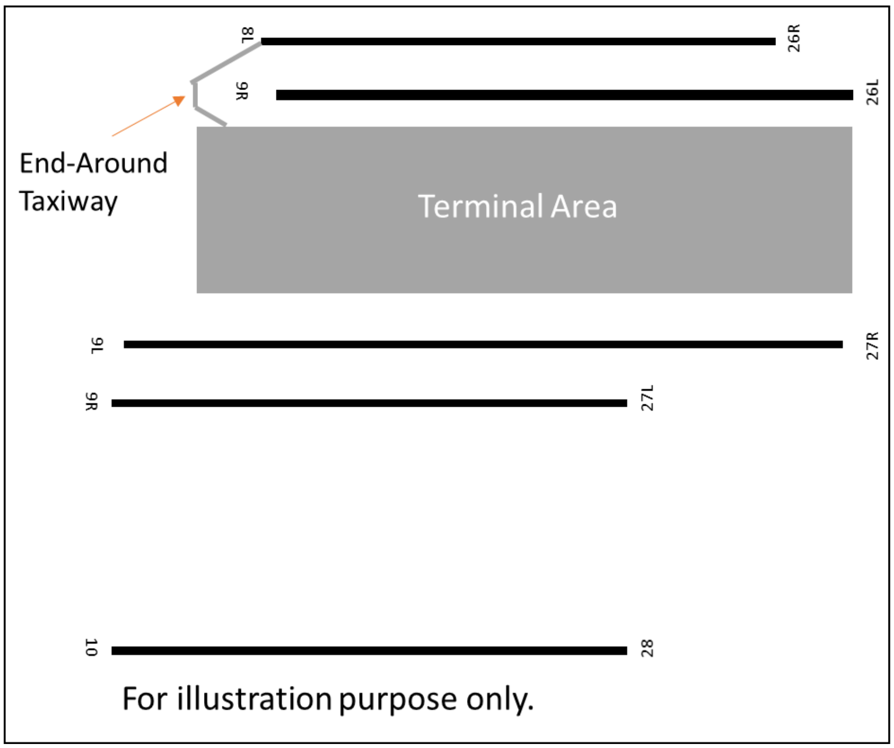

Figure 3. Hartsfield-Jackson International Airport map with the current EAT at the northwest airfield. Adapted from “Hartsfield-Jackson International Airport Map”, by FAA, 2018d, Retrieved from https://www.faa.gov/nextgen/snapshots/airport/?locationId=54.

DTW

The EAT of DTW, also called taxiway Quebec, came into service in 2004 (Le, 2014). Figure 4 is the illustration of the EAT at ATL. The EAT connects runway 4L/22R with the terminal area. Arrival aircraft that land on runway 22R, then, could taxi via the EAT to approach the terminal area without any runway crossings.

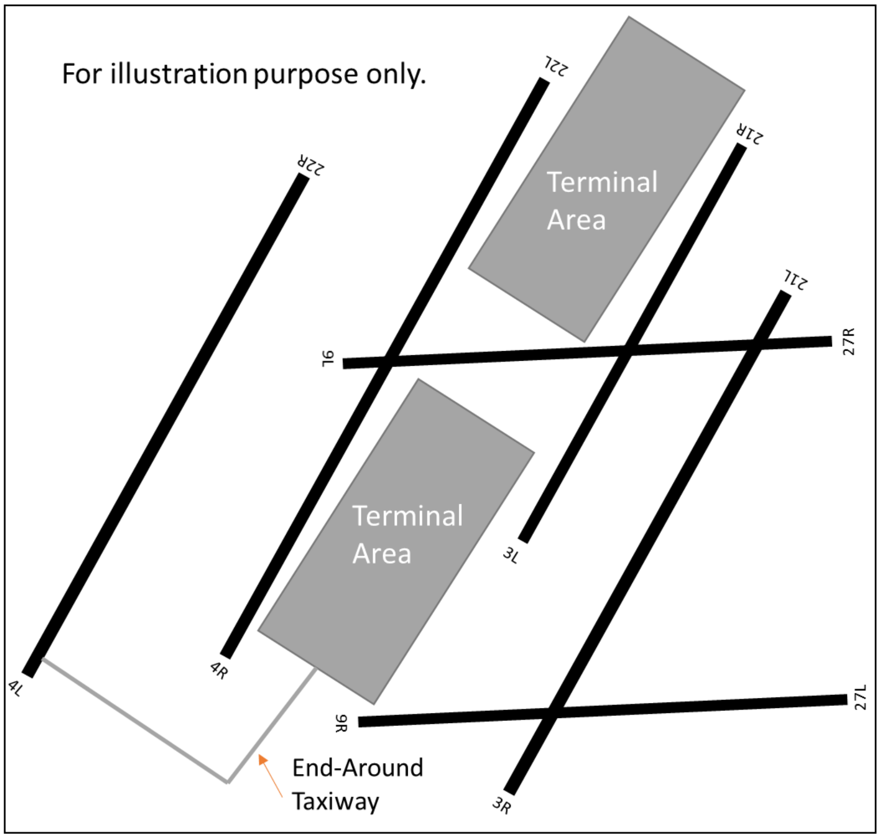

Figure 4. Detroit Metro Airport map with an EAT at the south airfield. Adapted from "Detroit Metro Airport Map", by FAA, 2018e, Retrieved from https://www.faa.gov/nextgen/snapshots/airport/?locationId=28.

MIA

The EAT at MIA connects runway 8L/26R with the terminal area. Arrival aircraft on runway 8L could taxi around the end of runway 8R without interrupting the departure operations on the inboard runway. Figure 5 is an illustration of the EAT at MIA. No information has been found about the operations of the EAT at MIA.

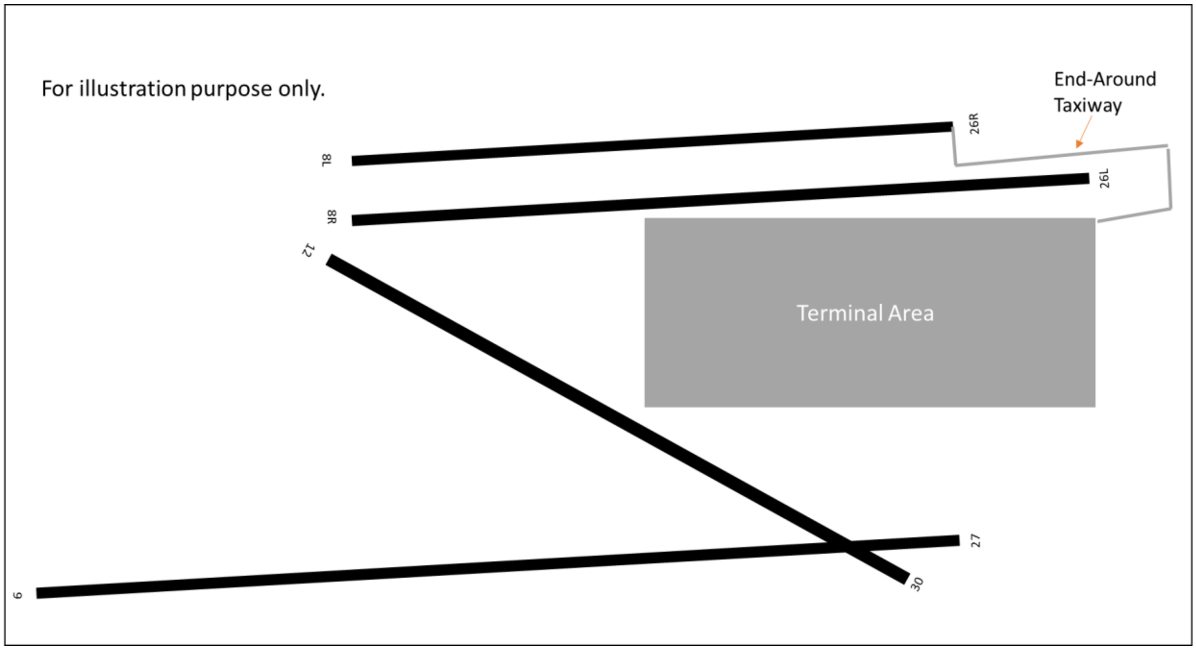

Figure 5. Miami International Airport map with an EAT at the south airfield. Adapted from "Miami International Airport Map", by FAA, 2018f, Retrieved from https://www.faa.gov/nextgen/snapshots/airport/?locationId=40.

EHAM

EHAM built a new runway 18R/26L in the northwest of the airport in 2003. Along with the new runway, EHAM also built two perimeter taxiways Yankee (Y) and Zulu which could allow aircraft that proceed to and from runway 18R/26L to taxi around the end of runway18C/26C instead of waiting for clearance (Air Traffic Control the Netherlands, 2019). The EATs would lighten the negative impact of the new runway 18R/26L on the capacity of runway 18C/26C through the reduction of runway crossings (Uday, 2011).

Airports that Plan to Build the EAT in the Future

IAH

In order to fulfill the increasing airfield demand, Leighfisher (2015) prepares for IAH an Airport Master Plan which consist of three stages: PAL25, PAL 33 and PAL 40. As a part of PAL 40, IAH plans to construct an EAT at the northwest quadrants of the airport. Figure 6 is an illustration of the location of the EAT. The proposed EAT would allow arrivals at Runway 8L/26R to taxi around the new Runway 8C/26C. The EAT would be 1,800 feet away from the end of the runway 8C which means that ADG III and smaller aircraft could use the EAT without penetrating the 40:1 departure surface of Runway 26C. The final decision of the EAT construction depends on the airfield demand, the apron layout, and the level of congestion at the nearby taxiways (Leighfisher, 2015).

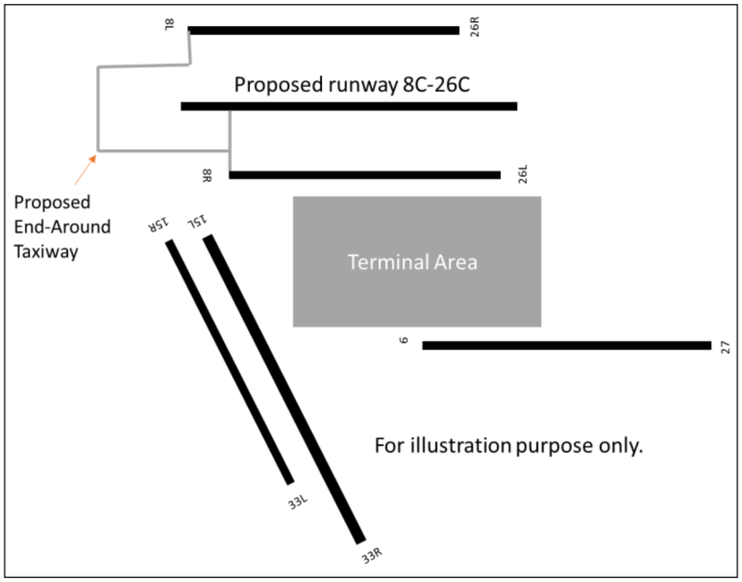

Figure 6. Houston-George Bush Intercontinental Airport map with a proposed EAT at the northwest airfield. Adapted from “Houston-George Bush Intercontinental Airport Map”, by FAA, 2018g, Retrieved from https://www.faa.gov/nextgen/snapshots/airport/?locationId=33.

CLT

CLT plans to build a fouth runway 1.450 feet west of runway 18C/36C and between the existing runways 18C/36C and 18R/36L. The plan also includes two EATs that will go around both ends of the runway 18C/36C. The estimated total cost of this project is $422 million. CLT plans to begin the construction in 2020 and complete the fourth runway and the two EATs in 2022 (CLT, 2015).

EWR

EWR plans to build two EATs at both ends of runway 4L/22R. The centerline of the EAT at the north end would extend 1,500 feet away northeast. The construction of the two EATs is supposed to begin in 2020 (FAA, 2018b).

Research on EATs

Previous research about the EATs mainly focused on two aspects: 1) analyzing the influence of the EATs on airport safety (Massidda & Mattingly, 2013), environment (Uday, Burder, & Marais, 2011) and airport capacity (Engelland and Ruszkowski, 2010; Massidda & Mattingly, 2013) based on the traffic and operation data from airports that have already implemented the EATs; and 2) simulating and estimating the performance of the EAT under given scenarios or at new airports (Satyamurti, 2007; Jadhav, Neogi, & Von Thaden, 2009; McNerney & Heinold, 2011; Jadhav, 2013; Le & Maraise, 2013; Ozdemir, Cetek, & Usanmaz, 2018).

Table 2 shows the EAT usage percentage for the arrival aircraft on the outboard runway at parallel runway systems with EAT at one end at DFW, ATL, and DTW (Engelland & Ruszkowski, 2010; Uday, et al., 2011; Le &Marais, 2013; Le, 2014). More than 50% of the arrivals on the outboard runway used the EATs to approach the terminal areas in 2012 at DFW, ATL, and DTW (Le & Marais, 2013). The historical data about DFW shows that the ATCs tend to use the EAT more and more frequently from 2009 to 2012, as the usage percentage of the EAT for arrivals on runway 17L at DFW increases from 35% in 2009 (Engelland & Ruszkowski, 2010) to 44% in 2010 (Uday, et al., 2011) to 55% in 2012 (Le, 2014).

Table 2.

EAT Usage at DFW, ATL, and DTW.

	DFW	ATL		DTW	
Arrival Runway	17L	26R	8L	22R	4L
EAT Usage Percentage	35% in 2009[c] 44% in 2010[a] 51% in 2011[d] 55% in 2012[b]	62% in 2012[b]	49% in 2012[b]	67% in 2012[b]	56% in 2012[b]

Note. [a] Information is obtained from "Environmental benefits of End-Around Taxiway operations," by Uday, P., Burder, D., & Marais, K. B, 2011. *Proceedings of the 11th AIAA Aviation Technology, Integration, and Operations Conference*, Virginia Beach, VA. doi: 10.2514/6.2011-7049.

[b] Information is obtained from "*Investigating surface performance trade-offs of unimpeded taxiways* (Master's thesis)," by Le, T.T., 2014. Retrieved from https://docs.lib.purdue.edu/open_access_theses/208

[c] Information is obtained from "Analysis of DFW perimeter taxiway operations" by Engelland, S.A., &Ruszkowski, L, M. (2010). *Proceedings of 2010 AIAA ATIO/IS SMO Conference*. Fort Worth, TX.

[d] Information is obtained from "Empirical assessment of the End-Around Taxiway's operational benefits at Dallas/Fort Worth International Airport using ASDE-X Data", by Massidda, A, & Mattingly, S.P, 2013. *Proceedings of the Transportation Research Broad 92nd Annual Meeting*, Washington D.C. Retrieved from https://trid.trb.org/view/1243064

Le and Marais (2013) investigated the usage percentages of the EATs in terms of different arrival times and found that the EATs were the primary taxiing route when the traffic level was high, especially during the peak departure times on the inboard runways.

EATs may also benefit the airport operations under adverse weather conditions. Engelland and Ruszkowski (2010) found an unusual 78.1% of arrivals on runway 17L at DFW used the EAT in October 2009, which was much larger than the usage percentages in the previous and preceding mouth: 28.4% and 29.1%. Based on their analysis, this significant change was due to the low-visibility weather conditions in October 2009 (Engelland & Ruszkowski, 2010). ATC could focus on the departure operations under adverse weather by letting the arrival aircraft taxi in via the EATs. Using the EAT could also reduce the ATC's workload by reducing the interactions between the departure aircraft and arrival aircraft.

Analysis of EAT Operations

In the literature, researchers reported their efforts to understand the impact of EAT operations on airport in terms of airport safety (Massidda & Mattingly, 2013), operational efficiency (Engelland & Ruszkowski, 2010; Uday, et al., 2011; Le &Marais, 2013), airport capacity (Massidda & Mattingly, 2013) and fuel consumption (Uday, et al., 2011; Le &Marais, 2013) by analyzing the Airport Surface Detection Equipment, Model X (ASDE-X) data. Key characteristics used in the literature to evaluate the influence of EATs included the number of runway crossings, average taxi-in time, average taxiing speed, daily maximum throughput rate, departure delay, and average fuel consumption per taxi-in. This section presents main findings of the literature.

Enhance Airport Safety

EATs could enhance runway safety by reducing the number of runway crossings. Instead of have aircraft holding and crossing active runways, arrival aircraft could use EATs to taxi around the inboard runway. Massidda and Mattingly (2013) found that about 83% of the arrivals on runway 17L at DFW used either the EAT or low-risk taxiways located at the end of runways. Nearly none of arrival aircraft on runway 17L crossed the inboard runway using the mid-runway crossings. Therefore, implementation of EATs could considerably reduce the possibility of runway incursion.

Improve Taxi-in Performance

EATs could improve the taxi-in performance of parallel runway systems by simplifying the taxi-in procedure. Instead of holding and waiting for ATC's order, arrival aircraft could taxi on the EAT without slowing down or stopping. Previous analyses show that the average taxi-in time on EAT is close to the average taxi-in time on the conventional taxiways (Engelland & Ruszkowski, 2010; Uday, et al., 2011; Le &Marais, 2013). Table 3 shows the average taxi-in time of arrivals via the EAT and via conventional taxiways at DFW, DTW, and ATL, respectively.

Table 3

Average Taxi Time at DFW, DTW, and ATL in 2012[a].

Airport	Runway	Configuration	Arrival Taxi Time (mins)	
			Taxi via EAT	Taxi via Conventional Taxiway
DFW	17L	South-flow	10.49	8.35
DTW	22R	South-flow	5.95	5.18
	4L	North-flow	8.55	5.96
ATL	26R	West-flow	4.57	3.21
	8L	East-flow	7.08	4.58

Note: [a] Information is summarized from "Optimization of end-around taxiway for efficient operations and environmental benefits", by Le and Marais, 2013. *Proceedings of the Aviation Technology, Integration, and Operations Conference*, Los Angeles, CA. doi: 10.2514/6.2013-4313

Aircraft could taxi under a relatively higher speed on EATs as they do not need to slow down or stop to wait for clearance from the ATC to cross the active runways. Table 4 presents the average taxi-in speed on EATs and conventional taxiways at DFW, ATL, and DTW (Le and Marais, 2013). The average taxiing speeds on EATs at DFW, ATL, and DTW are 16.2 knots, 16.8 knots, and 25 knots respectively, which are higher than the average taxiing speed on the conventional taxiways.

Table 4

Average Taxi-in Speed on EATs and Conventional Taxiways at DFW, ATL, and DTW [a].

	Average Speed (knots)		
	DFW	ATL	DTW
EAT	16.2	16.8	25
Conventional Taxiway	14.7	11	15

Note. [a] Information is summarized from “Optimization of end-around taxiway for efficient operations and environmental benefits”, by Le and Marais, 2013. *Proceedings of the Aviation Technology, Integration, and Operations Conference*, Los Angeles, CA. doi: 10.2514/6.2013-4313

Improve Airport Capacity

EAT could benefit the airport capacity because of the higher taxiing speed and the elimination of runway crossings. Massidda and Mattingly (2013) evaluated the impact of the EAT on departure and arrival capacity at DFW. The departure and arrival capacity were measured by the daily maximum throughput rate (DMTR), which was the “hourly arrival rate based on the shortest time interval for thirty arrivals at the airport” (Massidda & Mattingly, 2013, p. 4). The statistical analysis showed that the mean DMTR on runways 17R and 17C after using EAT were increased by 40% and 25% respectively at DFW. EAT also reduced the departure delay on runway 17R by 38% because departure aircraft did no need to wait for the arrival aircraft crossing the departure runway.

Yield Environmental Benefits by Reducing Fuel Consumption

Despite the fact that taxiing distance via EAT is much longer than that via conventional taxiway, sometimes even twice as much as the conventional taxiing path (Le & Marais, 2013), the average fuel consumption per taxi-in via EATs is close to the average fuel consumption per taxi-in via conventional taxiways (Uday, et al., 2011; Le and Marais, 2013). There are two potential reasons: 1) aircraft could taxi using a higher speed on EATs, and 2) aircraft do not need to stop on EATs. As discussed previously, airports with EATs could have a consistent fuel consumption performance between peak-traffic time and low-traffic time. Therefore, on average arrival aircraft could burn less fuel after EATs than before EATs.

Decision Rule to Maximize the Environmental Benefit

A decision rule is proposed to maximize the environmental benefit in terms of fuel savings based on data collected at DFW, DTW and ATL (Le & Marais, 2013; Fala, Le, Marais, & Uday, 2014). Both Le and Marais (2013) and Fala et al. (2014) explored five decision rules in their studies. The only difference between these two studies was the methods used to estimate the fuel consumption per taxiing, where Le and Marais (2013) ignored the "stop-and-start" and Fala et al. (2014) used Morris' model to estimate the fuel consumption during "stop-and-start". Five rules explored in these two studies (Le & Marais, 2013; Fala, et al., 2014) may be paraphrased as:

1) ***Always*** rule: All arrival aircraft would taxi in via the EAT.
2) ***Never*** rule: All arrival aircraft would taxi-in via the conventional taxiways. No EAT was used.
3) ***Arrival Time*** rule: The taxi-in route is decided based on "arrival time". Aircraft that land during the peak traffic period would approach the terminal area via the EAT, while aircraft that arrive during the low traffic period would taxi in via one of the conventional taxiways.
4) ***Terminal*** rule: The taxi-in route is decided based on "shortest taxi distance". Arrival aircraft would taxi in via the shortest taxi route no matter it is the EAT or conventional taxiway.
5) ***Multi-factor*** rule: The taxi-in route is decided based on both "arrival time" and "shortest taxi distance". During the peak traffic time, arrival aircraft would first be directed to the shortest taxiway. If the capacity of the shortest taxiway is exceeded, the proceeding arrival aircraft would taxi via the EAT.

The results show that the multi-factor rule would yield the largest fuel savings at DFW, DTW, and ATL, ranging from 18.8% fuel consumption reduction at ATL to 13.4% reduction at DFW to 25.4% reduction at DTW (Fala, et al., 2014).

Simulation Models of EAT Operations

Previous simulation studies of EATs were conducted at specific airports where the airport authorities were considering including EATs into their airport plan. For example, before DFW began their EAT construction, Satyamurti (2007) explored the potential impacts of EATs on DFW in terms of safety and operation.

Satyamurti (2007) simulated the operations of the proposed four EATs at DFW before the first EAT was built by building a discrete-event stochastic model in SIMMOD®. Four scenarios were tested in the research: south flow without the EATs, north flow without the EATs, south flow with the EATs, and north flow with the EATs. The impacts of EATs were evaluated in terms of the average taxi-in time, the average taxi-out time, the runway crossing delay, the Departure Efficiency Rate (DER), the Arrival Efficiency Rate (AER), and the hourly rate of runway use. This research found that the average taxi-in time increased greatly when aircraft used the EAT, and the average taxi-out time reduced with the help of the EATs. The overall airport efficiency at DFW would increase with the introduction of the EATs (Satyamurti, 2007).

Jadhav, Neogi, and Von Thaden (2009) used ARENA® to build a discrete-event model to explore the impact of the EAT on the operation of Chicago O'Hare Airport (ORD). The researchers chose three typical periods which represent low traffic level, high arrival level, and high landing level respectively. The results showed that although the use of EAT would increase the taxi-in time a little, it decreased the number of active runway crossings which would in return reduce the possibility of runway incursion. What's more, EAT could increase runways' utilization rates, especially the rates of departure runways (Jadhav et al., 2009).

McNerney and Heinold (2011) investigated the potential environmental benefit of the proposed EAT at IAH. The environmental benefit was measured by the emission reduction of several criteria pollutants, such as carbon monoxide (CO), non-methane hydrocarbons (NMHC), and nitrogen oxides (NOx) (McNerney & Heinold, 2011). The total emissions at IAH were estimated based on the Emissions and Dispersion Modeling System (EDMS). The results showed that using EAT would reduce the annual emission of CO by 33.4%, of NMHC by 21.1%, and of NOx by 7.4%. Aircraft which used the traditional taxiways had lower average speed than aircraft which taxied via EAT (McNerney & Heinold, 2011, p. 350). The lower power setting of aircraft at lower speed would be more likely to have incomplete combustion which would produce more CO. Conversely, NOx tended to be emitted more when the aircraft were at higher power setting. This may be the reason for the differences in the emission reduction percentages (McNerney & Heinold, 2011).

Based on Jadhav, Neogi, and Von Thaden's work in 2009, Jadhav (2013) built a model by ARENA® to evaluate the ground operations at ORD if EATs were used in terms of local-/global-level taxi-time, and number of runway crossings. The results showed that the local taxi-times increased by about 50% after the implementation of the EAT and the global taxi-time increased by about 15%. A total of 1,040 aircraft conflicts happened during the simulation. 19% of them were aircraft intersection, which mean that two aircraft used the same taxiway intersection at the same time, and the rest were queue conflict which mean that two aircraft tailed each other. None of the intersection conflicts, however, happened in the runway area which strongly pointed towards a reduction in the possibility of runway incursions (Jadhav, 2013, pp. 67-69).

Ozdemir, Cetek, and Usanmaz (2018) estimated the possible impact of two different EAT designs (named EAT-1 and EAT-2) at Istanbul Ataturk Airport (ISL). The model of ISL with the proposed EATs was built in SIMMOD®. The research team simulate the operations at ISL at peak traffic times used 102 departures and 98 landings. The research also considered four runway taking-off and landing models. Their study showed that the EATs had little impact on the runway system capacity. The research team also found that the EAT-1 could reduce the delay time by at least 73% and the taxi time by 37% while the EAT-2 would reduce the delay time by about 78% and the taxi time by about 52%. This research shed light upon the design of new EAT for airport authorities which planned to implement the EAT system (Ozdemir, et al., 2018).

A summary of the limitations of the previous simulation studies include:

1) Only point estimations of the input and output system parameters were provided.
2) Most of the previous studies did not clarify how the models were validated.
3) During the simulation, the arrival aircraft would use the EAT during both peak traffic time and non-peak traffic time. In daily operations, however, the air traffic controllers (ATCs) would prefer to use the shortest and fastest taxiing route during the low traffic period.

Research on Airport Simulation

Commercially available software, such as ARENA®, can be used to build discrete-event stochastic simulation models and run experiments. Kim, Akinbodunse, and Nwakamma (2005) used ARENA®, available from Rockwell Automation (Arena, 2020), to simulate the sequencing of aircraft arrivals at George Bush Intercontinental Airport (IAH). The results "have close values to the direct data analysis output" (Kim, Akinbodunse, & Nwakamma, 2005, p.6). Jadhav, Neogi, and Von Thaden (2009) used ARENA® to model the impact of EAT on the safety level of Chicago O'Hare Airport (ORD). The simulation model consisted of five modules: the approach module, the runway module, the taxiway module, the gate module, and the departure module. The results show that although the use of EAT would increase the taxi-in time "by a small factor", it would reduce the number of active runway crossings which would in return increase safety (Jadhav et al., 2009, p.12). However, the authors did not report verifying the model using real data. Another limitation of this model is that the model assumes that all taxi-in aircraft would use EATs even during a low traffic period, which is not realistic.

SIMMOD®, ProModel®, and Matlab® were used in airport simulation studies. Mori (2015) used Matlab®, which is a commercially available programming language and computing environment developed by MathWorks (MathWorks, 2020), to build a stochastic simulation model to explore airport congestion level under existing uncertainties at Tokyo International Airport (HND). The research results indicated that the airport traffic congestion level was mostly affected by the uncertainty of taxi-in or taxi-out and the traffic concentration (Mori, 2015).

Chen, Li and Gao (2015) used ProModel®, a commercially simulation software available from ProModel Corporation (ProModel Corporation, 2020), to build a simple and fast model to simulate the performance of Shanghai Hongqiao International Airport (SHA) under some potential scenarios that the airport would encounter in the future, such as the increasing traffic and changing traffic distribution. The results showed that the ground delays and the queueing sizes increased significantly when the flight traffic increased by 20%. The results also showed that a well-organized departure flight structure would trade off the impact of the increasing flight traffic on the waiting time of the aircraft in the departing queue and in turn improve the runway capacity (Chen, Li & Gao, 2015).

SIMMOD® (FAA, 2020a) is a fast-time simulation tool that is developed specifically for airport operation simulation. It could be used to estimate the taxi-in and taxi-out times, fuel consumption, and airport capacity under different scenarios (Lee & Balakrishnan, 2012).

Bubalo and Daduna (2011) used SIMMOD® to simulate the airport capacity and level of service at an independent parallel runway system at Berlin-Brandenburg International Airport (BER). Bubalo and Daduna designed six scenarios to test the possible future trends of preference for certain aircraft types. The results indicated that the capacity of BER would reach its maximum as early as 2018 if the average annual growth rate kept at 6%. Also, the results showed that the re-sequencing was effective when the sequences of flights were at the similar speed. This case usually happened when the airport was at peak traffic time and the aircraft were waiting for taking off or landing. However, the benefits of re-sequencing were overwhelmed by the efforts and costs. Although the re-sequencing would increase the airport short-term capacity, such reordering would increase air traffic controllers' workload and incurred delays on flights (Bubalo & Daduna, 2011).

Lee and Balakrishnan (2012) used SIMMOD® to evaluate the ground delays and taxi times of DTW in the presence of four specific uncertainties, such as the actual pushback times of departures, the taxiway entrance times of arrivals, the varying taxi speed on the taxiways and apron areas, and the different separation times between takeoffs and landings. All these uncertainties were simulated by random variables at microscopic level using Monte Carlo simulations. For example, the uncertainty of pushback time was simulated by a combination of a truncated Gaussian distribution with a uniform distribution. The model was validated using the actual data from DTW on August 1st, 2007. The unimpeded taxi times for departures of the model were "very similar" with those of a queueing model which had been validated by several major airports (Lee and Balakrishnan, 2012, p. 5). The research results indicated that the uncertainty in pushback times and the perturbations in taxiway speed would increase the ground delay while the uncertain runway exit times for arrivals would not influence the ground delay significantly. The uncertainty in the separation times between takeoffs would increase the total taxi-out time and reduce runway throughput (Lee and Balakrishnan, 2012).

Damgacioglu, Celik, and Guller (2018) presented a route-based network simulation framework that could comprehensively simulate airport surface network using SIMMOD®. The proposed simulation framework not only combined runway scheduling, taxiway planning, and apron operation, but also considered technical and regulatory constraints from safety and uncertainty aspects. To model the variables, the authors explored several distributions and chose the best-fitted one based on maximum likelihood estimation and Bayesian Information Criteria. The model was used to explore the impact of disruptive events, such as taxiway or runway closure, on airport ground system. The results could be a valuable reference to airport managers when they try to make proactive plans to deal with any potential disturbances that may happen in the airport system (Damgacioglu et al., 2018).

Conclusion

As for the EAT, both the ICAO and the FAA define it as a taxiway that crosses the extended centerline of a runway and the operations of which would not conflict the operations on the runway. The ICAO prescribes general requirements for the design of the EAT to ensure the safety of the departure and landing operations on the runway. The FAA provides more detailed and strict criteria about the construction of the EAT. Currently the FAA only allows the departure aircraft to fly over the active EAT. Arriving aircraft passing over the active EAT is still under analyses (Hoover, 2007). No explicit regulatory information about the operations of the EAT is found in the ICAO documents, SARPs, and FAA regulations during the literature review.

As for airport ground operations, the ICAO provides general guidelines and standards for runway-in-use and separation minima, while the FAA's regulations contain comprehensive information about the procedures of runway selection and separation minima determination. The FAA also presents procedures and standards to issue runway-crossing clearances. Such information could be used to build the logic modules in the simulation model so that the model could simulate the operations at airports more accurately.

Previous analyses of the traffic data at airports that have implemented the EATs indicate that the EAT would enhance airport safety by reducing the number of runway crossings (Massidda & Mattingly, 2013). Studies also indicate that the EAT could benefit airport operations by reducing average taxi times (Engelland & Ruszkowski, 2010) and improving runway capacity (Massidda & Mattingly, 2013), as well as yield environmental benefit (Uday, et al., 2011). No material was found during the literature review that could provide guidelines to ATCs about how to use the EAT properly. ATCs tend to use the EATs based on their own preference (Uday, et al, 2011). A deeper study about the EAT operation may provide some useful suggestions to air traffic controllers to use the EATs more efficiently.

The simulations of the EAT operations mainly focus on the estimation of the influence of the EAT at airports that do not have EATs (Satyamurti, 2007; Jadhav, et al, 2009, McNerney & Heinold, 2011; Ozdemir, et al., 2018). The mechanisms used in these studies to build the models, such as the modules included in the simulation models, the logic in each module, the input data, the validation method, and the selections of the responsible variables, are useful references to build the simulation model in the dissertation research.

3. RESEARCH METHDOLOGY

The research question of this research is "What is the impact of different take-off and landing runway and taxiway choices on airport performance in terms of taxi time, fuel consumption, and runway crossing during high traffic periods, as well as the ability to cope with increases in the load level". To explore the research question, a discrete-event stochastic model that could simulate different runway and taxiway choices is used to explore aircraft movements around a parallel runway system with EATs at both ends at a fictional commercial service airport. The simulation model is built in ARENA® which is a commercial simulation software package available from Rockwell Automation (Arena, 2020).

A system can be studied mathematically by using either an analytical model or a simulation model (Law, 2013). Compared to analytical models, one advantage of simulation models is that a lot of detailed and realistic information can be obtained from each simulation run (Ozdemir, Cetek, & Usanmaz, 2018). If a system is highly complicated, the related mathematical model may be too complex to find using analytical methods. Then, "the system must be studied by using simulation models" (Law, 2013, p. 5).

Based on these advantages of simulation, a discrete-event stochastic model is used in this research because that 1) airport runway-taxiway system is highly complex, therefore a mathematical model may be too complex to find; and 2) results obtained from a simulation model that contain more detailed and realistic information are preferred for further analyses.

To conduct a sound discrete-event simulation, researchers should pay attentions to different aspects such as scope and assumptions of the model, system randomness, model validation and verification, and statistical methods used to analyze the output data (Law, 2013).

The configuration information of the simulated parallel runway system and the traffic data used in the simulation model are inspired by the real data of DFW. DFW is selected as a reference because that one EAT is implemented at the south of the parallel runway system at the east of DFW, and DFW plans to construct three more EATs, which means that there would be EATs at the both ends of the parallel runway systems DFW in the future. The simulation model has six modules: the arrival aircraft generation module, the departure aircraft generation module, the take-off module, the landing module, the taxi-out module, and the taxi-in module. Detailed information of the simulation model is discussed in nine sections: configuration, scope of the model, assumptions, scenarios, theoretical setup, modules architecture, output data, simulation software, and model validation.

Configuration

The parallel runway system with two EATs at both ends used in the simulation is inspired by the configuration at DFW. Figure 7 shows the configuration of the parallel runway system used in the simulation model. G, M, and N are three designated near apron areas where the departure aircraft begin the taxi-out procedure and the arrival aircraft finish the taxi-in procedure. The taxiway that passes G, M, and N is called the near-apron taxiway in this research.

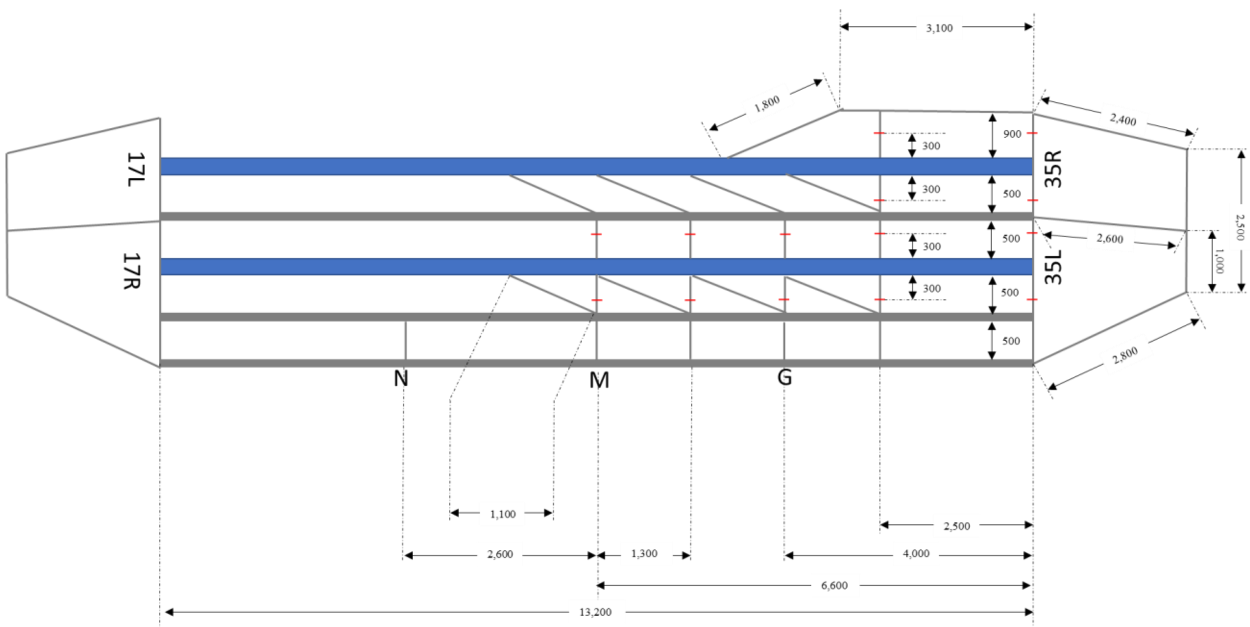

Figure 7. Configuration of the parallel runway system used in the simulation model (unit: feet).

Scope of the Model

It is impossible to simulate every aspect of a system in one model. The level of detail in a model should be decided so that the model has enough detail to generate reliable output, and is feasible and cost-efficient to build and run (Law, 2013).

As for this research, the results of the model need to be useful to answer the research question about the impact of different taxiway and runway choices on the performance of a fictional parallel runway system with EATs at both ends. Therefore, the simulation model should be able to simulate the aircraft movements on runways and taxiways at a parallel runway system under different taxiway and runway selection strategies. For the arrival aircraft, the model simulates procedures of 1) landing on the designated runway from the final approach fix (FAF), and 2) taxiing to the designated near apron area (G, or M, or N in Figure 13). For the departure aircraft, the model simulates procedures of 1) taxiing from the designated apron area (G, or M, or N) to the designated runway, 2) taking off from the designated runway, and 3) climbing to 3000 feet. Other operations, such as taxiing from the near-apron taxiway to the gates and terminal operations, are not considered in the model.

Other limitations of the model are:

- Human factors, such as the workload of air traffic controllers, the communication between the pilots and towers, and the experience and skills of pilots are not included in the model.
- No disruptive events, such as adverse weather, missed-approach, and rejected takeoff, are explored in the model.
- The parallel runway system is operated under VMC
- Operations at terminals and apron areas, such as the gate turnaround, the baggage delivery, and refilling, are not covered in the model.

Assumptions

- The simulation model provides a reasonable representation of a fictional airport that have some similar characteristics to airports in the real world.
- The data used is sufficient to reflect the traffic pattern during the peak traffic time at commercial service airports.
- The model of a fictional parallel runway system with two EATs will be useful to better understand the potential usage of EATs at airports.
- The configuration of the fictional runway system is inspired by DFW because DFW has parallel runways and the airport is implementing EATs at both ends.
- Fuel consumption estimated using ICAO engine emission databank is sufficient to compare the real fuel consumption differences.
- South flow and north flow are equivalent, therefore only south flow is studied.

- The characteristics, including the length of the aircraft, the fuel flow rate, and separation requirements, of Boeing 737-800 are used in the simulation model. Boeing 737-800 is one of the most widely used aircraft currently. Using Boeing 737-800 only could deconflict the multitude of variables from having various aircraft types and ensure that the simulation results could represent the real system to some extent.
- There is no missed-approach or rejected takeoff during the simulation.
- Aircraft begin to take off or land as soon as the runway is clear. There is no delay caused by the communication between the ATCs and pilots.
- The taxiing path for both departure aircraft and arrival aircraft is pre-determined and would not be altered during taxiing.
- Arrival aircraft only use high-speed exits to exit the arrival runway.

Scenarios

The model has four scenarios. Each of the four scenarios represents one type of the runway and taxiway choices investigated in the research project. Table 5 presents the runway and taxiway choices in each scenario.

Scenario 1 represents the traditional taxiway and runway choice that is widely used in current major airports. The outboard runway is used for arrival aircraft to land. The inboard runway is used for departure aircraft to take off. The arrival aircraft would use conventional taxiways to approach the terminal area.

Scenario 2 has the same runway choice with Scenario 1: the outboard runway is used for arrival aircraft to land and the inboard runway is used for departure aircraft to take off. The difference between Scenario 2 and Scenario 1 is that the arrival aircraft would taxi in through the EAT to approach the terminal area in Scenario 2. Scenario 2 simulates the way that the EATs are used at DFW, ATL, DTW, and MIA currently.

Scenario 3 and Scenario 4 are two proposed new taxiway and runway choices which are not used by any airports currently. Scenario 3 and Scenario 4 have the same runway and taxiway choices. Departure aircraft would use the outboard runway to take off, while arrival aircraft would land on the inboard runway. The EAT, then, would be used by the departure aircraft to approach the outboard runway. The difference between Scenario 3 and Scenario 4 is about the potential conflict between the landing aircraft and the taxi-out aircraft. The ICAO defines EAT as the operation on the taxiway would not interfere the operation on the runway (ICAO, 2018b). The FAA, however, currently only allows departure aircraft to fly over active EATs (FAA, 2014). Scenario 3 is built based on the ICAO specification, where arrival aircraft could land over an active EAT. Scenario 4 is built based on the FAA regulation, where departure aircraft must wait for the arrival aircraft to land over the EAT.

Table 5.

Runway and Taxiway Choices Used in the Four Scenarios.

Scenario	Runway		Taxiway
	Take-off	Landing	
1	Runway 17R35L (Inboard)	Runway 17L35R (Outboard)	Conventional taxiway without EAT
2	Runway 17R35L (Inboard)	Runway 17L35R (Outboard)	EAT is used for taxiing in
3	Runway 17L35R (Outboard)	Runway 17R35L (Inboard)	EAT is used for taxiing out Arrival aircraft could land over taxiing out aircraft on the EAT
4	Runway 17L35R (Outboard)	Runway 17R35L (Inboard)	EAT is used for taxiing out Arrival aircraft could not land over taxiing out aircraft on the EAT

Theoretical Setup

Path Selection

The paths available for each aircraft are determined in conformance with the runway and taxiway choices in each scenario. Figure 8, 9 and 10 show the available taxi-in (red lines) and taxi-out (yellow lines) paths in four scenarios, respectively. For each departure or arrival aircraft, one taxi-in path or taxi-out path would be selected from all of the available paths and assigned to the aircraft based on the gate assignment of the aircraft, distance, and the availability of each path. For example, an arrival aircraft would first be assigned to the shortest path based on the gate assignment. If the shortest path is not available, system would try the second shortest path. This step would continue until one available path is found.

Scenario 1. In scenario 1, arrival aircraft could choose from four different taxi-in paths (path1, path2, path3, and path4). For example, the process of taxi-in path selection for an arrival aircraft that is assigned to apron N is:

Step 1. Check path1. If path 1 is available, the aircraft would taxi in via path1. Otherwise,

Step 2. Check path2. If path 2 is available, the aircraft would taxi in via path2. Otherwise,

Step 3. Check path3. If path 3 is available, the aircraft would taxi in via path3. Otherwise,

Step 4. Check path4. If path 4 is available, the aircraft would taxi in via path4. Otherwise,

Step 5. Delay the aircraft for 5 second. Go back to step 1).

The departure aircraft would taxi out via path 5 unless there is a long queue of departure aircraft lined up on path 5. Path 6, then, would be assigned to the departure aircraft.

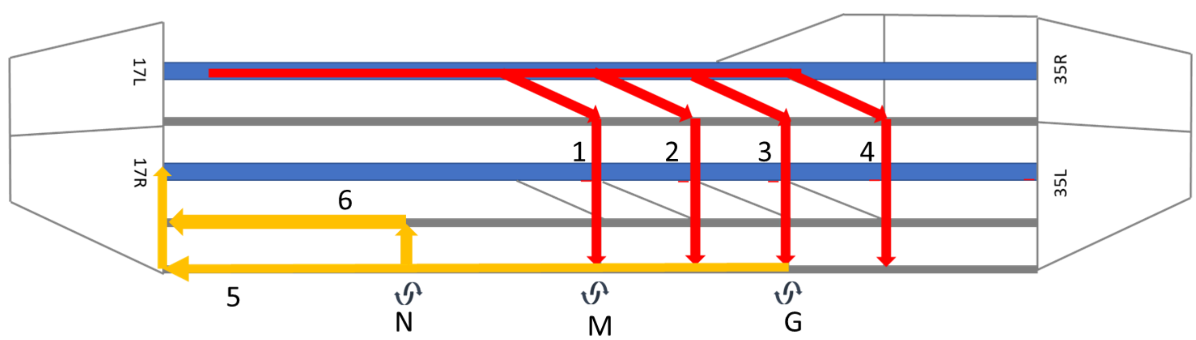

Figure 8. Available taxi paths in Scenario 1.

Scenario 2. In scenario 2, arrival aircraft would use the EAT to taxi-in. The logic of the taxi-out path selection in Scenario 2 is the same with Scenario 1.

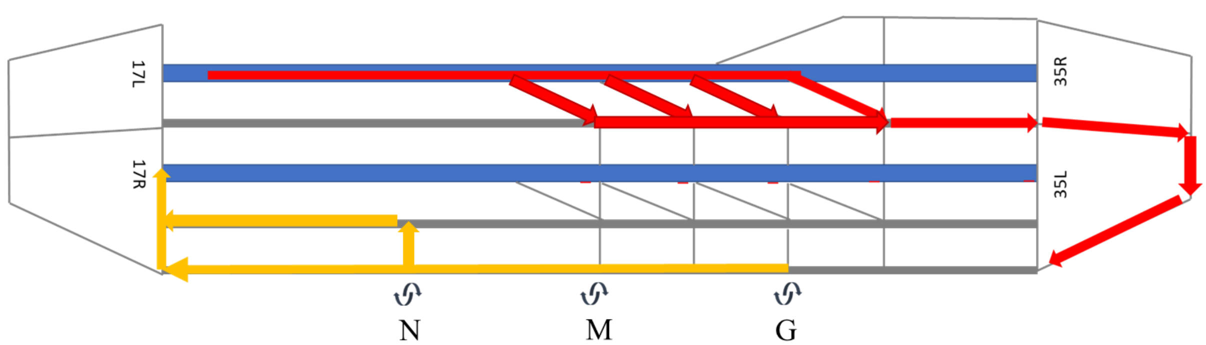

Figure 9. Available taxi paths in Scenario 2.

Scenario 3 and Scenario 4. There are four available paths for arrival aircraft to approach the terminal area in Scenario 3 and Scenario 4. The logic of the taxi-in path selection in Scenario 3 and Scenario 4 is the same with Scenario 1. The departure aircraft in Scenario 3 and Scenario 4 use the EAT to approach the outboard runway.

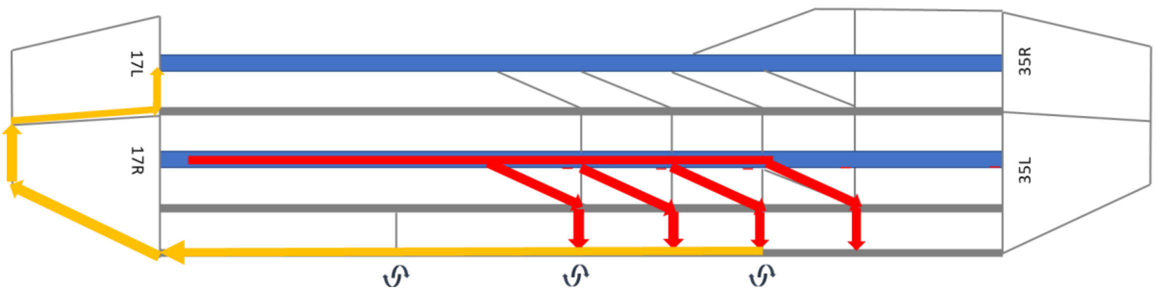

Figure 10. Available taxi paths in Scenario 3 and 4.

Aircraft Movement Speed

Aircraft movement speed would be influenced by the selected taxi path, the number of runway-crossings and taxiway-intersections and whether using the EAT or not. Previous study shows that the average taxiing speed varies from 16.2 to 34.8 knots when the EATs are used, while the average speed varies from varied from 11.1 to 17.2 knots when only conventional taxiways are used (Le and Marais, 2013). Previous airport simulation research (Jadhav, 2013) sets the maximum taxiing speed for medium aircraft at 15 knots and finds that the average taxiing-in speed for arrival aircraft is about 9 knots.

Bases on previous research and the requirements of the model, the taxiing speed in Scenario 1, where only conventional taxiways are available, is set at 10 knots and the taxiing speeds in Scenario 2, Scenario 3, and Scenario 4 are set at 20 knots.

Separation Standards

It is crucial that aircraft follow the separation standards during taking off or landing to avoid wake turbulence. As currently the model only includes one type of aircraft, Boeing 737-800, the minimum distance between two landing aircraft is 3nm. For departure, ATCs usually allow an aircraft to take off as soon as the leading aircraft has lifted off and is clear of the runway (Jahav, 2013).

The minimum distance between two taxiing aircraft from nose to nose is not specified by the FAA. Previous researchers apply different minimum distances based on their experience and research objectives. For example, the minimum distance is set as 60 meters in Pesic, Durand, and Alliot's research (2001), is set as 200 meters in Smeltink, Soomer, de Waal, and de Mei's research (2003), and 150 meters in Jahav's research (2013). Considering only Boeing 737-800 is used in the model, a minimum distance of 200 feet, which is approximately 60.96 meters, is applied in this simulation model.

Conflict

Conflicts occur when two or more aircraft intend to occupy the same space at the same time. Conflict may happen when there is an intersection between two taxiway or between one taxiway and one runway, or there is queue on a taxiway. In this simulation model, four types of conflicts are considered.

1) Intersection between a runway and a taxiway

This conflict represents the active runway crossing: taxi-in aircraft want to go cross the inboard runway when the departure aircraft is about to take off or is taking off. Figure 11 shows the four intersections where the runway crossing may occur in Scenario 1.

Normally, the aircraft on the runway have priority over the arrival aircraft waiting for runway clearance. One exceptional situation is that there are many taxiing aircraft waiting to go across the inboard runway (more than 5 in the model) while there are also many departure aircraft waiting to take off (more than 8 in the model). The departure aircraft, then, would wait for the arrival aircraft to cross the runway under such situation.

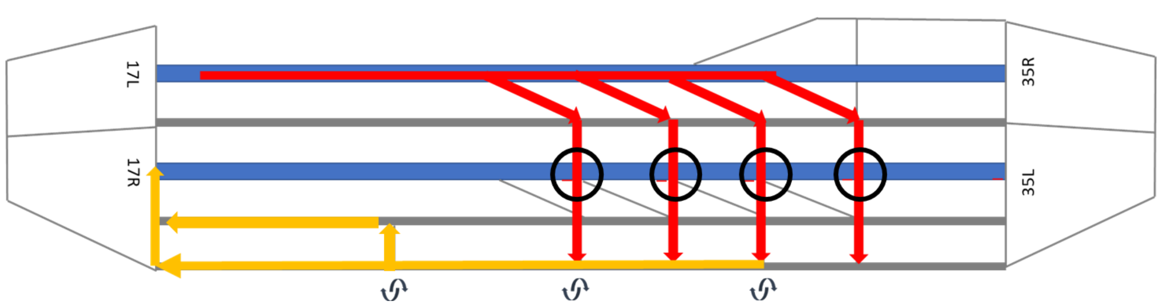

Figure 11. Example of intersection between a runway and a taxiway.

2) Intersection between two taxiways

This conflict happens when two or more taxiing aircraft want to use the same intersection at the same time. Figure 12 shows the slots in Scenario 1, Scenario 3, and Scenario 4 where the second kind of conflict may occur. The aircraft on the near-apron taxiway always have priority over the other aircraft.

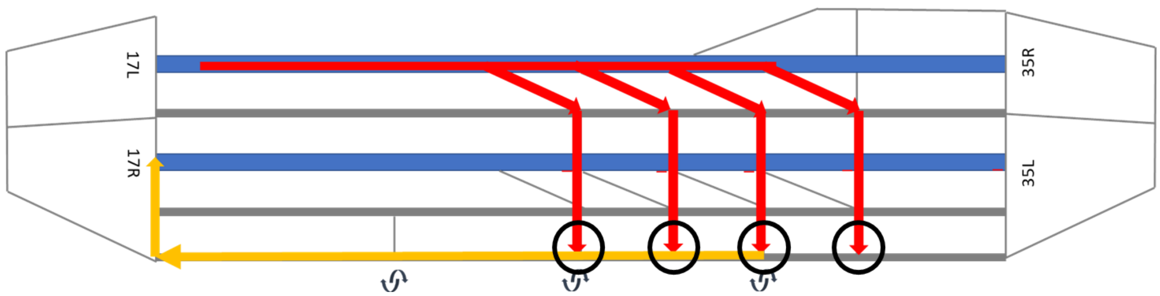

Figure 12. Example of intersection between two taxiways (in Scenario 1).

3) Conflict between landing aircraft and departure aircraft that are taxiing out via the EAT

This kind of conflict exists in Scenario 4 where arrival aircraft is not allowed to land over active EATs. Figure 13 shows the place where the third kind of conflict may occur. Normally the landing aircraft would have priority over the taxi-out aircraft, which means that departure aircraft must wait until the arrival aircraft land over the EAT. One exceptional situation is that there is a long queue of departure aircraft lined up waiting to cross the EAT (more than 8 in the model). The departure aircraft, then, would have the priority to use the EAT.

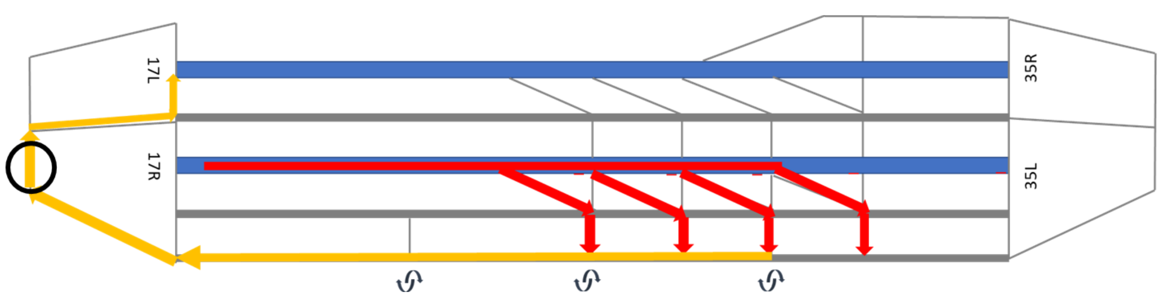

Figure 13. Example of conflict between landing and taxi-out aircraft.

4) Queue on a taxiway

This conflict exists in all of the four scenarios. Figure 14 demonstrates this kind of conflict. When there is a queue on a taxiway, the trailing aircraft would keep moving until the distance to the leading aircraft reduces to the minimum distance. Then, the trailing aircraft would stop and wait until the distance to the leading aircraft is larger than the minimum distance.

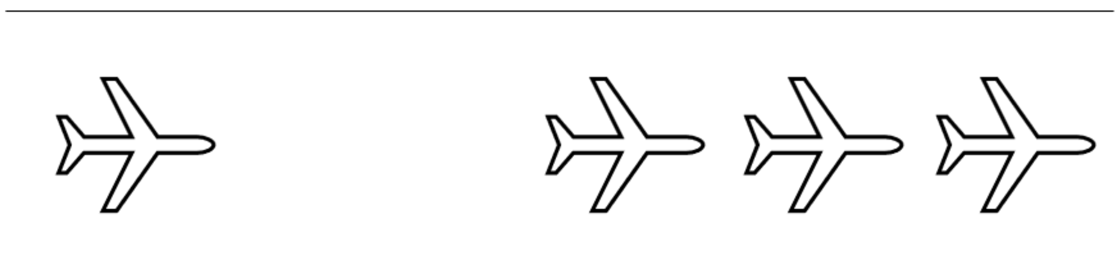

Figure 14. Example of queue on a taxiway.

Modules Architecture

The model consists of six modules: the arrival aircraft creation module, the departure aircraft creation module, the taking-off module, the landing module, the taxi-in module, and the taxi-out module.

Arrival aircraft creation module

This module creates arrival aircraft, assigns destination (G or M or N) to the aircraft, and transfers aircraft to the landing module. Each arrival aircraft is designated to one of the three destinations with same probability.

Departure aircraft creation module

This module creates arrival aircraft, assigns starting points (G or M or N) to the aircraft, and transfers aircraft to corresponding station. Each departure aircraft is designated to one of the three starting point with same probability

Landing module

This module begins when the arrival aircraft is transferred into the module, and ends when the aircraft completes the landing process, exits the runway, and turns to a taxiway. The intersection that aircraft use to exit the runway is determined by the selected taxi-in path. The process of taxi-in path selection is explained in the section of theoretical setup. Once the aircraft turns onto a taxiway, the aircraft would be transferred to the taxi-in module.

Figure 15 shows the flowchart of the approach module. If the waiting queue is empty and wake vortex separation requirements are satisfied when the aircraft enters the approach module, then time needed to complete this module equals the landing time. If the waiting queue is empty but wake vortex separation requirements are not satisfied when the aircraft enters the approach module, then time needed to complete this module equals the landing time plus time needed to satisfy the wake vortex requirements. If the waiting queue is empty but wake vortex separation requirements are not satisfied when the aircraft enters the approach module, then time needed to complete this module equals the landing time plus time needed to satisfy the wake vortex requirements.

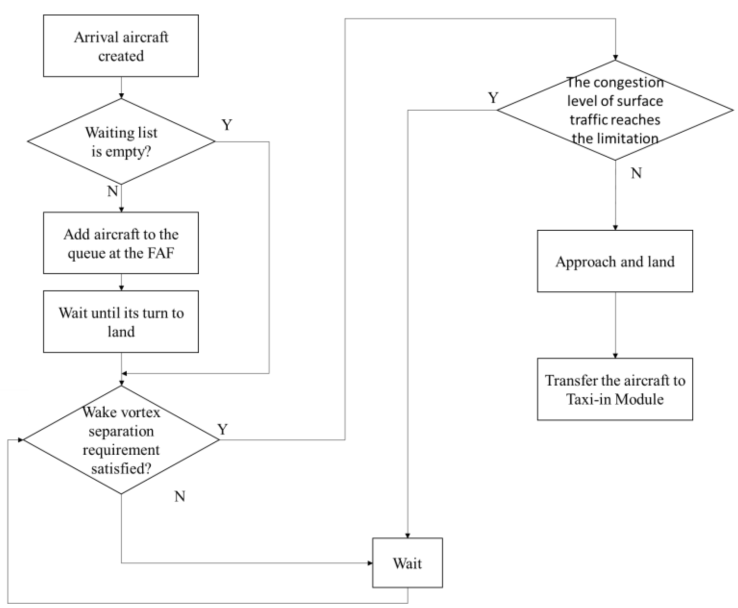

Figure 15. Flowchart of arrival module.

In this module, “miss approach” or “go-around” is not considered. If the runway is not available when a new aircraft enters the approach module, then the aircraft would queue at the final approach fix (FAF) and wait for its turn to land, which is different from the real operations at airports. An arrival aircraft would begin the approach process as soon as the runway is clear. Delay caused by the communication between the ATCs and the pilots is not considered in the simulation model.

Taxi-in module

This phase begins when the landing aircraft exits the runway and ends when the aircraft enter the designated apron area. An important issue in taxi logic is the conflicts that may occur. A conflict would happen when two or more aircraft want to use the same path at the same time. Two conflicts are considered in this module. Two kinds of conflict may happen in Taxi-in module.

1) Intersection between a runway and a taxiway (Under Scenario 1)

The aircraft on the runway always have priority over the aircraft on the taxiway. The taxiing aircraft must wait until the requirements of runway crossing clearance is satisfied. One exception is that there are many arrival aircraft waiting to cross the active runway (more than 5 in the model) while there are also many departure aircraft waiting to take off (more than 8 in the model). The departure aircraft would wait for the arrival aircraft to cross the runway under such situation.

2) Queue on a taxiway (Under all scenarios)

When there is a queue on a taxiway, the trailing aircraft would keep moving until the distance to the leading aircraft reduces to the minimum distance. The trailing aircraft would stop and wait until the distance to the leading aircraft is larger than the minimum distance.

In ARENA®, entity can be transferred from one station to another station via route, transporter, or convey. Route is the simplest method, where entities are transferred to the destination with a specified speed with no more constraints. Transporter works in a way like a bus, where one or more transporters move between two or more stations to transfer entities from one station to another. Convey works like a conveyor belt in real life, where stations are connected by conveyors. Entities, then could use the conveyors to move to the next station. Velocity, cell size, cell occupied by each entity, and accumulation length can be clarified for each conveyor, which could help to deal with the conflicts in the Taxi-in Module. Therefore, convey is used in the taxi-in module, as well as the taxi-out module, to ensure that the standard of the minimum distance between two taxiing aircraft is satisfied.

Taxi-out module

This phase begins when the aircraft is assigned as a departure aircraft and ends when the aircraft leaves the assigned taxi-out path and turns onto the departure runway. The logic of the taxi-out path selection is explained in the section of theoretical setup. Once the aircraft turns onto the departure runway, the aircraft would be transferred to the take-off module. Three conflicts are considered in this module.

1) Intersection between two taxiways (Under Scenario 1, Scenario 3, and Scenario 4)

The aircraft on the near apron taxiway always have priority over the other aircraft.

2) Queue on a taxiway (Under all scenarios)

When there is a queue on a taxiway, the trailing aircraft would keep moving until the distance to the leading aircraft reduces to the minimum distance. The trailing aircraft would stop and wait until the distance to the leading aircraft is larger than the minimum distance.

3) Confliction between landing aircraft and departure aircraft that are taxiing out via the EAT

The priority is determined based on the traffic condition. Normally, arrival aircraft would have priority over the taxi-out aircraft on the EAT. When there is a higher departure demand compared to the landing demand, the departure aircraft would have higher priority.

Take-off module

This phase begins when the aircraft turn on the departure runway and ends when the aircraft complete its departure process. Figure 16 shows the flowchart of the take-off module.

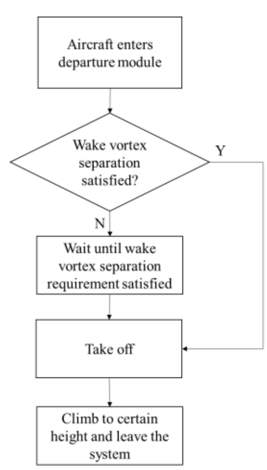

Figure 16. Flowchart of the take-off module.

Output Data

In this research, the impact of different runway and taxiway choices are evaluated based on the average taxi-in and taxi-out time, the fuel consumption per taxi-in and per taxi-out, number of runway crossings, and the ability to cope with increase in the traffic load level. This section explains the methods needed to collect the required data.

Taxi Time

Previous studies focus on the impact of the EAT on the taxi-in time (Uday, Burder, & Marais, 2011; Le & Marais, 2013). However, the different landing and take-off runways choices would influence both taxi-out and taxi-in performance. Therefore, both the average taxi-in time and the average taxi-out time are evaluated in this research.

The definition of taxi-in time in this model is the time interval between the “wheel-down” time and the time when the arrival aircraft reaches the edge of the terminal area. The model automatically records the “wheel-down time” as an attribution of the arrival aircraft when it touches down on the runway. When the arrival aircraft arrives at the assigned destination, the time interval between current time and the “wheels-down time” would be recorded as taxi-in time and stored into a data file. By repeating this process for each arrival aircraft, the taxi-in time for each arrival aircraft in a simulation run would be recorded in a data file.

The definition of taxi-out time in this model is the time interval between the time when the departure aircraft is released from the edge of the terminal area and the “wheels-off” time. The model automatically records the time when the departure aircraft enter the system as an attribution of the departure aircraft under the name of “release time”. The time interval between the “release time” and the time when the wheel of the aircraft is off the runway is recorded as taxi-out time and stored into a data file. By repeating this process for each departure aircraft, the taxi-out time for each departure aircraft in a simulation run would be recorded into a data file.

Number of runway crossings

In this model, runway crossing is defined as the interactions between arrival and departure aircraft along the centerline of an active runway. Runway crossing is determined by calculating the difference between the time one aircraft uses to go cross the inboard runway (in Scenario 1) or the EAT (in Scenario 4) and the unimpeded taxi time (the time needed to go cross the inboard runway or the EAT without stop). The system would record one runway crossing when one difference is found to be larger than zero. The total number of runway crossing is recorded into a data file at the end of each simulation run.

Fuel consumption

Previous studies focus on studying the changes of the average amount of fuel burned per taxi-in because of the usage of the EAT (Uday, Burder, & Marais, 2011; Le & Marais, 2013). However, the different landing and take-off runways choices would influence both taxi-out and taxi-in performance. Therefore, both the average fuel consumptions per taxi-in and per taxi-out are explored in the model.

The ICAO Engine Emission Databank (EASA, 2017) provides the fuel flow rates for all types of aircraft engines at four thrust levels. This research uses the fuel consumption rate for the engine that used by the Boeing 737-800, CFM 56-7B 27/3. A combination of the fuel consumption rate with the outputs of each simulation run (such as, the taxi times and the taxi routes) yields an estimate of the amount of the burned fuel during each taxi-in and taxi-out. It should be noted that the fuel consumption rates listed in the ICAO Engines Emission Databank are obtained under standard experimental conditions (EASA, 2017). The experimental conditions may not be the same as the conditions under which the aircraft operate in practice. So, the results obtained using this method could only be an estimation of the real fuel consumption. Detailed information about the procedure used to estimate fuel consumption is explained in section of Dependent Variables in Chapter 4.

Simulation Software

In this research, the discrete-event stochastic model is built in a commercially available simulation software named ARENA®. ARENA® is widely used by companies that need to simulate the business processes in many industries, such as automobile industry, logistics industry, manufacturing industry, aviation industry (Arena, 2020). ARENA® could help companies to address a variety of business challenges in many aspects, such as operational efficiency, reliability, decision-making, cost-saving, and throughout increase (Arena, 2020). ARENA® has been used to model the landing traffic at George Bush International Airport (Kim, Akinbodunse, and Nwakamma, 2005) and the ground operations of a proposed EAT at Chicago O'Hare International Airport (Jadhav, 2013). Some of the main features of ARENA® are:

1) Modeling of dynamic processes with variability.

2) Simulation of the system performance under some possible "to-be" alternatives.

3) Visualizing the operations with animation graphics (Jadhav, 2013).

Model Validation

The purpose of model validation is to decide whether the model is an appropriate representation of the target system in terms of the research objectives (Law, 2013). A model can be validated by comparing the real-world observations with the simulation output statistically, which is called result validation. The validation uses the logics in Scenario 1 which is consistent with the current operations at DFW.

Input data

The average south-flow departure aircraft /hour on Runway 17R and arrival aircraft/hour on Runway 17C at DFW (Le, 2014) are used as the input data for the model validation with the assumption that the interval time between two aircraft follows Exponential distribution. The average departure and arrival rates are calculated based on the traffic data at DFW from September 10, 2013 to February 28, 2014 obtained from the ASDE-X database (Le, 2014). Appendix A presents the detailed data.

Validation results

Le (2014) defines the "taxi-in time" for arrival aircraft on runway 17C as "the time an aircraft exits the arrival runway to the time it reaches the edge of the terminal area" (p. 63), which is slightly different from the definition of the taxi-in time used in the simulation model. The method used to record the taxi-in time during the model validation, then, is adjusted so that the definition of taxi-in time in the simulation model is consistent with the definition used in the research paper. The average taxi-in time for arrival aircraft on runway 17C at DFW is 227.4 seconds, and the standard deviation is 138.6 seconds (Le, 2014). The mean of the average taxi-in times obtained from the simulation model is 224.55 seconds. Table 6 shows the results of the simulation model.

Table 6.

The Population Mean of the Average Taxi-in Times and 95% Confidence Interval Obtained from the Simulation Model and DFW.

	Taxi-in Time (Second)	95% Confidence Interval (Second)
Arrival at 17C [a]	227.4	(206.7, 248.1)
Simulation Model	224.55	(223.46, 225.64)

Note. [a] Information is obtained from "*Investigating surface performance trade-offs of unimpeded taxiways* (Master's thesis)" by Le, 2014. Retrieved from https://docs.lib.purdue.edu/open_access_theses/208

A two-sample t-test is conducted to explore the difference between the taxi-in times of the simulation model and DFW with 0.95 confidence level. The null hypothesis and alternative hypothesis are:

H_0: The population mean of the average taxi-in time in the simulation model equals the mean of the taxi-in time of arrival aircraft on runway 17C at DFW.

Ha: There is a significant difference between the means of the taxi-in time of the simulation mode and DFW.

The t-score is 0.2686 and the p-value is 0.7886, which is greater than 0.05. Therefore, there is not enough evidence to reject the null hypothesis that the population mean of the taxi-in time of the simulation model equals the true mean of the taxi-in time of runway 17C at DFW. The simulation model could provide a reasonable representation of a fictional airport that have some similar characteristics to airports in the real world.

4. EXPERIMENT DESIGN

The research question of the dissertation is “What is the impact of different take-off and landing runway and taxiway choices on airport performance in terms of taxi time, fuel consumption, and runway crossing during high traffic periods, as well as the ability to cope with increases in the traffic load level?”. There are six sub-questions:

1. What is the impact of different runway and taxiway choices on airport performance in terms of taxi-in time during high traffic periods?
2. What is the impact of different runway and taxiway choices on airport performance in terms of taxi-out time during high traffic periods?
3. What is the impact of different runway and taxiway choices on airport performance in terms of fuel consumption per taxi-in during high traffic periods?
4. What is the impact of different runway and taxiway choices on airport performance in terms of fuel consumption per taxi-out during high traffic periods?
5. What is the impact of different runway and taxiway choices on airport performance in terms of runway crossings during high traffic periods?
6. What is the impact of different runway and taxiway choices on airport performance in terms of the ability to cope with increases in the traffic load level?

The features and characteristics of aircraft movements vary between high departure periods and high arrival periods. So, the influence of the four runway and taxiway choices on taxi time, fuel consumption, and number of runway crossings (Sub-questions 1, 2, 3, 4 and 5) is explored under high departure periods (Experiment 1) and high arrival periods (Experiment 2) separately. Experiment 3 is designed to answer sub-question 6.

Experiment 1 and Experiment 2

Experiment 1 and Experiment 2 are designed to explore Sub-questions 1, 2, 3, 4, and 5. The independent variable in Experiment 1 and Experiment 2 is a categorical variable: the take-off and landing runway and taxiway choice. These choices comprise four scenarios: the conventional one that is currently widely used at airports (Scenario 1) and three alternative choices that become possible because of the usage of the EAT (Scenario 2, Scenario 3, and Scenario 4). Table 7 presents the descriptions of the four scenarios. The dependent variables analyzed in Experiment 1 and Experiment 2 are the average taxi-in time, the average taxi-out time, the average fuel consumption per taxi-in, the average fuel consumption per taxi-out, and the number of runway crossings.

Table 7.

Four Scenarios of Different Take-off and Landing Runway and Taxiway Choices.

Scenario	Runway Departure	Runway Arrival	EAT	Note
1	Inboard	Outboard	Not used	Traditional runway and taxiway strategy
2	Inboard	Outboard	For taxiing-in	Strategy applied at DFW, DTW, ATL, and MIA
3	Outboard	Inboard	For taxiing-out	Aircraft are allowed to land over active EAT
4	Outboard	Inboard	For taxiing-out	Aircraft are not allowed to land over active EAT

Table 8 presents the key parameters of Experiment 1 and Experiment 2. Each scenario runs 100 times in Experiment 1 and Experiment 2. So, the sample size is 400 (100*4) for each experiment. Each simulation run in Experiment1 and Experiment 2 lasts for 90 minutes: 30 minutes to warm up, 30 minutes to record the dependent variables, and 30 minutes to cool down. In each simulation run, the taxi time and fuel consumption per taxi of every generated aircraft are recorded for further data processing. Detailed information about how to record each dependent variable is explained in the section of Dependent Variables in this chapter.

Table 8.

Key Parameters of Experiment 1 and Experiment 2.

	Sample size [b]	Significance level (α)	Power ($1-\beta$)	Departure rate [a] (aircraft/hour)	Arrival rate [a] (aircraft/hour)
Experiment 1 (High departure)	400	0.05	0.80	54	18
Experiment 2 (High arrival)	400	0.05	0.8	18	54

Note. [a] Departure and arrival rates used in Experiment 1 and Experiment 2 are estimated based on the traffic rates in the high traffic period at DFW. The criteria and steps to obtain and process the raw data are explained in Appendix B.

Experiment 3

Experiment 3 is designed to explore sub-question 6. In Experiment 3, the four scenarios are tested under four different load levels separately. The change in the average taxi-in time and the average taxi-out time in the four scenarios are compared to explore each scenario's ability to deal with the increase of the traffic load level. Therefore, the independent variables considered in Experiment 3 are one categorical variable, the runway and taxiway choice with four scenarios, and one continuous variable with four discrete levels, the load level. Four peak traffic load levels (arrival rate plus departure rate) are explored: 72 aircraft per hour, 80 aircraft per hour, 88 aircraft per hour, and 96 aircraft per hour. The rate of 72 aircraft per hour is regarded as the baseline as it is estimated based on the current peak traffic load level at DFW. The dependent variables in Experiment 3 are the average taxi-in time and the average taxi-out time. There are 16 different combinations of the scenario and the load level. The simulation model run 100 times under each combination. Therefore, the total sample size is 1600. Table 9 presents the key parameters of Experiment 3.

Table 9.

Key Parameters of Experiment 3.

	Sample size	Significance level (α)	Power (1-β)	Independent variable(s)	Dependent variables
Experiment 3	1600	0.05	0.80	1.Four runway and taxiway scenarios 2.Four Load levels	1. Taxi-in time 2. Taxi-out time

Each simulation run lasts for 150 minutes: first 30 minutes to warm up the system, 90 minutes to test the performance of the runway system and record results (includes one high departure period, one high arrival period, and one transition period between the high arrival period and the high departure period), 30 minutes to cool down. The arrival rate and departure rate used in each period are decided based on the peak traffic load level at fixed arrival-departure ratios inspired by the arrival-departure ratios at DFW. For high departure periods, the arrival-departure ratio is 25%-75%. For high arrival periods, the arrival-departure ratio is 75%-25%. Table 10 shows the specific arrival rates and departure rates under four load levels, respectively.

Table 10.

Departure and Arrival Rates Used under Each Load Levels in Experiment 3.

Load level	Rate (aircraft/hour)	Time (mins)				
		0-30	30-60	60-90	90-120	120-150
72	Departure Rate	20	54	20	18	20
	Arrival Rate	20	18	20	54	20
80	Departure Rate	20	60	22	20	20
	Arrival Rate	20	20	22	60	20
88	Departure Rate	20	66	24	22	20
	Arrival Rate	20	22	24	66	20
96	Departure Rate	20	72	26	24	20
	Arrival Rate	20	24	26	72	20

The time structure of one high departure period, one high arrival period, and one transition period between the high arrival period and the high departure period, as well as the traffic level at load level 1, is inspired by the traffic data at the DFW. Table 11 presents the average departure and arrival rate of a cycle that consists of one high arrival period and one departure period at DFW.

Table 11.

Average Departure and Arrival Rates at DFW.

	14:00-14:30	14:30-15:00	15:00-15:30	15:30-16:00	16:00-16:30
Arrival rate (/hr)	19.485	18.857	19.714	51.250	15.457
Departure rate (/hr)	16.425	56.097	22.510	21.063	22.126

Note. The average rates are generated based on the traffic data obtained from the FAA Aviation System Performance Metric (ASPM) database. The criteria and steps to obtain and process the raw data are explained in Appendix B.

Dependent Variables

Taxi time

Both the taxi-in time and the taxi-out time are collected from the simulation model directly. The definition of taxi-in time in this model is the time interval between the "wheel-down" time and the time when the arrival aircraft reaches the edge of the terminal area. The definition of taxi-out time in this model is the time interval between the time when the departure aircraft is released from the edge of the terminal area and the "wheel-off" time.

In each simulation run, the taxi time for each arrival and departure aircraft is recorded as raw data. Then, the data are organized and processed to calculate the average taxi-in and taxi-out times of each simulation run. The average taxi time data are used in further statistical analyses.

Fuel consumption

In each simulation run, the amount of fuel consumed by each arrival and departure aircraft is estimated based on the taxi time and recorded into a data file. Then, the data are organized and processed to calculate the average fuel consumption for taxi-in or for taxi-out in each simulation run. The average fuel consumption for taxi-in or taxi-out are obtained for each simulation run and used in the statistical analyses.

Three phases are considered in each taxiing: taxiing at a constant speed, turning, and stop-and-start. Previous studies (Wood & Herndon, 2008; Morris, 2005) estimated the thrust level of each taxiing phase, as well as the time needed for each turning and "stop-and-start". The thrust levels for taxiing at a constant speed, turning, and "stop-and-start" are 5%, 7%, and 9% respectively. Each turn is assumed to take 6 seconds, and each "stop-and-start" is assumed to take 8 seconds (Wood et al., 2008).

Table 12.

Thrust Level and Fuel Flow Rates at Three Taxiing Phases.

Phase	Thrust Level [c]	Fuel Flow Rate (kg/second)
Taxiing at constant speed	5%	0.089739[b]
Turning	7%	0.11[a]
Stop-and-start	9%	0.130261[b]

Note. [a] Fuel flow rate at 7% thrust level is obtained from the ICAO engine databank (ICAO, 2019). [b] Fuel flow rates at 5% and 9% thrust levels are estimated by linear interpolation using the ICAO engine data bank data. [c] Three thrust levels are selected based on previous studies (Wood & Herndon, 2008; Morris, 2005).

The fuel flow rate at each taxiing phase is estimated according to the fuel flow data of the engine used on Boeing 737-800, CFM 56-7B 27/3, which is obtained from the ICAO engine databank (EASA, 2018). The ICAO engine databank provides engine performance and emission data for most of the commercially available engines based on data obtained from laboratory engine tests. For each type of the tested engines, the databank provides the fuel flow rate and other indices under four conditions: take-off, climb-out, approach, and idle with the thrust levels set up at 100%, 85%, 30%, and 7%, respectively. The fuel flow rates for 5%, 7%, and 9% thrust levels required in the estimation of the fuel consumption per taxiing are estimated through linear interpolation of the ICAO engine databank data. Table 12 shows the results of the fuel flow rates of the three taxiing phases.

Then, the fuel burned during each taxiing can be estimated as:

$$Fuel = t_{constant} * f_{constant} + t_{turning} * f_{turning} + t_{stop} * f_{stop}$$

where $t_{constant}$, $t_{turning}$, t_{stop} are the duration of three phases in each taxiing; $f_{constant}$, $f_{turning}$, and f_{stop} are the fuel flow rates of three phases. Estimation for $t_{turning}$ and t_{stop} can be determined as (Wood et al., 2009; Morris, 2005):

$$t_{turning} = 6 * n_{turning}$$

$$t_{stop} = 8 * n_{stop}$$

where $n_{turning}$ is the number of turns in each taxi-in or taxi-out; $n_{stop}$is the number of "stop-and-start" actions in each taxi-in or taxi-out. Then, the duration of taxiing at constant speed can be estimated as:

$$t_{constant} = Taxi\ time - t_{turning} - t_{stop}$$

There are limitations of the method used to estimate the fuel consumption in the experiments. First, the fuel flow rates at the four thrust levels provided by the ICAO engine databank are obtained at an ideal experiment condition, on a test stand, in a test cell, with no load. The fuel flow rates in the practical world would be different from those obtained from the lab because of the environmental conditions and load. Second, the thrust levels of the three phases during taxiing are estimated based on previous studies, which may differ from the real conditions. Third, the fuel flow rates at the three phases (5%, 7%, and 9%) are obtained by linear interpolation using the fuel flow rates at 7% and 30% thrust levels. The assumption of the estimation is that there is a linear relationship between the thrust level and the fuel flow rate, which is not true in practice. Therefore, the fuel consumption estimated in the experiments may not present the exact fuel consumption in real life. It is assumed that the differences of the fuel consumptions among the four scenarios obtained from the experiments could reveal the patterns and trends of the real differences among the four scenarios.

Number of runway crossings

Runway crossing is defined as the interactions between two aircraft along the centerline of an active runway in this model. Based on the definition, there is no runway crossing in Scenario 2 and Scenario 3. In Scenario 1, runway crossings happen around the inboard runway when the taxi-in aircraft pass through the active runway. In Scenario 4, runway crossings happen along the centerline of the runway over the active EAT. Figure 17 shows the possible spots (circled ones) where runway crossings may occur in Scenario 1 and Scenario 4. For Scenario 1 and Scenario 4, the number of runway crossings that occur in each simulation run is recorded as raw data. Then, the data are organized and processed to be used in the statistical analyses.

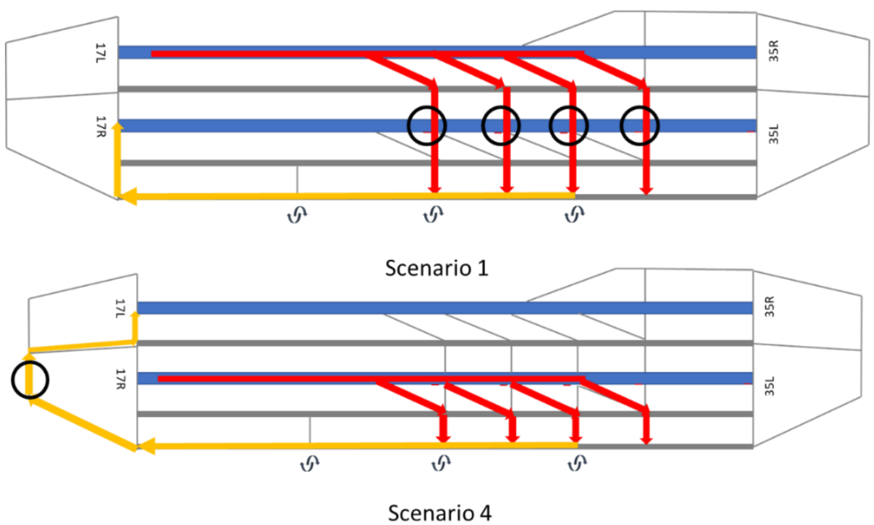

Figure 17. Possible spots where runway crossings may occur in Scenario 1 and Scenario 4.

The number of runway crossings is a count variable, which should be regarded as a rate (number of runway crossings during each simulation run). Two-Sample Poisson Rates test is used to explore the difference between the rates of runway crossings in Scenario 1 and Scenario 4.

5. RESULTS ANALYSES

The research question of the dissertation is "What is the impact of different take-off and landing runway and taxiway choices on airport performance in terms of taxi time, fuel consumption, and runway crossing during high traffic periods, as well as the ability to cope with increases in the traffic load level?", which includes six sub-questions:

1. What is the impact of different runway and taxiway choices on airport performance in terms of taxi-in time during high traffic period?
2. What is the impact of different runway and taxiway choices on airport performance in terms of taxi-out time during high traffic period?
3. What is the impact of different runway and taxiway choices on airport performance in terms of fuel consumption per taxi-in during high traffic period?
4. What is the impact of different runway and taxiway choices on airport performance in terms of fuel consumption per taxi-out during high traffic period?
5. What is the impact of different runway and taxiway choices on airport performance in terms of runway crossings during high traffic period?
6. What is the impact of different runway and taxiway choices on airport performance in terms of the ability to cope with increases in the traffic load level?

Sub questions 1 to 5 are explored during the high departure period (Experiment 1) and the high arrival period (Experiment 2) separately. For example, for taxi-in times (sub question 1), average taxi-in times obtained from Experiment 1 are analyzed to evaluated the impact of four different runway and taxiway choices during the high departure period, while average taxi-in times obtained from Experiment 2 are analyzed to evaluate the impact of four different runway and taxiway choices during the high arrival period. Sub question 6 is explored based on the data obtained from Experiment 3.

Sub Question 1 Taxi-in Times

High departure period

Average taxi-in time data obtained from Experiment 1 are used to analyze the influence of different runway and taxiway choices on the means of the average taxi-in times during high departure period. The null hypothesis and alternative hypothesis are:

$H_0$1: There is no significant difference between the population means of the average taxi-in time based on the four combinations of the runway and taxiway choices during high departure period.

H_a1: Not all the population means of the average taxi-in time grouped by the runway and taxiway choices are equal.

The confidence level is set as 95%. The power is set as 80%. The minimum difference that can be detected is 82.08 seconds. The descriptive statistics for each scenario are: Scenario 1 (Mean=490.2, SD=89.04), Scenario 2 (Mean= 476.17, SD=20.05), Scenario 3 (Mean= 105.85, SD=12.32), and Scenario 4 (Mean=107.60, SD=10.69). Table 13 presents some key descriptive statistics for the average taxi-in times. Detailed descriptive statistics for each scenario are included in Appendix C.

Table 13.

Key Descriptive Statistics for the Average Taxi-in Times during High Departure Period.

Variable	Scenario	n	Mean	StDev	Median
Taxi-in Time	1	100	490.20	89.04	476.20
	2	100	476.17	20.05	475.65
	3	100	105.85	12.32	106.10
	4	100	107.60	10.69	108.04

The results of a one-way ANOVA test on the influence of the runway and taxiway choices on the population means of the average taxi-in times are shown in Table 14. The impact of the runway and taxiway choices is statistically significant at the 95% confidence level. At least one mean of the taxi-in time is significantly different from the other three taxi-in times. Based on the results of the ANOVA test, the null hypothesis $H_0$1 is rejected.

Table 14.

One-Way ANOVA Test for the Means of the Average Taxi-in Time during High Departure Period.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Scenario	3	0.94574	0.315246	4148.57	<0.0001*
Error	396	0.03009	0.000076		
Total	399	0.97583			

Note. 1) *: Indicates a significant effect. 2) Box-Cox transformation is applied with λ=-0.4242.

A post hoc Tukey pairwise comparison test is conducted as the ANOVA test reveals significant differences. Table 15 shows the results of the Tukey pairwise comparisons test.

Table 15.

Grouping Information for the Means of the Average Taxi-in Times during High Departure Period Using the Tukey Method with 95% Confidence.

Scenario	Mean	Grouping	Simultaneous 95% CI of Mean Difference with Scenario			
			1	2	3	4
1	490.20	A	-	(-23.27, 41.34)	(366.11, 406.53)	(364.09, 405.58)
2	476.17	A		-	(350.24, 392.33)	(348.18, 390.38)
3	105.85	B			-	(-4.07, 1.99)
4	107.60	B				-

Note. Means that do not share the same grouping letter are significantly different.

Main findings from results of the statistical tests are:

1. These four different runway and taxiway choices (the four scenarios) have statistically significant influence on the population means of the taxi-in times during high departure period.
2. The difference between the population means of the average taxi-in times of Scenario 1 and Scenario 2 is not statistically significant.
3. The difference between the population means of the average taxi-in times of Scenario 3 and Scenario 4 is not statistically significant.
4. Compared with Scenario 1 and Scenario 2, applying the runway and taxiway strategy in Scenario 3 or Scenario 4 would decrease the mean of the average taxi-in times by 78%.

High arrival period

Average taxi-in time data obtained from Experiment 2 are used to analyze the influence of different runway and taxiway choices on taxi-in times during the high arrival period. The null hypothesis and alternative hypothesis are:

$H_0$2: There is no significant difference between the population means of the average taxi-in time based on the four scenarios of runway and taxiway choices during the high arrival period.

H_a2: Not all the population means of the average taxi-in time grouped by the runway and taxiway choices are equal.

The confidence level is set as 95%. The power is set as 80%. The minimum difference that can be detected is 70.36 seconds. The descriptive statistics for each scenarios are: Scenario 1 (Mean=292.67, SD=19.30), Scenario 2 (Mean= 479.96, SD=12.4), Scenario 3 (Mean= 108.37, SD=7.3), and Scenario 4 (Mean=108.19, SD=5.43). Table 16 presents some key descriptive statistics for the average taxi-in times. Detailed descriptive statistics for each scenario are included in Appendix C.

Table 16.

Key Descriptive Statistics for the Average Taxi-in Times during the High Arrival Period.

Variable	Scenario	n	Mean	StDev	Median
Taxi-in Time	1	100	292.67	19.30	290.70
	2	100	479.96	12.40	479.88
	3	100	108.37	7.30	107.77
	4	100	108.19	5.43	108.07

The results of a one-way ANOVA test on the influence of the runway and taxiway choices on the population means of the taxi-in times during high arrival period are shown in Table 17. The impact of the runway and taxiway choices is statistically significant at the 95% confidence level during the high arrival period. At least one population mean of the average taxi-in times is significantly different from the other three taxi-in times. Based on the results of the ANOVA test, the null hypothesis $H_0$2 is rejected.

Table 17.

One-Way ANOVA Test for the Means of the Average Taxi-in Times during High Arrival Period.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Scenario	3	290.822	96.9407	20880.36	<0.0001*
Error	396	1.838	0.0046		
Total	399	292.661			

Note. 1) *: Indicates a significant effect. 2) Box-Cox transformation is applied with λ=0.2844.

A post hoc Tukey pairwise comparison test is conducted to investigate the differences among the four scenarios. Table 18 shows the results of the Tukey pairwise comparisons test.

Table 18.

Grouping Information for the Means of the Average Taxi-in Times during the High Arrival Period Using the Tukey Method with 95% Confidence.

Scenario	Mean	Grouping	Simultaneous 95% CI of Mean Difference with Scenario			
			1	2	3	4
1	292.67	A	-	(-193.75, -181.48)	(180.26, 187.81)	(180.37, 187.91)
2	479.96	B		-	(366.81, 376.50)	(366.91, 376.61)
3	108.37	C			-	(-2.59,2.37)
4	108.19	C				-

Note. Means that do not share the same grouping letter are significantly different.

Main findings from the results of the statistical tests are:

1. These four different runway and taxiway choices (the four scenarios) have statistically significant influence on the population means of the taxi-in times during the high arrival period.
2. There is no statistically significant difference between the population means of the average taxi-in times in Scenario 1 and Scenario 2.
3. There is no statistically significant difference between the population means of the average taxi-in times in Scenario 3 and Scenario 4.
4. The population means of the average taxi-in times in Scenario 3 and Scenario 4 are significantly different from the means of the average taxi-in times in Scenario 1 and Scenario 2 with 95% confidence.
5. Compared with Scenario 1, applying the runway and taxiway strategy in Scenario 3 or Scenario 4 would decrease the mean of the average taxi-in time by 63%.

6. Compared with Scenario 2, applying the runway and taxiway strategy in Scenario 3 or Scenario 4 would decrease the mean of the average taxi-in times by 77.5%.
7. Compared with Scenario 1, applying the runway and taxiway strategy in Scenario 2 would increase the mean of the average taxi-in times by 64%.

Answer to Sub-Question 1

Experiment 1 explores the impact of four different taxiway and runway choices (four scenarios) on the population means of the average taxi-in times during high departure period, while Experiment 2 focuses on the high arrival period. Table 19 shows the brief results of the statistical analyses.

Table 19.

Summary of Statistical Analyses of the Means of the Average Taxi-in Times.

	Results of Tukey Comparisons with alpha=0.05
High departure	(Scenario 1, Scenario 2) > (Scenario 3, Scenario 4)
High arrival	Scenario 2 > Scenario 1> (Scenario 3, Scenario 4)

Based on the analyses of the data obtained from Experiment 1 and Experiment 2, findings about the effect of these four runway and taxiway scenarios on taxi-in times are:

1. The four different runway and taxiway choices (the four scenarios) have statistically significant effect (alpha=0.05) on the population means of the average taxi-in times during both the high departure period and the high arrival period.
2. There is no significant difference between Scenario 2 and Scenario 1 during the high departure period. The length of the taxi-in path is much longer in Scenario 2 in comparison to the taxi-in path in Scenario 1. However, there is no conflict between the taxi-in aircraft and the take-off aircraft around the inboard runway in Scenario 2. Therefore, taxi-in aircraft would taxi at a higher speed with no stops. Taxi-in aircraft in Scenario 1 may have to spend a lot of time waiting for departure aircraft to take off when the departure rate is high. Combining these two factors together, the taxi-in times in Scenario 1 and Scenario 2 are similar with each other during the high departure period.
3. The population mean of the average taxi-in time of scenario 2 is the longest during the high arrival period. The reason is that there are few interactions between the taxi-in aircraft and the

departure aircraft on the inboard runway in Scenario 1 as the departure rate is low. Therefore, it would be more likely that the arrival aircraft could go through the inboard runway without waiting for departure aircraft to take off. Compared with the high departure period, the taxi-in time in Scenario 1 decreases in the high arrival period while the taxi-in time in Scenario 1 remains the same.

4. The population means of the average taxi-in time under scenario 3 and 4 are the shortest under both high arrival periods and high departure periods. The main reasons are: 1) the taxi-in length is the shortest, 2) there is no active runway crossings for the arrival aircraft, 3) the interaction with the departure aircraft is reduced as the departure aircraft use the EAT as the route to queue out instead of congesting at the near apron area.

In general, Scenario 3 and Scenario 4 show great advantages in terms of the average taxi-in times during both high arrival periods and high departure period when compared with Scenario 1. The mean of the average taxi-in times in Scenario 2 is similar with scenario 1 during high departure period. During the high arrival period, however, the mean of the average taxi-in time in Scenario 2 is longer than the mean of the average taxi-in time in Scenario 1.

Sub Question 2 Taxi-out Times

High departure period

Average taxi-out time data obtained from Experiment 1 are used to analyze the influence of different runway and taxiway choices on taxi-out times during high departure period. The null hypothesis and alternative hypothesis are:

$H_0$3: There is no significant difference between the population means of the average taxi-out time based on the four combinations of the runway and taxiway choices during high departure period.

H_a3: Not all the population means of the average taxi-out time grouped by the runway and taxiway choices are equal.

The confidence level is set as 95%. The power is set as 80%. The minimum difference that can be detected is 88.63 seconds. The descriptive statistics are scenario 1 (Mean=672.10, SD=234.5), scenario 2 (Mean= 377.04, SD=89.9), scenario 3 (Mean= 552.30, SD=134.9), scenario

4 (Mean=586.20, SD=131.6). Table 20 presents some key descriptive statistics for the average taxi-in times. Detailed descriptive statistics for each scenario are included in Appendix C.

Table 20.

Key Descriptive Statistics for the Average Taxi-out Times during High Departure Period.

Variable	Scenario	n	Mean	StDev	Median
Taxi-out Time	1	100	672.10	234.5	578.6
	2	100	377.04	89.9	347.72
	3	100	552.30	134.9	509.0
	4	100	586.20	131.6	548.3

The results of a one-way ANOVA test on the influence of the type of runway and taxiway choices on the population means of the average taxi-out times are shown in Table 21. The impact of the runway and taxiway choices is statistically significant at the 95% confidence level during high departure period. At least one mean of the average taxi-in times is significantly different from the other three taxi-in times. Based on the results of the ANOVA test, the null hypothesis $H_0 3$ is rejected.

Table 21.

One-Way ANOVA Test for the Means of the Average Taxi-out Time during High Departure Period.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Scenario	3	0.000081	0.000027	157.65	<0.0001*
Error	396	0.000068	0.000000		
Total	399	0.000148			

Note. 1) *: Indicates a significant effect. 2) Box-Cox transformation is applied with λ=-0.9275.

A post hoc Tukey pairwise comparison test is conducted as the ANOVA test reveals significant differences. Table 22 shows the results of the Tukey pairwise comparisons test. Scenario 3 and Scenario 4 have the similar population means of the average taxi-out times. Applying the runway and taxiway choices in Scenario 3 or Scenario 4 would decrease the mean of the average taxi-in times compared with Scenario 1. Scenario 2 has the shortest average taxi-out time during high departure period. On average, Scenarios 2, 3, and 4 show decreases in average taxi-out times by 43.90%, 17.82% and 12.78% when compared with Scenario 1.

Table 22.

Grouping Information for the Means of the Average Taxi-out Times during High Departure Period Using the Tukey Method with 95% Confidence.

Scenario	Mean	Grouping	Simultaneous 95% CI of Mean Difference with Scenario			
			1	2	3	4
1	672.10	A	-	(219.38, 296.37)	(39.717, 138.83)	(0.712, 105.72)
2	377.04	B		-	(-199.14, -137.75)	(-238.14, -170.87)
3	552.30	C			-	(-80.91, 8.80)
4	586.20	C				-

Note. Means that do not share the same grouping letter are significantly different.

Main findings from the results of the statistical tests are:

1. These four different runway and taxiway choices (the four scenarios) have statistically significant influence on the population means of the average taxi-out times during high departure period.
2. There is statistically significant difference between the population means of the average taxi-out times of Scenario 1 and Scenario 2.
3. There is no statistically significant difference between the population means of the average taxi-out times of Scenario 3 and Scenario 4.
4. The population means of the average taxi-out times in Scenario 3 and Scenario 4 are significantly different from the means of the average taxi-out times in Scenario 1 and Scenario 2 with 95% confidence.
5. Compared with Scenario 1, applying the runway and taxiway strategy in Scenario 3 decrease the mean of the average taxi-out times by 17.82%. The reduction percentage is 8.53% for Scenario 4.
6. Compared with Scenario 2, applying the runway and taxiway strategy in Scenario 3 would increase the mean of the average taxi-out times by 46.5%. The increase percentage is 55.44% for Scenario 4.
7. Compared with Scenario 1, applying the runway and taxiway strategy in Scenario 2 would decrease the mean of the average taxi-out times by 43.90%.

High arrival period

Average taxi-out time data obtained from Experiment 2 are used to analyze the influence of different runway and taxiway choices on taxi-out times during the high arrival period. The null hypothesis and alternative hypothesis are:

$H_0$4: There is no significant difference between the population means of the average taxi-out time based on the runway and taxiway choices during the high arrival period.

H_a4: Not all the population means of the average taxi-out time grouped by the runway and taxiway choices are equal.

The confidence level is set as 95%. The power is set as 80%. The minimum difference that can be detected is 51.25 seconds. The descriptive statistics are scenario 1 (Mean=466.49, SD=41.83), scenario 2 (Mean= 261.58, SD=22.76), scenario 3 (Mean= 414.99, SD=22.48), scenario 4 (Mean=534.13, SD=71.78). Table 23 presents some key descriptive statistics for the average taxi-in times. Detailed descriptive statistics for each scenario are included in Appendix C.

Table 23.

Key Descriptive Statistics for the Average Taxi-out Times during High Arrival Period.

Variable	Scenario	n	Mean	StDev	Median
Taxi-out Time	1	100	466.49	41.83	464.57
	2	100	261.58	22.76	264.25
	3	100	414.99	22.48	412.07
	4	100	534.13	71.78	520.07

The results of a one-way ANOVA test on the influence of the type of runway and taxiway choices on the population means of the average taxi-out times are shown in Table 24. The impact of the runway and taxiway choices is statistically significant at the 95% confidence level. At least one mean of the average taxi-in time is significantly different from the other three. Based on the results of the ANOVA test, the null hypothesis $H_0$4 is rejected.

Table 24.

One-Way ANOVA Test for the Means of the Average Taxi-out Time during High Arrival Period.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Scenario	3	3604945	1201648	1160.49	<0.0001*
Error	396	396585	1035		
Total	399	4001530			

Note. *: Indicates a significant effect.

A post hoc Tukey pairwise comparison test is conducted as the ANOVA test reveals significant differences. Table 25 shows the results of the Tukey pairwise comparisons test.

Table 25.

Grouping Information for the Means of the Average Taxi-out Times during High Arrival Period Using the Tukey Method with 95% Confidence.

Scenario	Mean	Grouping	Simultaneous 95% CI of Mean Difference with Scenario			
			1	2	3	4
1	466.49	A	-	(194.83, 215.08)	(42.78, 67.12)	(-67.20, -39.19)
2	261.58	B		-	(-159.27, -140.73)	(-269.26, -247.05)
3	414.99	C			-	(-121.30, -94.99)
4	534.13	D				-

Note. Means that do not share the same grouping letter are significantly different.

As shown in Table 25, applying the runway and taxiway choices in Scenario 2 or Scenario 3 would decrease the mean of the average taxi-out times significantly compared with Scenario 1. Scenario 2 has the smallest population mean of the average taxi-out time during high arrival period. Scenario 2 and Scenario 3 show decreases in the mean of the average taxi-out times by 43.90% and 11.35% when compared with Scenario 1, while scenario 4 would increase the mean of the taxi-out time by 14.13%. Main findings from the statistical test results are:

1. These four different runway and taxiway choices (the four scenarios) have statistically significant influence on the population means of the average taxi-out times during high arrival period.
2. There is statistically significant difference between the population means of the average taxi-out times among Scenario 1, Scenario 2, Scenario 3, and Scenario 4.

3. Compared with Scenario 1, applying the runway and taxiway strategy in Scenario 2 would decrease the mean of the average taxi-out times by 43.90%. The reduction percentage is 11.35% for Scenario 3.
4. Compared with Scenario 1, applying the runway and taxiway strategy in Scenario 4 would increase the mean of the average taxi-out times by 14.13%.
5. Compared with Scenario 2, applying the runway and taxiway strategy in Scenario 3 would increase the mean of the average taxi-out times by 58.1%. The increase percentage is 103.5% for Scenario 4.
6. Compared with Scenario 3, applying the runway and taxiway strategy in Scenario 4 would increase the mean of the average taxi-out times by 28.7%.

Answer to Sub-Question 2

Experiment 1 explores the impact of four different taxiway and runway choices (four scenarios) on average taxi-in times during high departure period, while Experiment 2 focuses on the high arrival period. Table 26 shows the brief results of the statistical analyses.

Table 26.

Summary of Statistical Analyses of the Means of the Average Taxi-out Times.

	Results of Tukey Comparisons with Alpha=0.05
High departure	Scenario 1> (Scenario 3, Scenario 4)>Scenario 2
High arrival	Scenario 4 > Scenario 1> Scenario 3> Scenario 2

Based on the results of Experiment 1 and Experiment 2, findings about the effect of these four runway and taxiway scenarios on the average taxi-out time are:

1. The four different runway and taxiway choices (the four scenarios) have statistically significant influence (alpha=0.05) on the average taxi-out time during both of the high departure period and the high arrival period.
2. Despite of the same taxi-out length, the population mean of the average taxi-out times of Scenario 2 is significantly shorter than that of Scenario 1with 95% confidence and is the shortest during both high departure period and high arrival period.
3. The population mean of the average taxi-out times in Scenario 3 is significantly smaller than in Scenario 1 with 95% confidence during both high arrival period and high departure period.

In Scenario 3, which is under ICAO specification, there is no interaction between departure aircraft and landing aircraft around the EAT. So, departure aircraft could taxi out via the EAT without stop. Also, there are no potential runway crossings on the departure (outboard) runway. The take-off operations would not be interrupted by the arrival aircraft, which makes the movements more smoothly.

4. The population mean of the average taxi-out times in Scenario 4 is similar with Scenario 3 during high departure periods. The difference between Scenario 3 and Scenario 4 is that the interactions between taxi-out aircraft and landing aircraft in Scenario 4 would increase the taxi-out time. The effect of the interaction is limited during high departure periods as departure aircraft would not spend much time waiting for the landing aircraft to fly over the EAT when the arrival rate is low. Therefore, the difference between Scenarios 3 and 4 is not statistically significant.
5. The population mean of the average taxi-out times in Scenario 4 is the longest during high arrival period. In Scenario 4, landing aircraft has higher priority than the taxi-out aircraft on the EAT, which means that the departure aircraft are more likely to wait on the EAT. The departure aircraft may have to spend more time waiting for the arrival aircraft to land over the EAT when the arrival rate is high.

In general, Scenario 2 has the best performance in terms of the average taxi-in times during both high arrival period and high departure period. Scenario 3 shows great advantage in comparison to Scenario 1 during both high arrival period and high departure period. As for Scenario 4, the average taxi-out time is shorter than the average taxi-out time in Scenario 1 during high departure period. During high arrival period, however, the average taxi-out time in Scenario 4 is the longest.

Sub Question 3 Fuel Consumption per Taxi-in

High departure period

Average fuel consumption per taxi-in data obtained from Experiment 1 are used to analyze the influence of different runway and taxiway choices on the fuel consumption per taxi-in during high departure period. The null hypothesis and alternative hypothesis are:

$H_0$5: There is no significant difference between the population means of the average fuel consumption per taxi-in based on the four combinations of the runway and taxiway choices during high departure period.

H_a5: Not all the population means of the average fuel consumption per taxi-in grouped by the runway and taxiway choices are equal.

The confidence level is set as 95%. The power is set as 80%. The minimum difference that can be detected is 8.25 kg. The descriptive statistics are scenario 1 (Mean=44.93, SD=13.36), scenario 2 (Mean= 43.2, SD=1.798), scenario 3 (Mean= 9.738, SD=1.105), scenario 4 (Mean=9.895, SD=1.9592). Table 27 presents some key descriptive statistics for the average fuel consumptions per taxi-in. Detailed descriptive statistics for each scenario are included in Appendix C.

Table 27.

Key Descriptive Statistics for the Average Fuel Consumptions per Taxi-in during High Departure Period.

Variable	Scenario	n	Mean	StDev	Median
Fuel Consumptions per Taxi-in per engine (kg)	1	100	44.93	13.36	43.72
	2	100	43.20	1.798	43.153
	3	100	9.74	1.105	9.761
	4	100	9.90	1.9592	9.9348

The results of a one-way ANOVA on the influence of the type of runway and taxiway choices on the population means of the average fuel consumptions per taxi-in are shown in Table 28. The effect of the runway and taxiway choices is statistically significant at the 95% confidence level during the high departure period. At least one mean of the average fuel consumptions per taxi-in is significantly different from the other three. Based on the results of the ANOVA test, the null hypothesis $H_0$5 is rejected.

Table 28.

One-Way ANOVA Test for the Means of the Average Fuel Consumptions per Taxi-in during High Departure Period.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Scenario	3	2.8028	0.934267	3465.33	<0.0001*
Error	396	0.1068	0.000270		
Total	399	2.9096			

Note. 1) *: Indicates a significant effect. 2) Box-Cox transformation is applied with λ=-0.4242.

A post hoc Tukey pairwise comparison test is conducted as the ANOVA test reveals significant differences. Table 29 shows the results of the Tukey pairwise comparisons test.

Table 29.

Grouping Information for the Means of the Average Fuel Consumptions per Taxi-in during High Departure Period Using the Tukey Method with 95% Confidence.

Scenario	Mean	Grouping		Simultaneous 95% CI of Mean Difference with Scenario			
				1	2	3	4
1	44.93	A		-	(-2.37, 4.28)	(32.77, 36.78)	(32.59, 36.23)
2	43.20	A			-	(31.67, 35.41)	(31.49, 35.24)
3	9.74		B			-	(-0.54, 0.18)
4	9.90		B				-

Note. Means that do not share the same grouping letter are significantly different.

As shown in Table 29, Scenario 3 and Scenario 4 have the similar means of the average fuel consumptions per taxi-in. Scenario 2 has the similar mean of the average fuel consumptions per taxi-in with Scenario 1.

Main findings from the statistical test results are:

1. The four different runway and taxiway choices (the four scenarios) have statistically significant influence on the average fuel consumption per taxi-in during high departure period.
2. The difference between the population means of the average fuel consumption per taxi-in of Scenario 1 and Scenario 2 is statistically significant.
3. The difference between the population means of the average fuel consumption per taxi-in of Scenario 3 and Scenario 4 is not statistically significant.
4. There is a statistically significant difference between the two groups: Group 1 (Scenario 1 and Scenario 2) and Group 2 (Scenario 3 and Scenario 4).

5. Compared with Scenario 1 and Scenario 2, applying the runway and taxiway strategy in Scenario 3 or Scenario 4 would decrease the mean of the average fuel consumptions per taxi-in by 78% (about 35 kg).

High arrival period

Average fuel consumption per taxi-in data obtained from Experiment 2 are used to analyze the influence of different runway and taxiway choices on the fuel consumption per taxi-in during high arrival period. The null hypothesis and alternative hypothesis are:

$H_0$6: There is no significant difference between the population means of the average fuel consumption per taxi-in based on the runway and taxiway choices during high arrival period.

H_a6: Not all the population means of the average fuel consumption per taxi-in grouped by the runway and taxiway choices are equal.

The confidence level is set as 95%. The power is set as 80%. The minimum difference that can be detected is 6.5 kg. The descriptive statistics are scenario 1 (Mean=26.95, SD=1.741), scenario 2 (Mean= 43.54, SD=1.113), scenario 3 (Mean= 9.97, SD=0.655), scenario 4 (Mean=9.95, SD=0.487). Table 30 presents some key descriptive statistics for the average fuel consumptions per taxi-in. Detailed descriptive statistics for each scenario are included in Appendix C.

Table 30.

Key Descriptive Statistics for the Average Fuel Consumption per Taxi-in during High Arrival Period.

Variable	Scenario	n	Mean	StDev	Median
Fuel Consumptions per Taxi-in per engine (kg)	1	100	26.95	1.741	26.802
	2	100	43.54	1.113	43.532
	3	100	9.97	0.655	9.9106
	4	100	9.95	0.487	9.9375

The results of a one-way ANOVA test on the influence of the type of runway and taxiway choices on the population means of the average fuel consumptions per taxi-in during high arrival period are shown in Table 31. The impact of the runway and taxiway choices is statistically significant at the 95% confidence level during the high arrival period. At least one mean of the average fuel consumptions per taxi-in is significantly different from the other three. Based on the results of the ANOVA test, the null hypothesis H_06 is rejected.

Table 31.

One-Way ANOVA Test for the Means of the Average Fuel Consumption per Taxi-in during High Arrival Period.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Scenario	3	77715.0	25905.0	21000.50	<0.0001*
Error	396	488.5	1.2		
Total	399	78203.5			

Note. *: Indicates a significant effect.

A post hoc Tukey pairwise comparison test is conducted as the ANOVA test reveals statistically significant differences. Table 32 shows the results of the Tukey pairwise comparisons test.

Table 32.

Grouping Information for the Means of the Average Fuel Consumption per Taxi-in during High Arrival Period Using the Tukey Method with 95% Confidence.

Scenario	Mean	Grouping	Simultaneous 95% CI of Mean Difference with Scenario			
			1	2	3	4
1	26.95	A	-	(-17.17, -16.06)	(16.62, 17.30)	(16.59, 17.26)
2	43.54	B		-	(33.15, 34.02)	(33.12, 33.98)
3	9.97	C			-	(-0.24, 0.21)
4	9.95	C				-

Note. Means that do not share the same grouping letter are significantly different.

As shown in Table 32, Scenario 3 and Scenario 4 have the similar means of the average fuel consumptions per taxi-in. Applying the runway and taxiway choices in Scenario 3 or Scenario 4 would decrease the mean of the average fuel consumptions by 63% compared with Scenario 1. Compared with Scenario 1, taxi-in aircraft in Scenario 2 would burn more fuel on average. Main findings from the statistical test results are:

1. The four different runway and taxiway choices (the four scenarios) have statistically significant influence on the average fuel consumptions per taxi-in during high arrival period.

2. The difference between the population means of the average fuel consumptions per taxi-in of Scenario 1 and Scenario 2 is statistically significant.
3. The difference between the population means of the average fuel consumptions per taxi-in of Scenario 3 and Scenario 4 is not statistically significant.
4. The population means of the average fuel consumptions per taxi-in in Scenario 3 and Scenario 4 are significantly different from the means of the average fuel consumptions per taxi-in in Scenario 1 and Scenario 2 with 95% confidence.
5. Compared with Scenario 1, applying the runway and taxiway strategy in Scenario 3 or Scenario 4 would decrease the mean of the average fuel consumption per taxi-in by 63% during high arrival period.
6. Compared with Scenario 2, applying the runway and taxiway strategy in Scenario 3 or Scenario 4 would decrease the mean of the average fuel consumptions per taxi-in by 77.1%.
7. Compared with Scenario 1, applying the runway and taxiway strategy in Scenario 2 would increase the mean of the average fuel consumptions per taxi-in by 61.56%.

Answer to Sub-Question 3

Experiment 1 explores the impact of four different taxiway and runway choices (four scenarios) on the means of the average fuel consumptions per taxi-in during high departure period, while Experiment 2 focuses on the high arrival period. Table 33 shows the brief results of the statistical analyses.

Table 33.

Summary of Statistical Analyses of the Means of the Average Fuel Consumptions per Taxi-in.

	Results of Tukey Comparisons with Alpha=0.05
High departure	(Scenario 1, Scenario 2) > (Scenario 3, Scenario 4)
High arrival	Scenario 2 > Scenario 1> (Scenario 3, Scenario 4)

Based on the analyses of the data obtained from Experiment 1 and Experiment 2, findings about the impact of runway and taxiway choices on the means of the average fuel consumptions per taxi-in are:

1. The impact of runway and taxiway choices on the average fuel consumptions per taxi-in shares the similar pattern with the impact on taxi-in times as the fuel consumptions are estimated based

on the taxi time. The four different runway and taxiway choices (the four scenarios) have statistically significant influence (alpha=0.05) on the fuel consumption per taxi-in during both the high arrival period and the high departure period.

2. There is no significant difference between the population means of the average fuel consumptions per taxi-in among Scenario 2 and Scenario 1 during the high departure period. The arrival aircraft in Scenario 2 would approach the terminal area via the EAT without stop, while the arrival aircraft in Scenario 1 may have to spend a lot of time waiting for departure aircraft to take off.
3. The population mean of the average fuel consumptions per taxi-in under Scenario 2 is the largest during the high arrival period.
4. The population mean of the average fuel consumptions per taxi-in time under Scenarios 3 and 4 is the smallest under both high arrival period and high departure period because of the short taxi-in path and no runway crossing.

In general, Scenario 3 and Scenario 4 show advantages in terms of the average fuel consumptions per taxi-in during both high arrival period and high departure period 4 in comparison with Scenario 1. Scenario 2 and Scenario 1 have the similar performance in terms of the average fuel consumption per taxi-in during high departure period. During high arrival period, however, the mean of the average fuel consumptions per taxi-in in Scenario 2 is the largest.

Sub Question 4 Fuel Consumption per Taxi-out

High departure period

Average fuel consumption per taxi-out data obtained from Experiment 1 are used to analyze the influence of different runway and taxiway choices on the average fuel consumption per taxi-out during high departure period. The null hypothesis and alternative hypothesis are:

$H_0$7: There is no significant difference between the population means of the average fuel consumption per taxi-out based on the runway and taxiway choices during high departure period.

H_a7: Not all the population means of the average fuel consumption per taxi-out grouped by the runway and taxiway choices are equal.

The confidence level is set as 95%. The power is set as 80%. The minimum difference that can be detected is 4.85kg. The descriptive statistics are scenario 1 (Mean=45.25, SD=16.26), scenario 2 (Mean= 27.84, SD=8.559), scenario 3 (Mean= 39.50, SD=12.24), scenario 4 (Mean=42.57, SD=12.07). Table 34 presents some key descriptive statistics for the average fuel consumption per taxi-out. Detailed descriptive statistics for each scenario are included in Appendix C.

Table 34.

Key Descriptive Statistics for the Average Fuel Consumption per Taxi-out during High Departure Period.

Variable	Scenario	n	Mean	StDev	Median
Fuel consumption per taxi-out per engine (kg)	1	100	45.25	16.26	42.12
	2	100	27.84	8.559	26.976
	3	100	39.50	12.24	37.89
	4	100	42.57	12.07	41.20

The results of a one-way ANOVA test on the influence of the type of runway and taxiway choices on the population means of the average fuel consumptions per taxi-out are shown in Table 35. The effect of the runway and taxiway choices is statistically significant at the 95% confidence level during high departure period. At least one mean of the average fuel consumption per taxi-out is significantly different from the other three. Based on the results of the ANOVA test, the null hypothesis $H_0 7$ is rejected.

Table 35.

One-way ANOVA Test for the Means of the Average Fuel Consumption per Taxi-out during High Departure Period.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Scenario	3	0.01174	0.003914	104.65	<0.0001*
Error	396	0.01466	0.000037		
Total	399	0.02640			

Note. 1) *: Indicates a significant effect. 2) Box-Cox transformation is applied with λ=-0.84185.

A post hoc Tukey pairwise comparison test is conducted as the ANOVA test reveals significant differences. Table 36 shows the results of the Tukey pairwise comparisons test.

Table 36.

Grouping Information for the Means of the Average Fuel consumptions per taxi-out during High Departure Period Using the Tukey Method with 95% Confidence.

Scenario	Mean	Grouping	Simultaneous 95% CI of Mean Difference with Scenario			
			1	2	3	4
1	45.25	A	-	(14.31, 20.69)	(1.73, 9.86)	(-1.63, 7.05)
2	27.84	B		-	(-14.30, -9.11)	(-17.67, -11.92)
3	39.50	C			-	(-6.84, 0.67)
4	42.57	A C				-

Note. Means that do not share the same grouping letter are significantly different.

As shown in Table 36, Scenario 3 and Scenario 4 have the similar population means of the average fuel consumptions per taxi-out. The difference between the means of the average fuel consumptions per taxi-out of Scenario 1 and Scenario 4 is not statistically significant. The mean of the average amount of fuel burned per taxi-out under Scenario 3 is significantly smaller than the amount of fuel burned per taxi-out under Scenario 1. Scenario 2 has the smallest fuel consumption per taxi-out. Main findings from the statistical test results are:

1. The four different runway and taxiway choices (the four scenarios) have significant influence on the average fuel consumptions per taxi-out during high departure period.
2. There is a statistically significant difference between the population means of the average fuel consumptions per taxi-out of Scenario 1 and Scenario 2, Scenario 1, and Scenario 3, as well as Scenario 2 and Scenario 3.
3. There is no statistically significant difference between the population means of the average fuel consumptions per taxi-out among Scenario 1 and Scenario 4, as well as Scenario 3 and Scenario 4.
4. Compared with Scenario 1, applying the runway and taxiway strategy in Scenario 2 would decrease the mean of the average fuel consumptions per taxi-out by 34.10% during high departure period.
5. Compared with Scenario 1, applying the runway and taxiway strategy in Scenario 3 would decrease the mean of the average fuel consumptions per taxi-out by 6.51% during high departure period.
6. Compared with Scenario 2, applying the runway and taxiway strategy in Scenario 3 would increase the mean of the average fuel consumptions per taxi-out by 41.87%.

7. Compared with Scenario 2, applying the runway and taxiway strategy in Scenario 4 would increase the mean of the average fuel consumptions per taxi-out by 52.88%.

High arrival period

Average fuel consumption per taxi-out data obtained from Experiment 2 are used to analyze the influence of different runway and taxiway choices on the average fuel consumption per taxi-out during high arrival period. The null hypothesis and alternative hypothesis are:

$H_0$8: There is no significant difference between the population means of the average fuel consumption per taxi-out based on the runway and taxiway choices during high arrival period.

H_a8: Not all the population means of the average fuel consumption per taxi-out grouped by the runway and taxiway choices are equal.

The confidence level is set as 95%. The power is set as 80%. The minimum difference that can be detected is 4.08 kg. The descriptive statistics are scenario 1 (Mean=35.98, SD=3.642), scenario 2 (Mean= 18.75, SD=2.065), scenario 3 (Mean= 31.34, SD=1.773), scenario 4 (Mean=40.66, SD=4.781). Table 37 presents some key descriptive statistics for the average fuel consumptions per taxi-out under each scenario. Detailed descriptive statistics for each scenario are included in Appendix C.

Table 37.

Key Descriptive Statistics for the Average Fuel Consumptions per Taxi-out during High Arrival Period.

Variable	Scenario	n	Mean	StDev	Median
Fuel consumption per taxi-out per engine (kg)	1	100	35.89	3.642	35.999
	2	100	18.75	2.065	19.001
	3	100	31.34	1.773	31.101
	4	100	40.66	4.781	39.667

The results of a one-way ANOVA on the influence of the type of runway and taxiway choices on the population means of the average fuel consumptions per taxi-out during high departure period are shown in Table 38. P-value less than 0.05 indicates that the effect of the runway and taxiway choices is statistically significant at the 95% confidence level during the high arrival period. Based on the results of the ANOVA test, the null hypothesis $H_0$8 is rejected.

Table 38.

One-Way ANOVA Test for the Means of the Average Fuel Consumptions per Taxi-out during High Arrival Period.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Scenario	3	34.567	11.5223	1181.04	<0.0001*
Error	396	3.844	0.0098		
Total	399	38.411			

Note. 1) *: Indicates a significant effect. 2) Box-Cox transformation is applied with λ=0.06344.

A post hoc Tukey pairwise comparison test is conducted as the ANOVA test reveals significant differences. Table 39 shows the results of the Tukey pairwise comparisons test.

Table 39.

Grouping Information for the Means of the Average Fuel Consumptions per Taxi-out during High Arrival Period Using the Tukey Method with 95% Confidence.

Scenario	Mean	Grouping	Simultaneous 95% CI of Mean Difference with Scenario			
			1	2	3	4
1	35.89	A	-	(16.10, 18.06)	(3.21, 5.61)	(-6.07, -3.32)
2	18.75	B		-	(-13.56, -11.77)	(-22.84, -20.71)
3	31.34	C			-	(-10.40, -7.82)
4	40.66	D				-

Note. Means that do not share the same grouping letter are significantly different.

As shown in Table 39, applying the runway and taxiway choices in Scenario 2 or Scenario 3 would reduce the mean of the average fuel consumption per taxi-out by 17.14 kg and 4.55kg respectively when compared with Scenario 1. Scenario 4 would increase the mean of the average fuel consumptions per taxi-out by 13.28%. Main findings from the statistical test results are:

1. The four different runway and taxiway choices (the four scenarios) have statistically influence on the fuel consumptions per taxi-out during high arrival period.
2. There are statistically significant differences between the population means of the average fuel consumptions per taxi-out among Scenario 1, Scenario 2, Scenario 3, and Scenario 4.
3. Compared with Scenario 1, applying the runway and taxiway strategy in Scenario 2 would decrease the mean of the average fuel consumptions per taxi-out by 47.78%. The reduction is about 4.6 kg in Scenario 3, which may not be practically significant.

4. Compared with Scenario 1, applying the runway and taxiway strategy in Scenario 4 would increase the mean of the average fuel consumptions per taxi-out by 13.28%, which may not be practically significant.
5. Compared with Scenario 2, applying the runway and taxiway strategy in Scenario 3 would increase the mean of the average fuel consumptions per taxi-out by 67.21%. The increase percentage is 116.92% for Scenario 4.
6. Compared with Scenario 3, applying the runway and taxiway strategy in Scenario 4 would increase the mean of the average fuel consumptions per taxi-out by 29.73%.

Answer to Sub-Question 4

Experiment 1 explores the impact of four different taxiway and runway choices (four scenarios) on the means of the average fuel consumptions per taxi-out during high departure period, while Experiment 2 focuses on the high arrival period. Table 40 shows the brief results of the statistical analyses.

Table 40.

Summary of Statistical Analyses of the Means of the Average Fuel Consumptions per Taxi-out.

	Results of Tukey Comparisons with Alpha=0.05
High departure	Scenario 1 > Scenario 3 > Scenario 2 Scenario 4> Scenario 2
High arrival	Scenario 4 > Scenario 1> Scenario 3 > Scenario 2

Based on the analyses of the data obtained from Experiment 1 and Experiment 2, findings about the effect of runway and taxiway choices on the means of the average fuel consumptions per taxi-out are:

1. The four different runway and taxiway choices (the four scenarios) have statistically significant influence (alpha=0.05) on the fuel consumption per taxi-out during both the high departure period and the high arrival period.
2. Despite of the same taxi-out length, departure aircraft in Scenario 2 would burn significantly less fuel than departure aircraft in Scenario 1 during both high departure period and high arrival period at 95% confidence level. The reasons include the short taxi-out time and the less interactions with the arrival aircraft around the edge of the apron area.

3. The population mean of the average fuel consumption per taxi-out in Scenario 3 is significantly smaller than the average fuel consumption in Scenario 1 during both high arrival period and high departure period. The differences, however, are less than 6 kg, which is not practically significant. Therefore, the performance of Scenario 3 is similar with the performance of Scenario 1 in terms of fuel consumption per taxi-out.
4. The difference between the population means of the average fuel consumptions per taxi-out among Scenario 1 and Scenario 4 is not statistically significant during high departure period and statistically significant during high arrival period. The biggest difference, however, is 4.769 kg, which would not be practically significant. Therefore, Scenario 1 and Scenario 4 have similar performance in terms of fuel consumption per taxi-out.
5. Departure aircraft in Scenario 3 would on average consume less fuel to taxi out when compared with departure aircraft in Scenario 4. The reason may be that departure aircraft in Scenario 3 would taxi out without waiting for arrival aircraft to land over the EAT, while departure aircraft in Scenario 4 may need to hold on the EAT.

In general, Scenario 2 shows advantages in terms of the average fuel consumptions per taxi-out during both high arrival period and high departure period when compared with Scenario 1. The difference between the means of the average fuel consumption per taxi-out among Scenario 1 and Scenario 3 may not be practically significant. Scenario 4 would increase the average amount of fuel burned per taxi-out and the increment is not practically significant. Therefore, switching the runway and taxiway choices from Scenario 1 to Scenario 3 or Scenario 4 would not considerably affect the performance of the airport in terms of the average fuel consumption per taxi-out.

Sub Question 5 Runway Crossings

High departure period

The number of runway crossings data obtained from Experiment 1 are used to analyze the influence of different runway and taxiway choices on number of runway crossings during high departure period. The null hypothesis and alternative hypothesis are:

$H_0$9: There is no significant difference between the population means of the number of runway crossings per hour of Scenario 1 and Scenario 4.

H_a9: There is significant difference between the population means of the number of runway crossings per hour of Scenario 1 and Scenario 4.

The confidence level is set as 95%. The power is set as 80%. The minimum difference that can be detected is 1.001. The descriptive statistics are scenario 1 (Mean=11.24, SD=3.20), and Scenario 4 (Mean= 7.44, SD=1.68). Table 41 shows the descriptive statistics, as well as the 95% Confidence Interval of the average number of runway crossings in Scenario 1 and Scenario 4.

Table 41.

95% Confidence Interval of the Average Number of Runway Crossings in Scenario 1 and Scenario 4.

Scenario	n	Mean	StDev	95% CI
1	100	11.24	3.20	(10.56, 11.91)
4	100	7.44	1.68	(7.11, 7.77)

A two- sample Poisson Rates test is conducted to explore the mean difference between two groups. Table 42 presents the results of the Poisson Rates Test. The p-value that is less than 0.001 indicates that there is a statistically significant difference between the number of runway crossings among Scenario 1 and Scenario 4 during high departure period. Therefore, H_09 is rejected with 95% confidence. The observed difference is 3.80. The 95% confidence interval for the difference is (3.11, 4.5).

Table 42.

Two-Sample Poisson Rates Test for the Number of Runway Crossings in Scenario 1 and Scenario 4 during High Departure Period.

Method	Z-Value	P-Value
Exact		<0.001
Normal approximation	10.79	<0.001

Main findings from the statistical test results are:

1. There is a significant difference between the average number of runway crossings among Scenario 1 and Scenario 4 during high departure period.
2. The average number of runway crossings in Scenario 1 is significantly larger than the number in Scenario 4. The 95% confidence interval for the difference is (3.11, 4.5).

3. Compared to Scenario 1, applying the runway and taxiway strategy in Scenario 4 would decrease the average number of runway crossings by 33.81% during high departure period.

High arrival period

The number of runway crossings data obtained from Experiment 2 are used to analyze the influence of different runway and taxiway choices on number of runway crossings during high arrival period. The null hypothesis and alternative hypothesis are:

$H_0$10: There is no significant difference between the population means of the number of runway crossings per hour of Scenario 1 and Scenario 4.

H_a10: There is a significant difference between the population means of the number of runway crossings per hour of Scenario 1 and Scenario 4.

The confidence level is set as 95%. The power is set as 80%. The minimum difference that can be detected is 0.73. The descriptive statistics are Scenario 1 (Mean=12.27, SD=2.41), and Scenario 4 (Mean= 4.91, SD=1.18). Table 43 shows the descriptive statistics, as well as the 95% Confidence Interval of the average number of runway crossings in Scenario 1 and Scenario 4.

Table 43.

95% Confidence Interval of the Average Number of Runway Crossings in Scenario 1 and Scenario 4.

Scenario	n	Mean	StDev	95% CI
1	100	12.27	2.41	(12.07, 12.47)
4	100	4.91	1.18	(4.67, 5.14)

A two-sample t-test is conducted to explore the mean difference between two groups. Table 44 presents the results of the Poisson Rates Test. The p-value that is less than 0.001 indicates there is a statistically significant difference between the number of runway crossings among Scenario 1 and Scenario 4 during high arrival period. Therefore, H010 is rejected with 95% confidence. The observed difference is 7.36. The 95% confidence interval for the differences is (6.7, 8.03).

Table 44.

Two-Sample Poisson Rates Test for the Number of Runway Crossings in Scenario 1 and Scenario 4 during High Arrival Period.

Method	Z-Value	P-Value
Exact		<0.001
Normal approximation	21.77	<0.001

Main findings from the statistical test results are:

1. There is a significant difference between the population means of the number of runway crossings among Scenario 1 and Scenario 4 during high departure period.
2. The average number of runway crossings in Scenario 1 is significantly larger than the number in Scenario 4. The 95% confidence interval for the difference is (6.7, 8.03).
3. Compared to Scenario 1, applying the runway and taxiway strategy in Scenario 4 would decrease the number of runway crossings by 59.98% during high arrival period.

Answer to Sub-Question 5

Experiment 1 explores the impact of Scenario 1 and Scenario 4 on the means of the numbers of runway crossings during high departure period, while Experiment 2 focuses on the high arrival period. Table 45 shows the brief results of the statistical analyses.

Table 45.

Summary of Statistical Analyses of the Means of the Number of Runway Crossings.

	Average Number of Runway Crossing (/hour)		95% Confidence Interval for the differences
High departure	Scenario 1	11.24	(3.11, 4.5)
	Scenario 4	7.44	
High arrival	Scenario 1	12.27	(6.7, 8.03)
	Scenario 4	4.91	

Based on the analyses of the data obtained from Experiment 1 and Experiment 2, findings about the effect of runway and taxiway choices on the means of the number of runway crossings are:

1. There is a statistically significant difference between the means of the numbers of runway crossings among Scenario 1 and Scenario 4 during both the high departure period and the high arrival period.
2. Compared to Scenario 1, applying the runway and taxiway strategy in Scenario 4 would decrease the average number of runway crossings by 33.81% during the high departure period, and by 59.98% during the high arrival period. One of the reasons is that there are four intersections between the taxi-in path and the inboard departure runway in Scenario 1 where runway crossing could happen. In Scenario 4, however, runway crossing could only happen above the EAT.

In general, Scenario 2 and 3 could eliminate runway crossing as the operations on the EAT do not conflict the operations on the runway. Scenario 4 could not eliminate runway crossing as the interaction between taxi-out aircraft and landing aircraft around EAT requires clearance from the ATCs. But compared to Scenario 1, Scenario 4 could reduce the number of runway crossings significantly during both high arrival periods and high departure periods.

Sub Question 6 Ability to Cope with Increases in the Traffic Load Level

Two metrics, the average taxi-in time and the average taxi-out time, are used to measure the ability of each runway and taxiway choice to cope with increases in the traffic load level.

Average Taxi-in Time

The null hypothesis and alternative hypothesis are:

$H_0$11: There is no significant difference between the population means of the average taxi-in time based on the runway and taxiway choices.

H_a11: Not all the population means of the average taxi-in times grouped by the runway and taxiway choices are equal.

$H_0$12: There is no significant difference between the population means of the average taxi-in time based on load levels.

H_a12: Not all the population means of the average taxi-in time grouped by the load levels are equal.

$H_0$13: There is no interaction between the load level and the runway and taxiway choice.

H_a13: Not all the means of the taxi-in time grouped by the combination of the runway and taxiway choices and the load levels are equal.

The confidence level is set as 95%. The power is set as 80%. The minimum difference that can be detected is 36.49 seconds. Table 46 presents some key descriptive statistics for the average taxi-in time. Detailed descriptive statistics for each scenario are included in Appendix C.

Table 46.

Descriptive Statistics for the Average Taxi-in Times in Experiment 3.

Load level	Scenario1		Scenario2		Scenario3		Scenario4		Total	
	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
72	326.9	24.79	480.2	9.62	106.4	4.84	106.3	4.23	255.5	158.53
80	327.5	21.92	480.7	8.27	106.5	4.48	106.2	4.02	255.8	158.60
88	334.9	22.51	479.6	7.28	106.8	3.87	106.3	3.45	257.4	158.99
96	342.0	21.62	480.4	7.97	106.9	4.58	106.7	4.48	259.4	160.03
Total	332.8	23.48	480.2	8.08	106.6	4.44	106.4	3.89	257.0	158.90

The results of a two-way ANOVA test on the influence of the type of runway and taxiway choices and load level on the population means of the average taxi-in times for a parallel runways system with EATs at both ends are shown at Table 47. Both main effects and interaction are statistically significant at the 95% confidence level. Based on the results of the ANOVA test, the null hypothesis H_011, H_012, and H_013 are rejected.

Table 47.

Tests of Main Effect and Interaction Effect for the Means of the Means of the Average Taxi-in Times.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Load	3	0.00012	0.000041	7.72	<0.001*
Scenario	3	1.91786	0.639288	120089.54	<0.001*
Load*Scenario	9	0.00023	0.000026	4.90	<0.001*
Error	1584	0.00843	0.000005		
Total	1599	1.92665			

Note: 1) * indicates a significant effect. 2) Box-Cox transformation is applied with λ=-0.079.

1) Main Effects

The descriptive statistics of the main effect for the four runway and taxiway scenarios are: Scenario 1 (Mean=332.8, SD=23.48), Scenario 2 (Mean= 480.2, SD=8.08), Scenario 3 (Mean=

106.6, SD=4.44), and Scenario 4 (Mean=106.4, SD=3.89). Detailed descriptive statistics for each scenario are included in Appendix C. Results of a post hoc Tukey pairwise comparison indicates that there are significant differences among the four scenarios at 95% confidence level. Table 48 shows the results of the Tukey comparison test.

Table 48.

Grouping Information of the Effect of Runway and Taxiway Choices for the Means of the Average Taxi-in Time Using the Tukey Method with 95% Confidence.

Scenario	Mean	Grouping	Simultaneous 95% CI of Mean Difference with Scenario			
			1	2	3	4
1	332.8	A	-	(-151.71, -144.79)	(223.59, 227.19)	(223.82, 227.44)
2	480.2	B		-	(371.16, 376.12)	(371.40, 376.37)
3	106.6	C			-	(-0.563, 1.07)
4	106.4	C				-

Note. Means that do not share the same grouping letter are significantly different

The population mean of the aveage taxi-in times in Scenario 2 is significantly larger than that in Scenario 1 with an increase about 147.4 seconds. Scenaio 3 and Scenario 4 would decrease the mean of the average taxi-in time significantly when compared with Scenario 1. The average reduction is about 226 seconds.

The descriptive statistics of the main effect for the four load levels are load level 1 (Mean=255.5, SD=158.53), load level 2 (Mean= 255.8, SD=158.60), load level 3 (Mean= 257.4, SD=158.99), and load level 4 (Mean=259.4, SD=160.03). A Tukey pairwise comparison is conducted to explore the detail information about the main effects of the load level. Table 49 presents the results of the Tukey pairwise comparison.

Table 49.

Grouping Information of the Effect of Runway and Taxiway Choices for the Means of the Average Taxi-in Time Using the Tukey Method with 95% Confidence.

	Load Level	n	Mean	Grouping	
1	72	400	255.5	A	
2	80	400	255.8	A	
3	88	400	257.4	A	B
4	96	400	259.4		B

Note. Means that do not share the same grouping letter are significantly different.

The means of the average taxi-in time increases with the load level. The mean of the average taxi-in times under load level 4 is significantly larger than the means under load level 1 and 2. The increment, however, is less than 4 seconds, which is not practically significant. The reason that the average taxi-in time would not increase greatly against the load level in Scenarios 2, 3, and 4 is that the arrival operation is separated from other operations on the parallel runway system in those three scenarios.

2) Interaction

The effect of the load level on the means of the average taxi-in times is statistically significant in Scenario 1, while the average taxi-in times in Scenario 2, Scenario 3, and Scenario 4 are stable against the increases of the load level.

Table 50 shows the percentage changes on taxi-in time if the runway and taxiway strategy is changed from Scenario 1 to Scenario 2, 3, or 4 under each load level. When the load level is 72 aircraft per hour, switching the runway and taxiway strategy from Scenario 1 to Scenario 2 would increase the mean of the average taxi-in times by 44.29%. The percentage decreases to 40.47% when the load level is 96 aircraft per hour. Therefore, the difference between the mean of the average taxi-in times among Scenario 1 and Scenario 2 would become smaller when the load level is higher.

Table 50.

Percentage Changes on the Mean of the Average Taxi-in Times When Compared Scenario 2, Scenario 3, Scenario 4 with Scenario 1 under Each Load Level.

	Load Level			
	72	80	88	96
Baseline (Scenario 1)	-	-	-	-
Scenario 2	+44.29%	+46.80%	+43.22%	+40.70%
Scenario 3	-67.97%	-67.49%	-68.11%	-68.75%
Scenario 4	-68.02%	-67.54%	-68.26%	-68.81%

Changing the runway and taxiway strategy from Scenario 1 to Scenario 3 or Scenario 4 would decrease the average taxi-in time by 67.50% when the load level is 72 aircraft per hour. The percentage increases to 68.8% when the load level is 96 aircraft per hour. In other words, changing the runway and taxiway strategy from Scenario 1 to Scenario 3 or Scenario 4 would yield more benefit in terms of taxi-in times when the load level is higher.

Average Taxi-out Time

The null hypothesis and alternative hypothesis are:

$H_0$14: There is no significant difference between the population means of the average taxi-out time based on the runway and taxiway choices.

H_a14: Not all the population means of the average taxi-out time grouped by the runway and taxiway choices are equal.

$H_0$15: There is no significant difference between the population means of the average taxi-out time based on the load levels.

H_a15: Not all the population means of the average taxi-out time grouped by the load levels are equal.

$H_0$16: There is no interaction between the load level and the runway and taxiway choice.

H_a16: Not all the population means of the taxi-out time grouped by the combination of the runway and taxiway choices and the load levels are equal.

The confidence level is set as 95%. The power is set as 80%. The minimum difference that can be detected is 35.82 seconds. Table 51 presents some key descriptive statistics for the average taxi-out time. Detailed descriptive statistics for each scenario are included in Appendix C.

Table 51.

Descriptive Statistics for the Average Taxi-out Times in Experiment 3.

Load level	Scenario1		Scenario2		Scenario3		Scenario4		Total	
	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
72	521.3	72.79	314.7	46.15	464.6	58.41	510.3	72.05	452.7	103.90
80	574.0	114.3	338.53	57.58	496.1	79.80	552.5	87.63	490.3	126.72
88	646.9	157.7	377.6	78.37	537.7	106.3	609.8	110.9	543.0	155.69
96	713.6	181.7	412.6	108.6	577.8	130.3	661.7	127.4	591.4	180.01
Total	614.0	155.68	360.9	84.85	519.1	106.16	583.6	116.5	519.4	153.61

The results of a Two-way ANOVA test on the influence of the type of runway and taxiway choices and load level on the population means of the average taxi-out times are shown in Table 52. Both two main effects are statistically significant at the 95% confidence level, while the interaction is not statistically significant. Based on the results of the ANOVA test, the null hypothesis $H_0$14 and $H_0$15 are rejected. There is not enough evidence to reject $H_0$16 using an alpha of 0.05.

Table 52.

Tests of Main Effect and Interaction Effect for the Means of the Average Taxi-out Times.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Load	3	0.001219	0.000406	152.28	<0.001*
Scenario	3	0.007354	0.002451	918.99	<0.001*
Load*Scenario	9	0.000038	0.000004	1.56	0.121
Error	1584	0.004225	0.000003		
Total	1599	0.012836			

Note. 1) * indicates a significant effect. 2) Box-Cox transformation is applied with λ=-0.6896.

1) Main Effects

The descriptive statistics of the main effect for the four Scenarios are: Scenario 1 (Mean=614.0, SD=155.68), Scenario 2 (Mean= 360.9, SD=84.85), Scenario 3 (Mean= 519.1, SD=106.16), and Scenario 4 (Mean=583.6, SD=116.5). Results of a post hoc Tukey pairwise comparison indicates that there are statistically significant differences among all of the four scenarios with 95% confidence level. Table 53 shows the results of the Tukey comparison test.

Table 53.

Grouping Information of the Effect of the Runway and Taxiway Choice for the Means of the Average Taxi-out Times Using the Tukey Method with 95% Confidence.

Scenario	n	Mean	Grouping			
1	400	614.0	A			
2	400	360.9		B		
3	400	519.1			C	
4	400	583.6				D

Note. Means that do not share the same grouping letter are significantly different.

The means of the aveage taxi-out times in Scenario 2, Scenario 3, and Scenario 4 are all significantly smaller than the taxi-out time in Scenario 1 with 95% confidence. Compared with Senario 1, Sceanrio 2 would reduce the mean of the average taxi-out times by about 253.9 seconds. The decrase is about 94.9 seconds in Scenario 3, and about 30.4 seconds in Scenario 4.

Table 54.

Grouping Information of the Effect of the Load Level for the Means of the Average Taxi-out Times Using the Tukey Method with 95% Confidence.

Load Level	Traffic load (/hr)	n	Mean	Grouping			
1	72	400	452.7	A			
2	80	400	490.3		B		
3	88	400	543.0			C	
4	96	400	591.4				D

Note. Means that do not share the same grouping letter are significantly different.

The descriptive statistics of the main effect for the four load levels are: load level 1 (Mean=452.7, SD=103.9), load level 2 (Mean= 490.3, SD=126.72), load level 3 (Mean= 543.0, SD=155.69), and load level 4 (Mean=591.4, SD=180.01). A Tukey pairwise comparison is conducted to explore the detail information about the main effects of the load level. Table 54 presents the results of the Tukey pairwise comparison. There are statistically significant differences between the means of the average taxi-out times among the four load levels. The average taxi-out time surges by 30.63% when the load level increases from 72 aircraft per hour to 96 aircraft per hour.

2) Interaction

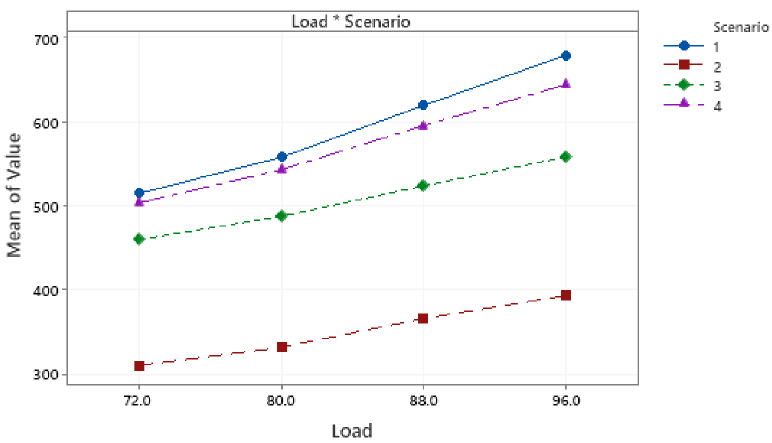

Figure 18. Interaction plots for taxi-out times in Experiment 3.

The nonsignificant interaction shown in Table 52 indicates that the trends of the change of the population means of the average taxi-out times among the four scenarios are similar under four load levels. Figure 18 shows the change of the means of the average taxi-out times with the increase of the load level in each scenario. Scenario 2 has the best performance in terms of average taxi-out times under each load level. Scenario 3 also shows benefit compared with Scenario 1 and Scenario 4. The difference between Scenario 1 and Scenario 4 is not statistically significant under each load level.

Table 55.

Percentage Changes on the Means of the Average Taxi-out Times When Compared Scenario 2, Scenario 3, Scenario 4 with Scenario 1 under Each Load Level.

	Load Level			
	72	80	88	96
Baseline (Scenario 1)	-	-	-	-
Scenario 2	-39.62%	-41.02	-41.63%	-42.19%
Scenario 3	-10.87	-13.56%	-16.88%	-19.04%
Scenario 4	-2.1%	-3.73%	-5.75%	-7.3%

Changing the runway and taxiway strategy from Scenario 1 to Scenario 2 when the traffic load is 72 aircraft per hour would reduce the mean of the average taxi-out times by 39.62%. The percentage, however, is 42.19% when the traffic load rises to 96 aircraft per hour. Similarly, compared with Scenario 1, Scenario 3 would decrease the means of the average taxi-out times by 10.87% under load level 1. The percentage jumps to 19.04% with the traffic load changing to 96 aircraft per hour. Table 55 presents the percentage changes of the means of the average taxi-out time when changing the runway and taxiway strategy from Scenario 1 to Scenario 2, Scenario 3, or Scenario 4 under each load. The ascending trends indicates that the higher the load level is, the better the performance of Scenario 2, 3, and 4 in terms of taxi-out times would be when compared with Scenario 1.

Table 56 shows the percentage increase of the means of the average taxi-out times in each scenario against the increase of the load level. The mean of the average taxi-out times increases by 10.11%, 24.11%, and 36.91% respectively in Scenario 1 when the load level increases from 72 aircraft per hour to 80, 88, or 96 aircraft per hour. In Scenario 2, the percentages are 7.57%, 19.99%, and 31.09%. In scenario 3, the percentages are 6.78%, 15.73%, and 24.35%. In Scenario 4, the percentages are 8.28%, 19.50%, 29.68%. Among the four scenarios, the increase percentage in Scenario 3 is the smallest while Scenario 1 has the largest increase percentage in terms of taxi-out times.

Table 56.

Percentage Change of the Means of the Average Taxi-out Times in Each Scenario Against the Increase in the Load Level.

	Load Level			
	72	80	88	96
Scenario 1	-	10.11%	21.11%	36.91%
Scenario 2	-	7.57%	19.99%	31.09%
Scenario 3	-	6.78%	15.73%	24.35%
Scenario 4	-	8.28%	19.50%	29.68%

Answers to Sub-Question 6

The influence of different runway and taxiway scenarios on the ability to cope with the increase in the traffic load level is explored by investigating and comparing the performance of four scenarios under four different load levels.

Findings from the statistical analyses of the results obtained from Experiment 3 are:

1. The abilities of the four scenarios to cope with the increase in the load level are different based on the analyses of the means of the average taxi-in times and the means of the average taxi-out times.
2. The traffic load level has a statistically significant effect on the means of the average taxi-in times in Scenario 1, while the effects are not statistically significant in Scenarios 2, 3, and 4.
3. The effect of the traffic load level on the means of the average taxi-out times is statistically significant in each scenario.
4. Compared with other three scenarios, Scenario 3 shows advantages against the increase of the load level. When the load level increases from 72 aircraft/hour to 96 aircraft/hour (33%), the percentage increase of the mean of the average taxi-out times (24.35%) in Scenario 3 is the smallest.
5. Compared with Scenario 1 and Scenario 2, Scenario 4 shows some advantages against the increase of the load level. The mean of the average taxi-in time is stable when the load level increase from 72 aircraft/hour to 96 aircraft/hour, while the average taxi-out time increases by 29.68%.The increase percentage of the average taxi-out time is smaller than the percentage increase of Scenario 1 and Scenario 2.

6. Compared with Scenario 1, Scenario 2 shows some advantage against the increase of the load level. The mean of the average taxi-in time is stable when the load level increase from 72 aircraft/hour to 96 aircraft/hour, while the average taxi-out time increases by 31.09%.The increase percentage of the average taxi-out time is smaller than the percentage increase of Scenario 1.

6. DISCUSSION

To examine the research question, three experiments are conducted to explore the impact of four runway and taxiway scenarios on airport performance. Experiment 1 focuses on the effect of the four runway and taxiway choices on taxi time, fuel consumption, and runway crossing during the high departure period. Experiment 2 studies the influence of different runway and taxiway choices during the high arrival period. Experiment 3 examines the interaction between the load levels and the four runway and taxiway choices in terms of the average taxi-in time and the average taxi-out time. Table 57 presents a summary of the statistical analyses of results obtained from Experiment 1 and Experiment 2.

Table 57.

Summary of the Statistical Analyses of Experiment 1 and Experiment 2.

		Results of Tukey Comparisons with alpha=0.05
Average Taxi-in time	High departure	(Scenario 1, Scenario 2)> (Scenario 3, Scenario 4)
	High arrival	Scenario 2 > Scenario 1> (Scenario 3, Scenario 4)
Average Taxi-out time	High departure	Scenario 1> (Scenario 3, Scenario 4)>Scenario 2
	High arrival	Scenario 4 > Scenario 1> Scenario 3> Scenario 2
Average Fuel Consumption per Taxi-in	High departure	(Scenario 1, Scenario 2)> (Scenario 3, Scenario 4)
	High arrival	Scenario 2 > Scenario 1> (Scenario 3, Scenario 4)
Average Fuel Consumption per Taxi-out	High departure	Scenario 1 > Scenario 3> Scenario 2 Scenario 4> Scenario 2
	High arrival	Scenario 4 > Scenario 1> Scenario 3 > Scenario 2
Number of Runway Crossings	High departure	Scenario 1 > Scenario 4 Scenario 2 =0, Scenario 3=0
	High arrival	Scenario 1 > Scenario 4 Scenario 2 =0, Scenario 3=0

Scenario 1 is the traditional runway and taxiway choices, where outboard runway and conventional taxiways are used for arrival aircraft. Scenario 2 represents the way that the EAT is currently used at DFW, DTW, ATL, and MIA: arrival aircraft that land on the outboard runway taxi through the EAT to approach the terminal area. Scenario 3 and Scenario 4 are the new runway and taxiway choices, where the outboard runway is used to take off and the EAT is used for the departure aircraft to approach the outboard runway. The difference between Scenario 3 and

Scenario 4 is whether landing aircraft are allowed to fly over the active EAT. Scenario 3 allows this kind of operation, while Scenario 4 does not.

Scenario 1

Scenario 1 is regarded as the baseline in the discussion because the runway and taxiway strategy in Scenario 1 is widely used in current major airports. The discussion section assesses the potential benefits of changing the runway and taxiway strategy to the one used in Scenario 2, 3, or 4.

Scenario 2

In Scenario 2, the inboard runway is used to take off, the outboard runway is used to land, and the EAT is used for arrival aircraft to approach the terminal area. The results indicate that compared with Scenario 1, Scenario 2 could decrease the average taxi-out time significantly by 42% during the high departure period and by 43.9% during the high arrival period. The average taxi-in time in Scenario 2 is slightly decreased by 2.86% during high departure period, which is not statistically significant. During the high arrival period, however, the average taxi-in time in Scenario 2 is the longest and 187.29 seconds longer than the average taxi-in time in Scenario 1. Runway crossing is eliminated in Scenario 2 because that the operations on EAT would not interrupt the operations on the inboard runway.

The result that the average taxi-in time in Scenario 2 is similar to the average taxi-in time in Scenario 1 during the high departure period is consistent with previous study about the historical traffic data at DFW (Uday, et al., 2011). Although the taxi-in distance is shorter in Scenario 1, arrival aircraft may need to spend more time waiting for runway clearance before taxiing cross the inboard runway when the departure rate is high. Arrival aircraft in Scenario 2 would taxi at a higher speed as there is no interaction between the operations on the EAT and the operations on the inboard runway. For Scenario 2, the benefit of the elimination of runway crossing offsets the increased taxi-in distance.

The difference of the average taxi-in times in Scenarios 1 and 2 becomes statistically significant during the high arrival period. Compared with the high departure period, the taxi-in time in Scenario 1 decreases greatly while the taxi-in time in Scenario 2 remains the same. The reason is that there are few interactions between the taxi-in aircraft and the departure aircraft on the inboard runway in Scenario 1 as the departure rate is low during the high arrival period. Therefore, the arrival aircraft would not spend a lot of time waiting for the departure aircraft to take off, which would decrease the average taxi-in time in Scenario 1. For Scenario 2, the benefit of the elimination of runway crossing could not offset the increased taxi-in distance.

The improvement in the average taxi-out times during both the high arrival period and the high departure period suggested in Experiment 1 and Experiment 2 may be attributed to the elimination of runway crossings and the simplification of taxi paths at the near apron area:

1) Instead of going across the inboard runway, arrival aircraft that land on the outboard runway use the EAT to approach the terminal area. The inboard runway would not be occupied by the arrival aircraft to taxi in. Therefore, the departure procedure would not be interrupted by the arrival aircraft taxiing across the runway. Runway crossing delay is eliminated for departure aircraft.

2) Scenario 2 could simplify the taxiing paths around the near apron area. Figure 19 shows the comparisons of the taxiing paths used in Scenario 1 and Scenario 2. There are three intersections between the taxi-in paths and the taxi-out paths around the near apron area in Scenario 1. The departure aircraft in Scenario 1 may need to slow down or stop to wait for other aircraft to cross the taxiway when they taxi through these intersections. Such conflict would reduce the taxi speed and cause delay. The arrival and departure aircraft in Scenario 2, however, taxi in the same direction with no intersections between the taxi-in and taxi-out paths. Departure aircraft would not need to slow down or stop when they taxi out to the departure runway, which would allow departure aircraft taxi at a higher speed.

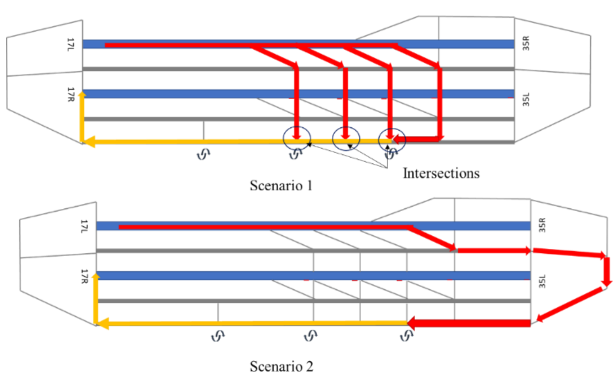

Figure 19. Comparison of the taxiing paths used in Scenario 1 and Scenario 2.

The analyses of the results of the average fuel consumptions show similar trends with the average taxi time. Compared with Scenario 1, Scenario 2 would decrease the average fuel consumption per taxi-out by 34.1% during high departure period and by 47.78% during the high arrival period. The average fuel consumption per taxi-in in Scenario 2 is decreased slightly by 3.85% during the high departure period and is 16.69 kg higher than Scenario 1 during the high arrival period.

Data obtained from Experiment 3 show that Scenario 2 has the best performance in terms of the average taxi-out times under each load level because of the short taxi-out path and elimination of interaction with arrival aircraft on the inboard runway and around the near apron area. The average taxi-in time in Scenario 2 is the longest under each load level due to the longer taxi-in distance.

Analyses of the data obtained from Experiment 3 indicate that Scenario 2 is more stable against the increase of the traffic load level in comparison with Scenario 1. The average taxi-out time in Scenario 2 is increased by up to 31.09% when the traffic load level rises from 72 aircraft per hour to 96 aircraft per hour. The percentage increase is 36.91% in Scenario 1. As for taxi-in time, Scenario 1 shows an increase of 4.42% when the traffic load level rises from 72 aircraft per hour to 96 aircraft per hour while the increase of the average taxi-in time in Scenario 2 is negligible. Compared with Scenario 1, Scenario 2 could better respond to the future growth in the airport traffic level at the cost of a longer average taxi-in time.

Scenario 3

In Scenario 3, the inboard runway is used for arrival aircraft to land, and the outboard runway is used for departure aircraft to take off. The EAT is used for departure aircraft to approach the outboard runway. Scenario 3 is designed and built based on ICAO’s definition of the End-Around Taxiway. ICAO specifies that the operation on the EAT would not interrupt with the operations on the runway (ICAO, 2018b). Arrival aircraft are allowed to land over the active EAT in Scenario 3. Therefore, runway crossing is eliminated in Scenario 3 as departure and arrival operations are separated from each other.

The results in Experiment 1 and Experiment 2 imply that compared with Scenario 1, Scenario 3 could decrease the average taxi-in time significantly by 78.41% during the high departure period and by 63.03% during the high arrival period. As for the average taxi-out times, Scenario 3 shows a decrease of 14.39% during the high departure period and a decrease of 11.35% during the high arrival period.

Scenario 3 could benefit airport operation in terms of the average taxi-in time during both high arrival periods and high departure periods. The main reasons are 1) the taxi-in path is shorter in Scenario 3 than Scenarios 1 and 2, and 2) arrival aircraft need not wait for clearance to cross any runways to approach the terminal area, which means that runway crossing is eliminated for arrival aircraft.

The improvement in the performance of the average taxi-out time during both high arrival periods and high departure periods in Scenario 3 may be attributed to the higher average taxi-out speed and the elimination of runway crossings.

1) As arrival aircraft are allowed to land over the active EAT in Scenario 3, departure aircraft could taxi out to the outboard runway via the EAT without stop. Therefore, the average taxi-out speed in Scenario 3 is higher than the taxi-out speed in Scenario 1.

2) The take-off operations on the outboard runway is independent from other operations in the parallel runway system. Therefore, the departure procedure would not be interrupted by the arrival aircraft taxiing across the runway. This feature would benefit the taxi-out time greatly when departure aircraft are waiting in a long line to take off during the high departure period.

Another potential advantage of Scenario 3 that could be a future research topic is the reduction of the congestion level at near apron area. Departure aircraft that taxi out via the EAT would leave the near apron area once they taxi on the EAT, which would reduce the number of aircraft around the terminal area. This feature may reduce the congestion level of the near apron area. Future research could be conducted to explore the reduction of airport congestion level mathematically, as well as explore further impacts of the congestion level reduction on airport performance.

The results of the fuel consumption show similar trends with the taxi times. Compared with Scenario 1, Scenario 3 would decrease the average fuel consumption per taxi-out significantly by up to 78.33% during the high departure period and by 63.03% during the high arrival period. The reductions of the average fuel consumption per taxi-in in Scenario 3 are statistically significant (5.75 kg and 4.55kg, respectively) but may not be practically significant during both high departure periods and high arrival periods. On average, aircraft in Scenario 3 could burn less fuel during both taxiing-in and taxiing-out when compared with Scenario 1.

Data obtained from Experiment 3 show that Scenario 3 has the best performance in terms of taxi-in times under each load level because of the short taxi-in path and elimination of interaction with departure aircraft. The average taxi-out time in Scenario 3 is shorter than Scenario 1 under each load level due to the higher taxi speed and elimination of runway crossings. Scenario 3 is more stable against the increase of traffic load compared with Scenario 1. The average taxi-out time in Scenario 3 is increased by up to 24.35% when the traffic load level rises from 72 aircraft per hour to 96 aircraft per hour. The percentage increase is 36.91% in Scenario 1. As for taxi-in time, Scenario 1 shows an increase of 4.42% when the traffic load level rises from 72 aircraft per hour to 96 aircraft per hour while the increase in Scenario 2 is negligible. Compared with Scenario 1 Scenario 3 could better respond to future growth in airport traffic level at the cost of increased average taxi-in times.

Scenario 3 may bring some new problems. Frist, pilots on the landing aircraft may mistake the departure aircraft taxiing on the EAT for taxiing across the inboard (arrival) runway. This kind of lapse in judgment may lead to aborted landing and go-around. Currently some of the pilots on the departure aircraft have trouble determining whether the taxi-in aircraft at the end of the departure runway is taxiing on the EAT or is going cross the departure runway when the EAT is used for arrival aircraft (FAA, 2014). Extra measures have been conducted to help pilots on the departure aircraft to determine the location of the taxi-in aircraft (FAA, 2014). It is reasonable to assume that a similar problem may exist for pilots on the landing aircraft when arrival aircraft are allowed to fly over the active EAT.

Secondly, landing over an active EAT requires the arrival aircraft not deviate too far away from the normal landing path. A previous study shows that the probability that arrival aircraft fly below the threshold limit is very low, around 0.000018 (Satyamurti, 2007, p.229). However, this requirement may increase the psychological pressure of pilots which could affect their performance adversely.

Thirdly, the FAA does not allow arrival aircraft to land over an active EAT. It would take the FAA a lot of time to conduct studies and analyses to demonstrate the risk of this kind of operation before the FAA allows such operation.

Scenario 4

In Scenario 4, the inboard runway is used to land, the outboard runway is used to take off, and the EAT is used for departure aircraft to approach the outboard runway. Scenario 4 is designed and built based on the current FAA's regulation about End-Around Taxiway. The FAA requires that only departure aircraft could fly over active End-Around Taxiways (FAA, 2014). Therefore, departure aircraft may need to wait for arrival aircraft to fly over the EAT when taxiing out to the outboard departure runway. Runway crossing happens at the intersection of the EAT and the centerline of the inboard runway.

The results in Experiment 1 and Experiment 2 imply that compared with Scenario 1, Scenario 4 could decrease the average taxi-in time significantly by up to 78.05% during the high departure period and 63.07% during the high arrival period. As for taxi-out times, Scenario 4 shows a significant decrease of 8.58% during the high departure period and an increase of 14.13% during the high arrival period.

As for the average taxi-in times, the results of Scenario 4 are similar to Scenario 3 as the logic of the taxi-in procedure in Scenario 3 is the same as the logic in Scenario 4.

Scenario 4 is different from Scenario 3 in the departure side as there is an interaction between the departure and arrival aircraft on the EAT in Scenario 4 which would increase the taxi-out time. During high departure period, the influence of the interaction is not that big as there are not so many arrival aircraft. Although the average taxi-out time in Scenario 4 is longer than Scenario 3, the difference is not statistically significant. During high arrival period, however, departure aircraft have to spend more time waiting for the arrival aircraft to land over the EAT, which would increase the taxi-out time greatly. The average taxi-out time in Scenario 4, then, becomes the longest.

The results of the average fuel consumption show similar trends with the results of the average taxi time. Compared with Scenario 1, Scenario 4 would decrease the average fuel consumption per taxi-in significantly by up to 77.98% during the high departure period and by 63.09% during the high arrival period. The average fuel consumption per taxi-out is slightly reduced by 2.684 kg during the high departure period and is increased by 4.769 kg. The differences may not be practically significant. On average, aircraft in Scenario 4 could burn less fuel to taxi in and similar fuel to taxi out when compared with aircraft in Scenario 1.

Data obtained from Experiment 3 indicate that Scenario 4 has the best performance in terms of the average taxi-in time under each load level because of the short taxi-in path and elimination of interaction with departure aircraft. The average taxi-out time in Scenario 4 is similar with Scenario 1 and longer than Scenarios 2 and 3 under each load level because of the interaction between departure and arrival aircraft on the EAT. Also, Scenario 4 is more stable against the increase of traffic load compared with Scenario 1. The average taxi-out time in Scenario 3 is increased by up to 29.68% when the traffic load level rises from 72 aircraft per hour to 96 aircraft per hour. The percentage increase is 36.91% in Scenario 1. As for taxi-in time, Scenario 1 shows an increase of 4.42% when the traffic load level rises from 72 aircraft per hour to 96 aircraft per hour while the increase in Scenario 2 is negligible. Compared with Scenario 1 Scenario 4 could better respond to future growth in airport traffic level at the cost of increased average taxi-in times.

The limitation of Scenario 4 is obvious. In Scenario 4, air traffic controllers are required to declare clearance to the departure aircraft to taxi through the EAT, which is different from the work that the ATCs are trained to do. Costly extra training to the ATCs, as well as to the pilots, may be needed if the EAT is used for departure aircraft under the current FAA’s regulation.

7. CONCLUSION

End-Around Taxiways, which connect the outboard runway and the terminal area, are proposed to solve the problems caused by runway crossings at a parallel runway system at major airports. The EAT has been used at DFW, DTW, ATL, and MIA in the U.S (Le, 2014). More EATs are planned to be added into the runway-taxiway system at a variety of major. Exploring potential usage of the EAT may help the airport authority to improve operation efficiency, enhance runway safety, and face the challenge of the increasing traffic demand in the future.

This research project concentrates on the impact of three new runway and taxiway choices brought by the implementation of the EATs on a parallel runway system during high traffic period. The reason that the research focus on high traffic period is that previous studies find that ATCs tend to use the EAT most during the high traffic period (Le, 2014; Uday, et al., 2011) and the usage of the EAT would benefit the airport most during the high traffic period (Le, 2014).

A discrete-event simulation model of a parallel runway system with EATs at both ends is used to study the EAT at a fictional airport. The simulation model includes four scenarios which represent four different runway and taxiway choices. Scenario 1 is the traditional choices where outboard runway and conventional taxiways are used for landing. Scenario 2 represents the way that the EAT is used currently: outboard runway and the EAT is used for arrival aircraft. Scenario 3 and Scenario 4 stands for the new way: outboard runway is used for taking off and the EAT is used for departure aircraft to approach the outboard runway. The layout and dimensions of the fictional parallel runway system used in the simulation model are inspired by the configuration of the parallel runway system in the east of DFW. The simulation model is validated by comparing the results of the average taxi time with the average taxi time at DFW obtained by Le (2014).

A detailed study of the influence of the four different runway and taxiway choices is undertaken through three experiments. Experiment 1 focuses on the impact of the four different runway and taxiway choices on taxi time, fuel consumption, and runway crossing during high departure period. Experiment 2 focuses on the high arrival period. Experiment 3 explores the abilities of the four scenarios to cope with increases in the traffic load level.

This research does not consider cost savings to airlines or potential economic benefits to airports. The research does not consider the influence of abnormal situations, such as adverse weather. This research does not explore the potential noise effect. These could be topics for future research.

Summary of Results

The advantages of Scenario 2 are the elimination of runway crossings, the orderly movement of taxiing aircraft, and the increase of average taxiing speed. The disadvantage of Scenario 2 is the increased taxi-in distance. According to the analyses of data from Experiment 1 and 2, Scenario 2 could reduce the average taxi-out time and average fuel consumption per taxi-out significantly in comparison to Scenario 1 at the expense of the increased average taxi-in time and increased average fuel consumption per taxi-in. One exception is during the high departure period, when there is no significant different between the average taxi-in times among Scenario 2 and Scenario 1. Scenario 2 may benefit the airports in terms of runway safety as runway crossing is eliminated. Compared with Scenario 1, Scenario 2 is more stable against the increase of the load level, which indicates that Scenario 2 may have more potential in airport capacity than Scenario 1.

The advantages of Scenario 3 are the elimination of runway crossings, the orderly movement of taxiing aircraft, the decrease of taxi-in distance, and the increase of average taxiing speed. The disadvantages of Scenario 3 are the increase of taxi-out distance, potential disturbance to the pilots on the landing aircraft caused by the taxiing aircraft on the EAT, and regulation restrictions. In general, Scenario 3 could reduce the average taxi-in time, average taxi-out time, and average fuel consumption per taxi-in and per taxi-out significantly in comparison to Scenario 1. Scenario 3 may benefit the airports in terms of runway safety as runway crossing is eliminated. Compared with Scenario 1, Scenario 3 is more stable against the increase of the load level, which indicates that Scenario 3 has more potential in airport capacity than Scenario 1.

The advantages of Scenario 4 are the reduction of runway crossings, the orderly movement of taxiing aircraft, the decrease of taxi-in distance, and the increase of average taxi speed. The disadvantages of Scenario 4 are the increase of taxi-out distance, potential disturbance to the pilots on the landing aircraft caused by the taxiing aircraft on the EAT, and extra training to ATCs. In general, Scenario 4 would reduce the average taxi-in time, average fuel consumption per taxi-in, and the number of runway crossings significantly in comparison to Scenario 1. For taxi-out, the performance of Scenario 4 is better than Scenario 1 during the high arrival period. During the high arrival period, however, the average taxi-in time in Scenario 4 is significantly larger than the average taxi-out time in Scenario 1, while there is no significant difference between the average fuel consumption per taxi-out. Compared with Scenario 1, Scenario 4 is more stable against the increase of the load level, which indicates that Scenario 3 has more potential in airport capacity than Scenario 4.

A runway crossing occurs when taxiing aircraft need to go cross the centerline of an active runway. Runway crossing could not only cause runway crossing delays for both arrival aircraft and departure aircraft, but also increase the possibility of runway incursion. As ATCs must declare runway clearance to aircraft that wait to cross an active runway, an increasing rate of runway crossing would also increase the workload of ATCs.

Elimination of runway crossing in Scenario 2 and Scenario 3 could benefit both arrival and departure aircraft by eliminating delay caused by runway crossing. Runway safety could also be enhanced as the possibility of runway incursion would be reduced. Elimination of runway crossing could also reduce the workload of the ATCs. Therefore, the ATCs could concentrate on other safety issues, which may possibly benefit the safety level of the whole airport. Although Scenario 4 could not eliminate runway crossing, the number of runway crossings in Scenario 4 is significantly smaller than the number in Scenario 1, which could also benefit airport operations and safety to some extent.

Future Research Areas

The research makes a variety of assumptions and restrictions to simplify the model. For example, only Boeing 737-800 is considered in the model, runways are used exclusively to take off or to land, and cargo operation is not included. Future research could relax some of the restrictions to make the model more sophisticated.

Changing the runway and taxiway choices would influence the noise impact of the airport operations on the neighboring communities. Future research could explore the way that the runway and taxiway choices of Scenario 3 and Scenario 4 may change the noise impact distribution.

The research only explores the impact of four runway and taxiway choices on airport performance under normal operations. Abnormal situations, such as adverse weather, are not included in the model. Future research could investigate the difference between the resilience of the four runway and taxiway scenarios against abnormal situation.

Using outboard runway to take off and the EAT as the taxi-out path would “push” departure aircraft out of the near apron area faster than the traditional runway and taxiway choice. This may benefit the apron operation and gate arrangement by reducing the congestion level at the near apron area. Future research on this aspect would help to draw a whole picture about the impact of new runway and taxiway strategy.

This research does not explore the potential economic benefit to airports because of the reduced taxi time and runway crossing delay, which should be a valuable reference for airports that consider implementing the EAT in the future.

Arrival aircraft flying over an active EAT may lead to some human factor issues. It may be difficult for pilots on the arrival aircraft to determine whether the departure aircraft is taxiing on the EAT or cross the runway, which could disturb the landing procedure. Also, landing over an active EAT requires the arrival aircraft must not deviate too far away from the normal landing path, which may increase the psychological pressure of pilots. Future research about these concerns is needed before the arrival aircraft are allowed to fly over an active EAT.

Contribution to Aviation Research and Industry

This research about the End-Around Taxiway operations is critical for the aviation industry because several US airports have already implemented or plan to build the EATs. Previous studies show that the usage of the EATs at four US airports were limited. Previous research of the usage of the EAT was limited at the taxi-in performance, such as the average taxi-in time or the average fuel consumption per taxi-in. Only one study was found that generally discusses the possibility of using the outboard runway to take off after the introduction of the EAT (McNerney & Heinold, 2011). This gap provided the researcher an opportunity to study in detail the impact of three new runway and taxiway choices that became possible because of the EATs. The influence was explored in terms of both taxi-in and taxi-out performance, as well as reduction of runway crossing and enhancement of runway capacity. The researcher used Arena® to build a discrete-even model to simulate the aircraft movement at a parallel runway system with EATs at both ends. Four runway and taxiway scenarios (one traditional one, and three new choices because of the EATs) were explored in the model. Three experiments were designed and conducted to investigate and compare the performance of the four scenarios.

This research explored the impact of the EAT operations on both taxi-in and taxi-out performances during both the high arrival period and the high departure period. This research also discussed the potential issues that might exist in the new scenarios. The results of this research indicated that both the taxi-in operation and the taxi-out operation would benefit from changing to use the outboard runway to take off and inboard runway to land with the EAT used as the taxi-out path. The new runway and taxiway choice would also improve the ability of the parallel system to cope with increases in the load level.

These innovations may inspire other researchers to explore other possible usage of the EAT and investigate the potential benefit of the introduction of the EAT on other parts of the airport, such as the gate arrangement, surface congestion level, and departure rate. A further cost-benefit analyses based on the results of this research may be a valuable reference for airports that consider adding the EATs in their plans. Many airport operators have proposed that the FAA consider approving that arrival aircraft may fly over an active EAT (Hoover, 2007). The results may serve as a support material to these types of proposals. The results may serve as a support material to the proposal.

APPENDIX A. INPUT DATA USED IN MODEL VALIDATION

Table 58.

Input Data Used in Model Validation.

	Aircraft Rate (number/hour)[a]	
	Arrival on Runway 17C	Departure on Runway 17R
0:00-1:00	2	2
1:00 -2:00	1	1
2:00 - 3:00	0	0
3:00 -4:00	0	0
4:00 -5:00	1	0
5:00 -6:00	7	1
6:00 -7:00	10	2
7:00-8:00	14	4
8:00 - 9:00	16	9
9:00 -10:00	17	16
10:00 -11:00	15	16
11:00 -12:00	18	14
12:00 -13:00	17	16
13:00 -14:00	21	15
14:00 -15:00	24	14
15:00 -16:00	20	14
16:00 -17:00	23	16
17:00 -18:00	18	15
18:00 -19:00	16	17
19:00 -20:00	17	18
20:00 -21:00	20	18
21:00 -22:00	14	16
22:00 -23:00	8	11
23:00 -24:00	5	4

Note. [a] Information is obtained from "*Investigating surface performance trade-offs of unimpeded taxiways* (Master's thesis)" by Le, 2014. Retrieved from https://docs.lib.purdue.edu/open_access_theses/208

APPENDIX B. DFW TRAFFIC DATA

The FAA Aviation System Performance Metric (ASPM) database provides the number of arrivals and departures on each runway per 15 minutes, as well as the average taxi-in time and taxi-out time, at the major airports in the U.S (FAA, 2020b). The number of departure and arrival aircraft on runway 17R and runway 17C are retrieved from the ASPM database. Two steps are applied to collect the appropriate data that could be used as a reference of the input data of the model.

Step 1. Decide date based on weather condition.

One assumption of the model is that the airport is operated under VMC, which means that the influence of adverse weather is not considered in the model. Therefore, the daily weather conditions at DFW in 2019 are obtained from the National Oceanic and Atmospheric Administration (NOAA) past weather database (NOAA, 2020).

Based on the assumption that only operations under VMC is considered in the model, the criteria to select appropriate date are:

1) PRCP =0, which means there is no precipitation,

2) SNOW=0, which means there is no snow,

3) WT01-WT08 = 0, which means there is no special weather condition. WT01-08 represent eight kinds of special weather conditions, such as fog, ice fog, ice pellets, hail, glaze, dust, volcanic ash, smoke, or haze (NOAA, 2020).

Table 59.

Dates Between June and September That Meet the Weather Condition Requirements.

Month	Day
June	4, 7, 8, 10, 11, 14, 15, 17, 18, 20, 21, 24, 25, 27, 28, 30
July	2, 3, 7, 8, 9, 11-21, 23-30
August	5-13, 15-23, 25-26
September	1-18, 20-30

Table 59 shows the dates between June and September that met the weather condition requirements. The traffic data on those dates would be retrieved from the ASPM database.

Step 2. Retrieve data from the ASPM

The ASPM provides the average taxi-in time, average taxi-out time, number of arrivals, and number of departures per quarter an hour on each runway at DFW. One limitation of the data is that the definitions of the taxi-in and taxi-out times collected from the simulation model does not match the definitions of the taxi-in time and the taxi-out time in the ASPM database. The taxi-in time published in the ASPM is the time interval between the Actual Gate In time and the Actual Wheels On time, and the taxi-out time is the time interval between the Actual Wheels Off time and the Actual Gate Out time (FAA, 2020). The model, however, only simulate part of the taxi-in and taxi-out process. The operations at the apron area are excluded from the simulation model. Therefore, although the departure and arrival rates could be used as references to the input data, the average taxi-in time and the average taxi-out time obtained from the ASPM database can not be used in the model.

APPENDIX C. DESCRIPTIVE STATISTICS OF OUTPUT DATA

Experiment 1

1. Taxi-in Time

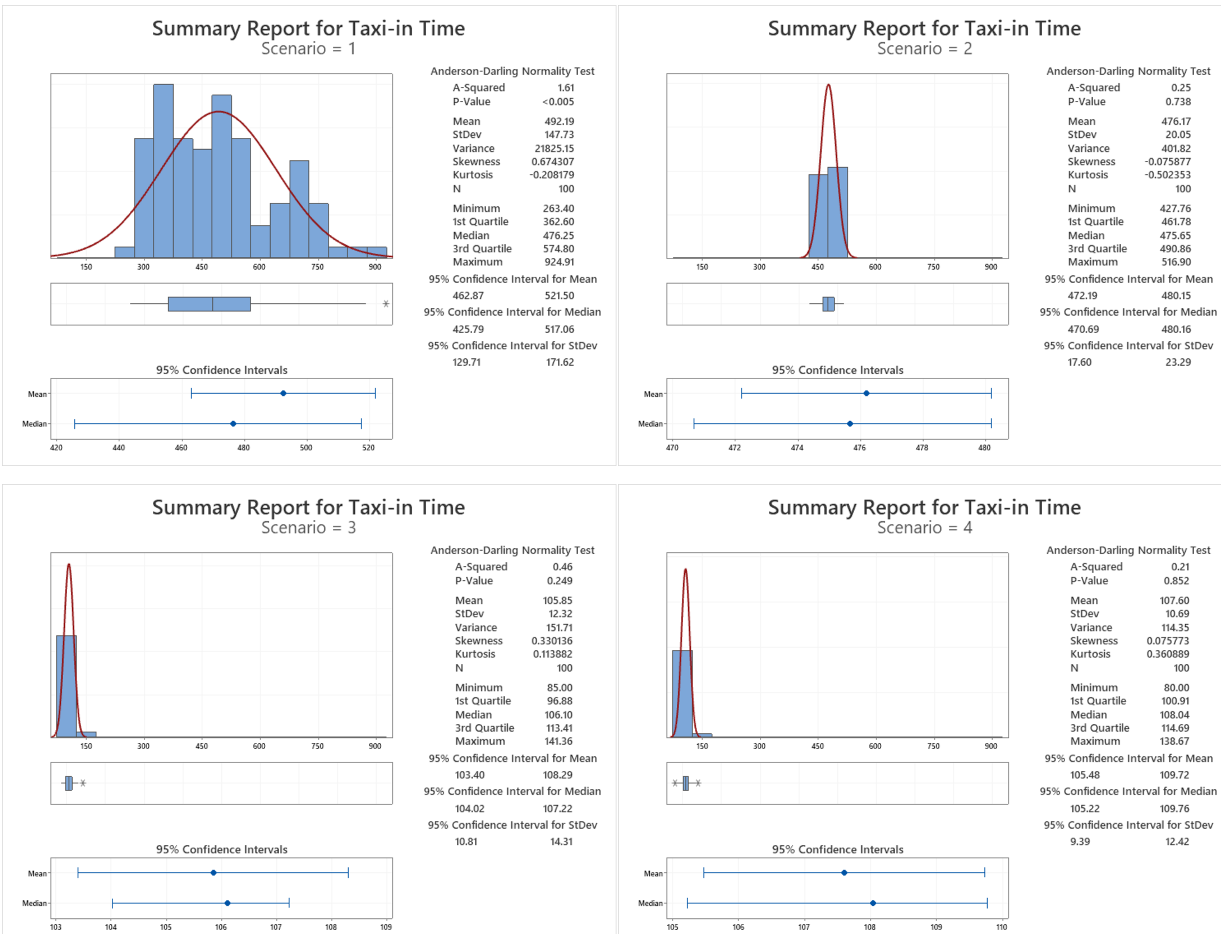

Figure 20. Descriptive statistics of the average taxi-in times of the four scenarios during the high departure period.

2. Taxi-out Time

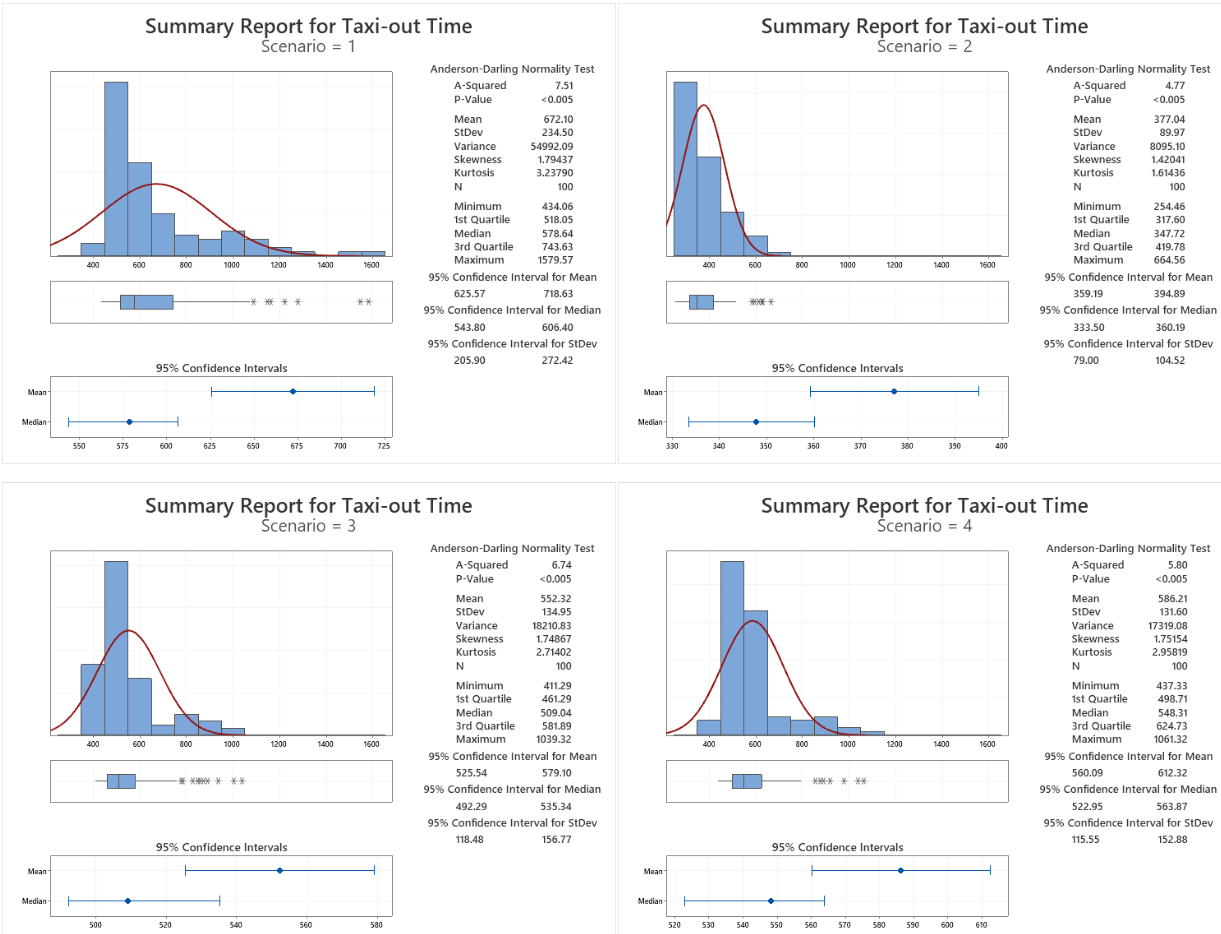

Figure 21. Descriptive statistics of the average taxi-out times of the four scenarios during the high departure period.

3. Average Fuel Consumption per Taxi-in

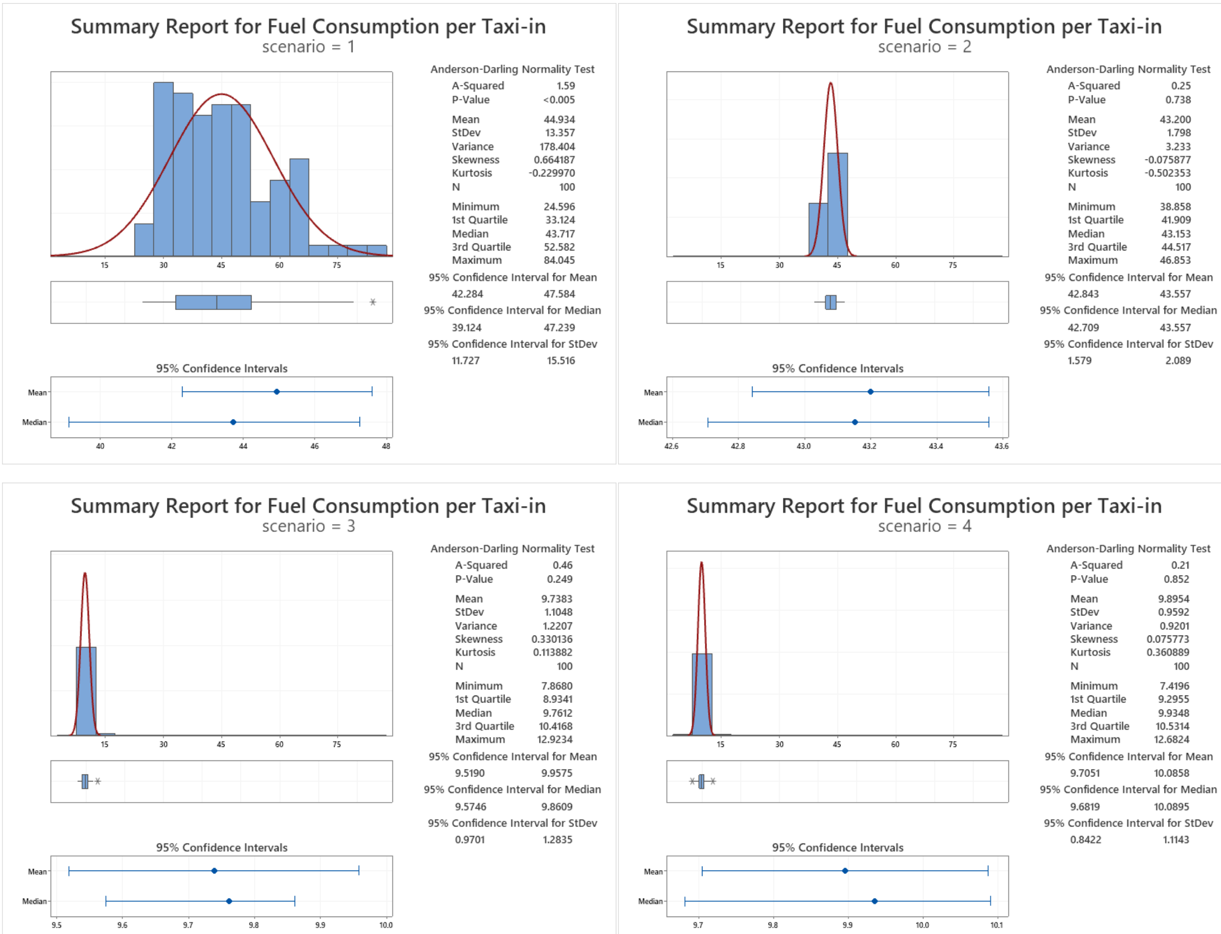

Figure 22. Descriptive statistics of the average fuel consumptions per taxi-in of the four scenarios during the high departure period.

4. Average Fuel Consumption per Taxi-out

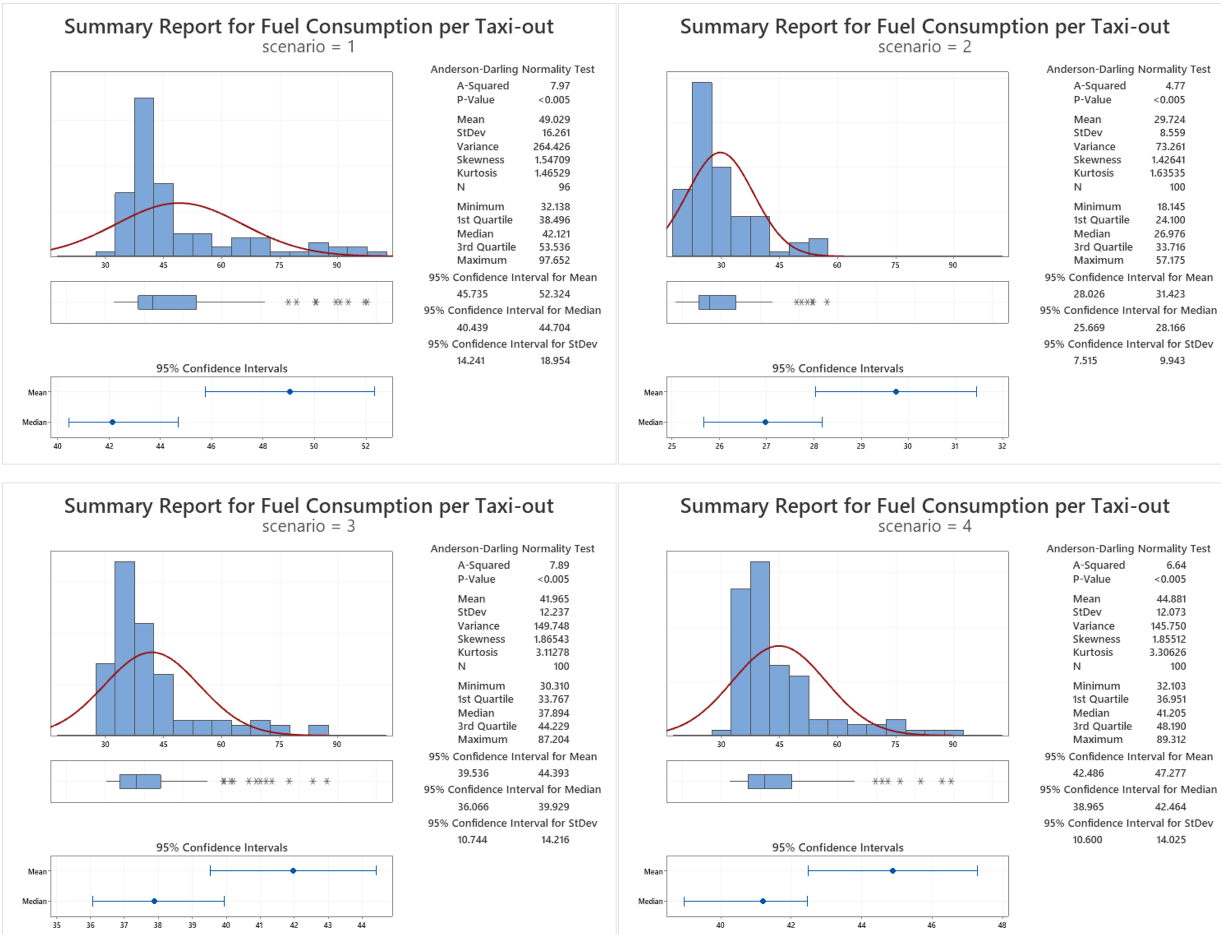

Figure 23. Descriptive statistics of the average fuel consumptions per taxi-out of the four scenarios during the high departure period.

Experiment 2

1. Taxi-in Time

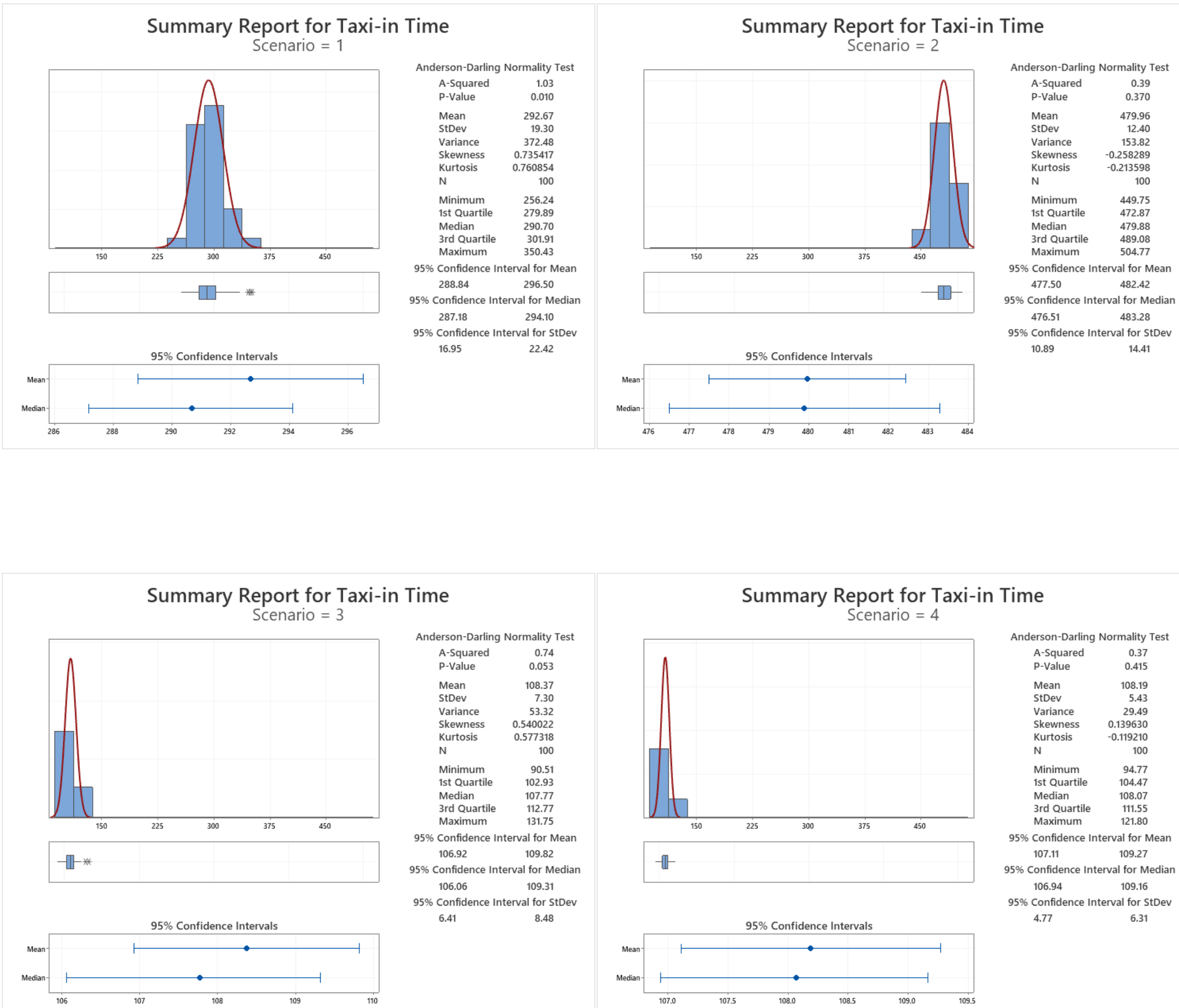

Figure 24. Descriptive statistics of the average taxi-in times of the four scenarios during the high arrival period.

2. Taxi-out time

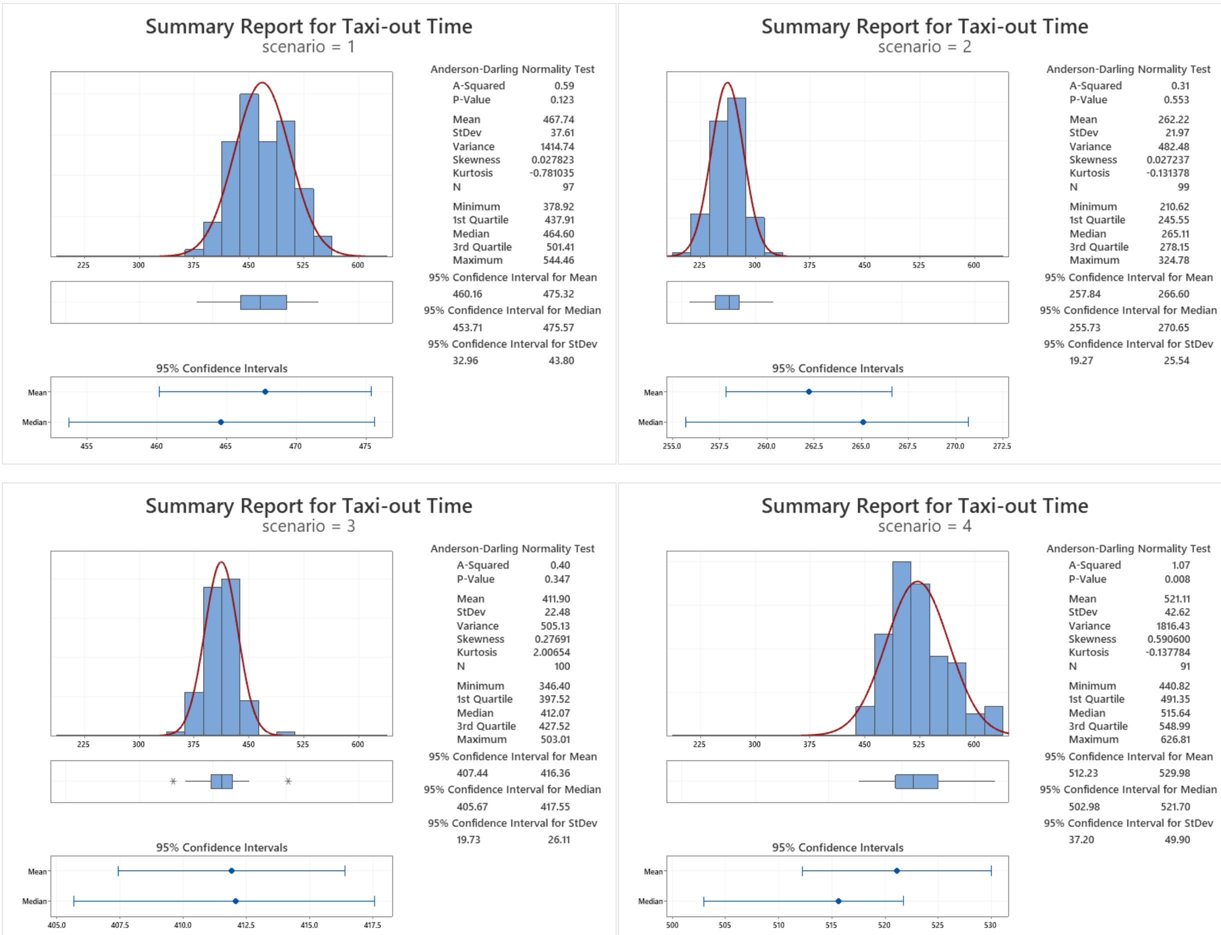

Figure 25. Descriptive statistics of the average taxi-out times of the four scenarios during the high arrival period.

3. Average Fuel Consumption per Taxi-in

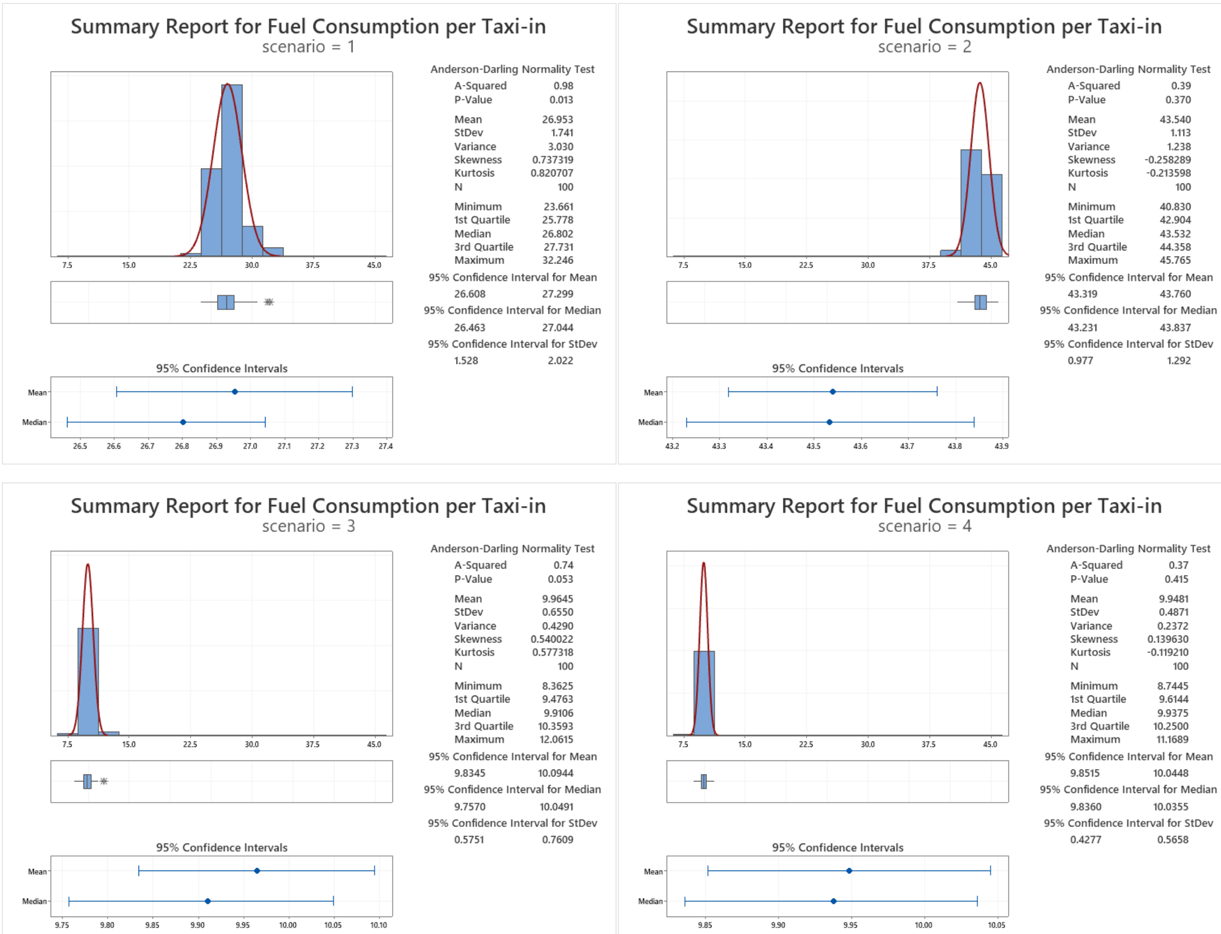

Figure 26. Descriptive statistics of the average fuel consumptions per taxi-in of the four scenarios during the high arrival period.

4. Average Fuel Consumption per Taxi-out

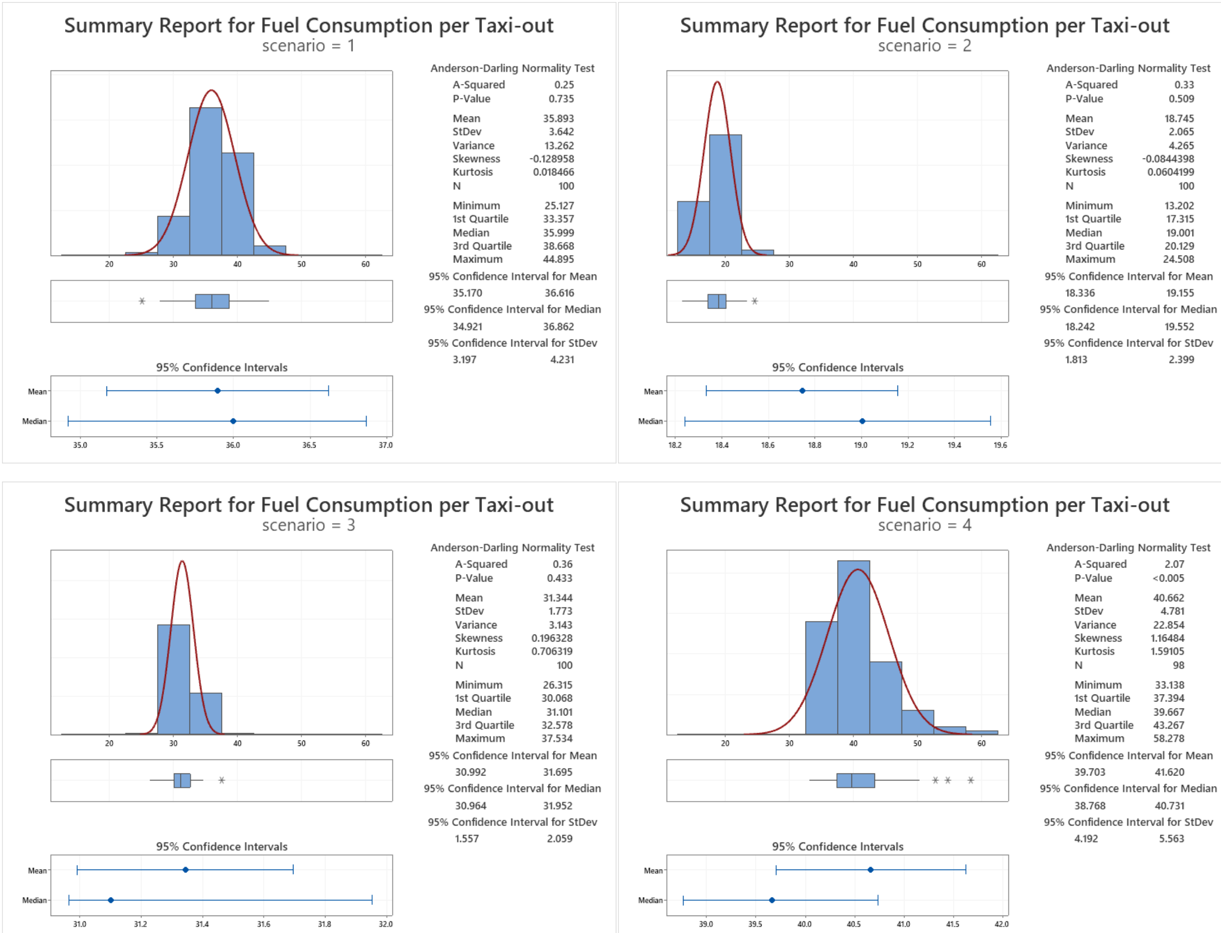

Figure 27. Descriptive statistics of the average fuel consumptions per taxi-out of the four scenarios during the high arrival period.

Experiment 3

1. Average Taxi-in Time

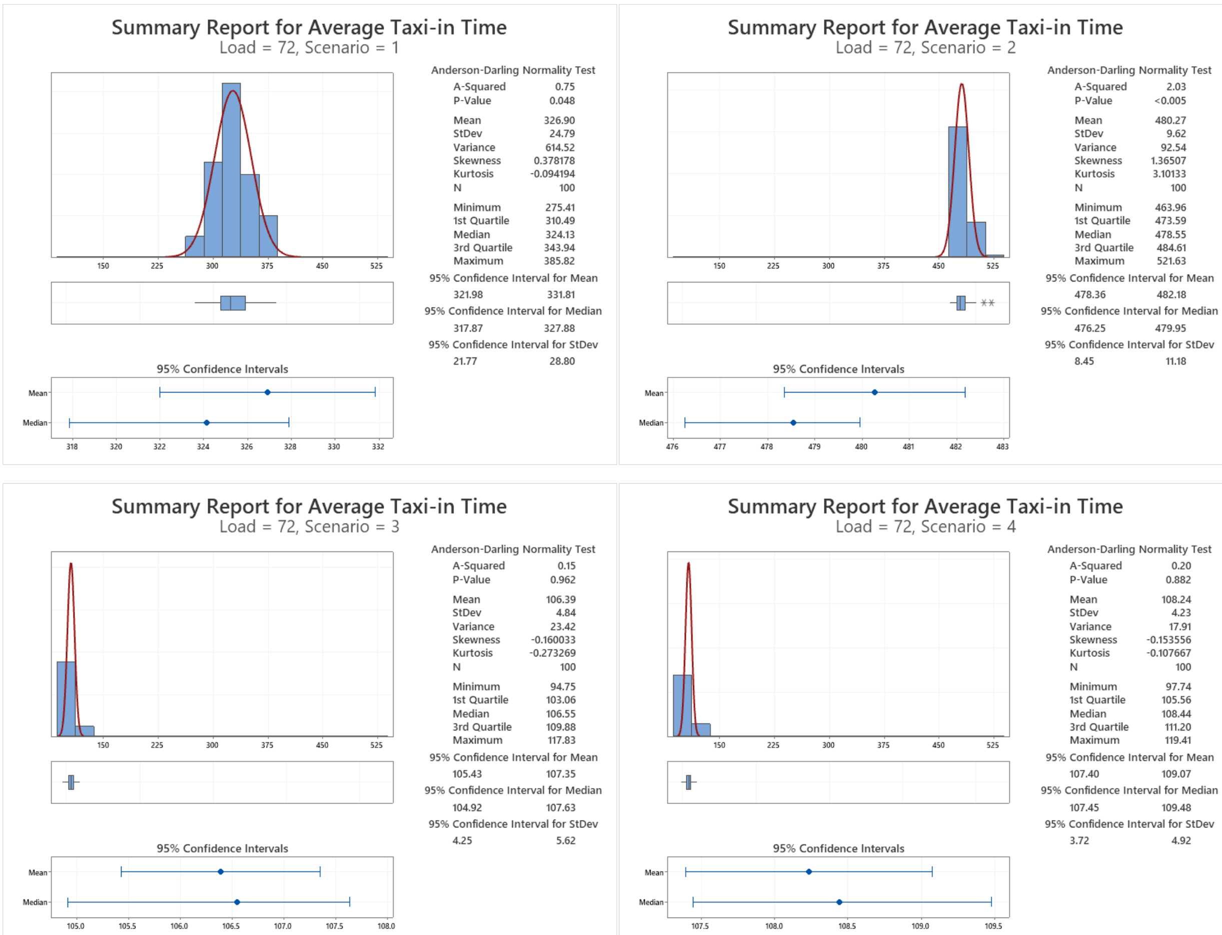

Figure 28. Descriptive statistics of the average taxi-in times under load level 1.

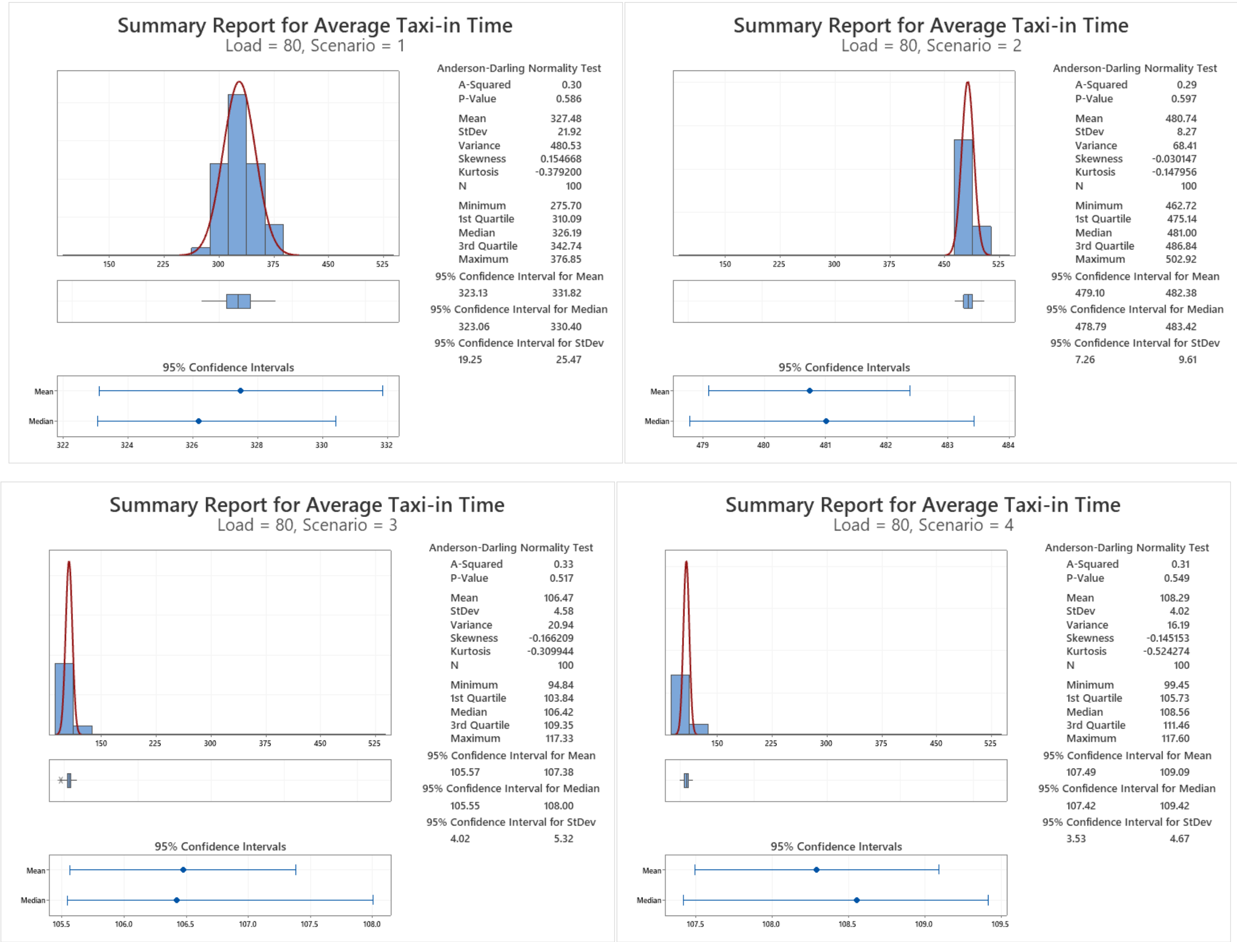

Figure 29. Descriptive statistics of the average taxi-in times under load level 2.

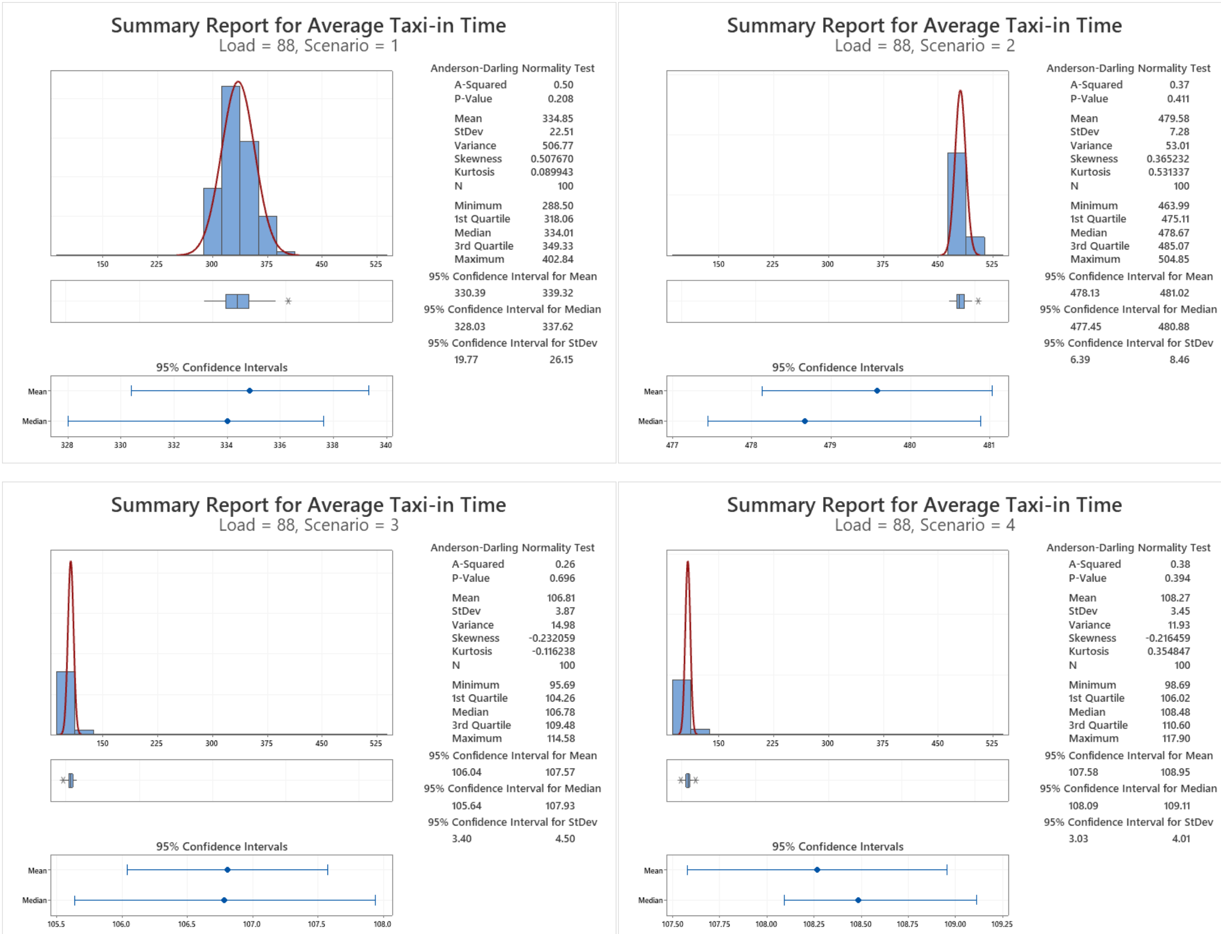

Figure 30. Descriptive statistics of the average taxi-in times under load level 3.

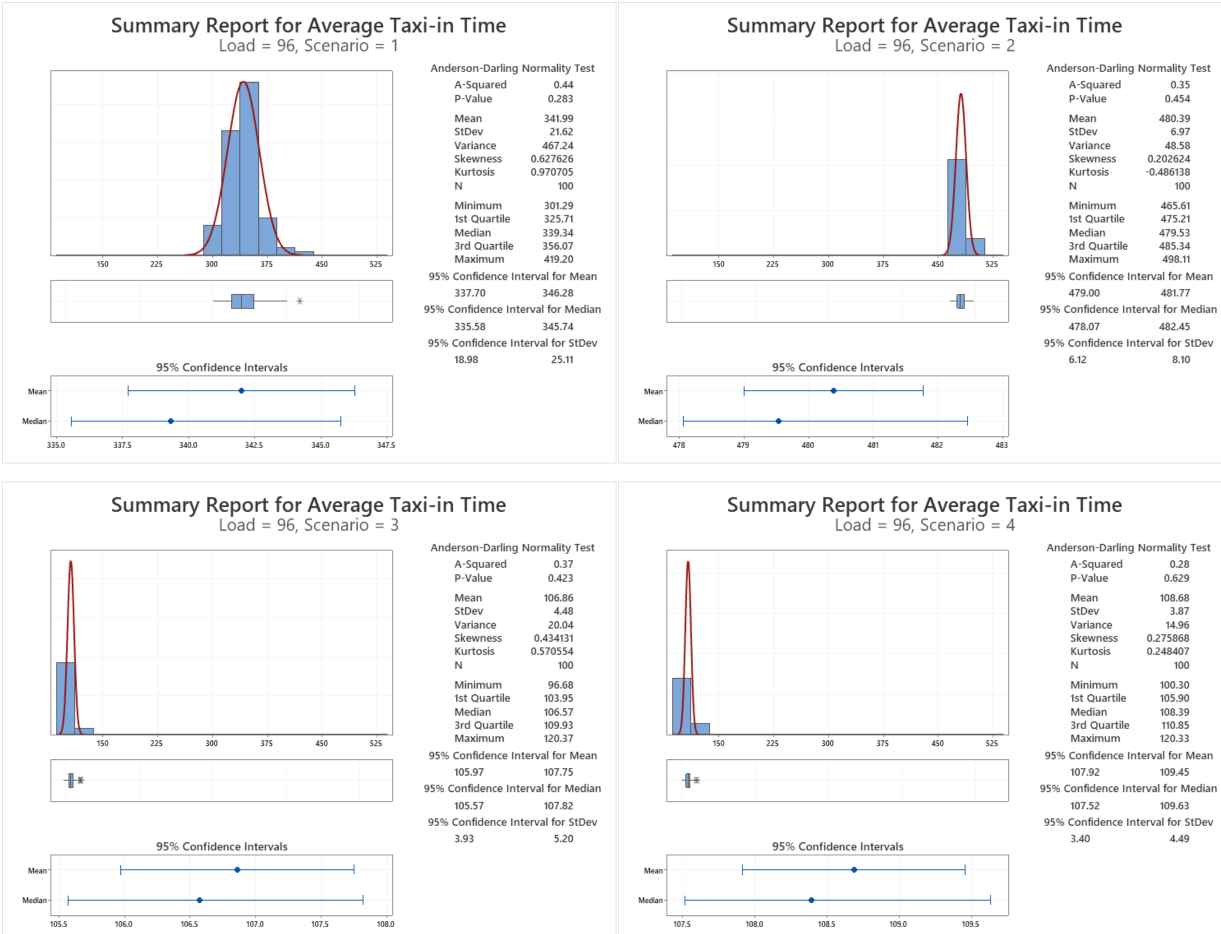

Figure 31. Descriptive statistics of the average taxi-in times under load level 4.

2. Average Taxi-out Time

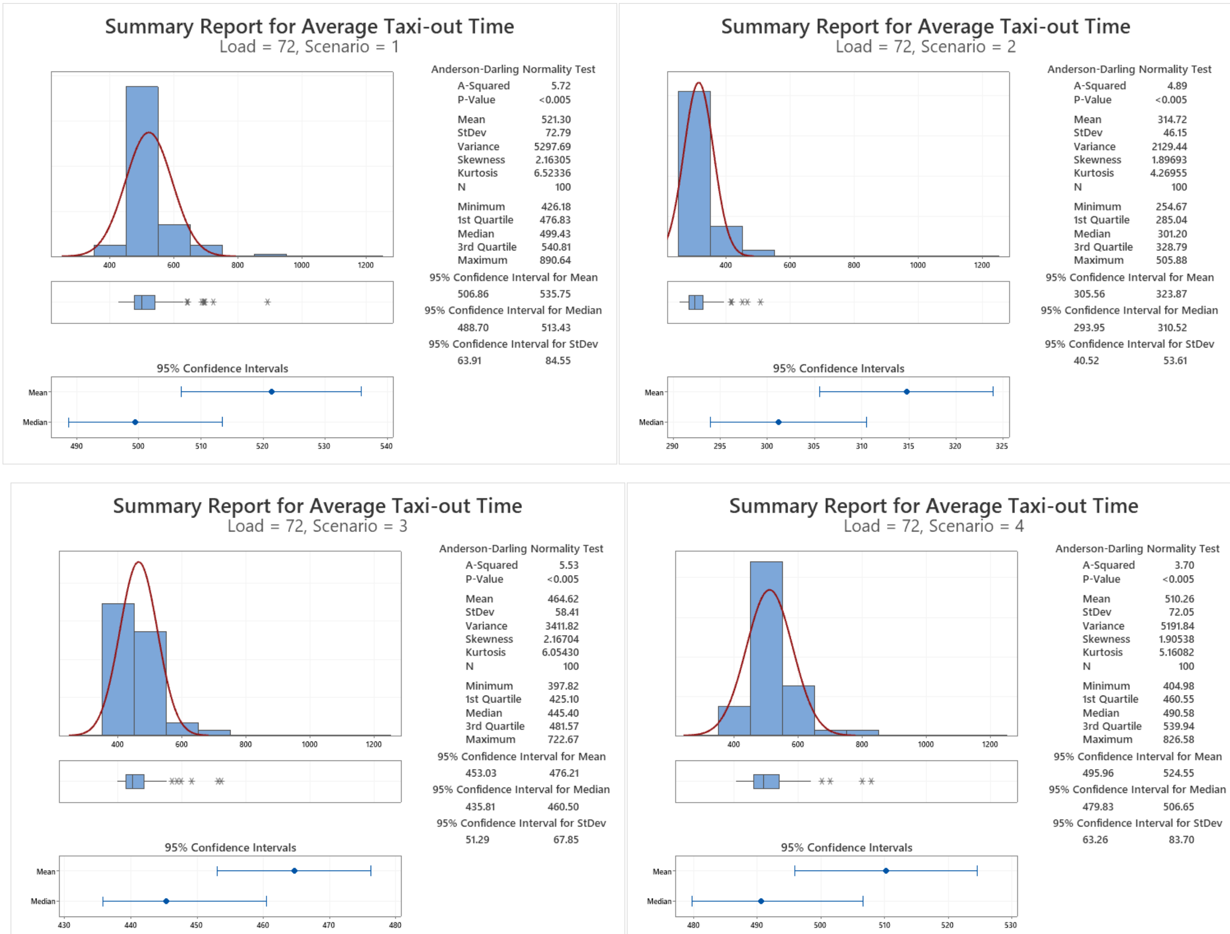

Figure 32. Descriptive statistics of the average taxi-out times under load level 1.

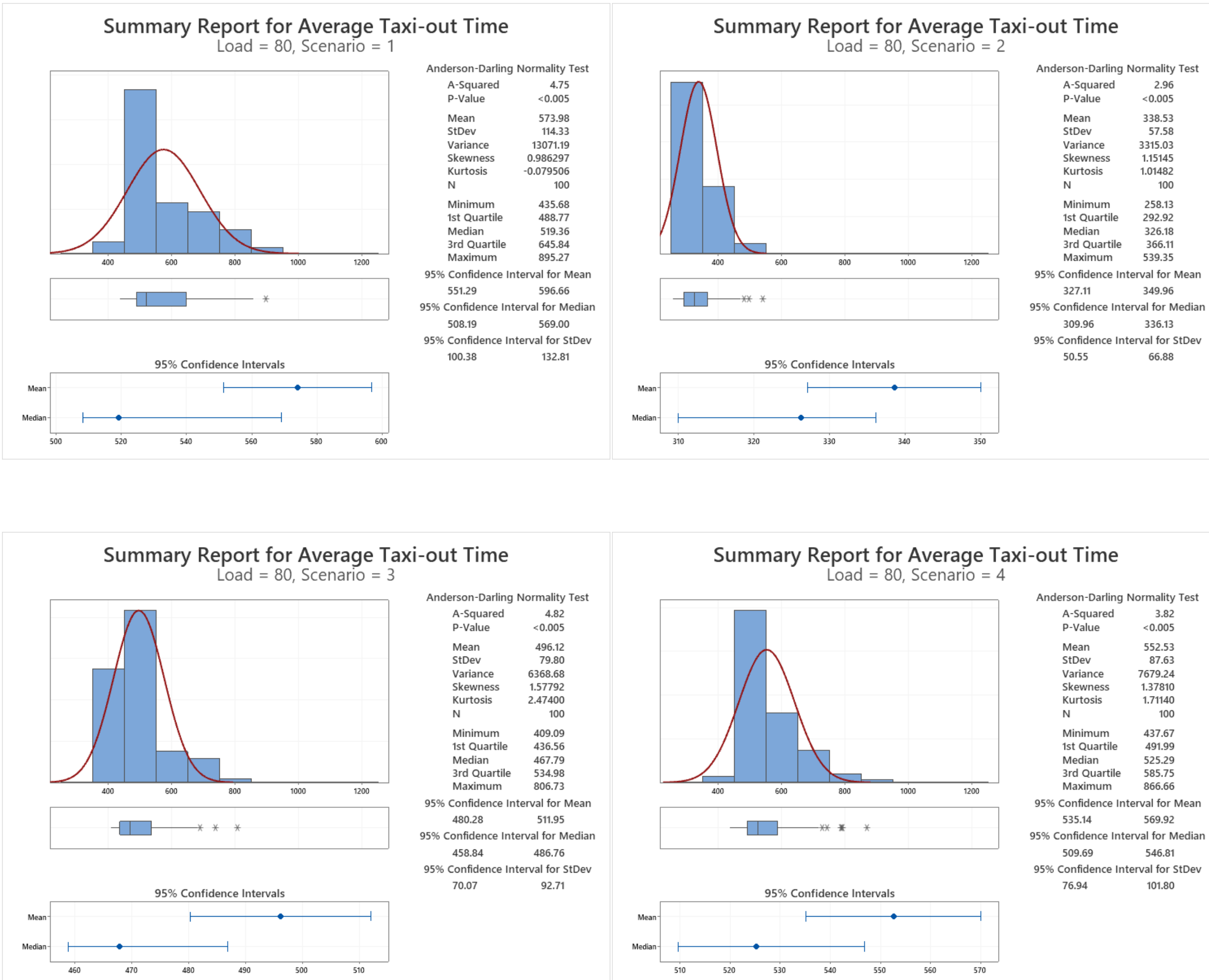

Figure 33. Descriptive statistics of the average taxi-out times under load level 2.

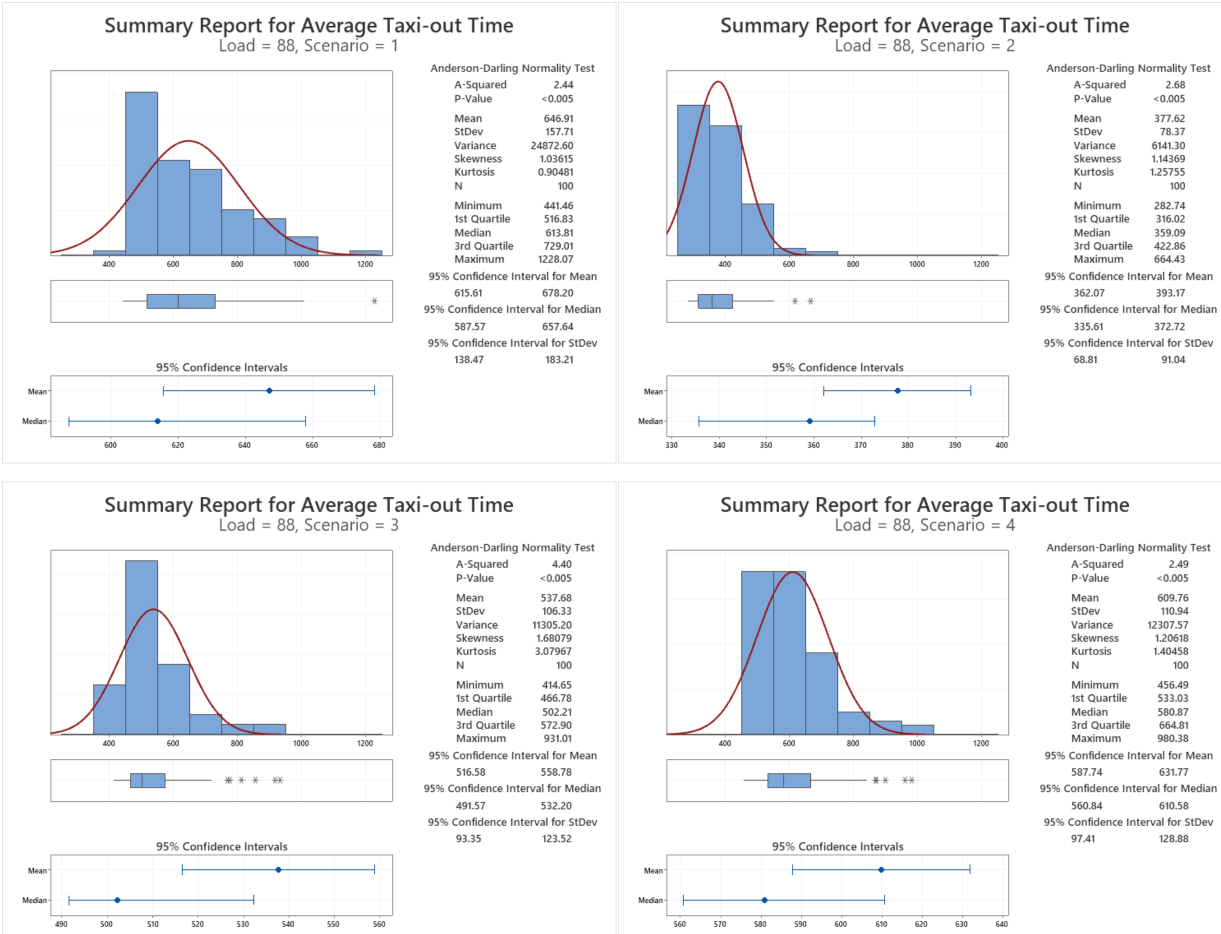

Figure 34. Descriptive statistics of the average taxi-out times under load level 3.

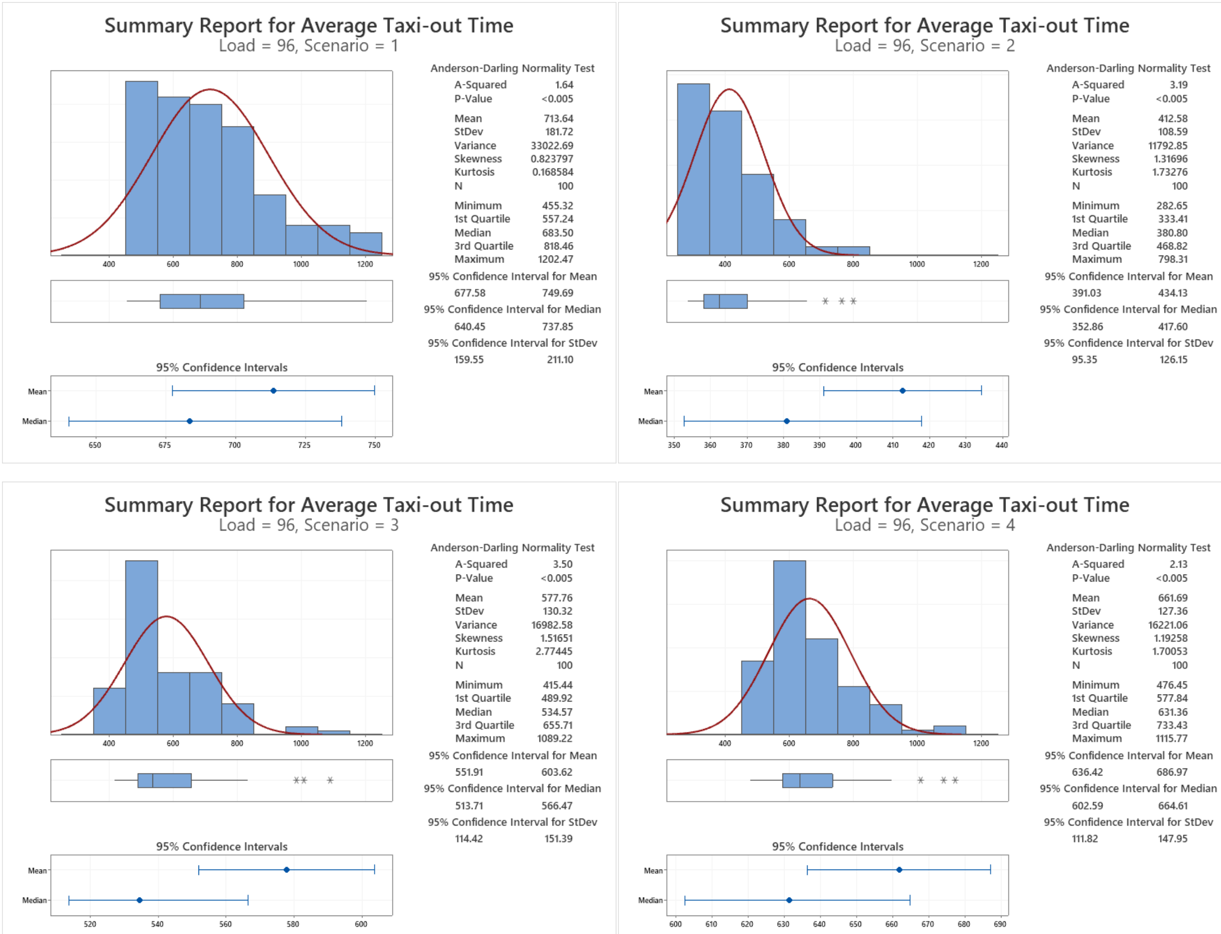

Figure 35. Descriptive statistics of the average taxi-out times under load level 4.

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