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A Preliminary Study of Taxi-out Times Using Discrete-Event Simulation of an Airport with Intersecting Runways

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INTRODUCTION

Aircraft taxi operations at airports affect fuel consumption, operation efficiency, and emissions. Taxi operations refer to the aircraft movement on airport ground movement area. Understanding taxi operation patterns may potentially improve airport capacity and reduce fuel burn and aircraft emission. Student use of queuing theory and statistical analysis to answer questions is a common objective in many engineering and technology courses from several disciplines such as industrial engineering, mathematics, operations research, aviation management, and information systems, among others.

In this paper, the researchers use ARENA® to build an exploratory dynamic, stochastic, discrete-event simulation model of aircraft taxi operations at an airport with two intersecting runways. The simulation model is based on a fictional airport inspired by the layout of William P. Hobby Airport (HOU), Houston, TX. In this study, the researchers develop and run a preliminary simulation model to measure aircraft taxi-out times and verify the model. The simulation model is tested with different take-off rates and number of runways used and the taxi-out time is analyzed. Deconfliction of runway and taxiway use are kept to one set of rules for all simulation runs.

Learning airport taxi operation patterns may help researchers to make better predictions about airport operations. Airport engineers and managers may use similar models to better improve airport total capacity, and reduce congestion and emissions. Engineering educators may use this paper for classes with projects that involve data collection, data consolidation, and simulation analysis. Using ARENA® to build simulation models provides students with graphical and statistical outputs that may be used to enhance achievement of learning objectives. This research may also be useful for undergraduate and graduate students to better understand queuing theory using an example of airport operation and airport design.

BACKGROUND

Aircraft taxi times affect airport capacity, aircraft emissions, fuel burn, and flight delays. Exploring potential factors that could reduce taxi times enables airport to operate more flights without expanding its land use, meanwhile reduce aircraft emissions and fuel burn.

Using simulation models to analyze complicated problems such as airport taxi operations allows the researchers to include more details and realistic information in the research. There are many simulation modeling techniques used in airport and taxi operation studies: Mori [1] used MATLAB to investigate the relief of congestion at Tokyo International Airport; Tang et al. [2] used MATLAB to identify repetitive aircraft movement behaviors that are related to delays; Cetek and Ginar [3] used SIMMOD to explore the location of congestion in ground movement at airports.

ARENA® is a commercially available software package that can be used to build stochastic discrete event simulation models. Previous research have used ARENA® to build airport simulation models to improve airport operations. Kim, Akinbodunse, and Nwakamma [4] proposed an arrival flight traffic model using ARENA® to analyze the holding procedure at airports and simulate the arrival rate of flights. The researcher concluded that the results of the simulation were close to the direct data analysis output. Jadhav, Neogi, and Thaden [5] built a simulation model in ARENA® to test the safety performance of the proposed airport layout based on O'Hare airport to reduce runway incursions. The results indicated an increased safety level with a 30% increase in taxi times [5]. In the research conducted by Feng [6], the researchers simulated the effects of four runway and taxiway choices using the End-Around Taxiway (EAT) in an ARENA® stochastic model based on Dallas Fort Worth International airport. The researchers assessed the performance of the proposed airport layout by comparing average taxi times, average fuel consumption, and number of runways crossing [6]. The findings indicated that the overall taxi times performance would be improved by using the EAT as taxi-in or taxi-out path [6]. A simulation study may consist of the following steps [7]:

1. Understand the system
2. Clarify the modeling goals
3. Develop the model concept
4. Input the model into the modeling software and document as you build the model
5. Verify that the model in the software reflects the conceptual model
6. Validate the model against expectations of the real-world system
7. Design and run the experiments
8. Analyze the results
9. Get insights
10. Document the model and the results [7]

In this paper, the researchers built a stochastic discrete event airport simulation model in ARENA® based on a fictional airport inspired by Houston Hobby (HOU) to compare the effects of different take-off rates at four runway usage combinations on aircraft taxi-out time. The data presented in the results section is a preliminary result to verify the simulation model, not the results of the experiment. This paper establishes a model and verifies model that would answer the research question:

What difference does it make on taxi-out time when there are two different rates of departures and four runway use combinations [Ho: $\mu_a = \mu_b$ versus Ha: $\mu_a \neq \mu_b$]?

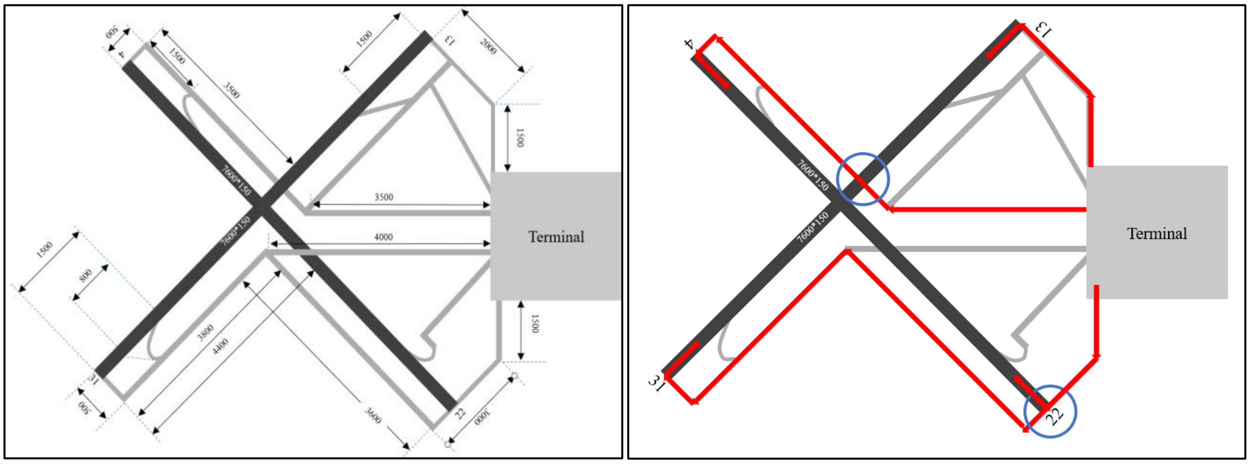
METHODOLOGY

This section describes the ARENA® airport simulation model, elements of the model, deconfliction rules, model assumptions and limitations, and model verification experiment design and data analysis.

1. ARENA® airport simulation model based on HOU

In this research, a discrete-event stochastic simulation model is built in ARENA® simulation to explore taxi-out time at a fictional airport inspired by HOU. Figure 1 shows the physical layout of the fictional airport, taxi-out routes for each runway are marked in red, and runway/taxiway intersections are circled in blue.

Figure 1. Physical Layout of the Simulation Airport and Taxi Route (highlighted in red)



Note. All lengths are in feet. Taxi routes for each runway are marked in red. Runway/taxiway intersections are marked in blue circles.

<u>Elements of the simulation model:</u> The simulation model contains seven modules: arrival aircraft creating module, departure aircraft creating module, access taxiway module, taxi-out module, exit taxiway module, hold module, and takeoff or landing module.

The arrival or departure aircraft creating module creates the arrival and departure aircraft. The time between two aircraft in arrival and departure operations are both assumed to follow a triangular distribution with a minimum of 1 minute, median of 10 minutes, and maximum of 20 minutes for low aircraft departure rate; and follow a triangular distribution with a minimum of 0.5 minute, median of 5 minutes, and maximum of 10 minutes for high aircraft departure rate. As this research only considers taxi-out time, the taxi-in operations are not simulated in the model.

The access taxiway module, taxi-out module, and exit taxiway module simulate the processes of aircraft taxiing from the gate to the start of the runway. The departure aircraft enters the access taxiway module after being generated. The access taxiway module assigns space on the taxiway to the aircraft if there is available space on the taxiway. The module will stop assigning if there are more than certain aircraft on the taxiway. The taxi-out module maintains aircraft to move at a constant speed of 10 knots with 200 feet minimum separations between aircraft. The exit taxiway module releases the aircraft from the taxiway after the aircraft arrives at the start of the runway and frees a space on the taxiway.

The vortex module allows the aircraft to satisfy the wake vortex separation minimum of 1.5 minutes before takeoff. *The takeoff and landing module* allow the departure aircraft to take off. The time between two operations on the runway is assumed to be 1 minutes. The arrival aircraft will join the queue after being generated and use the same runway resources.

The hold modules are used at the intersections of runway and taxiways (marked in blue circle in Figure 1 and Table 1) to prevent the aircraft to cross an active runway. When aircraft arrives at the hold module (the intersection), the module will scan the condition of the corresponding runway. If the runway is being used, the aircraft will be held from taxiing across the runway until the runway is no longer active.

In the simulation model, the departure aircraft creation module creates aircraft for taxi-out operations; the access taxiway module assigns space on the taxiway to the aircraft if there is available space on the taxiway; the taxi-out module moves the aircraft along the queue; the exit taxiway module releases the aircraft from the taxiway and clear the space for other aircraft; the hold module put the aircraft on hold for the wake vortex separation minimum; and the aircraft takeoff through the takeoff and landing module.

Deconfliction rules: Conflicts occur when more than one aircraft intends to cross the same location simultaneously. This usually happens at runway/runway, runway/taxiway, and taxiway/taxiway intersections. In this research, three types of aircraft conflicts are addressed in the simulation model: runway/runway intersection, runway/taxiway intersection, and taxi queue.

The runway/runway intersection conflict occurs between aircraft on runway 4/22 and aircraft on runway 31/13 (two operations happen at the same time on the two runways). In general, the departure aircraft would wait for the landing aircraft, which is adapted as a simulation deconfliction rule in this research.

The conflict of taxi queue happens when there is a queue on the taxiway, the aircraft at the end of the taxiway must keep a minimum separation distance of 200 feet with the aircraft in front of it to avoid conflict.

Assumptions and Limitations of the model: The Research is conducted with the following assumptions:

1. The simulation model built in this research can reflect the real airport operations.
2. The delay caused by the communication between pilots and ATC is not considered.
3. All departures and arrivals operations succeed at the first time. Touch and go are not considered.
4. The simulation model is inspired by airport configuration at HOU.
5. Only Boeing 737-800 are considered in the simulation model; the taxi speed of all aircraft is assumed to be 10 knots; the aircraft minimum separation for taxi operations is assumed to be 200 feet.
6. The time between two aircraft in arrival and departure operations are both assumed to follow a triangular distribution with a minimum of 1 minute, median of 10 minutes, and maximum of 20 minutes for low aircraft departure rate; and follow a triangular distribution with a minimum of 0.5 minute, median of 5 minutes, and maximum of 10 minutes for high aircraft departure rate.
7. The time the aircraft needs to takeoff or land is assumed to be 1 minutes. The time for waiting the wake cortex separation minimum is assumed to be 2 minutes.
8. Based on the taxi route distances, taxi speed, and taxi separation minimum, the researchers decided the maximum number of aircraft on each of the four taxiways – for runway 4 (8 aircraft), runway 13 (3 aircraft), runway 22 (4 aircraft), and runway 31 (12 aircraft)

This research follows the following limitations:

1. This research only considers operations under Visual Meteorological Conditions (VMC).
2. The disruptive events at airports such as extreme weather and runway incursions are not considered in the simulation model.
3. Human factors such as air traffic controller experiences are not considered.

4. The simulation model only considers taxi-out operations from terminal to the runway. Other operations such as taxi-in and refueling are not considered.
5. Taxi-in operations are not simulated in the model.

2. Experiment design and Data Analysis for Model Verification

The simulation model is run for four runway combinations and two rates of departures (low and high) to record aircraft taxi-out times. The length of each run was set to 16 hours and a total of 30 replications were run for each runway and rate combination. Therefore, in the experiment:

1. Response variable: Taxi-out time (data collection)
2. Factor 1: rate of operations (Slow or Fast)
3. Factor 2: Runways in use
    a. Runway 13&22 (0 runway/taxiway intersection)
    b. Runway 4&13 (1 runway/taxiway intersection)
    c. Runway 22&31 (1 runway/taxiway intersection)
    d. Runway 4&31 (2 runway/taxiway intersections)
4. Number of replications: 30
5. Length of run: 16 hours

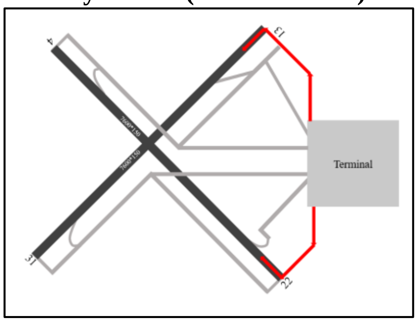
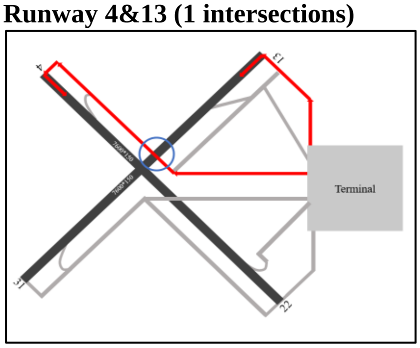
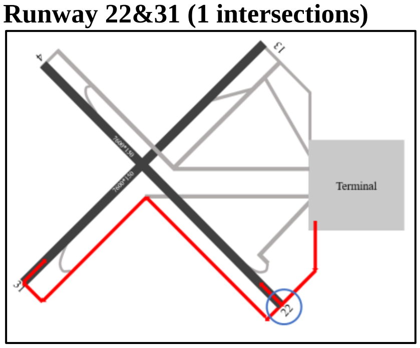
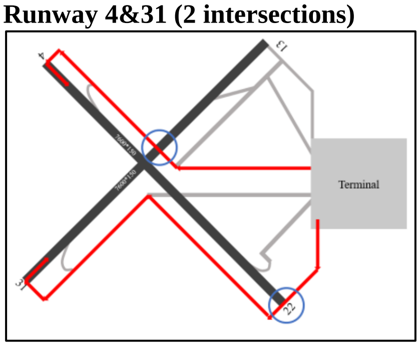
The researchers obtained average taxi-out time, 95% confidence intervals for average taxi-out times, and number of operations from the simulation output. Student's *t* 95% CI were used to compare the average taxi-out time at two rates of departures and four runways combinations.

RESULTS

In this paper, the researchers built a stochastic discrete event airport simulation model in ARENA® based on a fictional airport inspired by Houston Hobby (HOU) to compare the effects of different take-off rates at four runway usage combinations on aircraft taxi-out time. The simulation model is run for two rates of departures at four runway combinations to verify the model. This section presents the results of the model verification.

Using the Student's *t* test and 95% Confidence Intervals, the average taxi-out time of using runway combination 13&22 under a low departure rate (6.72 – 6.84 minutes) was found to be statistically shorter than that under a high departure rate (10.94 – 14.10 minutes). Using runway combination 4&13, the average taxi-out time under a low departure rate (8.74 – 9.02 minutes) was found to be statistically shorter than that under a high departure rate (16.52 – 21.10 minutes). Using runway combination 22&31, the average taxi-out time under a low departure rate (11.22 – 11.64 minutes) was found to be statistically shorter than that under a high departure rate (23.78 – 30.03 minutes). Using runway combination 4&31, the average taxi-out time under a low departure rate (14.30 – 14.58 minutes) was found to be statistically shorter than that under a high departure rate (36.12 – 42.90 minutes). Table 1 shows the consolidated results of model verification, and tabulates the number of take-offs, average taxi-out times, 95% confidence intervals, and maximum number of aircraft on taxiway.

Table 1. Average Taxi-out Time for Four Runway Configurations and Two Rates of Departures.

Runway Combinations		**Rate of Departures**	
		Low Rate Time Between Aircraft Release: Triangular (1, 10, 20)	**High Rate** Time Between Aircraft Release: Triangular (0.5, 5, 10)
Runway 13&22 (0 intersections) 	Average Taxi-out Time (in minutes)	6.78	12.52
	95% Confidence Intervals for mean (*Student's t*)	(6.72, 6.84)	(10.94, 14.10)
	Number of Take-offs	93	184
	Max Number of Aircraft on Taxiway*	3+4	3+4
Runway 4&13 (1 intersections) 	Average Taxi-out Time (in minutes)	8.88	18.81
	95% Confidence Intervals for mean (*Student's t*)	(8.74, 9.02)	(16.52, 21.10)
	Number of Take-offs	92	182
	Max Number of Aircraft on Taxiway*	8+3	8+3
Runway 22&31 (1 intersections) 	Average Taxi-out Time (in minutes)	14.43	26.90
	95% Confidence Intervals for mean (*Student's t*)	(11.22, 11.64)	(23.78, 30.03)
	Number of Take-offs	92	181
	Max Number of Aircraft on Taxiway*	4+8	4+8
Runway 4&31 (2 intersections) 	Average Taxi-out Time (in minutes)	14.44	39.51
	95% Confidence Intervals for mean (*Student's t*)	(14.30, 14.58)	(36.12, 42.90)
	Number of Take-offs	92	177
	Max Number of Aircraft on Taxiway*	8+12	8+12

Note. The runway/taxiway intersections are marked in blue circles. During taxi-out operation, runway combination 13&22 has no runway/taxiway intersection, runway combination 4&13, 22&31 have 1 runway/taxiway intersection, and runway combination 4&31 has 2 runway/taxiway intersections. *The max number of aircraft on taxiway was determined by the researchers based on the taxi route distance, taxi speed, and taxi separation minimum.

DISCUSSION AND CONCLUSION

In this paper, a preliminary stochastic discrete event simulation model was built in ARENA® simulation software and was verified using two departure rates on four runway usage combinations based on a fictional airport inspired by HOU. The results showed that a higher departure rate led to a higher average taxi-out time for four runway combinations.

In terms of runway/taxiway intersections, the average taxi-out time was statistically different for runway combination 13&22 (0 intersection), runway combination 4&13 (1 intersection), runway combination 22&31 (1 intersection), and runway combination 4&31 (2 intersections). The taxi time was longer for operations with 2 runway/taxiway intersections. The average taxi-out time was statistically different between the two runway combinations with 1 runway/taxiway intersection (4&13 and 22&31). This difference may be attributed to the different taxi distances and the maximum number of aircraft on taxiway at these two runway combinations.

Future research may focus on improving the model accuracy, validation of the model using real-world taxi-time data from the FAA ASPM dataset and the FAA Airport Master Record. In this paper, the simulation model assumed that the time between each departure and each arrival follow triangular distributions. In future, a more accurate and realistic estimation of this time may be obtained from FAA Aviation System Performance Metrics (ASPM) dataset or Bureau of Transportation Statistics (BTS). The simulation model can be expanded to include the taxi-in operations for a more realistic simulation output and an accurate experiment design. Future research could consider suing simulation models to test the effect of End-Around Taxiways on reducing the impact of runway/taxiway intersections on taxi times.

Educators and students may use the basic simulation model in this paper as an example for developing discrete-event simulation models of airports, build and apply deconfliction rules, vary traffic flow, collect simulation data, and run experiments. The model in this paper was developed for verification purposes only, and further data collection and research is needed for the validation of the model. Students and educators may use this paper as an example for demonstrating initial model development and verification steps. Students may learn data collection and data analysis techniques, simulation concepts, and modelling skills from this paper.

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