Simulation modelling of runway capacity for flight training airports

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ABSTRACT

This study aims to develop a practical discrete-event simulation model to analyse the single runway capacity of airports serving training flights under various operational scenarios. The number of operations per hour, average airborne and ground delays, queue lengths and runway utilisation are selected as performance measures for the analysis. The simulation model has been developed in ARENA in order to obtain a practical yet accurate analysis. The model can contribute to the efficient use of runway capacity as well as effective planning of flight training at airports.

1.0 INTRODUCTION

Air traffic volume has been growing rapidly in parallel to the increasing demand for air travel. Despite the adverse effects of specific shocks, such as terrorist attacks and the global financial crisis, the number of commercial flights has increased by more than 30% worldwide since 2001[1]. Projections of the ICAO and the industry point out that air traffic growth will continue to rise at an annual rate of 4·7-5·1% worldwide for the period 2011-2030[2-4]. This strong demand raises serious concerns regarding the operational and training capacities of airports. Many major airports in the US and Europe have already been suffering from delays and congestion due to the existing traffic demand. Expected traffic growth rates will not only aggravate the current capacity problems but also expand them to the entire airport network. In addition to increasing commercial IFR traffic, airports should accommodate a significant amount of VFR traffic for training flights due to the

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growing need for airline pilots. The industry will globally require 52,506 new airline pilots per year between 2010 and 2030 according to the most likely scenario[2]. Despite this high demand, commercial traffic growth imposes tight constraints upon the training capacity of airports, such as prohibitions and restrictions for VFR operations at many major airports. In addition, many regional and local airports will also become more crowded for safe and efficient flight training due to the traffic growth. Although new trends in airline pilot training, such as multi-crew pilot license (MPL) courses, can reduce the actual flight hours by more than half, the transition from traditional pilot training approaches to these new methods seems to be gradual for the projected period. Therefore, capacity development will still be an essential issue not only for the airports serving commercial IFR flights, but also for those serving primarily or partially for VFR training operations.

Airport capacity can be increased through physical expansion; however, such a practice requires high investment costs and sufficient physical land for expansion. Therefore, operating existing airports at maximum capacity is critical and requires an accurate analysis to determine the measures of improvement. Capacity studies can be performed using both analytical and simulation methods.

Analytical methods, such as time-space analysis and various queuing models, are simplified mathematical representations of airport operations for capacity analysis[5-7]. These methods are extremely efficient for the analysis of systems with a low level of detail. Existing analytical models are the LMI Runway Capacity Model, the FAA Airfield Capacity Model[8], MACAD[9], DELAYS and CAMACA.

Simulation methods, on the other hand, are the most convenient tools for analysing the behaviour of complex industrial systems under different scenarios[10]. Simulation techniques, such as the Monte Carlo and discrete-event simulation, provide more realistic results for the design and development of airport operations. Pitfield and Jerrard have used the Monte Carlo simulation to estimate the unconstrained runway capacity at Fiumucino International Airport for three alternative runway utilisation scenarios[11]. Discrete-event simulation techniques provide high-level-of detail models for the capacity analysis of airports. Numerous tools have been developed based on this technique, such as SIMMOD, CAST, TAAM, RAMS and Airport Machine. Detailed review regarding these tools is provided by Odoni *et al*[8], Mumayiz[12] and Zografos and Madas[13]. Using SIMMOD, Chao *et al* performed an airside capacity development study for Gaoqi International Airport[14]. The study proposed a set of procedural and infrastructure developments which offer 2·4 -17.1% increase in airport capacity for different traffic scenarios. Wai and Taobo also used SIMMOD to analyse the effect of parallel taxiway configurations on airport capacity[15]. As a result of the analysis, a capacity development strategy has been proposed for Xiaman Airport based on actual flight schedule data. In another study, Bazargan *et al*[16] used TAAM to investigate runway system capacity utilisation for different runway configurations under varying levels of ground and airspace constraints. In the analysis, two proposed expansion alternatives are compared in terms of maximum throughput capacity at Philadelphia International Airport.

Although these discrete-event simulation tools described above can provide detailed and reliable analyses, they require excessive input data regarding flight schedules and airport layout. Therefore, there is a trade-off between the reliability of results and the cost and effort required while selecting the simulation technique[12]. Barrer *et al* developed a practical simulation tool, called 'Airport Capacity Analysis Through Simulation' (ACATS) for estimating runway capacity for any given runway configuration and separation rules[17]. The tool can estimate the average capacities for given operation and aircraft type mixes rather than using detailed flight schedules. Therefore, the results are more accurate than analytical methods and can be produced faster than the described discrete-event models for complex runway configurations.

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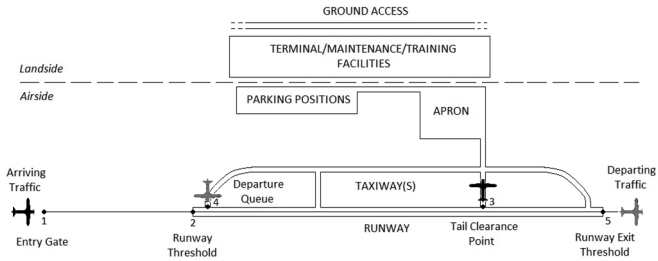


Figure 1. A generic airport layout with a single runway configuration.

As a general purpose discrete-event simulation tool, ARENA allows fast and accurate analysis of many industrial processes including manufacturing, logistics, distribution, warehousing, and service systems. There have been several studies performed using ARENA regarding land-side airport operations, such as evaluation of air cargo operations[18], analysis of passenger flows in terminal buildings[19] and modelling passenger check-in procedures[20]. Airside simulation studies with ARENA are limited with arrival traffic modelling[21] and analysis of gate and taxiway capacities and their environmental impacts[22]. No study has been found in the literature concerning runway capacity modelling using ARENA.

This study aims to develop a practical discrete-event simulation model to analyse single runway capacity of airports serving training flights under various operational scenarios. In addition to the estimation of runway capacity (throughput), the analysis includes airborne and ground delays, queue lengths and runway utilisation. The simulation model has been developed in ARENA in order to obtain a practical yet accurate analysis. The model can contribute to the efficient use of runway capacity as well as effective planning of flight training at airports.

2.0 MODEL DESCRIPTION

2.1 Runway system capacity analysis

The term 'capacity' can be defined as the physical capability of an airport system to accommodate flight operations (i.e. arrivals and departures) for a specified period of time[7]. While performing capacity analysis for an airport system, its components are generally studied independently as airside and landside elements (Fig. 1). Airside consists of runways, taxiways, aprons and parking positions, whereas landside includes ground access systems and various buildings depending on the services offered by the airport (i.e. passenger and cargo terminals, maintenance and/or training facilities). If an airport primarily serves flight training operations rather than commercial air transportation operations, its airside capacity will be more critical than its landside capacity. The overall capacity of the airside is mostly limited by the capacity of the runway[5]. This study focuses on a capacity analysis of a single runway since it is the most commonly-used and usually the most adequate runway configuration for training flights besides providing good traceability of operations, especially for planning purposes.

The single runway system is considered as an open system accommodating landing and take-off operations. The system consists of two resources: final approach path and runway segments, which are defined using five critical points shown in Fig. 1. The entry gate (1) is the point where arriving aircraft start their descent for final approach. It is located at a fixed distance from the runway threshold (2). The final approach (service) time depends on this distance and the approach

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speed of the aircraft. Landing operation begins as the aircraft crosses the runway threshold (2) and ends as it leaves the runway plane at the tail clearance point (3). The time interval between these two points is defined as the runway occupancy time (ROT) of landing of this particular aircraft. The departing aircraft enters the runway at the departure queue or line-up point (4) and leaves it at the runway exit threshold (5). If the aircraft performs its take-off without any heading change immediately after lifting its landing gear, the location of the point (5) will be at the runway end as shown in Fig. 1. In case the aircraft performs a turning manoeuvre immediately after the lift-off, the point (5) will be located at the point where the aircraft leaves the runway plane. In any case, the time interval between points (4) and (5) corresponds to the ROT for take-off of the aircraft.

The primary input of the system is the total number of arriving and departing aircraft, which represents the traffic demand, whereas the primary output of the system is considered as the hourly capacity or throughput, or the number of take-offs and/or landings completed per hour under specified operating scenarios. Besides the hourly capacity, three more measures are considered in the analysis as the system outputs: average delay per aircraft, queue lengths and hourly runway utilisation.

Average expected delay per aircraft is an important output for measuring the performance of the system. There are two types of delay for the given system: ground and airborne delays. Average ground delay provides the average waiting time at the departure queue point for each aircraft. Average airborne delay, on the other hand, gives the average holding time for each aircraft before starting final approach at the entry gate. Queue length represents the number of aircraft waiting at the departure queue point for take-off or at the entry gate for landing. The queue length can be expressed in terms of time-average and maximum number of aircraft waiting in the queue for the given simulation period. These are useful for determining the position and magnitude of possible congestions in the system for the given operation scenario. The last system output, runway utilisation, can be described as the proportion of time the runway is busy for take-off and/or landing operations. It is quite useful in identifying whether the runway is heavily congested or is being used below capacity.

While defining the model, the following assumptions have been made:

1. No simultaneous aircraft occupancy is allowed for the runway and final approach path.
2. Arriving aircraft have a constant speed in the final approach path.
3. The runway primarily serves training flights.
4. Safe separation minima between aircraft are determined according to VFR separation standards[23].
5. Landing and/or takeoff demand are assumed continuous.
6. Capacities of other airside elements (i.e. apron, taxiways and parking positions) and aerodrome control zone (i.e. aerodrome traffic circuit) are not accounted for in the model.
7. Landing and takeoff operations are performed in one-direction. Changes in the direction and magnitude of wind are disregarded.
8. All operations take place under standard atmospheric conditions at the given runway elevation.

2.2 Simulation parameters

In order to analyse the system capacity for a specific traffic scenario, the model requires two important user-defined input parameters: aircraft type mix and operation type mix. Aircraft type mix is the ratio of aircraft performance categories in the total traffic demand per unit time (i.e. one

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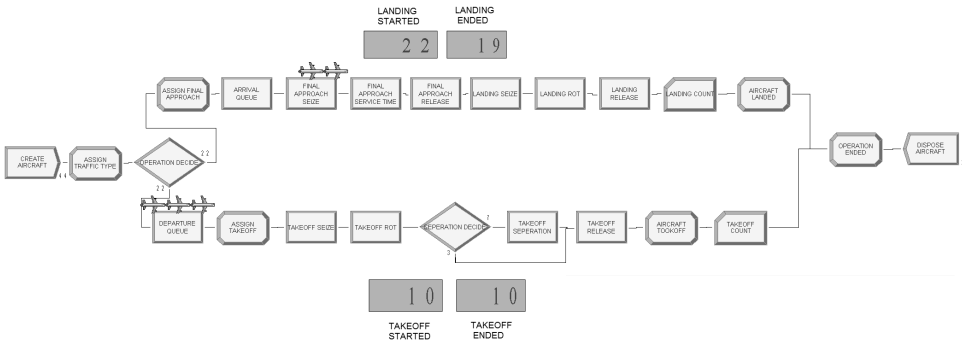


Figure 2. Arena simulation model layout for a single runway system.

hour). Operation mix, on the other hand, is the landing and/or take-off ratios in the total traffic demand per hour. Both aircraft and operation type mix strongly depend on the variety of flight operations and time period to be analysed.

Aircraft performance categories are determined using clustering techniques based on approach speeds, and the landing and take-off times of the aircraft models having operations to the runway. When an aerodrome primarily serves training flights, aircraft types are usually restricted to small single and twin-engine propeller aircraft. Although many flight training courses require a wider use of single-engine aircraft in terms of number of sorties and flight hours, type mix of the twin-engine aircraft can change over a broad range depending on training schedules. Since different stages of training require different numbers of landings and take-offs, as well as touch-and-go operations which are treated as one landing and one take-off, operation mix can also change extensively based on the hourly composition of the training stages performed at that particular aerodrome.

After determining the type and operation mixes, two types of time input, interarrival and service times, are necessary to run the simulations for chosen scenarios. The interarrival time is the duration between any two aircraft entering the runway system consecutively. It represents the total landing and/or take-off demand for a given period of time. Exponential distribution is used to model the interarrival times. The mean of the distribution is selected as one operation per minute to provide continuous traffic demand. This value represents the maximum hourly departure capacity obtained through the analytical formula[5] based on assumption 4 in the previous section.

Service times include the final approach time, landing and take-off ROTs. These services times are calculated analytically based on the performance of aircraft types i.e. approach speed, landing and take-off distance[24]. The airport layout data is obtained from the Aeronautical Information Publication (AIP) of the chosen airport, whereas aircraft performance data is collected from the related flight manuals of the aircraft types existing in the traffic mix. All service times are defined in terms of triangular distribution, which includes the maximum, minimum and average performance values of the aircraft types.

2.3 Simulation model

The simulation model has been developed using Arena software, a flexible and powerful simulation tool used in the creation of any industrial system accurately. The software provides numerous process modules which allow users to construct the model and define simulation parameters easily[10]. In the model (Fig. 2), the 'Create Aircraft' module generates aircraft entering the system

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for arrival and departure using exponential distribution. The 'Traffic Assignment' module assigns operation type (landing or take-off) and aircraft category (single or twin engine) for each entry. These attributes are assigned randomly using pre-determined operation and type mix probabilities for each particular run. The model includes different processes for landing and take-off operations. The 'Operation Decide' block checks the operation type of the entry and sends it to the related process using a two-way condition.

In the landing process, the model checks for the availability of the final approach path and runway first. In case of occupancy, the arriving aircraft is held in the air. If there is no occupancy, the aircraft can proceed through the final approach and landing phases. Similar to landings, no take-off is allowed if there is any aircraft on the runway or in the final approach path. Demanded and completed landing operations are counted using the 'Landing Count' module and displayed separately in the model. The departing aircraft wait in the departure queue until these resources are cleared. The departure process also ensures a one-minute time separation between two consecutive take-offs according to standards[23] using the 'Separation Decide' module. The 'Takeoff Count' module counts the demanded and completed take-offs and shows them in a separate display. After the completion of take-off or landing, each aircraft exits the simulation using the 'Dispose Aircraft' module.

3.0 SAMPLE STUDY: ANADOLU UNIVERSITY AIRPORT

Anadolu University Airport is a typical example of small-scale airport primarily serving training flights. Traffic data shows that 85% of its operations were various training flight exercises conducted between 2007 and 2010[25]. These flight operations included landing, take-off, touch-and-go and traffic circuit exercises in the control zone of the airport. Although, the airport also serves for domestic and international flights, these operations are infrequent and irregular compared to the training flights and therefore, they do not change the main operational characteristics of the airport.

Flight training operations are performed using five different aircraft types owned by Anadolu University. In this study, three of them (Cessna 172 SP, SocataTB-9 Tampico and TB-20 Trinidad) are grouped in a single-engine propeller category, whereas the other two (Beechcraft C90 and B200) are included in a twin-engine propeller category. The service times for each category are calculated based on aircraft performance data collected from the related flight manuals[26-30]. In order to obtain triangular distribution, the minimum, average and maximum service times are calculated for each category at the given airport elevation (i.e. 790m)[23] (see Table 1).

Table 1
Service times according to aircraft performance categories at Anadolu University Airport

Aircraft Performance Category		SERVICE TIMES (secs) Final Approach Occupancy	Landing ROT	Take-off ROT
Single-Engine	Min.	126	30	40
Propeller	Ave.	133	32	42
(TB9, TB20, C172)	Max.	140	34	44
Twin-Engine	Min.	89	24	31
Propeller	Ave.	94	27	33
(C90, B200)	Max.	99	29	35

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Table 2
Simulation scenarios for Anadolu University Airport

Scenario	Runway Operation Type	Operation Mix (Takeoff %)	Type Mix (Single Engine %)
I	Take-off Only	Constant (100%)	Variable (0-100%)
II	Landing Only	Constant (0%)	Variable (0-100%)
III	Mixed	Constant (50%)	Variable (0-100%)
IV	Mixed	Variable (0-100%)	Constant (50%)

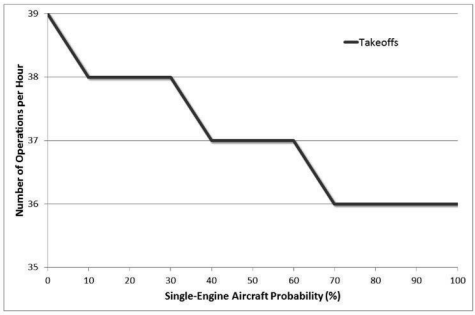


Figure 3. Take-off operations and/or landings completed per hour for 100% take-off probability.

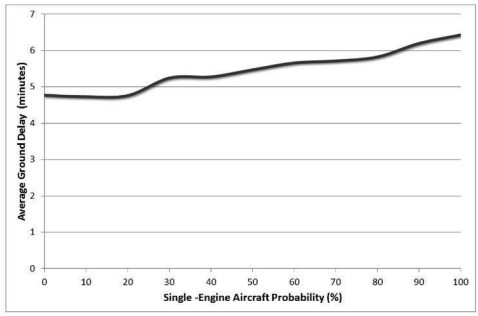


Figure 4. Average ground delay per aircraft at the departure queue for 100% take-off probability.

After determining the service times, simulations are run for four different scenarios to analyse the effects of type and operation mix on the airport capacity (Table 2). In the first scenario, the take-off capacity of the runway is investigated for different single-engine aircraft probabilities in the type mix. A similar analysis is repeated for landing capacity in the second scenario. In the third scenario, 50% landing and 50% take-off probabilities are chosen as an operation mix in order to determine the mixed runway capacity. In the final scenario, the effect of the operation mix is analysed for the constant type mix of 50% single-engine and 50% twin-engine aircraft performance categories. In order to estimate hourly throughput, airborne and ground delays, queue lengths and utilisation, simulations are repeated for 10% of increments of aircraft or operation type mix for each scenario.

3.1 Scenario I: 100% take-off

In this scenario, the take-off capacity, average ground delay, average and maximum departure queue lengths and runway utilisation are studied for different single-engine aircraft probabilities. Fig. 3 indicates the runway throughput variation with respect to the aircraft type mix for 100% of take-offs. Increasing the probability of single-engine aircraft slightly reduces the hourly operation capacity due to their higher take-off ROT. This decrease in the throughput leads to an increase in average delay at the departure queue point of about 35% (Fig. 4). Similar to ground delays, the average queue lengths are also increased moderately from 3·62 to 4·97 aircraft (Fig. 5). Maximum queue length shows the difference between demanded and completed operations per hour. During the simulations, the total demand is calculated as 47 operations per hour while the throughput changes at between 36 and 39 depending on the traffic mix (Fig. 3). As the throughput decreases,

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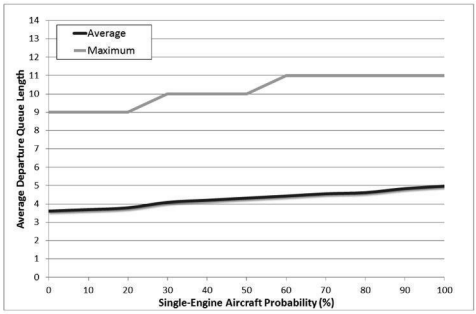


Figure 5. Average and maximum queue length at departure queue point for 100% take-off probability.

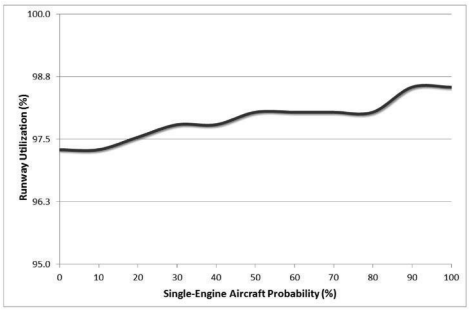


Figure 6. Runway utilisation for 100% take-off probability.

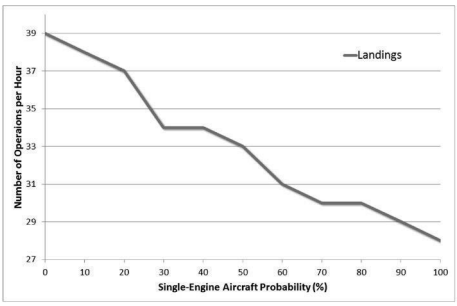


Figure 7. The number of landing operations completed per hour for 100% landing probability.

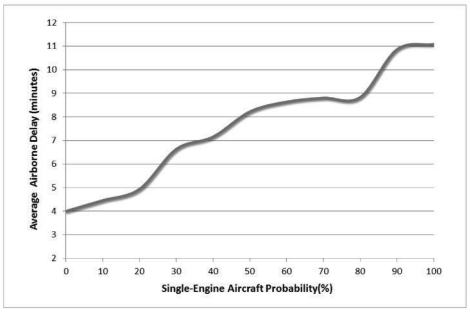


Figure 8. Average airborne delay per aircraft at the entry gate for 100% landing probability.

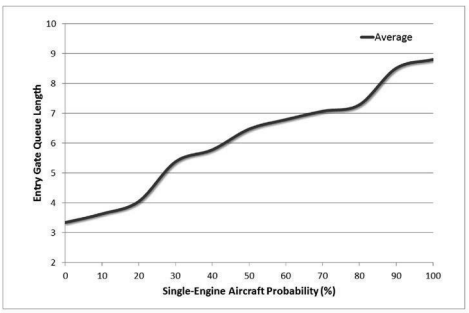


Figure 9. Average queue length at the entry gate for 100% landing probability.

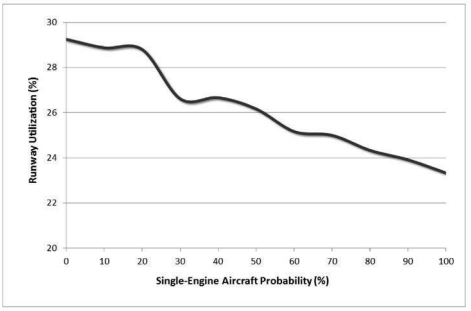


Figure 10. Runway utilisation for 100% landing probability.

the maximum queue length increases from 9 to 11 aircraft. Fig. 6 shows that runway utilisation is very high for 100% take-off traffic and increases slightly with single-engine probability.

3.2 Scenario II: 100% landing

In this scenario, the landing capacity, average airborne delay, average queue length at the entry gate, and runway utilisation are considered for 100% landing demand. When the runway systems accommodates landing operations only, the average throughput becomes more sensitive to the

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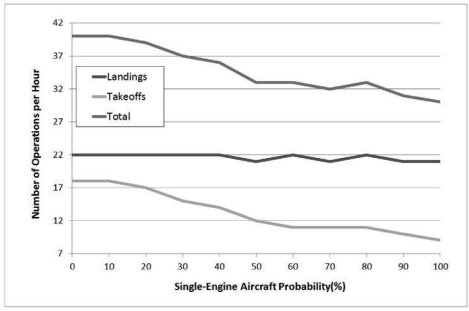


Figure 11. Landing and takeoff operations completed per hour for 50% takeoff probability.

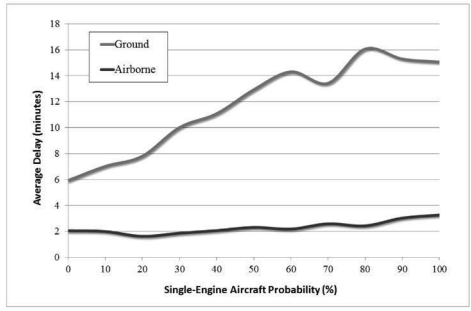


Figure 12. Average ground and airborne delay per aircraft for 50% takeoff probability.

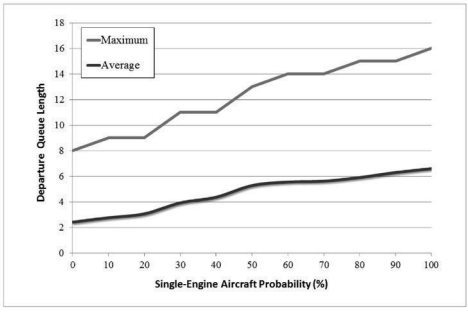


Figure 13. Queue length at the departure queue point for 50% take-off probability.

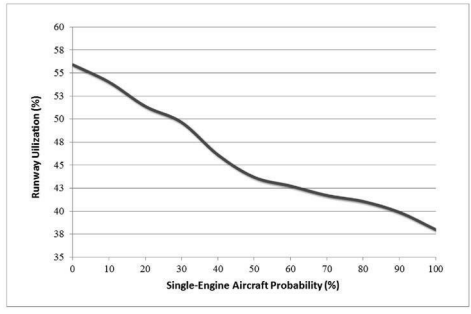


Figure 14. Runway utilisation for 50% take-off probability.

traffic mix (Fig. 7) compared to the take-off traffic. Due to their higher final approach and landing occupancy times, single-engine aircraft reduce the capacity significantly. This decrease leads to higher airborne delays and more aircraft holding in the air (Figs 8 and 9). Increasing single-engine aircraft probability also reduces the utilisation from 29·2% to 23·3% (Fig. 10). These values are very low compared to those in the 100% take-off scenario due to the minimum separation minima constraints in the final approach path.

3.3 Scenario III: 50% landing-50% take-off

In this scenario, both landing and takeoff performance measures are included in the analysis since the runway serves for mixed operations. Figure 11 provides the changes in the takeoff, landing and total operations with increasing single-engine aircraft probability. For the given 50% operation mix, the number of total operations reduces from 40 to 30 per hour as the single-engine probability increases from 0% to 100%. Since landings take priority over takeoffs, the number of the landings completed remains almost constant at around 22 per hour for any type mix probability. Takeoff operations per hour, on the other hand, decrease because aircraft have to wait longer on the ground as the low performance single-engine aircraft increases in the type mix (Fig. 12). Similar to average ground delays, average and maximum lengths increase as the single-engine aircraft probability increases (Fig. 13) at the departure queue point. The single-engine aircraft probability also affects the runway utilisation negatively for mixed operations (Fig. 14).

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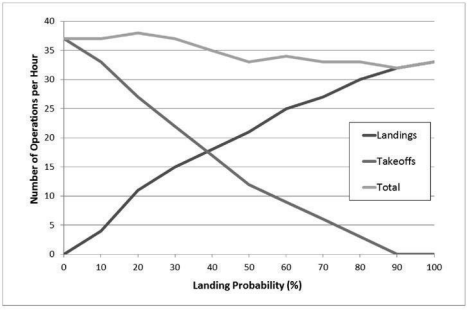


Figure 15. Landing and takeoff operations completed per hour for 50% single-engine probability.

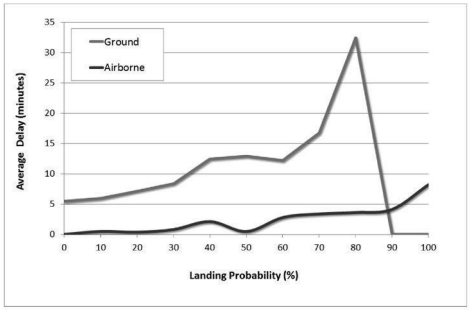


Figure 16. Average ground and airborne delays per aircraft for 50% single-engine aircraft probability.

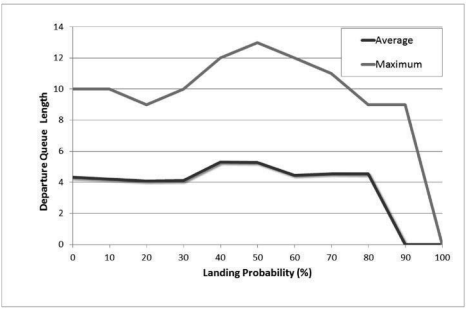


Figure 17. Departure queue length for 50% single-engine aircraft probability.

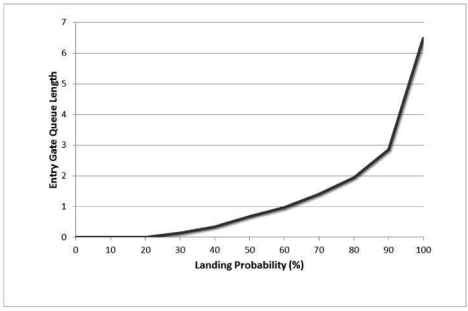


Figure 18. Average queue length at the entry gate for 50% single-engine aircraft probability.

3.4 Scenario IV: Mixed operation capacity with a 50% single-engine aircraft probability

The effect of landing probability on runway throughput is given for the constant aircraft type mix of 50% single-engine and 50% twin-engine in Fig. 15. Increasing the landing probability naturally decreases the number of takeoffs while increasing the number of landings. Above 40% landing probability, the landing throughput exceeds the takeoff throughput. The total throughput also reduces slightly from 37 to 33 operations due to increasing final approach and landing occupancy times for the arriving traffic sequence. Increasing landing probability aggravates the average delays per aircraft on the ground, since more aircraft have to wait longer at the departure queue point for landings (Fig. 16). The delay reaches its peak value of 32·47 minutes per aircraft for an 80% landing probability. This situation corresponds to a serious congestion at the departure queue point. As the landing probability increases further, the average delay drops abruptly down to zero because no takeoffs can be completed for the given period. The average airborne delay increases slightly with an increasing number of landings. For 100% landing probability, the average delay reaches 8·21 minutes per aircraft which indicates potential congestion in the holding pattern. Departure queue lengths reach their highest value around 50% landing probability (Fig. 17). For higher probabilities, especially the maximum queue length, these reduce due to a decreasing number of takeoffs in the operation mix. The number of aircraft waiting in the air increases exponentially with the landing probability (Fig. 18). For 100% probability, the average queue

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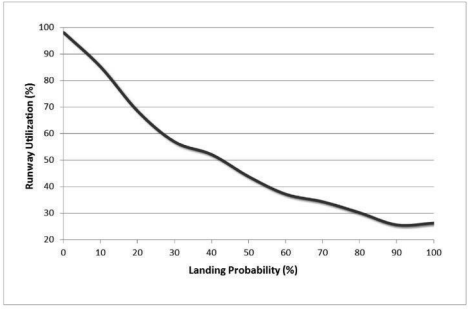


Figure 19. Runway utilisation for 50% single-engine aircraft probability.

length at the entry gate becomes 6·48 aircraft. This value shows the need for capacity development for holding patterns in the aerodrome control zone. Runway utilisation is affected adversely by the landing probability. While it is around 98% for full takeoff operations, it drops down to 26% for full landing operations.

4.0 CONCLUSION

A practical discrete-event simulation model has been developed using ARENA to analyse single runway capacity of airports serving for training flights. Simulations have been run for four different operational scenarios. In each scenario, the type and operation mix of the traffic are defined as the system inputs. Runway throughput, average ground and airborne delays, departure and entry point queue lengths, and runway utilisation have been evaluated as the system outputs for the given inputs. Service times used in the model are calculated based on the layout and traffic data of the sample airport chosen for this study, yet they can be adapted to similar airports with small modifications. The model provides a fast and sufficiently accurate analysis for flight training airports since it does not require the entry of extensive input data. The accuracy of the results can be further increased using different probability distributions for interarrival and service times based on real traffic measurements. The touch-and-go capacity of the runway can also be estimated with resetting service times and the operation mix accordingly. Therefore, it allows trainers and air traffic controllers to plan the efficient use of runway capacity as well as effective planning of flight training for various alternative traffic scenarios. Although this study focuses on runway capacity, the results of the analysis provide an important insight for aerodrome circuit patterns and procedures within the control zone.

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