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# An Aircraft Evacuation Simulation Baseline Using DES for Passenger Path Planning

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# AN AIRCRAFT EVACUATION SIMULATION BASELINE USING DES FOR PASSENGER PATH PLANNING

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Building an aircraft evacuation model came to me as an idea back in the spring of 2014. Halfway through my master's studies, this idea transformed to a research project. This thesis is more than a work at the keyboard. It is a milestone in my academic life which began at ERAU. My experience at ERAU has been nothing short of adventures. Since my first day during the orientation on August 22nd, 2012 I have felt at home at ERAU. I have been given exposure to unique opportunities and complete knowledge of aviation studies and taken advantage of them. Throughout the years I have learned that there are knowledge and skills that are not only for sustaining the current conditions, but also for innovations; my passion is to use the knowledge of different fields and innovate the skills. This research is the result of many experiences that I have encountered at ERAU from professors, friends, classmates and my work colleagues in the Florida NextGen Testbed.

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Abstract

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This paper introduced a Discrete Event Simulation (DES) model that simulates passengers' evacuation paths and decision-making processes during aircraft certification. The model was built using ARENA® 14, which is a DES simulation tool. This model used A380 cabin configuration with capacity of 538 passengers. Each passenger was considered as an independent human being with variations in walking speed, decision-making processes, and evacuation path. This model generated total evacuation time and presented total congestion conditions of each gate. Federal Regulation has suggested that all passengers in the airplane should finish the evacuation within 90 seconds. The model was validated with the A380 certification evacuation, which was 78.2 sec. This model was tested and statistically validated for aircraft evacuation. However, the validation model has limitations in passengers' freedom of choosing a gate. To advance the simulation, an experiment was conducted based on the modification of the validation model to simulate the effect on total evacuation time of passengers switching gates while waiting to exit. At the end of this paper, future study directions were suggested to innovate the baseline by adding human interactions and advanced methods in dynamic simulation technology.

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# Chapter I

## Introduction

Efficient aircraft evacuation is of vital significance for passengers to survive an aircraft accident. It is widely acknowledged that the majority of aircraft accidents are survivable. To ensure travelers live and to improve aviation safety, Title 48 Code of Federal Regulations (CFR) part 121.291 requires that passengers must evacuate from the aircraft within 90 seconds with half of the exits available during aircraft certification (Federal Aviation Regulation, 2015). Meanwhile, the regulation also requires that airlines' crewmember emergency training programs must include emergency evacuation training. Under the regulation's rules, aircraft manufacturers are required to conduct live evacuation demonstrations and computer simulations to meet the regulations. Airlines train their crews to assist passengers and conduct evacuation drills on various scales. To improve the efficiency of evacuation planning and to save costs, airlines and aircraft manufacturers have used computer-based models to simulate the evacuation scenarios. From the review of the simulation models presented in Chapter II, it was found that a majority of these models focused on modeling the interactions of a human with human, structure and hazards. Some other simulation models are focused on evacuating path optimization. Data from real-world evacuation scenarios are extremely limited; this limitation in turn has made the computer-based simulation an important alternative to live evacuation demonstrations for evacuation studies (Togher, Galea, & Lawrence, 2009). Since the computer-based models cannot replace the real situation completely, it is essential that the goals of simulation modeling should not only be describing human behaviors and interactions with the environment, but also analyzing the passenger evacuation path and predicting the total time of the evacuation process. The passenger path plan should be one of the capabilities that computer-based simulation should address.

**Purpose Statement**

The purpose of this study was to construct a valid model to investigate the evacuation process for a commercial aircraft, more specifically, to investigate the evacuation efficiency by considering the passenger's path from the seat to the exits, and the slide-down processes in the evacuation. With the evacuation path plan being considered, the model was intended to predict the total evacuation time while demonstrating the usage of each exit and congestion conditions at each exit and aisle. The model can be beneficial for both the aviation industry and research community. Airlines and aircraft manufacturers can use the results from the simulation model to plan evacuation paths based on each seat location, and investigate the planned evacuation path for each seat. Meanwhile, in aircraft evacuation demonstrations, this model can be used as a test bed to assist evaluating and optimizing the evacuation path plan, and guiding flight attendants as well during evacuation demonstrations.

To investigate the evacuation path, a baseline evacuation model was first developed. A discrete event simulation (DES) software program known as ARENA® 14 was used to build an empirical evacuation model for Airbus 380 (A380) configuration. Developed by Rockwell Automation, ARENA modeling software has been widely used in various industries as operation simulation software (Kelton, Sawdowski, & Swets, 2010).

An A380 certification evacuation demonstration was used to validate this model. By using the time taken for evaluation as the dependent measure for the comparison, a significance level of .05 was set as the threshold for the statistical comparison test. With the validated model, the wide-body commercial airplane evacuation simulation baseline was developed as the test bed for experimentation (Snow, Carroll, & Allgood, 1970).

The model can also provide a baseline for pathfinding studies. ARENA integrated the programming functions with modules. With the necessary modules, the model is capable of modeling the evacuation process for any aircraft configuration. Each entity (Passenger) is trackable and capable of further modification. The aircraft can be configured using a cellular automata method that enables customization for other types of aircraft. For research purposes, this baseline is capable of further alternations in the entity (passenger) characters, aircraft configurations, and other evacuation scenario-based simulations. In this thesis, following the evacuation validation, experiments were designed to test whether passengers changing their evacuation gate decision affected the total evacuation time.

**Hypothesis**

The null hypothesis for the simulation validation was that the average of the total evacuation time will be different from the actual evacuation time; the null hypothesis for the experiment was that passengers changing their evacuation gate decision does not affect the total evacuation time.

In the next chapter, the related literature is reviewed. Chapter III describes the model structure, including the model logic, data format and sources, and validation methods. Chapter IV presents the results of the model validation and experimentation.

Based on the results, discussion is presented in Chapter V, and conclusions and future research directions are presented in the end.

**Model Assumptions**

Simulating human behavior while evacuating involved many parameters from the environment. Meanwhile, the scope of this thesis and software are limited, which affects the final results. Thus, there were assumptions required for the completion of the model. The assumptions were passenger-related and aircraft-related.

**Passenger-related assumptions.** There are parameters that related to the reaction time once a signal was sent out. It is hard to predict and record it precisely. However, during the time when the passengers were detaching the seat belts, the slides were deploying. According to the research of Galea, Finney, Dixon, Siddiqui, & Cooney (2006), the time for passengers to stand up and move from the seat is shorter than six sec, which was the average time for the slides to deploy and be ready to use. Hence the time for slides to deploy was regarded as critical time and the time for passengers to move from seat to aisle was ignored.

Assumptions are also made due to the cost and time constraints. In this study, during evacuation simulation validation, the passenger was not allowed to change it once the selection of the gate was made.

As the report of A380 certification evacuation suggested, the stairs connecting the upper deck and lower deck were not frequently used; passengers in the upper deck evacuated using the slides that connected to the emergency exits of the upper deck in this study (Rosenkrans, 2007); the researcher assumed that the stairs were not used.

There were also factors such as panic level, emotion changes, and injury that were not considered in this study due to the limitations of the scope of the study.

**Aircraft related assumptions.** As the resources relating to the fuselage measurements were limited, the researcher had to rely on critical datasets that were based on other research and company data sources, as mentioned previously in this chapter. Based on the seats capacity during evacuation in the A380 evacuation report and released A380 video, the lower deck seats were arranged in a 3-4-3 seat arrangement (Rosenkrans, 2007).

As demonstrated previously in this chapter, the friction coefficient was considered to be the same among all the slides. To focus on the evacuation configuration effects on the total evacuation time, and reduce the complexity of the model in slides-deploy time, it was fixed at six seconds based on the A380 evacuation report (Rosenkrans, 2007).

## Definitions of Terms

| | |
|---|---|
| Body circle | The circle represented the minimum area that a passenger can move around his/her body with the shoulder and torso on average (Author). |
| Departure timing | Departure timing refers to the entire period of the evacuation process, from the start to the last person evacuating the plane (Southworth, 1991). |
| Destination choice | Destination choice is an assignment problem, which is illustrated as evacuees being assigned to an appropriate exit from the risk area (Southworth, 1991). |

| | |
|---|---|
| Egress Time | The time taken to evacuate the entire group of evacuees (McLean, 2001). |
| Route choices | Route choice would be the routes leading to the destination choice (Southworth, 1991). |
| Shoulder circle | The circle represented the minimum area that passengers can move around their shoulder while remaining in the original position (Author). |
| Torso circle | The circle represented the minimum area that passengers can move their body without moving their shoulder and arms on average (Author). |
| Trip generation | Trip generation is related to the number of evacuees originating in the risk area and the demographics of individuals in the risk area, such as population density, participation rate, and household size (Southworth, 1991). |
| Type III Exits | This type is a rectangular opening of not less than 20 inches wide by 36 inches high with corner radii not greater than seven inches, and with a step-up inside the airplane of not more than 20 inches. If the exit is located over the wing, the step-down outside the airplane may not exceed 27 inches (Federal Aviation Administration, 2012). |
| Type A Exits | This type is a floor-level exit with a rectangular opening of not less than 42 inches wide by 72 inches high, with corner |

radii not greater than seven inches (Federal Aviation Administration, 2012).

**List of Acronyms**

| | |
|---|---|
| AASK | Aircraft Accident Statistics and Knowledge Database |
| ATSB | Australia Transportation Safety Board |
| CFR | Code of Federal Regulation |
| DES | Discrete Event Simulation |
| FAA | Federal Aviation Administration |
| FAR | Federal Aviation Regulation |
| GPSS | General Purpose Simulation System |
| PSO | Particle Swarm Optimization |
| R&D | Research and Development |

# Chapter II

## Review of the Relevant Literature

Evacuation modeling is a method to describe evacuation behaviors and dynamics, and determine evacuation time for areas such as buildings, transportation, and cities. Travelers, evacuation areas, hazards, and surrounding environment are the main components of any evacuation (Snow et al., 1970). These components interact with each other and create chaos during hazardous conditions. To ensure human lives are not lost, and reduce the influences of the hazards, the related service provider's or government authority's guide ensures the evacuation to be efficient. In this section, factors that influence evacuation efficiency for various types of evacuation are reviewed to identify the fundamental issues and variables for the evacuation model development.

### Factors for Aircraft Evacuation Efficiency

Because the structure of areas within an aircraft cabin is unique compared to buildings and other public places, the models of specific evacuation behaviors and dynamics are affected by different cabin factors. Snow et al. (1970) found that there were four factors that determine the aircraft evacuation efficiency: (a) configurational factors, (b) environment factors, (c) procedural factors, and (d) biobehavioral factors. Later on, with the development of aircraft safety management, Muir, Thomas, and Wilson (2004) added two more factors, which are crashworthiness, and evacuation aids. These six factors were deemed as the basic determining variables for aircraft evacuation efficiencies.

**Configurational factors.** Configurational factors include seating configuration, aisle width, bulkhead width, and exit locations, as these factors influence passengers' access to exits (Thomas, O'Ferrall, & Caird-Daley, 2006). Under the emergency situation, configurational factors could play a significant role impacting the evacuation process. For example, an accident evacuation of a Boeing 737 in Manchester, England, which was referred to by Snow et al. (1970), found that the smoke and alarm set-off during the evacuation made the passengers panic, which led to chaos and congestion during the evacuation process. The bulkheads leading to the front exits were so narrow that passengers were stuck at the bulkhead and exit rows, which slowed down the evacuation process significantly. Additional to the congestion and panic, making the exit available quickly could also cause injury. A study conducted by the Federal Aviation Administration (FAA) in Type-III exits found that passageways between 13 inches and 25 inches provide the optimal flow rates (McLean, 2001).

**Environmental factors.** Environmental factors consist of issues associated with the orientation of the aircraft, presence of smoke and toxic gasses, cabin exposed to water, nature of the cabin atmosphere concerning temperature dramatically increasing, lighting levels, and debris in the cabin (Galea, Blake, & Lawrence, 2004). Accident reports showed that these environmental factors increase the chance of injury of passengers during the evacuation (Aviation Institude of George Washington University, 2008). The cognitive and behavioral impairment as a result of these factors made escape more challenging and thus less likely to be successful. For example, Muir, Marrison, and Evans (1990) conducted studies to assess the influences of non-toxic smoke on evacuation efficiency. Their studies showed that the non-toxic smoke significantly slowed the evacuations with multiple cabin configurations.

**Procedural factors.** Procedural factors include the verbal, physical and written instructions from the crew members before, during, and after the evacuation. Studies from the Australia Transportation Safety Board (ATSB) Thomas et al. (2006) have indicated that flight attendants giving commands to guide and instruct passengers during evacuation situations significantly impacted evacuation outcomes in terms of evacuation starting, exits selection, and sliding.

**Bio-behavioral factors.** This factor is related to the nature of passengers. The individual behaviors during evacuation differ among genders, age, and physical ability of an individual, and social affiliation among passengers; for example, family members or traveling companions tend to stick together when evacuating, which creates groups of passengers moving together. By analyzing passenger behaviors in past accidents, researchers from the University of Greenwich had found 947 passengers made 1048 companion references (Galea et al., 2006). Galea et al. (2006) also concluded that there were 104 instances reported where assistance was rendered to a traveling companion during evacuation by 87 individual passengers who were involved in emergency evacuations. Bio-behavioral factors, specifically, refer to human movement speed, path decision, and exit selection. Under the influences of these factors, Galea et al. had showed that the movement speed varies from 1.08 to 1.27 m/s, as shown in Table 1.

Table 1

*Walking speed according to influencing factors.*

| Occupant type | Speed (*m/s*) |
|---|---|
| Children | 1.08 |
| Female elderly | 1.04 |
| Male elderly | 1.05 |
| Elderly | 1.04 |
| Female adult | 1.24 |
| Male adult | 1.30 |
| Adult | 1.27 |

*Note*. The walking speeds according to occupant type are average data. All of these data were taken when pedestrian density was less than 0.43 person/$m^2$. Adapted from "Commuter characteristics in mass rapid transit in Singapore" by Yeo, S.K. and He, Y., 2008, *Fire Safety Journal*, Copyright by Yeo, S.K. and He, Y.

**Passenger Behaviors in Aviation Accident Evacuation**

All these factors mentioned previously affect evacuation efficiency by influencing human behaviors and decisions. In the report of the A380 certification evacuation demonstration, crucial behaviors and measures such as response time, climbing over seats, and corporate behaviors have been observed (Rosenkrans, 2007). Thus, studying behaviors and decisions in evacuations can provide insights for strategies to improve the evacuation efficiency. In evacuation studies, information from the Aircraft Accident Statistics and Knowledge (AASK) database has been used to study the passenger behaviors. According to the explanations from Galea et al. (2006), AASK is designed for managing massive information for passenger behavior studies during survivable accidents and emergencies. The analysis of the AASK database by Galea et al. (2006) suggested that 111 out of 1917 passengers had difficulty in releasing seat buckles, and a higher fraction of older travelers encountered difficulty in releasing seat buckles. There were other difficulties observed during the A380 evacuation. Some passengers experienced language difficulty. As the flight attendants were giving commands in German, some passengers took a longer time to react due to the language barrier (Rosenkrans, 2007). Other typical behaviors were also observed, for example, during the evacuation, some passengers were found climbing the seats for the shortest route to the exit. Forty cases of climbing seats were recorded and altered the evacuation path in the AASK database by Galea et al. (2006).

Besides the individual behavior, group behavior is another aspect of human evacuation behaviors. Human behaviors that have been suggested by Galea et al. (2006) were not limited to the behaviors that cause difficulties during evacuation, but also related to corporate behaviors such as offering help to other passengers and actions to require external assistance.

Generally, in a standard 90-seconds evacuation certification trial, the passengers were selected as unconnected individuals to prevent the effect from groups of people. However, this is not typical for airline travel, as according to the AASK database by Galea et al. (2006), about 49.5% (947) of the passengers were traveling with companions. The assistance among group members was the most common behavior during evacuation. The assistance includes adults assisting children in locating an exit, sliding down from the deployed slides, and releasing the seatbelt. All of these could alter the evacuation time. However, as the data related to group dynamics are difficult to record and analyze, the impacts of such behaviors are not well understood.

**Exit Selection Decision in Aircraft Evacuation**

Exit selection decision determines passengers' path and personal evacuation time. It also influences the utilization of each exit and total evacuation time. As with most pathfinding problems, normally the shortest way is not the fastest way in aviation due to congestion, physical obstacles, and availability of the exits. However, research by Galea et al. (2006) has shown that 89% of passengers attempted to utilize the nearest exit strategy during the evacuation. One of the factors that contributed to the poor exit selection decisions was passengers having a limited understanding of aircraft exit location and configuration, and poor estimation of the current evacuation process (Togher, Galea, & Lawrence, 2009).

Most commercial aircraft are equipped with two pairs of exits distributed near the two ends, and another pair located over the wings. However, few people know that the over-wing exits are smaller than the other ones. Passengers neglect this fact, especially during the evacuation when panic sets in. Research found that with a queue at each exit, almost two-fifths of the entire population elect to use the centrally located, smaller over-wing exit (Togher et al., 2009). This result also showed that the general population does not realize that their choice of the middle exit has led them to a longer evacuation process.

**General Steps of Evacuation Modeling**

Procedures to implement evacuation modeling are relatively simlilar; the procedures include trip generation, departure timing, destination choice, route choice, plan setup and analysis (Southworth, 1991). Trip generation is related to the number of evacuees originating in the risk area and the demographics of individuals in the risk area, such as population density, participation rate, and household size. In aircraft evacuation, trip generation involves the number of passengers on board, limited space, and hazardous situations. Departure timing refers to the entire period of the evacuation process, from the start to the last person evacuating the plane. Some researchers divide the entire period into different intervals, estimate the number of evacuees, and differentiate an evacuation rate at the different time intervals (Southworth, 1991). Destination choice is an assignment problem, which is illustrated as evacuees being assigned to an appropriate exit from the risk area. As suggested by Togher et al. (2009), if destination choice is the objective function, route choices would be the routes leading to the destination choice, with consideration of different constraints applied in various evacuation scenarios.

In aircraft evacuation studies, it is typical to consider that trips are fully generated based on regulations, and evacuees are assumed as consisting of 100% of the passengers and crews on board. The overall evacuation efficiency might vary as the departing procedures with participation rate vary, and different strategies for route choices are applied with different optimization methodologies.

## Human Behavioral Issues in Evacuation

From the previous human factors research in the evacuation process, human behaviors were found to be one of the most significant constraints, especially when considering destination choices and route options. From the 1990s, behavioral issues observed in evacuations were given much attention, and most research was focused on passenger emotion factors and pedestrian behaviors.

**Passenger emotions.** During an emergency situation, when passengers turn into evacuees, often the chaos present in human behavior affects the process of evacuation, such as disordered movements and reduced evacuation speed. The time taken to evacuate the entire group of evacuees is defined as egress time, which is an important measure for evacuation performance (Miyoshi, Nakayasu, Ueno, & Patterson, 2012). Researchers showed that the egress times are significantly increased as more passengers panic (Sharma, Singh, & Prakash, 2007). Panic behaviors are further influenced by factors such as remaining time, frequency of wait, and difficulty to find a gate. All those indicators further directly or indirectly affect panic levels. When passengers are thrown into a panic situation, people move in an unorganized pattern, which causes congestion, slowing down the overall movement speed, and reducing the utilization of the exit doors as suggested by Miyoshi et al. (2012). Furthermore, Miyoshi et al. (2012) stated that congestion of evacuees also causes an increase in passenger panic level, which propagates to other evacuees

**Pedestrian behaviors**. Another research area in human behavioral issues is related to pedestrian behaviors that provide optimization approaches for crowded places such as the area around aircraft exit doors and aisles. Pedestrian modeling provides a basis to simulate human behavior around those areas (Yeo & He, 2008).

In the study of pedestrian approaches for navigation, complexity is involved in simulating real pedestrian behaviors. In the simulation model of evacuation, the pedestrians are usually represented by agents (evacuees) whose movements are described by a navigation model (Yeo & He, 2008). Human behaviors and self-motivation need to be taken into consideration, which provides better simulation validity. However, these factors are difficult to quantify for the simulation. A large degree of variability is often involved; for example, individuals in simulations may have their judgments as pedestrians considered fast by one pedestrian, or may be regarded as slow by another, and the resulting disparity in judgment might impact their decisions regarding exit choice as suggested from the research by Togher et al. (2009).

Moreover, factors such as smoke, light, or decrease in temperature could also impact pedestrians' behavior; new pathfinding and behaviors in passenger groups, such as separation, cohesion, and alignments, also need to be taken into consideration (Yeo & He, 2008). As human behavior is being modeled, to ensure accuracy and validity, sensory estimation errors are added to introduce human-sensing errors into an agent's sensory inputs, such as a human's reaction time to the alert before initial actions during the evacuation. In some research, these errors are quantified as a random value in a predefined range (Koh & Zhou, 2011).

## A Review of Aircraft Evacuation Simulation

**General Purpose Simulation System (GPSS) and airEXODUS**. Evacuation has been the subject of simulation study since the 1960s. One of the first computer-based aircraft evacuation simulation models that appeared in the open literature was the General Purpose Simulation System (GPSS) model in the 1970s by Snow et al. (1970). It was designed using the massive mainframe computer environment. This model had limited capabilities due to the limitations of the computer technologies at that time. With development of fast computer technology in both hardware and software, simulation models have advanced rapidly. In the 1990s, Graphical User Interface based simulation software first appeared for use in aircraft design and evaluation, to include evacuation. For example, the airEXODUS software developed scenarios for aircraft certification purposes. airEXODUS software considers interactions among people, hazards, and structure in the evacuation process as referenced in the report by Galea et al. (2004). This model predicts the total evacuation time under certification scenarios for both narrow-body and wide-body aircraft. airEXODUS provides the total estimated evacuation time within 5.3% or 3.8 seconds variation on average, as suggested by Galea et al. (2004). Because the realistic accident data is hard to obtain, validating simulations for evacuation of real aircraft accidents, which is also called unplanned aircraft evacuation, has become extradinarily difficult.

**AvatarSim**. Compared to unplanned evacuation in the real-world situation, evacuation trials using simulation models have eliminated factors such as travel companions, hazardous environments, aircraft structure, and available exits conditions as a means to simplify the problem, in order to focus on the main factors. Furthermore, the simulations and modeling techniques make use of knowledge from previous accident investigations in order to make the model more comprehensive. As another example, Sharma et al. (2007) have presented AvatarSim to simulate emotions in passengers. It incorporates fuzzy behavior characters for passengers and crew, social forces for passenger movement speed, and geometric models for aircraft configuration and simulation construction. As suggested by Sharma et al. (2007), AvatarSim produced similar results to airEXODUS in certification trials simulation. Sharma et al. (2007) observed an increase in evacuation times when passengers are in a highly panicked situation.

airEXODUS and AvatarSim represent two instances of the application of simulation that are used to investigate the certification scenarios and recreation of real emergency evacuations after aircraft landing. Due to the fact that the research and development (R&D) cycle of aircraft emergency evacuation requires a relatively long time, and the factors that relate to evacuation simulation typically include human factors, operations research, artificial intelligence, and computer science, building a comprehensive simulation model with all these factors considered is extraordinarily difficult. Such a model usually has high complexity that involves multiple software modules and is often multidisciplinary in nature.

In addition to the computer-based simulation models described above, to aid the certification evaluation for the evacuation process, several other commercial computer simulation models that include more factors have been developed over the last three decades, such as AIREVAC, ARCEVAC, VacateAir, and Robbin's Discrete Element Method (Xue & Bloebaum, 2008). Xue and Bloebaum (2008) have summarized that these evacuation models simulated passengers' movements and some human behavioral factors. The movement and speed of humans were simulated via fluid or molecular mechanics; human behavioral models considered each individual passenger with different characteristics, such as age, gender, emotion, etc.

**VacateAir**. Xue and Bloebaum (2008) had presented in their research that VacateAir considers cabin configuration, fire hazards, human behavior, and simulation behavior subsystems. VacateAir was validated by comparing the time for first passenger evacuation and total evacuation time with documented real experimental data. The experimental total evacuation time was compared with the VacateAir results to validate the sensitivity of cabin configuration design and human behavior in competitive and corporate scenarios by Xue and Bloebaum (2008). The results of the VacateAir model were found to match the hypothetical distribution of the total evacuation times for a given aircraft scenario combination by Xue and Bloebaum (2008).

**Particle Swarm Optimization (PSO)**. In 2008, a new simulation model, the Particle Swarm Optimization (PSO), was developed to demonstrate a method that can be used in both certification and emergency scenarios suggested by Xue and Bloebaum (2008). It proposed a new method to optimize the path for passengers to evacuate the nearest gate. The PSO uses a heuristic algorithm. Originating from birds flocking theory, the PSO model determines individual's velocity change by the current distance from the personal best goal and the global best goal. A global best perspective of the occupants views the environment as a whole to find the best path to reach the final goal, while the personal best shows the occupant's perspective as an individual that will lead the occupant to the next personal best goal (Xue & Bloebaum, 2008).

The PSO model is also a coordinate-based algorithm. All the obstacles and passenger movements are recorded in coordinates. It breaks down the procedure by cutting the cabin layout into grids and nodes, which saves substantial computational expense. Some of the models have more generality in application beyond aircraft evacuation, for example, the PSO model, social forces model, and molecular motion model. The molecular motion model is a method of describing passenger movements and interactions which is widely used in pedestrian behaviors studies. The PSO model was initially proposed as a universal method in fire evacuation simulations (Tyagi, 2004).

**Social Forces Model**. Besides the PSO model, there are other techniques that have been adopted from building and other public open area evacuation simulations which could potentially be used in further examination of aircraft evacuation in a microscopic level study of pedestrian behaviors. To simulate the crowd behavior during an emergency, the social forces model approach uses forces that show the desires of people reaching a certain destination. The assumption of the social forces model is that pedestrians are willing to move at a velocity and a given direction in order to reach the destination. They accelerate or decelerate based on their “desire” (Sharma et al., 2007).

In the social forces model, the interaction of paired occupants is also described by social forces. The feeling of preserving their private space becomes stronger as people get closer. The third force, which is “granular forces”, describes the contact and friction that appears between people or between people and walls. All three forces influence the pedestrian’s dynamics by changing the actual velocity (Frank & C.O., 2011).

**Summary**

Aircraft evacuation simulation was developed as an important branch of public area evacuation. Evacuation research has been frequently tied to fire and hazards research in the U.S., Europe, and Asia. Software such as airEXODUS, AIREVAC, and ARCEVAC has been focused on simulation of human behaviors, movements, and pedestrian behaviors. Methods such as the PSO and social forces models have been adopted to many industries and applications such as human factors, medicine, physics, and electrical engineering.

In recent years, the focus of simulating human movements has expanded to path planning and dynamic programming, which could also be potentially used in aviation evacuation simulation. However, aircraft evacuation has unique characteristics, and the factors that affect the evacuation efficiency differ from evacuation simulations from other evacuation models. The researcher has found that to study the evacuation efficiency, precision in individual passenger paths and movements is required in the simulation, which is influenced by the passenger's decision-making process. To develop a more complete simulation for evacuation, individual passengers' evacuation paths and decision-making processes should be taken into consideration, as well as modeling the human behaviors and movements. Developing a baseline for such evacuation simulation is a necessary step, and is outlined in the next chapter.

# Chapter III

# Methodology

Chapter II reviewed relevant literature on aircraft evacuation simulation studies and modeling techniques. This chapter starts with the introduction of the simulation software in terms of the software constituents and capabilities. The second part of this chapter contains the explanation of the model structure in flow charts. Additionally, the assumptions and limitations of the model are discussed in this chapter. The model structure description also includes the explanations of queuing theory and the forms of queues used in these simulations in detail. The third part of this chapter provides data source and output parameters as preparation for presenting the results. The last part of this chapter provides simulation validation methodology and simulation experimental methodology.

## ARENA Simulation Software

It is well known that general programming languages such as JAVA, C++, or Visual Basic could be used to develop simulation models. A programming language provides simulations with high flexibility and customization, but less accessibility to people who have limited knowledge in programming, which makes them complex to use. However, there are simulation languages such as GPSS, Simscript, and SIMAN designated in simulation development. Simulation languages build a better framework for simulations with less flexibility than general programming languages, but these simulation tools provide a better framework for simulation software. ARENA simulation software was written in SIMAN language with functions to adopt Visual Basic and C++ code, which means that ARENA maintains its flexibility in addition to better accessibility to people with limited knowledge in programming (Kelton, Sawdowski, & Swets, 2010). The software hierarchical structure is shown in Figure 1.

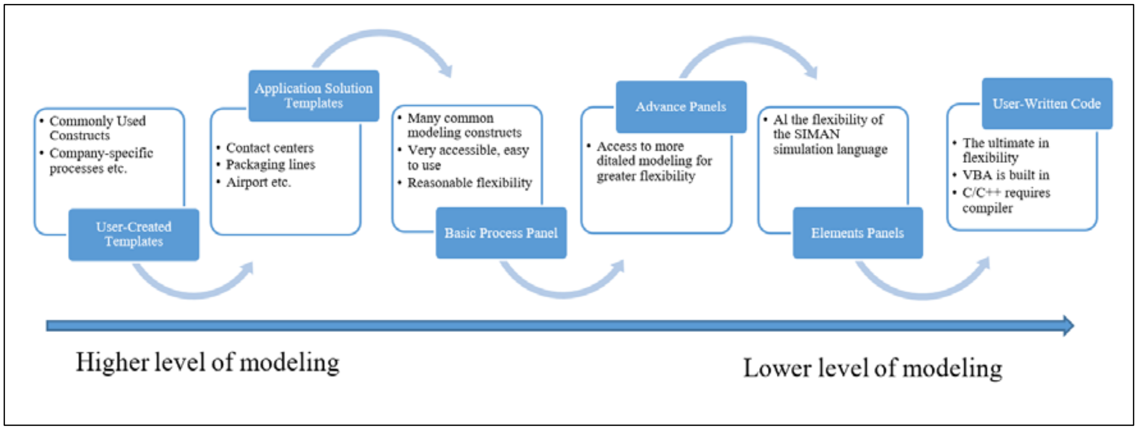


*Figure 1.* ARENA's Hierarchical Structure. *Note.* Adapted from *Simulation with Arena* by W. D. Kelton, R. P. Sadowski, & N. B. Swets, 2010, New York, NY: McGraw-Hill Companies, Inc. Copyright 2010 by the McGraw-Hill Companies, Inc.

The development of the simulation used in this thesis utilized the Basic Process Panel and Advance Panels as the baseline and experimental design, respectively.

**Model Structure**

ARENA is an event-driven simulation system. An event describes any identifiable occurrences to the system to process. It brings changes in the parameters of the system. In ARENA simulations, entities cause events. When an event happens, the attributes or variables in the system change. At the start of a simulation, an entity is generated to start the simulation and trigger the time counter in ARENA. However, after the start is triggered, the simulation also requires a series of events to continue the simulation proceeding to the end. The following flowchart (Figure 2) describes the simulation in this study as an example of the chain of events.

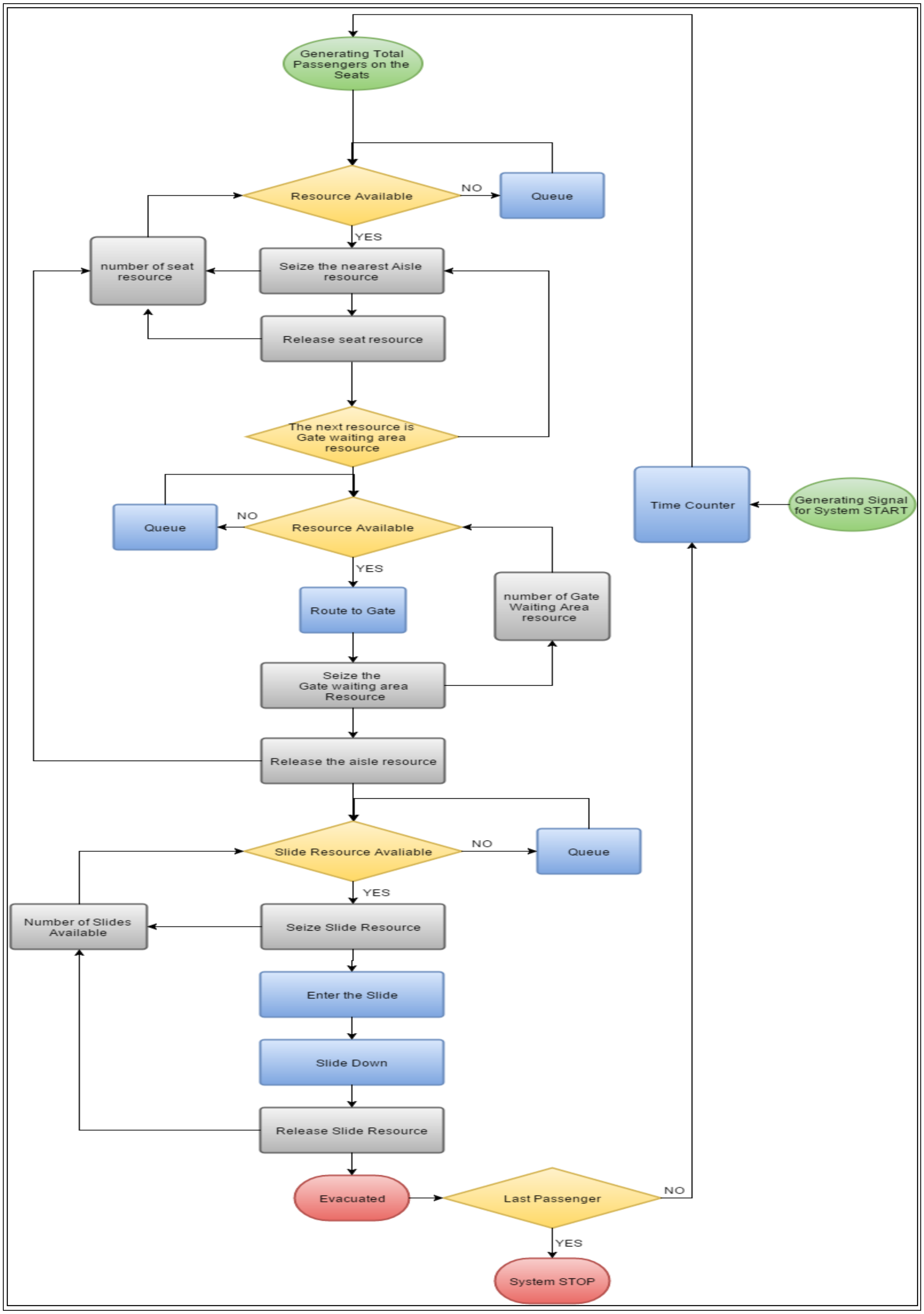


*Figure 2.* Passenger Evacuation Events Flow.

## Flowchart

**Generate passengers in the seats.** The green-colored icon on the right in Figure 2 stands for the system start point. As the trigger of the simulation to start, a single entity was created and triggered the time counter to record the total time that each simulation process was taking to complete. The other green icon on the top of the flowchart in Figure 2 stands for the passenger entities that were aimed to trigger each evacuation event.

Following the creation module, the passengers were located to each station that represents their seats. The stations are also physical locations that can be observed in animations. The total number of passengers was defined in the creation module. In this case, the time that was taken generating passengers in the simulation should not be counted as part of the total time consumed in the evacuation. Thus, the time started to accumulate when the first passenger moved from his/her seat.

**Passengers move from seats to the gates.** Diamond icons that are color coded in yellow in Figure 2 include the decision modules that directed the system flow. After passengers were created and seated, they would move to the aisle. Based on the seat configuration, only the seat by the aisle can access the aisle directly. Passengers in the seat by the window and the middle seat had to wait for the seat by the aisle to be vacant, which formed a queue to get access to the aisle.

In this simulation model, the access was described as resources that had limited capacity. For instance, the resource to access the aisle from each seat group (seat by window, middle seat, and seat by aisle) had a capacity of 1, which meant that only one passenger can get through the seat-by-aisle to the aisle and evacuate. When this resource is not available, the queue was formed.

To physically move to the aisle, the passenger had to seize the resource. When the resource was not necessary to the passenger, then the resource could be released. As described in the flowchart, after the passengers were created, each of them performed a check of the available resource that he/she could access to move to the aisle. If the resource were available, the passenger could seize the resource to the aisle and release the resource of that seat.

At the aisle, the passenger could move forward to the designated gate. Passengers' movement process was included in ARENA as a route module. It described the action that passengers transferred from the current module to the destination station within a certain time.

The blue icons in Figure 2 represent the actions that consumed either queuing movement. By contrast, the gray icons represent the processes that related to seizing and releasing modules. The Leave modules combined both Release and Seize modules that describe the process of seizing a resource and leaving the current station while releasing the previous resource.

**Passengers slide down from the gates.** It was widely implemented in the evacuation simulation to simulate a passenger entering the aisle, moving through the aisle, and entering the gate. Once the passenger entered the gate, they had carried *slides* as a resource. The actions of sliding down on the slides were interpreted via a process module. To end the simulation, the passengers had to release the slide resource, which meant that they evacuated successfully. The last passenger who evacuated successfully indicated that the simulation had just finished one iteration. The red icons in Figure 2 refer to the end of the system.

**Configuration of the Aircraft**

Figure 3 shows one of the typical configurations of the A380 lower deck. It is one of those certification evacuation demonstrations for wide-body commercial aircraft that has relatively complete records revealed to the public. Passenger capacity varies with the seat configuration chosen by the airline; for example, the A380-800 is certified for up to 853 passengers with 538 on the main deck. All the seats used in this simulation are referred to as a comfortable third class. There are five passenger/crew gates distributed on both sides of the fuselage, including one emergency exit over the wing on each side. All the exits are type A exits with a rectangular opening of not less than 42 inches wide by 72 inches high, with corner radii no greater than one-sixth of the width of the exit (Federal Aviation Regulation, 2015).

During the evacuation, after passengers were generated and evacuation started, passengers moved to the aisle. To simulate the congestion condition into a range that is closer to reality, the researcher put a capacity limitation on the resource. The aisle reached its capacity when the queue of the gate extended and filled up the aisle. Thus, the capacity of the aisle equaled the number of people in the queue that occupied the aisle space. The calculation of the aisle's capacity required the dimension of the fuselage and passenger body width. Figure 4 is the cabin cross section provided by the Airbus official website. The official seat configuration with seat measurement used in the demonstration described in Chapter II is not available. The researcher collected data on A380 seat pitch from Qatar Airlines as a means to represent the most common seat pitch and width used by the airlines (Travel Trade Gazette, 2007). Seat pitch refers to the distance between the back of the seat in a row and the back of the seat in the row in front of it. For the A380, the seat pitch for economy class is normally 31- 32 inches and the seat width is 18 inches for 388 passengers (Travel Trade Gazette, 2007). Based on the seat map, the length of each aisle could be calculated. With the cabin length and width that Airbus had published, the basic cabin measurement was completed.

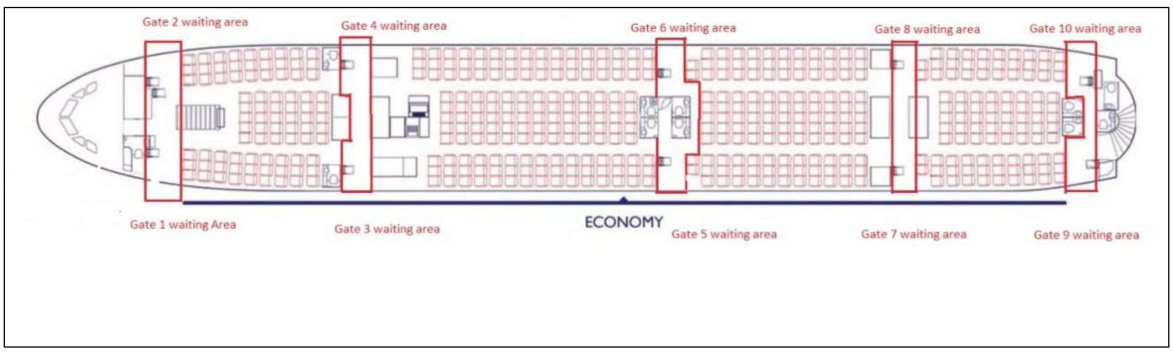


*Figure 3.* A380 main deck configuration. Adapted from Amedeo in *Runway Girl Network.* Retrieved October 21, 2015 from *http://i0.wp.com/www.runwaygirlnetwork.com/wp-content/uploads/2014/05/Amedeo.jpg*.

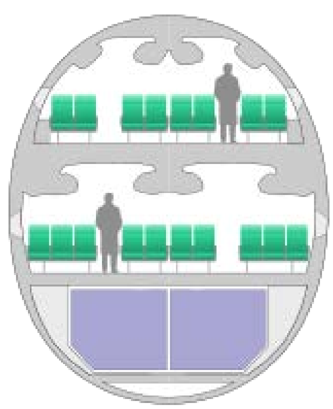

*Figure 4.* The A380 cabin cross section with economy class seating. Retrieved from Airbus A380 seat configurations in *Wikipedia, n.d.,* Retrieved October 21, 2015, from https://en.wikipedia.org/wiki/Airbus_A380_seat_configurations.

The model used by Thompson et al. (2003) assigned body measurements through the use of three circles, as in Figure 5. The three circles represent the radii of whole body circle, torso circle, and shoulder circle. The radii of the whole body circle (Rb) was 10.6 inches; the radii of torso circle (Rt) was 6.3 inches; and the radii of the shoulder circle (Rs) was 3.9 inches, respectively, which represent the body of an adult as suggested by Thompson et al. (2003). This simulation also adopted the three-circle model to assign passengers' body dimensions. However, the aisle capacity did not include the space connecting aisle and gate, which has an estimated capacity of 10 to 12 people, as shown in Figure 3 by the highlighted spaces outlined in red.

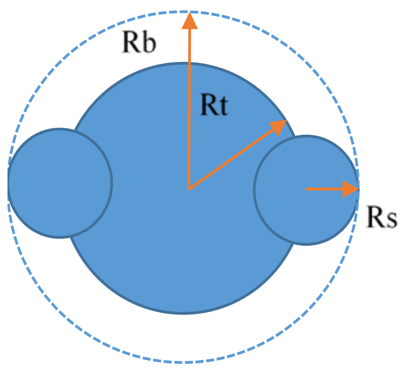


*Figure 5.* Representation of an Adult Human Body.

**Emergency Inflatable Slides**

As dictated by 14 CFR 25.810, the assisting means (which must be capable of carrying simultaneously two parallel lines of evacuees) for emergency evacuation must meet the following requirements (Federal Aviation Administration, 2012):

1) must be automatically deployed

2) must be of such length after full deployment that the lower end is self-supporting on the ground and provides safe evacuation of occupants to the ground after collapse of one or more legs of the landing gear

3) must have the capability, in 25 knot winds directed from the most critical angle, to deploy and, with the assistance of only one person, to remain usable after full deployment to evacuate occupants safely to the ground. (pp. 458-459)

The inflatable slides are located on commercial aircraft doors for evacuating passengers and crew in the event of an emergency.

In 2008, sponsored by the FAA's airport cooperative research program, the George Washington University conducted a series of research studies on evacuation and mitigation of aircraft slide evacuation injuries. In the study of emergency evacuation challenges on large transportation aircraft, they developed a dynamic model to determine the velocity of a person during the slide. The output of the modeling program provides the velocity of an individual and time as a function of position. To calculate the velocity at any point of the evacuation, one needs to find the optimal curve that describes the aircraft evacuation sliding velocity (Aviation Institute of George Washington University, 2008) which was used to calculate the time that the slide was occupied by each individual on average. Figure 6 demonstrates the vectors of the forces that each passenger had during sliding down. The method to calculate the velocity of sliding down was demonstrated as the following:

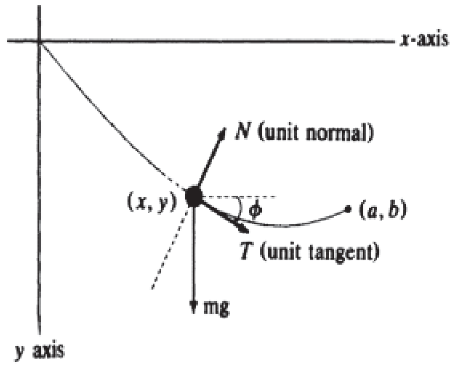


*Figure 6*. Unit Normal and Unit Tangent Vectors at Point (*x*, *y*).

*N* is the force that a passenger of mass m took as seating on the slides, while *g* is the gravitational acceleration. *T* represents the unit tangent of keeping the passenger moving forward with a certain acceleration rate. The x and y components of distance were calculated based on the unit vectors from point to point.

In the following equation, $\theta$ represents the angle between the passenger's sliding direction and the x axis. The distance were calculated as shown in the following formulas:

$$x(\theta) = x_c(\theta) + \mu\rho(1 - cos\,\theta) \quad (1)$$

$$y(\theta) = y_c(\theta) + \mu\rho(\theta + \sin\theta) \quad (2)$$

where $x_c(\theta) = \rho(\theta - \sin\theta)$ $and$ $y_c(\theta) = \rho(1 - \cos\theta)$, (3)

and $\rho$ and $\theta$ are determined with the end point (*a*, *b*). The coordinates of *a* and *b* are needed. The y-component is the height (*h*) from the ground to the top of the evacuation slide. The x-component is unknown. When no person slides down, the x component of the slide should be the maximum value of

$$\sqrt{l^2 - h^2} \tag{4}$$

The equation for *v* is

$$v = \sqrt{2g(y - \mu x)} + {v_0}^2 \tag{5}$$

This equation is used in the program to calculate the velocity at any given point *(x, y)* on the curve. In the research conducted by Aviation Institute of George Washington University (2008), the coefficient of friction $\mu$ is 0.4, and initial velocity ($v_0$) is 6ft/sec.

**Passenger Moving Speed**

As illustrated in the research by Galea et al. (2006) in Chapter II, the recorded passengers' average speed during emergency evacuation varies for different age groups and by gender. The values were between 1.04 m/s and 1.30 m/s; the mode was 1.27 m/s. In this baseline simulation, the researcher assigned speeds to passengers following the Triangular Distribution *T* ~ [1.04, 1.27, 1.30].

**Input and Output**

**Input.** Table 2 displays the time for each passenger to slide down from the top to the bottom of the slides. In reality, while one passenger has slid halfway, the next passenger starts to slide. However, in ARENA, it is default that when the resource (slide) was used, the next entity (passenger) has to wait for the resource to be released. In order to simulate the usage of the slide as the actual, the slide down time was recalculated based on the total passengers per second. The new slide down time turned out to be *T* ~ [0.5, 0.6, 0.9]. There were also distance input arrays, which are presented in Appendix A. The distance was measured to be the distance of each row to the nearest gate. Table 4 is the result of that capacity calculation based on human body dimensions and fuselage dimensions, which is close to the actual usage. The column *Total number of passengers* in Table 4 was calculated based on the number of seats in each seat section.

Table 2

*Passenger Input and Output Parameters*

| Parameters | Value | Unit |
|---|---|---|
| Slide Down Time | TRIA(0.50, 0.60, 0.90)* | second |
| Walking Speed | TRIA(40.94, 46.06, 51.18)** | inches/second |
| Slide deploy time | 6.00*** | second |

*Note*.* Adapted from “Study on Emergency Evacuation Challenges on Large Transport Aircraft” by V. Motevalli, L. Monajemi, M. Rassi, 2008, *Airport Cooperative Research Program*, 66-67. 2008. Copyright 2008 by Federal Aviation Administration.
** Adapted from “Developing a database for emergency evacuation model” by Shi et al., 2009, *Building and Evacuation*,1724-1729. Copyright 2009 by Elsevier Ltd.
*** Adapted from assumption.

Table 3

*Aisle Capacities*

| Aisle sections | Capacity (Passengers/per aisle) | Total number of passengers |
|---|---|---|
| gate 1 to gate 3 | 13 | 102 |
| gate 3 to gate 5 | 27 | 192 |
| gate 5 to gate 7 | 20 | 142 |
| gate 7 to gate 9 | 14 | 102 |

**Output**. The output data was recorded in the outcome array of total evacuation time in each model iteration. The final result was compared with the A380 evacuation demonstration result from Chapter II. A *t*-test was performed to test the significance of the difference between the average total simulated evacuation time and the A380 demonstration evacuation time. To validate the system, performance charts with gate-waiting queue-length distribution were also recorded.

**Validation**

To validate the simulation model, the face validation was performed to verify if the ARENA model behaved in the way that it was intended to do. Face validation can support the researcher by confirming that the system covered the concept that it was supposed to measure. Except for face validation, statistical validation would tell the difference between the current simulation system and the real scenario via statistical proofs.

This simulation was built using data collected by a massive number of research studies, which enabled the comparison of the output data to the actual certification evacuation scenarios. The actual evacuation time was compared to the average total evacuation time from each iteration. A *t*-test was used to compare actual data to the simulation data.

**Experimentation**

It was assumed in the baseline evacuation simulation that once the passengers made the choice of which gate to escape towards, the decision was not going to change. However, it is not always the case. When passengers proceed to the gate and join the queue, they might find out that the queue was longer than the queue at other gates. Driven by the goal of evacuating as quickly as possible, passengers can have impulsive behavior and decide to switch the queue to the fastest gate queue and escape. The experiment was designed to test if the total evacuation time would be less if passengers were able to be assigned to an alternative gate.

In the experiment, passengers made the decision of switching the gate based on the difference between the current queue length and the adjacent queue's length. Passengers were allowed to make the decision to proceed to the shortest queue. The first experiment simulated that once the lengths of the queues were different, passengers started to switch. The second experiment set the condition that when the length difference between two queues was able to stay over five people, then the passenger switched to the alternative gate. A one-way ANOVA test was conducted to test whether the differences between the results of experiments one and two were significant, which meant that the adjustment based on difference of queue length results in a variation of the total evacuation time.

# Chapter IV

# Results

## Validation Model Structure

The model was built in 4 (four) sections, which describe (a) generating passengers; (b) the passengers transfer from creation to allocate to seats; (c) passengers routed from seats to the gates; (d) passengers routed from the gates to slide down. Figure 7 shows the first section with the first row as an example. The aisles had divided seats of each row into three sections, which were named sections a, b, and c. Combined with seat row, which was named after row numbers, the '1_1a' in Figure 7 represents the first row in a section. Each section was generated by one created module. As the first created module, a time counter, which recorded the beginning time of the simulation, was injected after the creation module before the passenger entity would go to the seat station. Once a passenger was created, it went to the seat station such as 1_1a and 1_3b, as shown in Figure 7. Using 'station' as a module provided a seat node in animation. As the creation module functioned simultaneously, the allocation of the seat was not taking system time. Once the passenger was seated, it started to evacuate. When the seats were located in the middle of the row, it required a 'decide' module to choose the aisle. The passengers were assigned with a resource that had the same capacity as that of the aisle. The screen shot of the complete model is attached in Appendix B.

The second section, as shown in Figure 8, was an example to demonstrate passengers' movement from the seat to aisle, and then to the gate. The aisles were considered as a set of 'stations' that connected the gates and the seats. The aisle stations were named as a combination of a letter, such as *a*, and a number, such as *15*. The Enter and Leave modules contained the processes of ‘seize’ and ‘release’ resources, and route to the designated station.

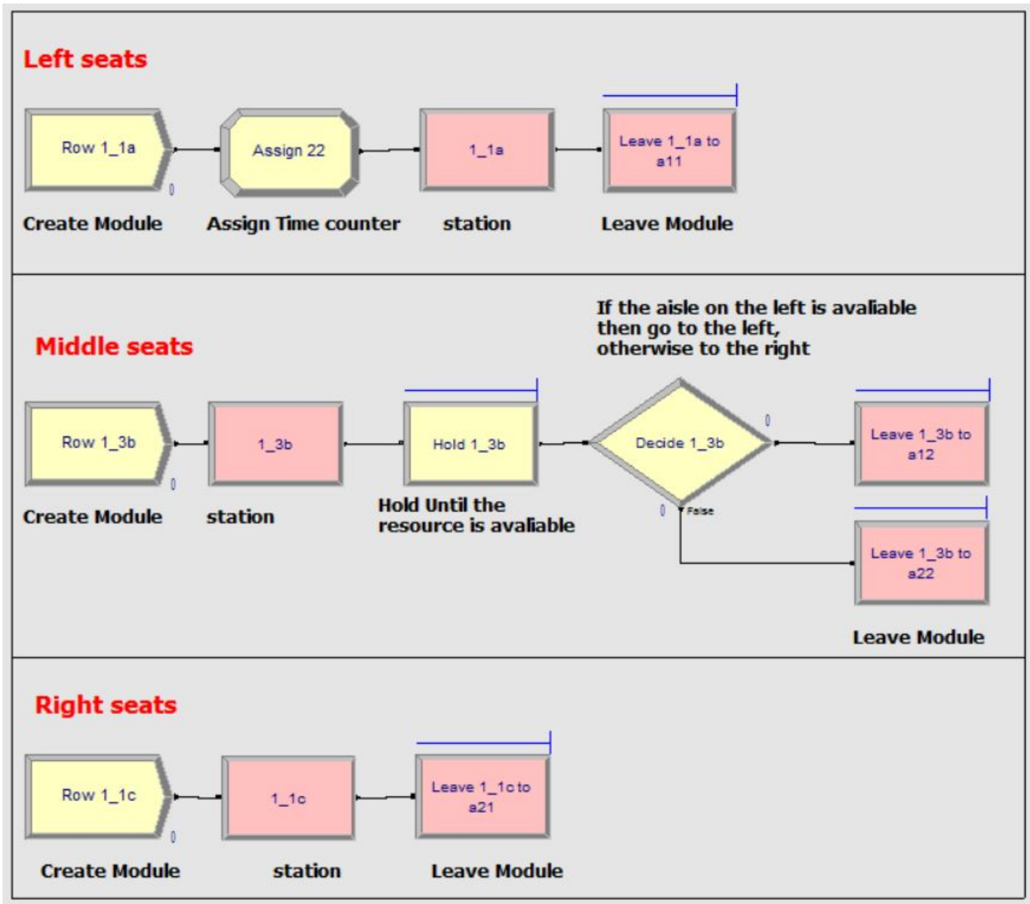


*Figure 7.* Screen Shot of the First Row Passenger Creation to Seat Stations.

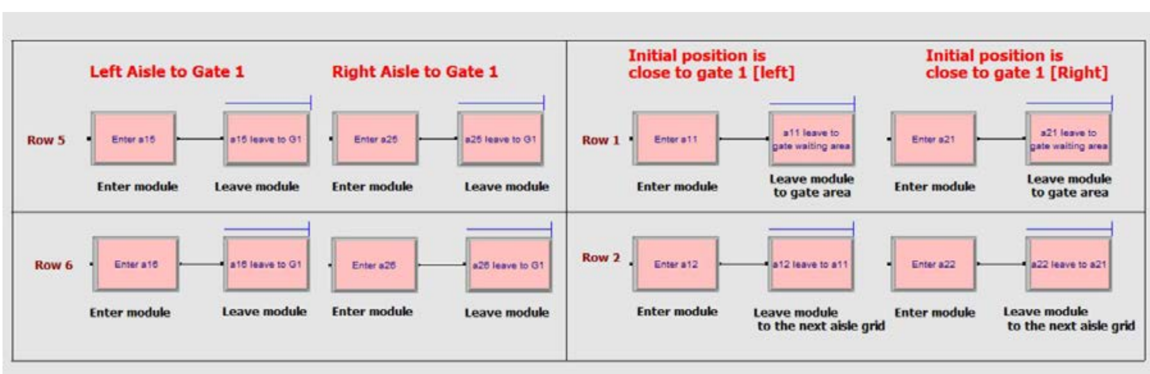


*Figure 8.* Sample Screen Shot of Aisle Transfer.

Figure 9 illustrates the process of waiting for the gate to be available. Gate utility is one of the main constraints to the evacuation efficiency. As an aircraft has a relatively limited space for passengers to move, compared to buildings, the queues are easier to form than in buildings, especially at the gate. How to simulate the gate queue was one of the main sections that required creativity. The researcher had named the open space before the gate as the ‘gate waiting area station’, which functions as the connection between the aisles and the gate. Two aisles were connected to one gate-waiting area, where two queues were served by one gate. The resource that passengers had seized while transferring from the aisle to the gate was the access to enter the gate-waiting area. Passengers who went into the gate area had to release the gate-waiting resource while seizing the slides so that they can complete the route to the gate.

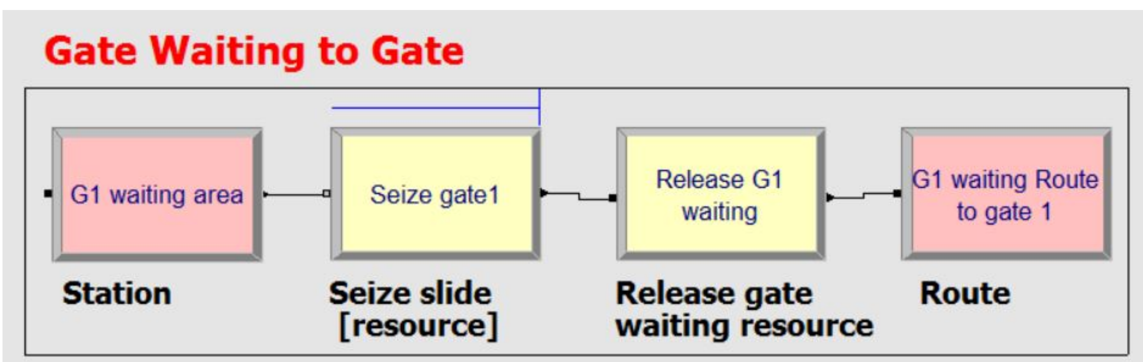


*Figure 9.* The Screen Shot of the Gate Waiting Process.

Figure 10 presents the sliding process once passengers cross the gate.

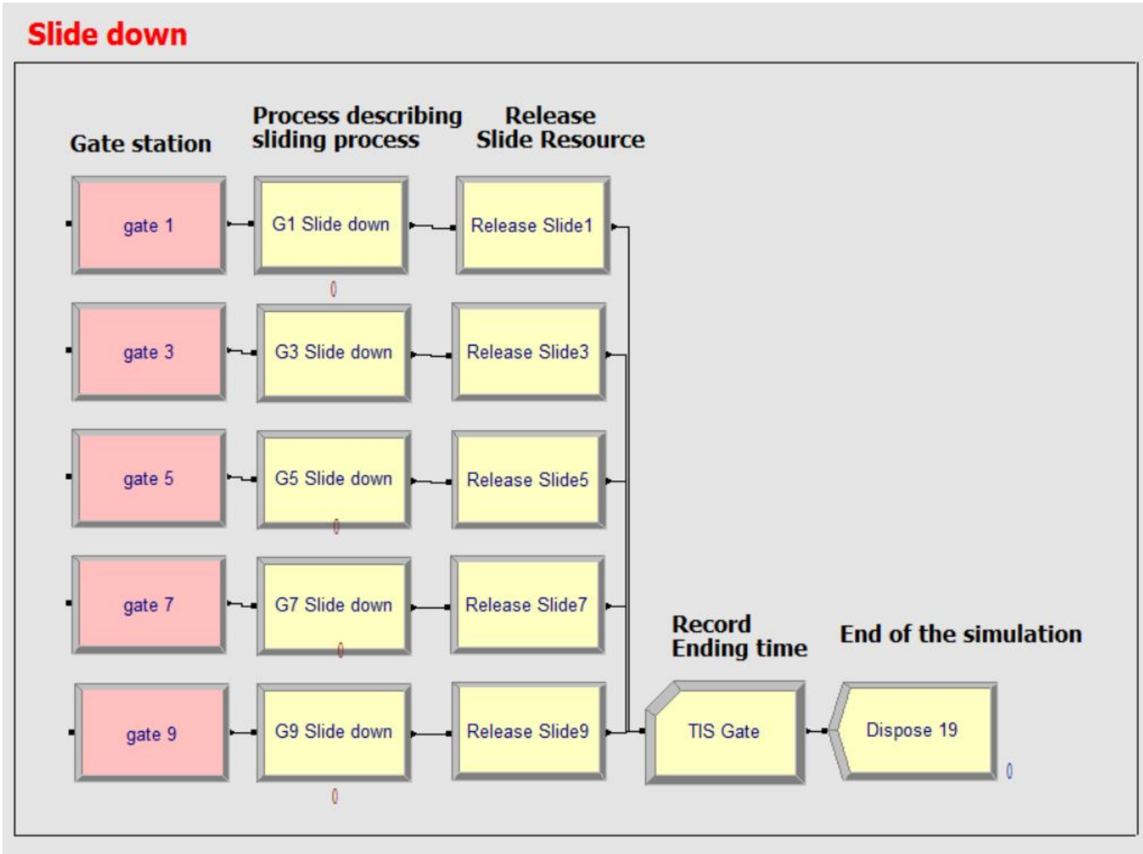


*Figure 10*. Screen Shot of Sliding Down Process.

As with gate-waiting areas and aisles, gates were also defined as stations in the simulation. It was connected with the slides, which were defined as resources. Each gate was connected with a slide that had a capacity of two, which meant that the slide could process two passengers at the same time. Once the passenger reached the ground, the slide resource was released. The last passenger's release resource time was recorded as the simulation end time. The time interval between the first passenger starting and the last passenger ending the simulation was calculated as the simulated total evacuation time.

**Validation Model Results**

The model was run 100 times. The total evacuation time was recorded. The average of the 100 total evacuation time record (EvacuTime) was compared with the actual A380 evacuation time in the 2007 certification evacuation demonstration.

The *t*-test was based on the null hypothesis that the average of the total evacuation time was different from the actual evacuation time. Figure 11 shows the distribution of the total evacuation time in the 100 simulations. Results of the *t* tests are shown in Table 4 and Table 5.

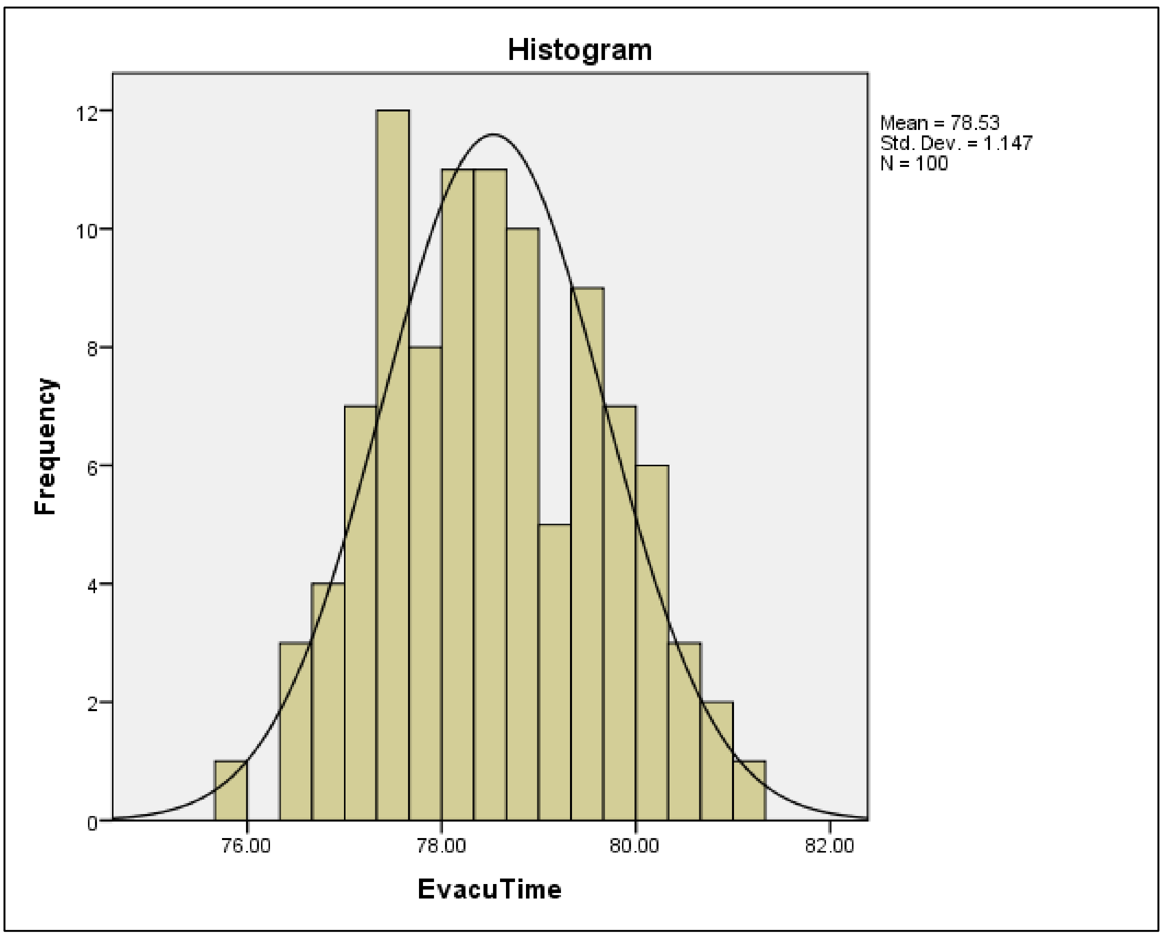


*Figure 11*. Simulated Total Evacuation Time Distribution.

Table 4

*One-Sample Statistics*

| | N | Mean | Std. Deviation | Std. Error Mean |
|---|---|---|---|---|
| EvacuTime | 100 | 78.53 | 1.147 | .115 |

Table 5

*One-Sample Test*

| | Test Value = 78.5 | | | | | |
|---|---|---|---|---|---|---|
| | | | | | 95% Confidence Interval of the Difference | |
| | t | f | Sig. (2-tailed) | Mean Difference | Lower | Upper |
| EvacuTime | .273 | 99 | .786 | .0312 | .20 | .26 |

The total evacuation time for the baseline simulation has a sample mean of 78.53 seconds and *SD* = .12 sec. With alpha set at .05, the one-sample *t*-test revealed that the simulated evacuation times were not statistically significantly different from the actual total evacuation time, which was 78.5 sec, $t(99) = .273$, $p < .001$, $d = .79$ which indicated a large effect size.

**Experiment Design**

The simulation experiment was aimed at testing whether the total evacuation time would be lower if passengers were able to be assigned to an alternative gate. A new variable, difference (*D*), was defined as

$$D = NR(Current\ Queue) - NR(Alternative\ Queue), \qquad (6)$$

where *NR* represents the number of entities in queue. The Difference (*D*) measures the difference of number of people in two adjacent gate queues that possibly drove passengers to switch their gate decision and join another gate queue. The simulation experiment set *D* as zero (0) and five (5) in two sub-experiments.

Figure 12 illustrates the modified section two, which was the passengers' transfer from the seat to the gates.

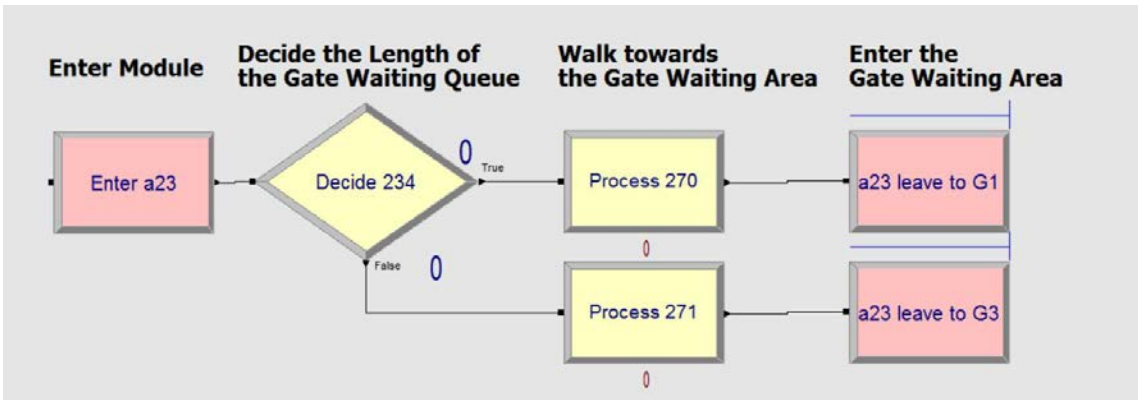


*Figure 12.* Screen Shot of Modified Passenger Transfer from the Aisle to Gate Waiting Area.

After passengers entered the aisle, instead of assigning the distance of the current seat to the gate, the researcher inserted a 'decide' module to choose the gate that has the shortest waiting queue. After a passenger reached the gate-waiting area, the third section also changed to the model shown in Figure 13. Passengers comparing the lengths of the nearby gates queue chose the queue with least number of people in queue to join.

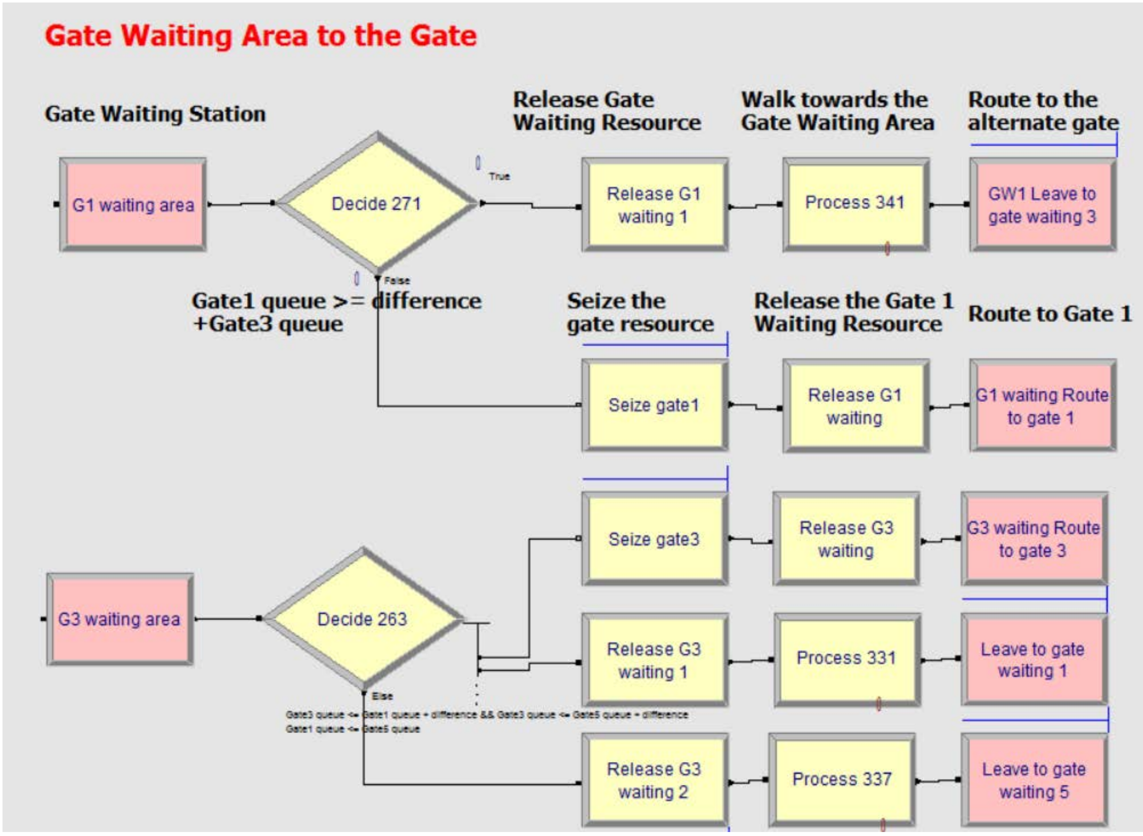


*Figure 13*. Screen Shot of Modified Gate Waiting Area to the Gate.

## Experimentation Results

The experimental simulation was run 100 times for each scenario. The first scenario was when difference (*D*) equaled zero (0), and the second scenario was when the difference (*D*) equaled five (5). A one-way ANOVA was run to evaluate the relationship between total evacuation time and the difference (*D*). The independent variable, the difference (*D*), included not applying the difference, the difference being set to zero, and the difference being set to five. The dependent variable was the total evacuation time. The null hypothesis was that there will be no significant difference in the means of total evacuation time based on the difference value levels.

The alpha value was .05. The outcome had shown significance when different variances of groups were used. The mean of the evacuation experiment group with *D* = 5 (*M* = 85.28, *SD* = 3.77) was the smallest, and the mean of the group without adjustment based on difference (*M* = 96.31, *SD* = 3.32) was smaller than the group with gate alternation with difference (*D)* = 0 (*M* = 123.67, *SD* = 14.48). The null hypothesis was rejected with $F(2,297) = 498.61$, $p < .05$, $\eta^2 = 0.77$. Running the post hoc revealed that the three groups were significantly different from each other.

# Chapter V

# Discussion and Conclusions

## Discussion

**Simulation validation.** The results of the simulation validation revealed that the simulation was very close to the certification evacuation in total simulation time. During simulations, the most important factor that affected the time was the queue at the gates. Ideally as passengers were assigned with the best gate based on the seat locations, the amount of passengers that each gate was supposed to process should have been the same because the size of the gates was the same, which means each passenger should have had the same process time in an ideal situation. Additionally, the sliding speed followed a distribution, which was the major cause of the difference between each iteration, in which case the simulation accuracy also depends on the accuracy of the study in slide efficiency. Not only was there a dependency on the slide efficiency, the randomness of the gate queue also relied on the movement speed of each passenger. The difference between each passenger's moving speed led to the difference of queue length at each gate. To research further on the moving speed’s effects on the queue length, the researcher recorded the length of each gate-waiting queue during the simulation. Figure 14 presents a sample result of this measurement.

In Figure 14, the horizontal axis represents time (in seconds) and the vertical axis represents the number of busy resource units. Each series represents one gate-waiting resource. It is obvious that the resource was fully occupied even before the slide deployed, which proved that the assumption of the passenger’s reaction time to the evacuation signal was not a critical time node in the evacuation event chain. It also provided the information that the gate-waiting queue was starting to be cleared between 50 seconds and 70 sec. However, the gate-waiting queue was not cleared at the same time, which indicated that passengers were not equally distributed to each gate. However, it is obvious that the ideal condition of a simulation is to distribute the passengers to the available gates equally. This result suggests that there is potential to further optimize the passengers' paths to the gates.

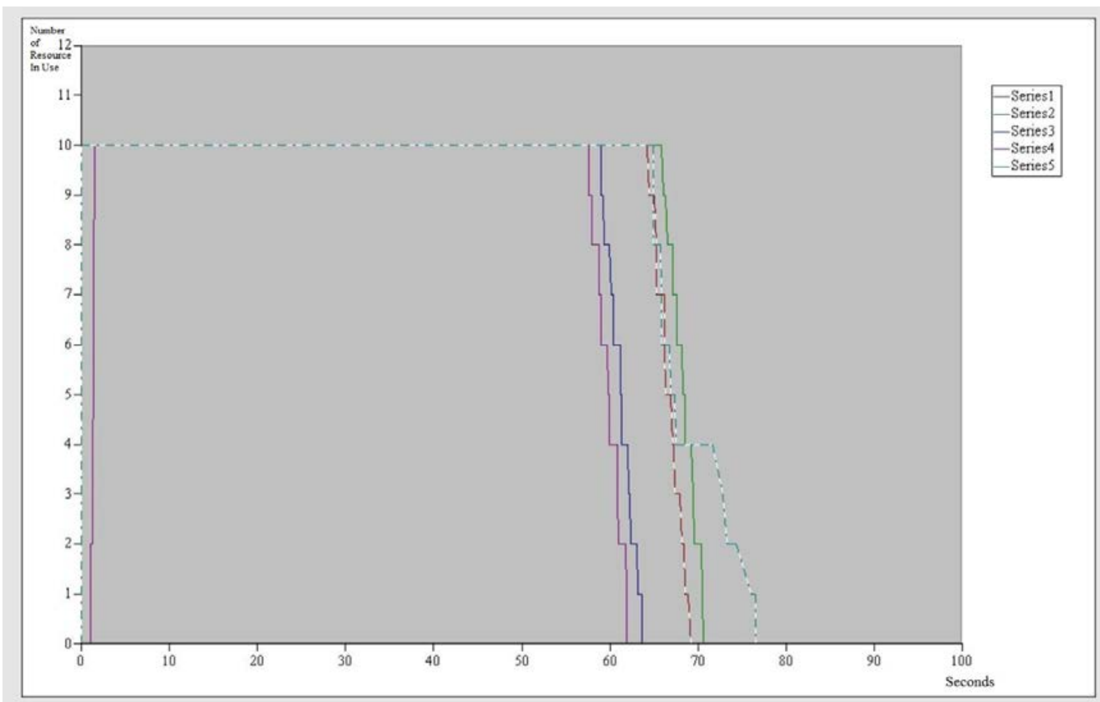


*Figure 14.* Gate Waiting Resource Usage Distribution.

Due to lack of certification evacuation data, this simulation validation was not able to verify the details during the certification evacuation. The evacuation does not have an official report released to the public except for an official video. The actual evacuation time was used for this simulation validation. It is not possible to verify whether the certification evacuation was performed with detailed records saved. Besides this fact, the resources involved in the preparation and organization of the volunteers were unknown to the public. The assumption that passengers were assigned with a gate based on the seat zone has not been verified so far.

Besides the resources from the A380 certification being limited, the amount of research and experiments involving wide-body commercial jets is less than for the narrow-body jets. Additionally, much of the research in narrow-body commercial jets was not able to be applied directly to wide-body jets, mainly because the equipment size and capability were different. For example, the evacuation research of congestion conditions at the gate in narrow-body jets was based on different type of exits (McLean, 2001). The congestion condition as described in research of narrow-body jets was not applicable to wide-body jets such as the A380 since all gates in the latter were type A gates. Hence, developing various studies designed for commercial jets in specific model and sizes is going to be very helpful to improve the accuracy of study in wide-body jet evacuation simulations.

The accuracy of this evacuation simulation also depends on the simulation of human behaviors. In these results, it is hard to validate if the human behaves the same and displays a decision-making process in the simulation that is close to reality. One of the reasons was the limitation of the usage of this software. Due to the limited time available for the study, the researcher could not program the simulation of detailed passenger acceleration and deceleration while moving to the gate. The researcher was limited to providing dynamic programming to adjust the passenger's path decision based on the real-time congestion condition at the gate. All these limitations kept the researcher from developing a more complete model with advanced functions that could improve the accuracy of the simulation.

**Experimentation results**. The experimentation tested when the passengers were given two options while moving towards the gates. Passengers decided which gate they would move towards based on the queue length comparison of two gates. The results of the simulations have suggested that when passengers were given choices to choose the gate to evacuate, switching gates after joining the gate-waiting queue could reduce the total evacuation time. The effect size is 0.77, which also suggests a strong effect of the difference (*D*) on the total evacuation time. It could prove that flight attendants diverting passengers to a less-crowded queue could possibly reduce the total evacuation time, which also appears in the real evacuation demonstration.

The researcher also recorded samples for the gate-waiting resource usage during the simulation. Figure 15 shows the result of a simulation without the module that the passenger can switch to the adjacent gate. This result is more similar to a case where the passengers were assigned gates randomly. The result in Figure 15 showed a longer evacuation time compared to the validation model. It is possible that a number of passengers made the decision at the beginning of the simulation simultaneously before they started to seize the resources, and they are going to seize the resources within a very close time period. With the limited resources available, the passengers who were going to seize the resource successfully were going to be processed by ARENA randomly. However, when they were started to seize the gate-waiting resource, it reached its capacity suddenly. As the gate queue adjustment was not enabled in this version of the simulation, passengers have to stay at the same queue and wait for the slides to be available.

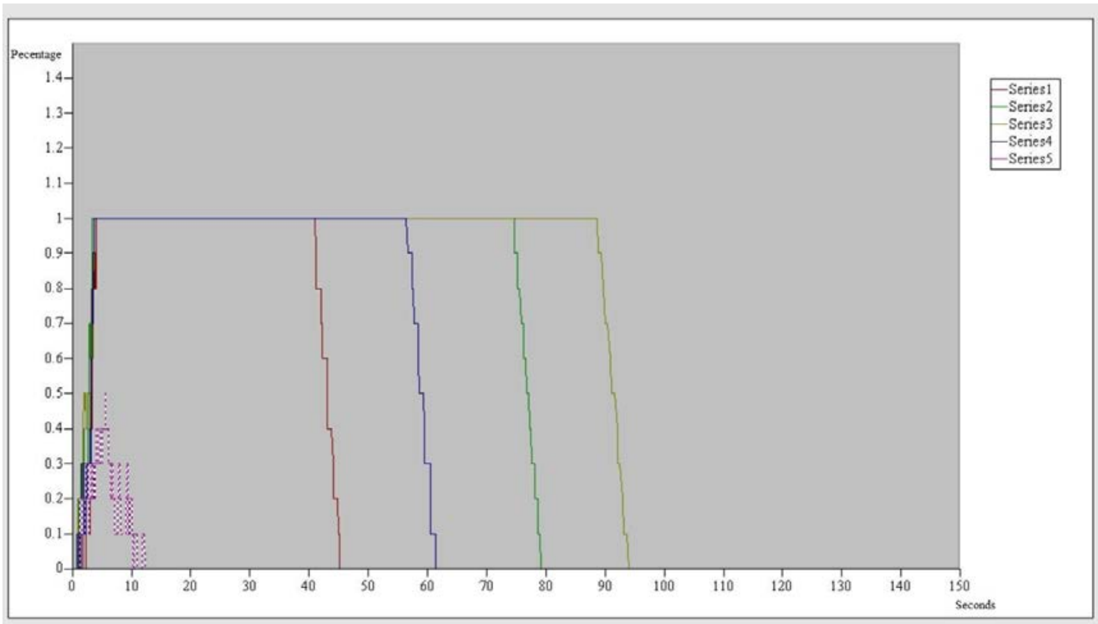


*Figure 15.* Experimental Model No Adjustment Result of Gate Waiting Resource Usage.

In contrast to the baseline simulation, Figure 16 displays the simulation group in which the passengers were able to switch to an alternate gate as long as the alternate gate had fewer passengers in the queue. Instead of speeding up the evacuation process, this change caused passengers to waste time on transferring from one gate to another, which caused a very long evacuation time. It is not a case which is close to reality. However, when the frequency of the passengers transferring between two gates is reduced, the simulation time was reduced dramatically, as illustrated in Figure 17. From the figure it is evident that there are improvements that can reduce the unnecessary transfer between two gates.

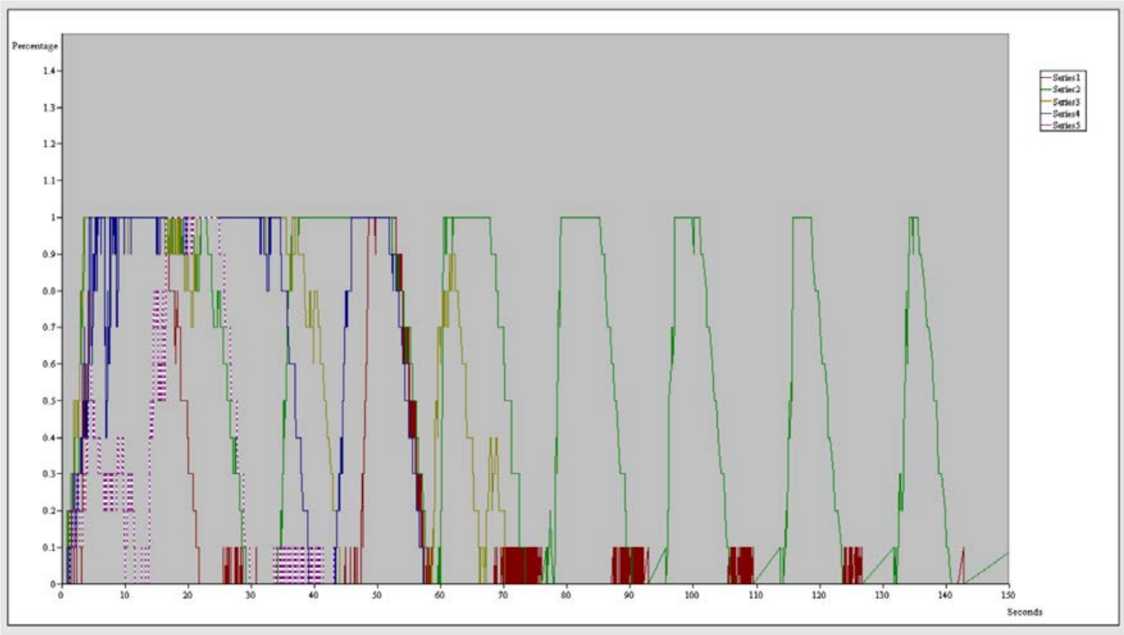


*Figure 16.* Experimental Model Zero Difference Result of Gate Waiting Resource Usage.

When comparing the total evacuation time of the experiments shown by Figure 17 with the validation model, it is obvious that the experimental model consumes less time than the validation model. The reason why the experimental model uses less time is that it ignores the coordination of the passengers in the same aisle moving in opposite directions. As mentioned earlier in this chapter, it is not close to reality when passengers in the same aisle move in different directions while maintaining the same speed. This is another flaw of the experimental model. On the contrary, passengers make compromises during their decision making due to the direction of the most people moving, in reality Galea et al. (2006). The experimental model could be improved by adopting functions such as decision correction and path-planning functions.

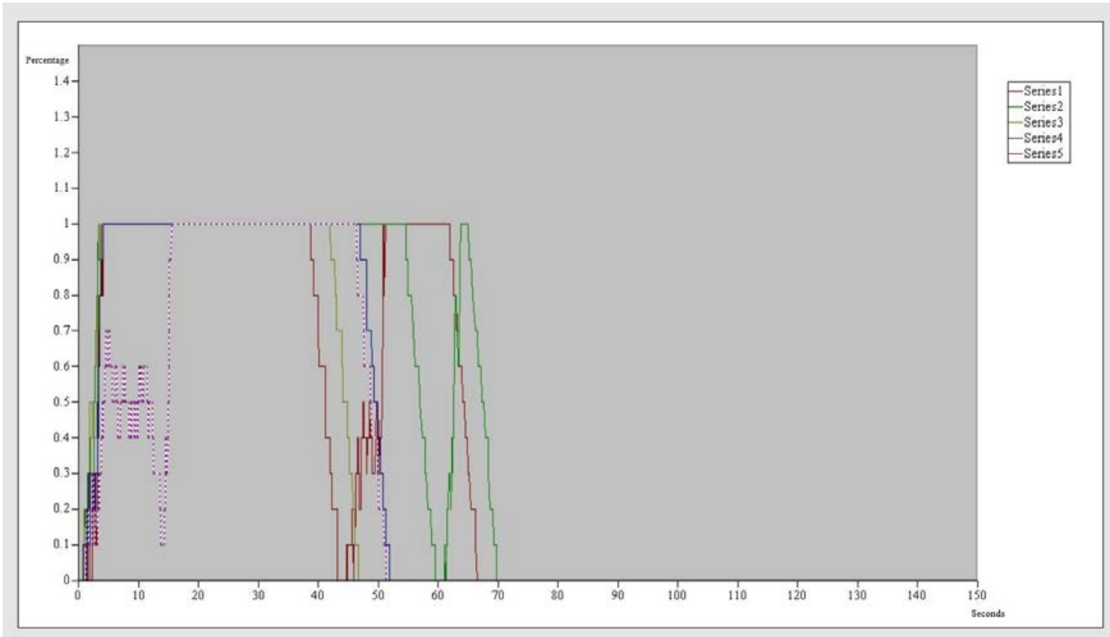


*Figure 17.* Experiment Model Ten Difference Result of Gate Waiting Resource Usage.

Even though the experimental models had factors that reduced their accuracy, all the models were running the same parameters under the same conditions. The results of the comparisons among the sample simulation groups still suggests that the length difference among gate queues affects the total evacuation time with a strong effect.

**Conclusions**

This thesis developed a validated baseline to simulate passengers' evacuation paths from a large aircraft (A380) considering passenger path plan. This baseline connected the aircraft configuration with human movements and pedestrian behaviors. Researchers could use this baseline to develop more advanced interpretations of human behaviors, pathfinding algorithms, and transfer this model to other cabin configurations to simulate the effects of configuration changes on the total evacuation time. It also provides guidance to evacuation seat planning. With this simulation, an airline could analyze the evacuation plan by simulation and thus improve the evacuation seat plan.

This study also had limitations, which were lack of accurate data sources (e.g., evacuation certification results) and relevant research, limitations of the software capability and flexibility, and time constrains.

To take a step further, the next direction would be focusing on taking the experimental results from this study and finalizing the best difference level with the least unnecessary transfer. This requires functions to coordinate the passenger's movement in the aisle and the gate-waiting area. For better accuracy in simulating the passenger's decision, it is also necessary to develop dynamic programs to calculate and predict the resource availability and queue length.

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# Appendix A

Table A1

*Cabin Distance input*

| Front | Back |
|---|---|
| 27.5 | 385 |
| 55 | 357.5 |
| 82.5 | 330 |
| 110 | 302.5 |
| 137.5 | 275 |
| 165 | 247.5 |
| 192.5 | 220 |
| 220 | 192.5 |
| 247.5 | 165 |
| 275 | 137.5 |
| 302.5 | 110 |
| 330 | 82.5 |
| 357.5 | 55 |
| 385 | 27.5 |
| 27.5 | 742.5 |
| 55 | 715 |
| 82.5 | 687.5 |
| 110 | 660 |
| 137.5 | 632.5 |
| 165 | 605 |
| 192.5 | 577.5 |
| 220 | 550 |

| | |
|---|---|
| 247.5 | 522.5 |
| 275 | 495 |
| 302.5 | 467.5 |
| 330 | 440 |
| 357.5 | 412.5 |
| 385 | 385 |
| 412.5 | 357.5 |
| 440 | 330 |
| 467.5 | 302.5 |
| 495 | 275 |
| 522.5 | 247.5 |
| 550 | 220 |
| 577.5 | 192.5 |
| 605 | 165 |
| 632.5 | 137.5 |
| 660 | 110 |
| 687.5 | 82.5 |
| 715 | 55 |
| 742.5 | 27.5 |
| 27.5 | 522.5 |
| 55 | 495 |
| 82.5 | 467.5 |
| 110 | 440 |

| | |
|---|---|
| 137.5 | 412.5 |
| 165 | 385 |
| 192.5 | 357.5 |
| 220 | 330 |
| 247.5 | 302.5 |
| 275 | 275 |
| 302.5 | 247.5 |
| 330 | 220 |
| 357.5 | 192.5 |
| 385 | 165 |
| 412.5 | 137.5 |
| 440 | 110 |
| 467.5 | 82.5 |
| 495 | 55 |
| 522.5 | 27.5 |
| 27.5 | 440 |
| 55 | 412.5 |
| 82.5 | 385 |
| 110 | 357.5 |
| 137.5 | 330 |
| 165 | 302.5 |
| 192.5 | 275 |
| 220 | 247.5 |

| | |
|---|---|
| 247.5 | 220 |
| 275 | 192.5 |
| 302.5 | 165 |
| 330 | 137.5 |
| 357.5 | 110 |
| 385 | 82.5 |
| 412.5 | 55 |
| 440 | 27.5 |

# Appendix B

Appendix B Baseline Full Validation Result Screen Print

Figure B1. Full validation simulation results.