OPTIMIZING PASSENGER MOVEMENTS THROUGH AIRPORT TERMINALS

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Degree of Doctor of Philosophy

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Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering

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DECLARATION OF THE CANDIDATE & SUPERVISOR

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Abstract

Minimizing walking distances, waiting times and delays at critical service centers such as ticket counters, immigration, baggage claim and security checks and optimal spacing of other services or frictions such as shops, washrooms, food cabins and internet accesses within a terminal could contribute much towards passenger comfort. Knowledge regarding arrival and waiting patterns of passengers at mandatory service centers and other services helps model passenger flow through the terminal. This knowledge depends on airport location, the operating strategy of the terminal and the frictions placed in between mandatory service centers.

Existing simulation and analytical models for walking distances and waiting times are for specific use at one airport or one part of the airport only. They cannot be used elsewhere. Therefore, finding out flexible mathematical models for common use at all airport terminals is the main purpose of this research. The research concentrates on two main objectives, of which, the first is to develop mathematical models to optimize passenger flow through different servers and other facilities minimizing total waiting time at all mandatory service centers. The other objective is to evaluate the different terminal configurations and find the optimum terminal configuration with the least waiting time for passengers.

Data related to waiting time and service time at different mandatory service centers helped find placements for suitable frictions to be located before the mandatory service centers. Criteria developed for the purpose were means and variances of waiting times at mandatory service centers with and without frictions. If the mean waiting time at a mandatory service center without friction is less than that at a mandatory service center with friction, a friction before the mandatory service center gets rejected. Queuing theory helped fix suitable frictions before the mandatory service centers. These analytical solutions were verified using the Monte Carlo simulation using queuing theory.

Secondly, proper frictions to be placed before the gates in terminal configurations to minimize passenger delays were realized with the pier type terminal configuration, where the three pier type terminal configurations with frictions was considered for optimal terminal configuration to minimize passenger delays. The optimum terminal configuration to minimize passenger delays appeared to be the terminal with three piers holding an unequal number of gates. The developed models include the common features of all airport terminals and are capable of describing any terminal configuration.

- *Keywords:* Waiting time, Walking distance, Frictions, Terminal configuration, Simulation

DEDICATION

To,

My ever loving…

Parents,

Husband

&

Sister!!

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LIST OF ABBREVIATIONS

BIA - Bandaranaike International Airport

FIFO – First in – First out

CDF – Cumulative Density Function

AD – Anderson Darling

ANOVA – Analysis of Variance

1. INTRODUCTION

Walking around and waiting at airport terminals often frustrate people anxious to travel by air. Airport planners and designers try various means to minimize the discomfort of walking and waiting at different service centers such as check-in counters, ticketing counters, immigration counters and baggage stations. This chapter is about a solution to the problem with the creation of a flexible simulation model. The flexible simulation model attempts to optimize passenger movements and minimize walking distances, making it less of a hassle for a passenger. The motive for the creation is to ease passenger discomfort and make air travel more enjoyable for travelers.

1.1. Background

Air travel is a very important means of transportation, especially long-distance travel. It opens up a larger field of exploration for many people, allowing modern citizens to travel significantly more than their predecessors. However, when using air travel, passengers sometimes have to pass through complicated airport terminals and negotiate with busy corridors rushing through crowded luggage during busy hours, or up and down the stairs to the gates or boarding. Most importantly, they reach their gate by a certain deadline or miss their flights, resulting in the loss of time and money. This is very complicated when connecting flights are complicated. Passengers must arrive at another gate within a short period of time, and the airport may not be completely familiar with them.

According to available literature, some research has been done about simulation and analytical models for passenger movements in airport terminals (Tosic,1992, De Neufville & Odoni, 2003, Brunetta & Romanin-Jacur, 1999, Gatersleben & Van Der Wej, 1999, Joustra & Van Dijk, 2001). This knowledge on simulation models for passenger and baggage flow in an airport terminal contributes significant importance to motivate the creation of a simulation models using queuing theory adaptable to various airport configurations. The new model takes into account the time behavior of passenger and baggage flows, the capacity of the elements, and delays in airport terminals. The entire process of terminal processing depends on the individual behavior of the passenger. A valid and calibrated agent-based model allows detailed evaluation of system performance and determines optimization capabilities. The verification of this model was compared with the previous findings on the average behavior of future specific airports. At the same time, the proposed model provides interesting dynamic results on the movement of passengers in the system.

Currently most of the passengers do not like the airport environment for different causes. The risk of attempts on life does not in anyway, appear to reduce the numbers of travelers travelling by air. In addition, the emergence of a large number of passengers at the airport may even trigger a terrorist attack from the airport. In order to cope with this concern, strict safety checks must be carried out on passengers, luggage and cargo. The time spent on this rigorous inspection will affect all movements within the terminal, so passengers need to extend their stay at the terminal before boarding. Passengers must move between the arriving and departing terminals. As a result, a large number of transit passengers affected the hub terminal. These changes help to increase the number of passengers asking for the same facilities at ticket counters, boarding stations, security inspections and baggage conveyors during the peak hours of the day.

The passenger flow in the terminal can be subdivided into three sub-processes:

- Departure;
- Arrival;
- Transfer.

The departure process begins when passengers enter the terminal and finish when they leave the structure. The arrival process begins when the passenger lands at the airport and completes when they leave the terminal. The transfer process includes the operations of the departure and arrival processes: passengers participate in the procedures (safety controls) related to the departure process and some procedures related to the arrival process.

Perhaps, a generalized and flexible simulation model can be used to analyze the general problems seen at airport terminals under different operating scenarios. This study focuses on a flexible simulation model of an airport terminal that can be easily modified for use in any air terminal.

1.2. Literature Review

There are some simulation models adaptable to various airport configurations to estimate the time behavior of passenger and baggage flows for one airport, but cannot be extended to other ones (Brunetta & Romanin-Jacur, 1999, Gatersleben & Van Der Wej, 1999, Joustra & Van Dijk, 2001). Some have analyzed the system performance for average wait time of passengers to reach the gate area, but it can have some disadvantages due to model flexibility (Curcio et al., 2006): a different model to satisfy specific requests could not be applied to solve problems of an airport terminal. There are also studies about the airport security, to study baggage-screening strategies using artificial intelligence techniques (Candalino et al., 2004, Babu et al., 2006, Olapiriyakul & Das, 2007, Yfantis, 1997). Studies on simulation frameworks to determine optimal gate assignments under possible delay are also carried out (Yen et al., 2001). Furthermore, simulation frameworks for ticket counters are available. Their work seeks to minimize passenger travel distance. Some studies are carried out to find the aspects of passenger terminal planning under some factors of number of gates (Barros & Wirasinghe, 1997, Bandara, 1990, Bandara & Wirasinghe, 1989), apron layout, passenger processing and lounges (Wirasinghe & Shehata, 1993, Chevallier & Gamper, 1996, Barros & Wirasinghe, 1997) and check-in/baggage handling/security/curbs (Chevallier & Gamper, 1996). There are some analytical works with simulation to determine the terminal configuration with passenger walking distances (Wirasinghe & Vandebona, 1988, Wirasinghe et al., 1987, Bandara, 1990, Bandara & Wirasinghe, 1992), baggage handling distances (Robuste & Daganzo, 1991, Wirasinghe et al., 1987), aircraft taxiing distances and configuration and sizing of the ramp services (De Barros, 2001). Most of the simulation models seem not flexible because all models are developed for one part of the airport or a specific airport and it cannot be extended to the other part of the airport or another airport.

1.3. Research Problem

Optimizing passenger movements through an airport terminal is one of the important activities to be attained in the efficient functioning of an airport. Minimizing walking distances, waiting times and delays at critical service centers within terminal such as ticket counters, immigration, baggage claim and security checks and optimal spacing of other services such as shops, washrooms, food cabins and internet accesses could improve passenger throughput. Arrival and waiting patterns of passengers at different service centers could vary depending on the airport location and the operating strategy of the terminal. Further, these patterns could depend on the frictions due to other services such as shops, washrooms, etc. that are placed in between mandatory service centers. Knowledge on arrival and waiting patterns at the mandatory service centers will help modeling the passenger flow through a terminal.

The developed analytical and simulation models to consider all walking distances and waiting time between mandatory service centers and the placement of the optional service centers are lacking and a model to determine the terminal configuration considering all above factors is not found yet. Therefore, finding out the flexible mathematical models which can be applied to other parts of the airport or other airports is indeed a daunting but very important task.

Existing models can be applied for one airport or one part of the airport and they cannot be applied for other airports or other parts of the airport. The suggested model includes the common features of all airport terminals and is capable of describing any terminal configuration as it can be applied in any part of any airport by changing the parameters of models.

1.4. Research Objectives

Most people prefer to travel by air to cut down on time spent for travelling. Time, to a busy business magnate or any other top executive in a similar capacity means much more than the extra amounts required to pay for an air ticket. Therefore, their preference is to travel by air. But this does not necessarily mean they welcome walking around or waiting for long at airport terminals. As such, this research is about a solution to make air travel more comfortable for passengers at airport terminals. It is done under two main objectives and they both aim to make air travel more inviting and pleasurable. The two objectives are as follows.

1) Develop mathematical models for:

- Optimizing passenger flows through different servers/facilities.
- Minimizing the total waiting time at all mandatory service centers.

2) Evaluate the different terminal configurations and find out the optimum terminal configuration which has the least waiting time for passengers.

1.5. Research Methodology

There have been attempts by researchers to find solutions to the problems of walking around dragging bag and baggage and waiting for long in queues, air passengers encounter at airport terminals. Available literature on such attempts provided the much needed background help necessary for this research. Guided by this information, the following procedure is followed for the research.

- A Literature review on the analysis of overall flow movement of passengers and baggage through airport terminals and terminal configuration and planning will be done.
- Identification of factors such as mean waiting time, variance of waiting time, mean service time, variance of service time at mandatory service centers, mean waiting time, variance of waiting time, mean service time, variance of service time at gates etc. to minimize waiting time and walking distance as well as to evaluate the different terminals will be done.
- The methods for optimizing waiting time, service time, queue length from individual research for ticket counters, check-in gates, baggage stations, security checks and etc. will be found.

- A methodology to develop a mathematical model to study the overall passenger/baggage flow through an airport terminal will be found.
- A methodology to develop a mathematical model to evaluate the different pier type terminal configurations will be found.
- Optimum terminal configuration which has the least waiting time will be found.
- All models will be verified through Monte Carlo simulations.

1.6. Data Collection

Data collection for the research is explained in detail in the chapters to follow. The procedure to be followed is as shown below.

- All mandatory terminal service centers in arrival and departure procedure at Bandaranaike International Airport (BIA) will be observed.
    - Checking counters
    - Ticket counters
    - Immigration counters
    - Baggage stations
    - Security checks

- The data on waiting time, service time and queue length at each terminal center on rush hours (night shift) and non-rush hours (day shift) of rush days and non-rush days will be collected.

- The data on waiting time of different frictions at BIA will be collected.
    - Washrooms
    - Different type of shops
    - Food cabins
    - Internet access

Chapter 3 is about data collection and the methodology used for the purpose. Details regarding data collection gets discussed therein.

1.7. Data Analysis

The procedure for data analysis is as follows.

- Passenger arrival and waiting patterns at terminal service centers for arrival and departure procedure will be found.

- The distributions of waiting time and service time at the mandatory service centers with means and the variances will be found.

- The sample models to optimize the waiting time will be identified.

- The distributions of waiting time of frictions will be stimulated.

- The distributions of mandatory service centers with placing frictions will be found.

- The Conditions for placing the frictions before the mandatory service centers will be identified.
  - Hypothesis testing
  - Welch's t – test
  - F test
  - ANOVA test
  - Levene's test
- The most suitable friction/frictions which can be located before the mandatory service centers in arrival and departure procedures will be found by applying Hypothesis Testing for Means and variances.

- By using queuing theory, the above mentioned proper frictions will be fixed before the mandatory service centers in arrival and departure procedures to minimize passenger delays at mandatory service centers.

- Proper frictions which can be placed before the gates in terminal configurations will be found using queuing theory.

- Few pier type terminal configurations were compared and optimal terminal configuration will be found.

- It will be verified through Monte Carlo simulations.

1.8. Summary

Guided by available literature on existing simulation models to suit airport terminals, an attempt is made to derive a model acceptable for use in any section of any airport terminal. Previous attempts appear to suit only one part of the airport or one airport and they cannot be extended to the other parts of the airport or other airports. However, the suggested model from this research could be modified to suit any airport terminal by changing the values of the parameters in the model to suit the relevant airport.

2. LITERATURE REVIEW

2.1. Introduction

This Chapter concentrates on available literature related to optimization of airport terminal usage. It highlights several attempts towards models aimed at minimizing walking distances and reducing waiting hours at various landside counters in airport terminals. What has been done so far, reveal both strengths as well as weaknesses. Although these models have contributed to ease congestion and cut down on waiting times, to some extent, especially for a specific situation, it is found that these models cannot be easily modified to handle any terminal geometry. In other words, available models are not flexible enough for use across different types and sizes of airport terminals. Therefore, an extensive literature review was made to identify requirements for a flexible model that could fit in to any airport terminal configurations. Some highlights from the review areas related to waiting time and walking distances at airport terminals as revealed in available literature, are described below.

2.2. Passengers' waiting time at airport terminals

Literature reveals information about the existence of simulation models that have contributed to ease congestion and cut down on waiting times to some extent, especially for a specific situation. However, these models cannot be easily modified to handle any terminal geometry. In other words, available models are not flexible enough for use across different types and sizes of airport terminals. Therefore, there appears to be a need for a more flexible, user friendly simulation model towards minimizing passenger waiting times and walking distances at airport terminals.

Available literature regarding some analytical models proposed for check-in counters are based on Queuing Theory Models. Most of the other processing facilities in airport operations were also formed by Queuing theory models. Lee is credited with an initial application of M/M/n queuing systems to check-in procedures (Lee, 1966) whereas

Newell introduced a deterministic model with graphical analysis which used cumulative diagrams by considering number of passengers and aircraft departure time as variables (Newell, 1971).

They are also the basis for most other processing facilities in airport operations. Lee credited the initial application of the M / M / n queuing system (Lee, 1966), and Newell initially proposed a deterministic model with graphical analysis using a cumulative figure of the number of passengers and aircraft departure time. It is apparent that this model heavily influenced further developments. Accordingly, more applications of models with several types of facilities for service to individuals provided by a "processor" of some kind came to be developed. Piper (1974) is an example for such a practical application. On the whole, it is a graphical model. Total waiting time of passengers could be calculated by the above method. It is considered that the cumulative arrival function at the check in counter and service rate of each period is known. Tosic extended this simulation model which is able to use more than one flights. Monte Carlo method has been utilized for new simulation. (Tosic et al., 1983; Lalik & Choy, 2018). Since it is a simulation model it needs detailed data to provide quite realistic information on the behavior of check-in counters. Literature is abundant with proposals for both stochastic and deterministic queuing models. Examples of application of the stochastic models are in (Rallis, 1958, 1963, 1967). M/D/n queuing systems were applied for analysis at the Copenhagen terminal building.

Several models have been proposed for gate allocation. Edwards and Newell investigated a random model of the use of the gate (Edwards & Newell, 1969). Steuart (1974) proposed a different stochastic model. Some models consider the type of aircraft and the walking distance of passengers. They are based on threshold allocation of first in, first out (FIFO) rules. (Hamzawi, 1986; Le et al., 1978). Babic et al. (1984) proposed a method of reducing passenger walking distance by appropriately allocating airplanes to gates every day, taking into account the passenger flow on that particular day. Mangoubi and Mathaisel (1985) included transfer passengers in their development of flight-to-gate distribution issues. Both methods assume that a specific configuration is given so that the walking distance is known and fixed, and therefore these models are appropriate at the tactical level. Wirasinghe et al. (1987) proposed a long-term planning model. As for gate position requirements, Bandara and Wirasinghe (1989) proposed a method for determining gate position requirements based on a deterministic model.

In the literature, mathematical queuing and simulation models have been developed to predict the arrival of baggage claim areas (falling passengers and baggage) and to predict possible future conditions. The deterministic queuing model was developed to correlate the arrival distribution of passengers (and the arrival distribution of baggage) with the number of passenger baggage at a given time on the carousel (Barbo, 1967; Horonjeff, 1969). Browne et al. (1970) studied the baggage claim area of the New York JFK airport. Their goal is to use the inventory type model to calculate the expected maximum inventory of passengers and baggage. Newell (1971) analyzed a baggage retrieval device and proposed two queuing systems, one for passengers waiting for the package and another for packages waiting for their owners. The problem is to estimate the number of passengers waiting for their luggage in front of these devices. Tosic et al. (1983) proposed a Monte Carlo-type simulation model to evaluate the elements of the baggage field. In this model, each passenger and his/her luggage are handled separately.

The identification and classification of landside elements mainly involves the special report of the Transport Research Council (TRB, 1987). Tosic (1992) made a brilliant review of the airport passenger model. Odoni and De Neufville (1992) emphasized the methodological issues in the design of passenger terminals. The passenger control area is usually reserved for passengers. Passengers use these holding areas to move around while waiting for a flight to take off and arrive. In the passenger control area, there are usually lobbies, gate lounges, transit passenger lounges, baggage claim areas, arrival areas, areas reserved for ancillary facilities, etc. The number of waiting passengers depends on the number of aircraft serving areas and their functional characteristics, including capacity and loading factors. Other factors are also related to the number of passengers waiting at the terminal. The arrival time of passengers at the airport, the degree to which the passengers are accompanied by family members or friends, and the length of time from the start of boarding to departure are all factors. The time spent in a specific area is only a small part of the passenger's stay. This is the core of determining the number of people in a given area at the same time.

The “slack” time passengers spend in different parts of the terminal building comprise dwell time, which, later gets allocated among the terminal holding areas. The load or the number of passengers occupying an area at a time results in fraction from the slack time spent in that area as related to both departing and transit passengers. However, for arriving passengers the idea of slack time is negligible as their anxiety is to leave the airport as soon as possible. Stochastic model to estimate the dwell time is offered in (Odoni & De Neufville, 1992).

How a passenger regards the service quality and service conditions of a functional component or a set of functional components determines the service level. The standard metrics for using component service levels are: waiting time, processing time, walking time, congestion level and availability of passenger comfort (Brunetta et al., 1999). Other features are also relevant. The number of passengers with a behavioral characteristic reflects the strength of a functional component or a group of components to successfully complete the task assigned to it. Factors such as when the passenger arrives at the airport, age, purpose of travel, payment, baggage carried or checked, and whether the passenger has an airline ticket and boarding pass are often important.

However, simulation models of more recent times appear to show two main shortcomings. For example, Gatersleben and Van Der Wej (1999) and Joustra and Van Dijk (2001) model fits one airport only. Their models are incapable of being used in other airports or their models suit one particular area of the airport only such as check-in counters only, immigration counters only, etc. whereas other models from developers like (Brunetta & Romanin-Jacur, 1999, 2001) get wide flexibility. In other words, they are able to describe different airports in detail with limited adjustments. Yet, they are not user friendly because they cannot be applied to other airports. Inevitably, the absence of a satisfactory tactical simulation model of landside operations such as waiting time was instrumental towards the creation of a new flexible simulation model to estimate the time behavior of passenger and baggage flows, the capacity and the delays in a generic airport terminal.

The new model for land operations must be adapted to different airport configurations in order to estimate the time behavior of passenger and baggage flows, the capacity of the elements and delays at the terminals of the generic airport. Brunetta and Romanin-Jacur (1999) brought forward a model that promised the dynamical results about baggage and passenger movements in the system. This model was less expensive and showed more promise towards tackling inherent problems of the old simulation models of landside operations related to huge data requirements and deficiency of flexibility. The rise in the modeling of airport terminals over the period of 1977 - 1992 is noteworthy as has been shown by De Neufville and Odoni (2003) and Tosic (1992). Furthermore, these new models have displayed improvements with regard to detail and reliability and are seen to be more user-friendly. Therefore, they are used as management decision support tools or design tools in terminal development projects.

Baggage handling is a crucial activity at an airport terminal as baggage handling directly affects airport performance. Baggage handling, badly managed may cause serious passenger dissatisfaction as well as airline disappointment, because damaged, delayed and lost luggage also damage the airline's reputation (Cavada et al., 2017). Sometimes the problems could be serious and serious problems might arise especially during peak periods when a large amount of baggage needs to be contemporarily processed, well over the capabilities of system capacity in use (Johnstone et al., 2015).

The dramatic increase in air passenger traffic and the resultant increase in luggage throughput (Danesi et al., 2017), affects Baggage Handling Systems. They may often be overloaded, demanding infrastructure expansion of terminal facilities at heavy costs to airlines (Malandri et al., 2018). It is a crucial activity to transfer baggage handling. Mishandling can lead to considerable costs for airports (SITA, 2017). However, available literature reveals only a few works directs towards a solution to address this problem. Barth (2012) modeled transfer baggage handling system at Frankfurt Airport taking into account uncertainty in input data (Barth & Pisinger, 2012). Several recent works tackled the problem of assigning incoming baggage to carousels (Delonge, 2014). For example, Frey et al. (2017) propose a mathematical model to optimize inbound baggage handling process and tested it at Munich's Franz and Josef Strauss Airport, showing a reduction of 11% for passengers' waiting times and of 38% of baggage peaks at the carousel.

With regard to modern baggage handling systems, the understanding is that they are complex and difficult to model. They require elaborate tools of analysis to be managed correctly (Johnstone et al., 2010; Le et al., 2012; Nahavandi et al., 2009; Johnstone et al., 2015; Cavada, 2017). Lazzaroni (2015) also employed simulation to create a detailed model of passenger flows at various terminal points (check-in, security screening, departure lounges and baggage claim) at Vancouver International Airport.

Further, the elderly population of the modern day appears to be more travel inclined. This interest drives for more transportation assistance service at airports for travelers with special needs as both the popularity of air transportation and the size of the elderly population continue to increase (IATA, 2015; Department of Transport, 2015; Darcy & Ravinder, 2012). Transportation assistance services are available at most airports around the world (Chang & Chen, 2012a, 2012b; Konert & Ephraimson, 2008; Reinhardt et al.,2013) in the form of wheelchairs and electric carts (golf carts) that are used to transport special-needs passengers (elderly, sick, unaccompanied minors and disabled) to and from airplanes and terminals.

Brunetta et al. (2001) proposed two models to evaluate an airport terminal taking into consideration their merits. The proposed simulation model AIRLAB is an action discrete event simulation model. Decisions made by passengers arriving in the airport terminal, leaving and transiting, and their baggage movements are considered as purposes. The proposed analysis model SLAM includes a modular network, one for each terminal device. The goal of both models is to analyze any particular facility, including estimating the capacity of the facility, the number of passengers/baggage per hour and the level of service associated with it, compared to internationally accepted standards, for example, in the IATA manual (IATA, 1982).

The behavioral model is easy to implement and simply represents the way in which passengers make decisions while moving within the terminal (eg, choosing a ticket office, spending time in the lounge, selecting a specific route, etc.). The same abstraction mechanism was used to model decision-making and policies for specific facilities within the terminal building through appropriate "facility selectors". For the physical relationship between the terminal layout and the facility, the user can define the location of each facility and the surface area of each terminal. The decision to choose a check-in counter or the security gate they must pass is usually made when they need it, and past decisions may affect future actions. In addition, certain types of behavior, such as delaying stay in the lounge, can be easily expressed.

However, it cannot be pre-determined when and where the requests would come. The passengers may request assistance at any time before or during their progress through the airport (Air Canada, 2016; WestJet, 2016) and each air carrier sets its own definition of acceptable customer service levels and practices (Personal communication, 2004, 2016; The Airport, 2016). The proposed centralized system was expected to provide uniform service levels, increase efficiency and use fewer resources. With ever-increasing passenger volumes, a more efficient transport assistance system will become increasingly important in future years (Begen et al., 2018).

Drawing on passenger demand data, available from flight schedules, a simulation model was developed in Arena (Rockwell, 2015). Once passenger demand was generated, a logical network guided the passengers through their respective airport processes. The data collected from the past historical pattern was analyzed to develop a predictive model using decision tree to forecast the passenger load based on certain criteria (Laik et al., 2014; Laik, 2017). Furthermore, there are some research works to find the correlation between air passenger transport and gross domestic product. To estimate the future growth rates of air passenger transport, information is used to formulate correlating the number of air trips per inhabitant with the gross domestic product (Profillidis& Botzoris, 2015; Tan, 2014). There is also some research towards analyzing the passenger network changes in Hong Kong International Airport (HKIA) and forecasting passenger throughput (Tsui & Fung, 2016; Tsui et al., 2014).

Nagoya University used Arena (Appeltetal, 2007; Joustra & Van, 2001; Verbraeck & Valentin, 2002) to simulate passengers leaving the port from Japan's international Kansai Airport to reduce the number of passengers in the queue due to the long waiting time at the peak and not to avoid delays, they lost their flights (Takakuwa & Oyama, 2003). A preliminary analysis of the waiting time for passengers showed that the total time spent by passengers at the airport was as follows: 48% moved within the terminal in one place, 25% were waiting, and only 4% were in the process of accepting formalities, boarding, etc. In addition, it has been found that the time spent on the waiting queue at the boarding station exceeds 80% of the total time before boarding. This output highlights that check in should be seen as a major bottleneck.

Express check in counters could minimize the numbers of passengers missing flights. Such express check in counters can also be used for security checks on economy-class passengers and big families. Work on this project proceeds with more accurate results and enhanced applications currently under development. The research presented by Carlton University School of Mathematics and Statistics (Ontario, Canada) is very interesting. It shows that a linear programming model minimizes the total working hours for check-in and ensures that satisfactory customer service levels have been developed (Cao et al., 2003). The results of this alternative approach reveal significant performance improvements because it provides a shorter queue length, reduced latency, and increased percentage of customer satisfaction.

Security screening is usually a single (or multiple if multiple channels) service counter facility. It can easily be modeled using a queuing model. However, delays with regard to waiting in queues affect security screening level of service in the passenger security screening area (Branker, 2003; Correia & Wirasinghe, 2004). Meanwhile, Candalino et al. (2004) dealt with baggage screening strategies using artificial intelligence techniques. Babu et al. (2006) considered the security problem at a US airport. Olapiriyakul and Das (2007) analyzed the problems related to the design and analysis of security screening and inspection system whereas Yfantis (1997) introduced a new baggage-tracking system to improve airport security. Curcio et al. (2006) used effects from different scenarios characterized by different resources allocation and availability in their proposal to develop a simulation model to investigate system behavior. Their interests centered round: passengers' arrival time at the airport before the flight, check-in points available and security control lines available as parameters to find the passengers' average waiting time for reaching the gate area as system performance.

Guizzi et al. (2009) described the analysis of passenger flow from the entrance to the boarding in the terminal airport. This study developed a simulation model based on discrete event theory, which helps to predict delays and reasonably manage reasonable check-in and security checkpoints in airport terminal buildings. The proposed model tested in the realities of southern Italy (Capodichino-Naples International Airport) has a modular architecture and interfaces to quickly and easily model and provide capabilities to adapt to various airport configurations and operating characteristics.

Despite this, airport passengers' experience may be demanding and time consuming. Parking, boarding, security checks and checking can all cause delays. The less time customers spend on the system, the higher the satisfaction. However, the airport is obliged to hold the standards that passengers must meet. These criteria include proper identification, limited baggage weights, and security procedures for security checkpoints (Manataki & Zografos, 2010). Passengers acknowledged the need to improve safety, but delayed boarding and canceled flights. Waiting too long has caused dissatisfaction among passengers.

Wang (2012) proposed a method for developing a simulation model. It shows the passenger flow under different types of facility modes to optimize the simulation model's resources and estimate the benefits that may be brought about by system changes. The proposed simulation model is used to describe the MIA. The simulation results were positively checked compared to the non-optimized available conditions. The results show that the average queue length and queuing time are reduced by about 10%-20%.

2.3. Passengers' walking distance at airport terminals

It has been realized that technical assessments made earlier regarding the relative merits of airport passenger buildings were more of a descriptive nature and were not clear enough (De Neufville, 1976; Parsons & ATA, 1973) unlike the later architectural presentations (Blow, 1991; Hart, 1985). Technical studies that followed calculated the expected walking distances associated with various configurations without using other means of transport like buses to carry passengers to aircraft. It would also not be smart in many situations due to an increase in the minimum time taken to connect between the aircraft and exits or transfer aircraft.

Other factors too contributed towards the final selection. The final choice of a terminal design depended on additional factors such as: available land area, construction cost and baggage handling, many of which are discussed by De Neufville (1976), Hart (1985) and USDOT (1973). It is possible to consider a terminal as a set of nodes (e.g. ticketing area) and links (e.g. concourses). Available theoretical literature is on problems about queuing at nodes. But reference in the research is to an analysis of passenger walking distances along the links where the major level of service factor affected by the terminal geometry is seen as the passenger walking distance. The research was aware of the planned number of aircraft gate positions, the spacing between piers and the dimensions of the terminal block. Gates were all uniform. They were on each side of the piers and space between was uniform. The number of piers of equal length and the gates in each pier, that will minimize the mean mandatory walking distance of originating, terminating and transferring passengers within the terminal, is to be determined for each major pier—finger configuration: centralized -radial, centralized—standard and semi—centralized.

Many authors have discussed the determination of the number of gate positions. Among them are Horonjeff (1975), Steuart (1974) and Wirasinghe et al. (1985). Identical gates mean access to all types of aircraft. Uniform spacing of gates meant that all aircraft can use the same in/out procedure. Standard spacing for gates and piers are given by USDOT (1973). The dimensions of the terminal block were dependent on the number of levels, queuing at ticketing booths, baggage carousel sizes and locations, retail space etc. Hart (1985) suggested space calculation procedures for terminals.

Previously completed studies seem to ignore the effect of transfer traffic on the distribution of walking distance. However, the transfer of traffic is now considered to be a major factor in determining the walking distance of airport passenger terminals. De Neufville and Rusconi-Clerici (1978) and De Neufville (1995) discussed its importance to the deployment of airport terminals, and De Neufville (1996) proposed a preliminary calculation of the selected configuration. Another factor left out of previous research is the failure to examine the effect on walking distances of intelligent management of the gate assignments, a very important factor for consideration with the operations of transfer hubs. Airlines were concerned with the assurance that bags transfer along with passengers so that the "tail-to-tail" distances between aircraft with significant amount of transferring traffic could be brought down. It is vital to have some form of simulation for an in depth study of implications with different configurations. The determination of the performance of these buildings can only be compared with the movement of the assumed smooth probability distribution only in the actual situation of the actual load. This observation produced five simulation analyses, as described by McKelvey (1989) and Mumayiz (1991, 1998).

Going by an assumed description of traffic from the landside entrance to the airport terminal and the gates the later designs defined optimal shapes (Bandara, 1990; Bandara & Wirasinghe, 1992; Robuste, 1991; Robuste & Daganzo, 1991; Wirasinghe et al., 1987). All in all, the later body of work concluded that finger pier configurations were more suitable towards minimizing walking distances, especially where the number of piers was uneven and had a longer central pier for close access to the central entrance to an airport terminal.

Detailed simulations were not of much use in deciding on suitable configurations to be built. Yet, they have been of value to designers in sizing spaces after a determination of the configuration of the building. They were even helpful to managers to operate the completed building. Detailed simulations are also too expensive, require much time for 'build and run' purposes and are rather impractical towards decisions regarding which is best out of many to suit a given situation. Planning purposes require fairly simple, inexpensive and rapid forms of simulation. Analyzing the consequences of alternative configurations was proposed by Odoni and De Neufville (1992) and Svrcek (1992, 1994). However, it was not easy to implement this proposal in general practice at that time as planners were more or less unfamiliar with efficient computational mechanisms.

Wirasinghe et al. (1987) developed a simulation model to generate walking distances of individual passengers in an airport terminal. Considerations were regarding the movement of the three types of passengers: originating, terminating and transferring and were simulated for the three types of terminal configurations. In here some certain configurations have lower mean walking distances compared to others (e.g. semi centralized compared to centralized standard). The analytical and simulation models presented here could be extended to terminals with different airline operating concepts.

Meanwhile in a papers by Wirasinghe and Vandebona (1988), Wirasinghe and Bandara (1992), the focus appeared to be on walking distances. Proceeding, they opined that walking distances are a major consideration to determine the geometry of an airport terminal configuration. They were also of the view that selection, in initial planning, should be from among several configurations. With regard to a given number of gates, G, in a pier—finger type terminal, an analytical modeling of walking distances was done. The results revealed that a geometry that minimizes the mean walking distance of passengers (originating, terminating and transferring) exists for the three major pier—finger configurations. The optimum number of piers was nearly proportional to square root of number of gates for two configurations. Simulation generates the probability distributions of the walking distance of a passenger. With an acceptable maximum walking distance, the mean excess walking distance is suggested to be a suitable parameter to select from among several configurations with optimal geometries.

De Neufville et al. (2002) made a new analysis to determine the optimal configuration of the passenger terminal for the airport passengers. A simple spreadsheet is used to calculate the possible configuration of the airport terminal in any configuration and traffic mode. Trying to seriously consider the task of geometry and intelligent management of the gate. The move was directed against the need to develop and apply detailed probabilistic simulation programs. Accordingly, it may be possible for people with little knowledge of computers to easily develop their own version of the method given, based on the information provided. It would be helpful for architects and planners to use this easily with their evaluations of alternative configurations at the initial design stage.

This analysis specifically mentions two important practical facts, such as the importance of transit passengers and how airlines can intelligently locate aircraft at the gates in order to minimize the walking distance between connected flights. In addition, this analysis divides the problem of finding the distance traveled by travelers into two parts: distance or passenger difficulty, and the number of passengers crossing the gate. It revealed the impact of different configurations of airport passenger terminals on passengers. Although older materials are about measuring and minimizing maximum walking distance, recent reports have highlighted the average distance traveled by passengers. Observations are based on the uniform traffic distribution of different gates.

However, two important facts appeared to have been left out of those observations. They were about: the role of transfer passengers and the fact that airlines and airports minimize walking distances operationally. Meanwhile, it must also be noted that some configurations driven towards minimizing walking distances, like the X-shaped concourses at Pittsburgh, Hong Kong/Chep Lap Kok and Kuala Lumpur/Sepang, apparently, are seen as inferior to linear mid-field concourses similar to those in Denver or Atlanta.

2.4. Gate Position Estimation

The objectives of the research relate to the placement of suitable frictions before the mandatory centers in a proper manner to suit arrival and departure procedures. The effort is intended to minimize passenger delays with the whole procedure. Obviously, this effort is meant to minimize passenger delays from the entrance to boarding gates in an airport terminal. To achieve the purpose of minimizing passenger delay, gate assignment needs to be considered. It will also be necessary to find the optimal terminal layout by placing suitable frictions before the gates so that passengers' waiting time can be minimized.

Knowler (1964), for his part, recommends the use of the Erlang loss formula developed for telephone traffic. In the loss formula the arrival process is again assumed to be homogeneous Poisson. The loss formula has the proven ability to determine the probability of finding a set of gate positions of known size completely occupied is not dependent on the distribution of the gate occupancy time. Neither does the model consider an assumption of gate occupancy times to be exponentially distributed (empirical evidence indicates the distribution is not exponential), yet, the arrival process is still assumed to be Poisson. The loss system presumes that a flight arriving at the air terminal to find all gate positions full is unlikely to be attended to. Therefore, the flights form a queue to be served when a gate position is available. This queue will influence the probability of finding all the gate positions full. Both proposed models – deterministic and stochastic fail to recognize an underlying schedule exists. This is seen as a major drawback for both models.

The authors of a Russian (Mogilevskiy, 1965) and an American (Horonjeff, 1962) textbook on air terminal planning have proposed similar deterministic models to estimate airport gate position requirements whereas Rallis (1967) recommended the use of a queuing model. The queuing model assumes times and arrival procedures for aircraft to be similar. Poisson and the gate occupancy times are exponentially distributed. However, several factors contribute towards limiting the application of this well-known stochastic model to gate positions. Such factors relate to an unlikely balance with the system with different arrival patterns seen at an air terminal. Besides, the arrival process may not change properly with a schedule that contains bank operations. This would make the number of arrivals in non-overlapping time intervals to be statistically independent, perhaps, due to the influence of a schedule where the position assumption could lead to the belief that the variance in the number of arrivals in a time interval heavily increases in a situation where the interval becomes large. However, with a guided schedule this may not be the case.

Probability distributions formed the basis for McKenzie et al. (1974). They used the probability distributions of the preceding two parameters and simulation techniques for the purpose of studying the effect of adding one extra gate to the existing ones. Meanwhile, Steuart (1974) brought up a stochastic model. It was based on empirical information relating actual flight arrivals and departures to the schedule, to study the influence of “bank operation" on the gate requirement. He came up with the idea of a possibility for a uniform schedule to generate the minimum requirement and that banking tended to increase the number of gates. The number of gate positions required at an airport, or the number of flights accommodated at a given number of gate positions can easily be determined by the efficient use of a given number of gate positions. It is a fact that the airlines' schedule and the airport's operating policies reflect on the efficient use of the gate positions. Accordingly, a simple stochastic model was developed based on empirical information describing the behavior of flights relative to their schedule. A study was undertaken to determine the influence of a common scheduling practice of bank operation on the requirements for gate positions. The results were convincing that a completely uniform schedule generates the minimum requirement. A procedure is presented to estimate the number of gate positions required at an airport (Steuart, 1974).

Most studies already done regarding aircraft gate positions fall into two categories: planning and operational. Planning studies are concerned with the estimation of gate location requirements for a given demand (Horonjeff, 1975; Steuart, 1974). The operational study is about the allocation of the aircraft to the existing gate location. Limits and preferences at the gate location and optimization of aircraft delays and passenger travel can be addressed by the latter model requiring large amounts of information (Babic et al., 1984; Hamzawi & Mangano, 1986).

In the planning of a terminal, the gate position requirement happens to be an essential requirement where, the passenger terminal and apron design are dependent on it. Moreover, it influences the configuration of the terminal building and the layout of the apron area reflecting on passenger walking distances and aircraft taxi lengths. Airline schedules, airport operating policy, the type of gates available, and the efficiency, with which each gate position is used, determine the number of gate positions required to accommodate a given number of flights (Bandara & Wirasinghe, 1988). There are many studies that have been made to determine the correct gat position requirement, gate utilization and where gates should actually be. Horonjeff (1975) brought up the deterministic model. This model could compute the required number of gate positions taking into consideration the design volume for arrivals and departures in aircraft per hour, mean gate occupancy time in hours and a utilization factor. In planning new terminal buildings, it is essential to get at the number of aircraft gate positions. This is crucial. Cost of construction and maintenance of gate positions also needs to consider costs associated with delaying aircraft. They need to be balanced appropriately. Hence, a determination regarding the number of aircraft gate positions is essential input towards airport terminal configuration (Wirasinghe et al., 1987).

It is apparent that deterministic methods are used to plan aircraft gate requirement for a planned airport terminal. This does not, however, leave out other relevant parameters such as aircraft arrival gat, gate occupancy time and aircraft separation at a gate which, were identified as random quantities. Another factor, validity of utilization depends on the available number of gates together with the schedule in use at the airport where the calculation gets done. The mean and variance of aircraft arrival rate, the time of gate occupancy and the separation time of the aircrafts would help to estimate the mean and variance of the gate requirement. If used, some probability requirements are likely to arise. In this case, the required design gate needs to be selected to meet a given reliability, which in turn is defined as the probability that there are sufficient gates to ensure that the aircraft seeks a gate with zero delay. This method is suitable for the policies of common and better gate and can also be used to estimate the required number of remote aircraft stands for use in overflow situations. The required number of gates to meet a given reliability was estimated based on the aircraft arrival rate at the gates, the gate occupancy time and the aircraft separation (buffer) time (Bandara & Wirasinghe, 1988).

A strategy schedule of great importance towards generation of aircraft occupation of gate positions at airports was available. To accommodate the flights in a schedule with banking operations requires an account of the minimum number of gate positions necessary for the purpose. It also requires information regarding the ability of flights to stick to their schedule. With the model presented, it would be possible to find out the likely reflection on gate position requirements of different scheduling practices. However, such a study requires enough data to support the study the probability of a flight occupying a gate given in the schedule and to study the correlation between flights. If the operation proves to be irregular due to bad weather or other conditions Steuart (1969) has shown that the variance in the number of flights presents will increase. It is especially important with irregular schedules. As such an account of gate position requirements using the above formulation needs to be minimal. Therefore, the required number of additional gates will depend on the character of the irregular days, mostly with the number of cancelled flights, and operating procedures of gate positions on irregular days. With their study, Wirasinghe and Bandara (1992) highlighted an analysis for future benefits to ascertain the required number of gate positions to minimize gate expenses and total deterministic delay cost.

2.5. Terminal Configuration Models

The existing literature on this topic is mainly concerned with situations where different terminal configurations will apply (De Neufville 1976; Hart 1985; Horonjeff 1975; Correia, 2000). In some cases, the walking distance within the terminal has been used for comparison (De Neufville & Rusconi-Clerici 1978). De Neufville and Rusconi-Clerici (1978) studied digitally comparing the eight gates at each terminal in the four-pier terminal and a 32 gates with linear arrival terminal. The geometry of the four piers with eight gates is not necessarily optimal. Wirasinghe et al. (1985) analyzed the walking distance characteristics of some linear (single- concourse, dual- concourse, closed-loop) and equal length pier finger terminals relative to different passenger groups. Subsequently, Wirasinghe et al. (1987) analyzed the optimal geometry of an equilength pier finger terminals based on the number of gates in the terminal and the scores of different passenger groups. The results show that the optimum number of piers is almost proportional to the square root of the number of gates. Wirasinghe et al. (1987) first proposed an analytical method to determine the optimal geometry of the terminal. The configuration chosen for their analysis was parallel equal-length pier-fingers. Their goal was to determine the number of piers that could minimize passenger walking distance on a given number of aircraft gates of the same type.

What came next was an attempt to embed realistic descriptions of the complex ways airlines and airport managers operate the passenger buildings. A point to be noted was to assign aircraft with heavy transfer traffic to the closest possible gate. This is in contrast to the following studies: either simply calculating the maximum and average distance implicit in various layouts (Anglo Japan Airport Alliance, 1992; Parsons, 19 73) or using a formula to describe the aircraft distribution at the gate and optimization of the number and shape of finger piers and midfield concourses (Bandara & Wirasinghe, 1988, 1992; Wirasinghe et al., 1987; Wirasinghe & Bandara, 1992). These studies discuss the elements of the inspection: the configuration of airport passenger terminals; their size; and the corresponding transportation technologies, including passengers and luggage. The comparative baggage transport technologies are DCV, Telecar and tugs and carts, which are also assumed to be supplementary automation systems. What is more important here is the originating traffic in comparison to terminating traffic. Baggage is critical with originating traffic unlike heavy terminating traffic. The reason for originating traffic to be more critical is due to flight close-out times that depend largely upon the delivery times of the last departing bag**.** There is dynamic change with the congestion that often happens in airports. As a result, the queuing process rarely reaches a steady state (Odoni & De Neufville, 1992). A suitable method for dealing with these transients is the approximate fluid dynamics method (Newell, 1971). It has been used to specify the size of departure lounges (Horonjeff & Paullin, 1969) and the ticket counter (De Neufville & Grillot, 1982).

Wirasinghe and Vandebona (1988) analyzed the distribution of walking distances at pier-finger terminal with only two piers. They set the same walking distance as Wirasinghe et al. (1987). In addition, it is not based on the average walking distance to determine the optimal geometry of the terminal, but rather the distribution of walking distances for service level analysis. For this reason, they made the assumption that in the long run, the arrival and departure of passengers are evenly distributed on all the gates. The assessment of the walking distribution allows one to select the best configuration based on the proportion of passengers who are forced to walk over walking distance. Bandara (1990) and Bandara and Wirasinghe (1992) evaluated the average walking distance of several terminal configurations and determined the optimal terminal geometry for each terminal. Wirasinghe and Bandara (1992) took a slightly different approach to remote parallel pier terminals with Automated People Movers (APM). They modeled the negative effects of the passenger movement as a disadvantage of walking and riding on APM. Given the number of gates, the spacing between gates, and the spacing between piers, the model will seek the number of piers and the length of each pier to minimize the overall failure of passenger movement. It was proven that the optimal terminal geometry depends on the ratio of walking and APM cycling.

Robuste (1991) analyzed and compared several airport terminal configurations (single-concourse, closed-loop and multiple pier) based on the average total walking distance. Here, all transit passengers are considered hub transfers. He showed that the parallel pier should be shorter and farther from the terminal block. The continuous approximation is used to simulate the walking distance between piers and within piers. Wirasinghe (1988) has shown that for arriving-departing and non-hub transferring passengers, the average walking distance in the terminal is not different when calculated on the basis of continuous approximation. In addition, for hub transfers, when there are at least five gates per terminal, the percentage error associated with continuous approximation is negligible. However, he showed that continuous approximation is not suitable for simulating the average walking distance between piers because the score error is high and equal to the inverse of the number of piers in the terminal. It is assumed that the gates are located on each side of the pier at a known uniform spacing. The size of the terminal block can be done independently of the terminal geometry (Hart, 1985; Horonjeff, 1975).

Robuste (1991) analyzed several centralized hub terminal layouts, determined the walking distance of each hub, and used it to select the optimal terminal geometry. Robuste and Daganzo (1991) extended this work to include baggage handling. They used simulated annealing to determine the optimal geometry of parallel pier-finger terminals, as studied by Wirasinghe et al. (1987), except they allow different pier lengths. They also showed that the optimum geometry of the parallel piers has a longer pier near the terminal block. All of the above works have a common drawback: They assume that passengers are evenly distributed along the length of the terminal. This is often incorrect.

To select a suitable terminal geometry for a pier-type airport terminal, they use a quantitative methodology. To give the geometry for the minimization of passenger walking distance, the geometry to minimize passenger walking distance is based on the fraction of arriving-departing and transferring (hub and non-hub) passengers, gate spacing and spacing between piers in a situation where the size of a terminal in terms of aircraft gates is given. The selection criterion to suit the major level of service factor, affecting terminal geometry, is passenger walking distance. Passenger walking within piers is modeled with a continuum approximation. Discrete methods are used to model walking distances between piers. The terminal geometry, the number of piers, and the number of gates in each pier (or pier lengths), minimize the mean mandatory walking distance of arriving, departing, and transferring passengers within the terminal are used for major pier-finger configurations. However, other factors too contribute to the determination of a terminal design. Such additional factors are: availability of land area, construction cost, and the cost of baggage transport, aircraft taxiing, and automated people movement (Bandara & Wirasinghe, 1992).

The terminal is about the general physical and functional shapes of the terminal building. The literature on airport planning (Ashford & Wright, 1992; De Neufville, 1976; FAA, 1988; Hart, 1985; Horonjeff & McKelvey, 1994; IATA, 1995) divides existing terminal concepts into four categories:such as linear, pier, satellite and transporter. These terminal concepts can be combined. A good example is the pier-satellite concept. Almost all existing airports are suitable for one or more of these categories.

There are similarities between the pier and the linear terminal. The plane was parked on both sides of the pier. Passenger handling is mainly at the pier. This allows more efficient use of terminal resources. The piers provide a low walking distance for central transport and are very easy to expand, but non-transferred passengers have a long walking distance. Calgary, Vancouver and Baltimore/Washington airports are examples of pier terminals.

Simulation and analysis models can be found in the literature on the choice of terminal configuration, divided into two categories. The system simulation model is about establishing a mathematical model to represent the terminal entities and their relationships. Operational parameters can be deterministic - either expressed as mean - or random - modeled using a probability distribution function. If random variables are involved, these variables are assigned to randomly generated values using the given distribution, so each concept requires several runs. The simulation model is very useful for detailed analysis of specific scenarios.

However, they only allow modelers to compare modelling concepts because no optimal solution is given. However, the main drawback of simulation models is that they require a complete understanding of the operating rules and parameter behavior that are not available in the early stages of terminal planning. Examples of recent terminal simulation models are found in Brunetta et al. (1999), Jim and Chang (1998) Mumayiz (1990), Setti and Hutchinson (1994), and an overview of terminal simulation models developed in the 1970s and 1980s.

De Neufville (1996), in a study, has identified the optimal configurations for complexes of large airport passenger buildings, including their internal transport systems for passengers and bags. Queuing theory and decision analysis are used to define the performance, over multiple criteria and in a range of situations, of combinations of configurations and technologies. It is indeed an issue to select a design for an airport passenger building and the technology to be used since both passengers and their baggage have to keep moving. A wrong design or one that does not suit these movement requirements can be quite costly. Perhaps, the design may have been proper for a start but thoughts for the future, apparently, had been ignored. As transfer traffic increased, the terminals buildings were found to be inadequate. This increase in transfer traffic is witnessed at many major international hubs.

Recent research looks at the problem in different ways. Richard De Neufville highlighted three ways for investigations as appearing in recent research. First, is the need for the analyses to include the latest most important innovation in airport planning, use of internal transport systems such as people movers and destination coded baggage systems. The focus in previous research was on buildings. Multiple criteria, including passenger waiting times and aircraft taxi times, over a broad range of loads, come next. The purpose behind the thinking was to select designs that could appeal to different needs of different users to make good performance a certainty as traffic levels increase. This approach contrasted sharply with the traditional focus to minimize walking distance for travelers.

2.6. Summary

The absence of a user-friendly and more flexible model for use with landside operations such as waiting time and walking distance at air terminals arose since those available for use failed in this regard. Moreover, the better ones failed to meet with requirements of other airport terminals and so, could not be used elsewhere. Their usability remained confined to some airport terminals only. The literature review above highlights previous attempts by different researchers towards making this vision a reality. Their studies, over the years, contributed much towards the attempted new model for use with landside operations. The new model concentrates on different airport configurations towards estimating the time behavior of passenger and baggage flows, the elements' capacities and the delays in a generic airport terminal.

3. DATA COLLECTION AND METHODOLOGY

3.1. Introduction

This Chapter highlights the theory and the methodology followed to develop the model using collected data about passenger arrival patterns. Accordingly, both waiting time and service time, passengers are compelled to go through at mandatory service centers for security checks, check-in counters, immigration counters, baggage claims, etc. received consideration. However, waiting times for passengers are not limited to mandatory services alone. Passengers also have to endure waiting times to use available optional services. Waiting times at these optional services such as wash rooms, shops, food cabins, etc. are also required information for model development. Therefore, towards the development of the model under consideration, passengers' waiting time and service time at both mandatory service centers and at optional services with both arrival and departure procedures at the Bandaranaike International Airport (BIA), Sri Lanka, were collected. Data were collected from other sources too. To suit certain situations, data were collected from literature. Nevertheless, waiting time and service time values can change from airport to airport. The outcome from the sampled data of waiting time and service time at mandatory service centers and optional services was extensively looked at, in detail, for justification with procedures to come. This chapter is mainly about details regarding data collection and the types of testing and analyses done.

Basically the operations inside the airport are considered as two procedures: arrival and departure. Two main mandatory service centers in the arrival procedure are baggage stations and immigration counters and three main service centers in the departure procedure comprise security checks, check-in counters and immigration counters. They all have been considered as mandatory service centers for this research. In addition, some optional services such as wash rooms, food cabins, internet accesses, varies types of shops, etc., have been considered as frictions in this research because these optional services can be placed between mandatory service centers.

The first objective of the research was to develop the mathematical models to minimize the total waiting time and walking distance inside the terminal building i.e. passage through check-in counters, immigration counters, security clearance at gates, baggage stations and customs checks etc. The second objective was to evaluate the different terminal configurations and find out the optimum terminal configuration layout with respect to placement of other service centers. Towards consideration of these objectives, the mean and variance of passengers’ waiting time, mean and variance of passengers’ service time, mean and variance of waiting time at frictions, total arrival rate and the number of service counters in each service center, are necessary. For use with this research, the data regarding passengers’ service time and waiting time at each mandatory service center in arrival and departure procedures and passengers’ waiting time at frictions and the number of service counters in each service center were collected from the Bandaranaike International Airport (BIA).

To collect the data in an effective and efficient way, the aircraft schedule of BIA came in useful. This schedule helped with proper collection of data without wasting much time. According to the aircraft schedule of each month, data collected time slots were selected as rush hours (night shift) and non-rush hours (day shift) on rush days (Thursday, Saturday and Sunday) and non-rush days (Monday, Tuesday, Wednesday and Friday). Then the data of passengers’ waiting time and service time at security checks, check-in counters, immigration counters and baggage claims were collected in relation to the above surroundings. Furthermore, the data of passengers' service time at frictions or optional services such as wash rooms, shops, food cabins, internet access, etc., were also collected.

3.2. Data Collection

The procedure for the collection of data is described hereafter. A passenger joins the queue of a particular service center. As each passenger started receiving services from a counter, the service time was set to 'start' and it 'stopped' after the particular passenger left that counter. When there was a queue, to measure service time, 10 or 20 passengers were selected at a time and it was assumed that all of them got into the queue at the same time. Because of this assumption, it was easy to calculate waiting time of a passenger since waiting time is calculated from the service time to be discussed later. By measuring the time, a passenger receives for service, the service time for individual passengers in the selected group was measured. When people go in and come out, the time difference between going in and coming out was measured and it was considered as service time for an individual passenger making use of that counter.

The waiting time of the passenger in a particular counter was calculated in the manner shown in Table 3.1 to follow. It explains the way to calculate waiting time by getting at the cumulative service time. The waiting time of the passenger in mandatory service centers of check-in counters, ticketing counters and immigration counters depend on the numbers of counters at these service centers. For baggage station this will depend on the size of the belt and the total number of passengers in the belt. It was assumed that waiting time of the first passenger in a particular service center is zero.

It is necessary to have the total arrival rate and the number of service counters to calculate the service time and the waiting time at a counter. If we have to do this for a given terminal we may require a relationship between waiting time and (arrival rate and number of service counters) service time will be very much the same (with a given mean and variance) as the procedures will not change frequently.

Table 3. 1: Service and waiting times at Immigration counter in departure procedure

Service Time (Seconds)	Waiting Time (Seconds)
S_1	$W_1 = 0$
S_2	$W_2 = S_1$
.	.
S_i	$W_i = S_1 + S_2 + .. + S_{i-1}$
.	.
.	.
S_n	$W_n = S_1 + S_2 + S_3 + S_4 + \ldots + S_{n-1}$

S_i = Service time of i^{th} passenger

W_i = Waiting time of i^{th} passenger

$$W_n = \sum_{i=2}^{n-1} S_{i-1}$$

Figure 3.1 and Figure 3.2 explains the queue space of each mandatory service center, which was considered for the data collection for waiting time and service time of passengers in departure and arrival procedures.

In the departure procedure,

t_{SC} = the waiting time at security checks (The time between the passenger entering the entrance queue to finishing with the security checking)

t_{CC} = the waiting time at check in counters (The time between the passenger entering the check-in queue and completely finishing the check-in service)

t_{IC} = the waiting time at immigration counters (The time between the passenger entering the immigration queue and completely finishing the immigration service)

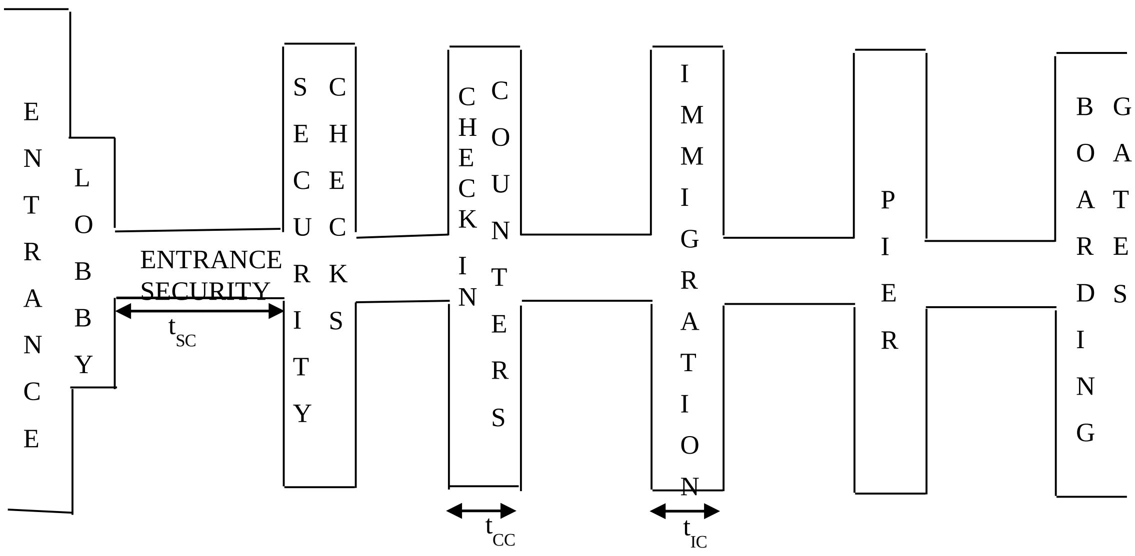


Figure 3. 1: Waiting times at mandatory service centers in departure procedure

In the arrival procedure,

t_{IC} = the waiting time at immigration (The time between the passenger entering the immigration queue and completely finishing the immigration service)

t_{BC} = the waiting time at baggage claims (The time between the passenger coming to the baggage station and finishing with collecting the baggage)

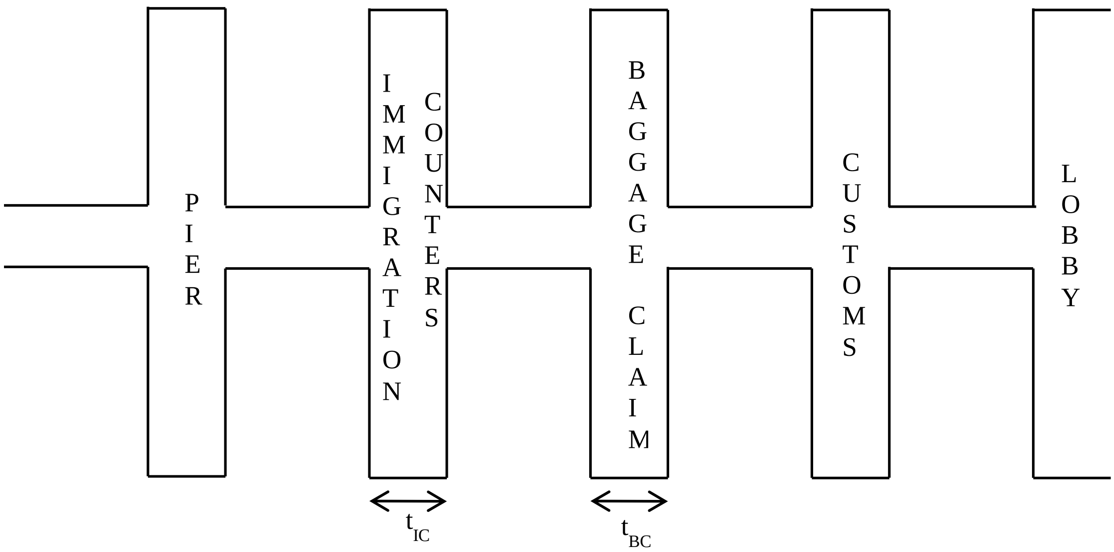


Figure 3. 2: Waiting times at mandatory service centers in arrival procedure

3.3. Identify outliers of the datasets

With the collection of data about passengers' service time and waiting time at mandatory service centers, it was observed that some passengers took more time to get their services from the service counters. For example, a passenger taking in forbidden items with hand luggage gets turned down at the check-in counters. This temporary rejection compels the passenger to wait longer for clearance after either disposing of or settling matters in some way. Another case in point is where a passenger fails to satisfactorily answer questions of immigration officers' or if the immigration officers have doubts regarding a passenger in a passenger group. Such people will necessarily have to spend more time at the immigration counters until all questions get cleared. Sometimes such situations have been considered as outliers of waiting time or service time of the data set.

Outliers are observations that deviate from other observations. Outliers may be due to changes in measurements or experimental errors or heavy-tailed distributions. The common cause of outliers is a mixture of two distributions, which may come from two different subgroups. Outliers that are the most extreme observations may sometimes contain sample maxima or sample minima, or both, depending on whether they are extremely high or low. However, the maximum and minimum values of the sample are not always outliers because they may not be too far away from other observations.

To identify the outliers, box plots can be used. The box plot is a graphical interpretation of the data based on the minimum, first quartile, median, third quartile, and maximum values. Outliers are plotted as single points. They show changes in the samples of a statistical population without making any assumptions about any basic statistical distribution. The spacing between the different parts of the box indicates the degree of dispersion and skewness in the data set, and show outliers. It can be sketched as follows.

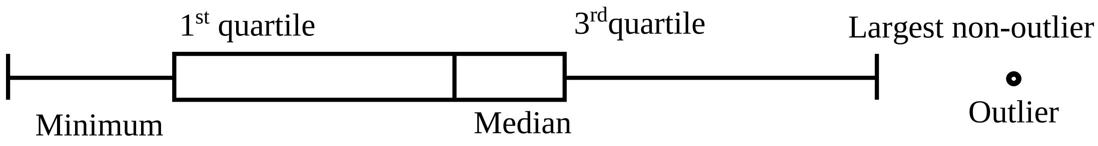


Figure 3. 3: Box plot graph

If the data of passengers' waiting time at immigration counters in departure procedure was sketched through the box plot, it can be seen that there are some outliers in that dataset, as shown in figure 3.4.

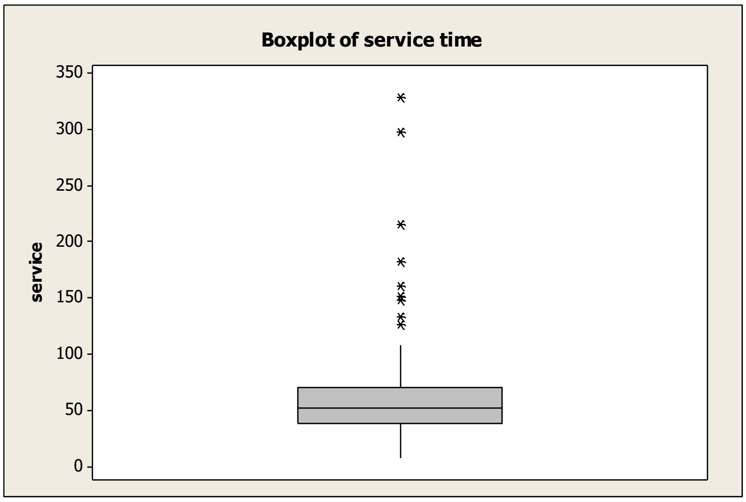


Figure 3. 4: Box plot for waiting time data of Immigration counters with outliers

If the dataset has outliers, the distribution taken from the dataset might be incorrect or it may be difficult to fit the distribution for the dataset. On the other hand, the results taken from the analysis may be wrong. So it is necessary to remove the outliers from the dataset before further analysis.

Once outliers are identified, they were removed from the dataset. Then again box plot is sketched to confirm that the dataset is free of outliers.

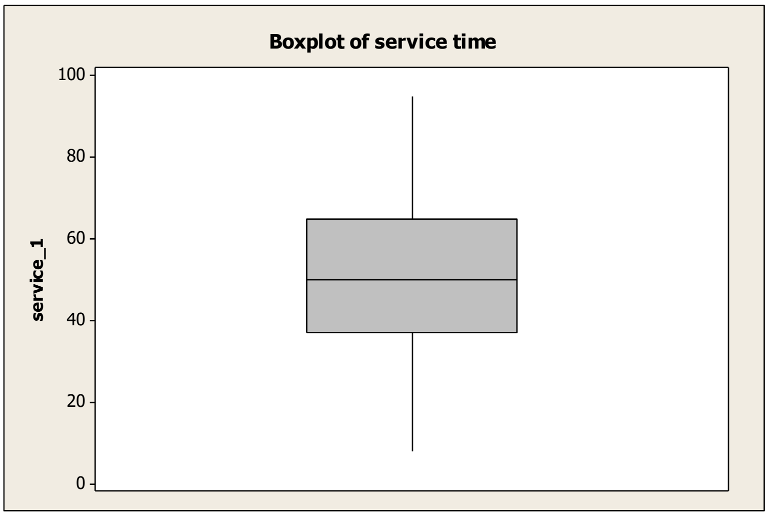


Figure 3. 5 Box plot for waiting time data of Immigration counters without outliers

3.4. Distribution Assessment Techniques

The cumulative waiting time of all mandatory service centers in each procedure is essential towards finding the waiting time of the entire procedures of arrival and departure. The distributions of the waiting time at each service center are necessary to find the cumulative waiting time of the service centers. Once the distributions are known with their parameters, it is easy to find the cumulative waiting time of the entire procedure by transforming the distributions in a suitable manner.

Datasets free of outliers were used to find the distributions of service time and waiting time at security checks, check-in counters, immigration counters and baggage claims for arrival and departure procedures. Probability plots, empirical cumulative distribution functions and histograms were used for the purpose.

3.4.1. The Probability Plot

The probability plot is a graphical technique to access the distribution of the dataset. It helps to check whether that the data set follows the given distribution and distributional assumptions. It may be Normal, Weibull, Lognormal, Exponential etc.

The data is plotted against the theoretical distribution, and the points should form a straight line. Leaving this line indicates deviation from the specified distribution.

Empirical CDF, Anderson Darling Test, Correlation coefficient and Chi-Square Test are used to verify the coming results of probability plots. Since probability maps can be generated for multiple competing distributions to see which one provides the best fit, and because the most direct probability map is generated, the probability map that produces the highest correlation coefficient is the best choice, so these techniques are used.

3.4.2. Empirical CDF and Histogram

The empirical cumulative distribution function is a cumulative distribution function related to the sample empirical measure. It estimates the cumulative distribution function under the sample point and converges with probability.

The definition of the distribution function is $F(t) = P(X \leq t)$

Then CDF can be estimated by finding $G_n(t)$

$G_n(t) = (\text{Number of sample values} \leq t) / n$

Histograms can be used to identify the pattern of the dataset or shape of the distribution. A histogram is a graphical representation of the distribution of digital data. It is an estimate of the probability distribution of continuous variables (quantitative variables).

3.5. Tests for identifying distributions

The distributions of service time and waiting time at mandatory service centers in arrival and departure procedures were found by using probability plots, Empirical Cumulative Distribution Function (CDF) and histogram. Taking distributional assumptions, it was necessary to verify the results collected from Probability plots, CDF and histograms i.e distributions collected using these techniques. Anderson Darling test and Chi-Square Goodness of Fit Test were used for the purpose.

3.5.1. Anderson Darling Test

The Anderson Darling test is a goodness of fitness test to determine if a given data sample is drawn from a given probability distribution. The test assumes that there are no parameters to be estimated in the distribution being tested, in which case the test and its set of thresholds are non-distributive.

Anderson-Darling test is restricted to continuous distributions. It can be used to check the following distributions.

- Normal distribution
- Log-normal distribution
- Weibull distribution
- Exponential distribution
- Logistic distribution

The Anderson-Darling test is defined as:

H_0 : The data follow a specified distribution

H_1 : The data do not follow the specified distribution

The critical values for the Anderson-Darling test are dependent on the specific distribution with that being tested.

$A^2 = -n - S$ where $S = \sum_{i=1}^{n} \frac{2i-1}{n} \{\ln(\varphi(Y_i)) + \ln(1 - \varphi(Y_{n+1-i}))\}$

The computation differs based on what is known about the distribution.

Case 1: The mean and the variance are both known

Case 2: The variance is known, but the mean is unknown

Case 3: The mean is known, but the variance is unknown

Case 4: Both the mean and the variance are unknown

$$A^{*2} = \begin{cases} A^2\left(1 + \frac{4}{n} - \frac{25}{n^2}\right) & \text{, if the variance and the mean are both unknown} \\ A^2 \text{ ,} & \text{otherwise} \end{cases}$$

Table 3.2 shows the Anderson Darling values under different level of significance values by considering above mentioned four cases. This formula was found by Stephens in 1976.

Table 3. 2: Anderson Darling values under different level of significance values

Case	Sample Size (n)	Level of Significance				
		15%	10%	5%	2.5%	1%
1	≥ 5	1.610	1.933	2.492	3.070	3.857
2			0.908	1.105	1.304	1.573
3	≥ 5		1.760	2.323	2.904	3.690
4	10	0.514	0.578	0.683	0.779	0.926
1, 2, 3, 4	20	0.528	0.591	0.704	0.815	0.969
1, 2, 3, 4	50	0.546	0.616	0.735	0.861	1.021
1, 2, 3, 4	100	0.559	0.631	0.754	0.884	1.047
1, 2, 3, 4	∞	0.576	0.656	0.787	0.918	1.092

Since the population mean and variance are unknown and taking 0.05 level of significance, Anderson Darling value 0.787 is considered for the research (Table 3.2).

The test is a one-sided test and the hypothesis that the distribution is of a specific form is rejected if the test statistic, AD Value, is greater than the critical value.

3.5.2. Chi-Square Goodness of Fit Test

The test is applied when one categorical variable from a single population is available. It is used to determine whether sample data are consistent with a hypothesized distribution.

The chi-square goodness of fit test is appropriate when the following conditions are met:

- The sampling method is simple random sampling.
- The variable under study is categorical.
- The expected value of the number of sample observations in each level of the variable is at least 5.

Using sample data, it is needed to find the degrees of freedom, expected frequency counts, test statistic, and the P-value associated with the test statistic.

- Degrees of freedom: DF = $k - 1$; where k is the number of levels of the categorical variable.
- Expected frequency counts: $E_i = n\, p_i$; where E_i is the expected frequency count for the i^{th} level of the categorical variable, n is the total sample size, and p_i is the hypothesized proportion of observations in level i.
- Test statistic: $\chi^2 = \sum\left(\frac{(O_i - E_i)^2}{E_i}\right)$; where O_i is the observed frequency count for the i^{th} level of the categorical variable, and E_i is the expected frequency count for the i^{th} level of the categorical variable.
- *P*-value: which is the probability of observing a sample statistic as extreme as the test statistic.

The chi-square test is defined for the hypothesis:

H_0 : The data follow a specified distribution

H_1 : The data do not follow the specified distribution

Therefore, the hypothesis that the data are from a population with the specified distribution is rejected if $\chi^2 > \chi^2_{k-1,\propto}$, $\nu = k - 1$, where ν degree of freedom and $\propto$ level of significance.

3.6. Conversion to Normal Distribution

By applying probability plots, empirical cumulative distribution functions and histograms for the data sets of service time and waiting time at mandatory service centers for arrival and departure procedures, it was found that they tend to Normal distribution, Log-normal distribution and Weibull distribution. These distributions were confirmed by taking Anderson darling test and Chi-Square Goodness of Fit Test. The next step is finding the distributions of cumulative service time and waiting time by combining the service centers. For example, if the passenger goes to a security checks first and a check-in counter second, his total waiting time is needed for the calculation. To get this, the individual distributions of waiting times at security checks and check-in counters have to be added and used to find the new distribution of cumulative waiting time with new parameters. To execute this process, it is better to convert all non-normal distributions to normal distribution by using suitable approximations.

Two or three different distributions such as Log-normal distribution, Weibull distribution, Exponential distribution have to be added to find the distributions of cumulative service time and waiting time after combining the service centers, Once the different distributions are added, the resultant distribution will be a new distribution which might be totally different from Log-normal or Weibull or Exponential distributions. To get the new parameters of resultant distribution, the relevant parameters of log-normal, Weibull and exponential distributions have to be added. Then the new parameters of resultant distribution may be totally different from that of original distributions. It is difficult to create the theory manually to add distributions if the distributions are different from each other. So it is better to convert all different distributions to one particular distribution to create the theory to add distributions to find above mentioned cumulative values. If all non-normal distributions are converted to normal distribution by using suitable approximations, it is easy to create the theory to find the new parameters for resultant distributions.

3.6.1. Transformation of Log-Normal to Normal

Let X is a continuous random variable.

$X \sim \text{Log} - \text{Normal}\ (M, S^2)$

$E(X) = e^{(M+\frac{S^2}{2})}$

$V(X) = e^{\left(2M+S^2\right)}(e^{(S^2)} - 1)$

If $E(X) - 2\sqrt{V(X)} \gg 0$

Then it could conceivably approximate log-normal distribution with a normal distribution.

Transformation is $Y = LN(X)$

Then $Y \sim \text{Normal}\ (\mu, \sigma^2)$

Then $\mu = E(X)$ and $\sigma = \sqrt{V(X)}$ (Xia et al., 2009)

3.6.2. Transformation of Weibull to Normal

Let X is a continuous random variable.

$X \sim \text{Weibull}\ (\lambda, k)$ Where λ is a scale parameter and k is a shape parameter and $\lambda, k > 0$

$E(X) = \lambda\Gamma\ (1 + \frac{1}{k})$

$V(X) = \lambda^2 \left[\Gamma\left(1 + \frac{2}{k}\right) - \left(\Gamma\left(1 + \frac{1}{k}\right)\right)^2\right]$

It could conceivably approximate Weibull distribution with a normal distribution.

Transformation is $Y = X^{(1/2)}$

Then $Y \sim \text{Normal}\ (\mu, \sigma^2)$

Then $\mu = E(X)$ and $\sigma = \sqrt{V(X)}$ (Kulkarni & Powar, 2011)

3.7. Cumulative Distributions

After finding the distributions of waiting time and service time at mandatory service centers, the non-normal distributions of service centers are converted to normal distributions by using the above transformations. Then mandatory service centers for each procedure are joined to find out the total waiting time of a passenger. After that optional services are placed before the mandatory services and passengers' total waiting time after going through the frictions, were found. For this purpose, to find the cumulative waiting time or cumulative service time at mandatory service centers after combining other service centers or frictions, the method shown below is used.

3.7.1. Moment generating function of a continuous variable

When two or three normal distributions are added, the resultant distribution is also a normal distribution. To find the parameters of resultant normal distribution, it is required to use moment generating functions.

Given a continuous random variable X, the moment generating function satisfies.
The moment generating function of a random variable X is a function
$M_X : R \rightarrow [0, \infty)$ given by

$$M(t) = \int_{-\infty}^{\infty} e^{tx}\, f(x)\, dx = E(e^{(t\,x)})$$

$$M(0) = e^{(0)} = 1$$

$$M'(t) = \frac{d}{dt}\big(M(t)\big) = \frac{d}{dt}\int_{-\infty}^{\infty} e^{tx}\, f(x)\, dx = \int_{-\infty}^{\infty} \frac{d}{dt}(e^{tx}) f(x)\, dx = \int_{-\infty}^{\infty} (x\, e^{tx}) f(x)\, dx$$

$$= E(x\, e^{(t\,x)})$$

$$M'(0) = E\big(x\, e^{(0)}\big) = E(x) = \overline{x}$$

$$M''^{(t)} = \frac{d^2}{dt^2}\big(M(t)\big) = \frac{d^2}{dt^2}\int_{-\infty}^{\infty} e^{tx}\, f(x)\, dx = \int_{-\infty}^{\infty} \frac{d^2}{dt^2}(e^{tx}) f(x)\, dx$$

$$= \int_{-\infty}^{\infty} (x^2 e^{tx}) f(x)\, dx = E(x^2 e^{(t\,x)})$$

$M''(0) = E(x^2e^{(0)}) = E(x^2)$

Mean $(X) = \mu_x = E(X) = \bar{x}$

Variance $(X) = \sigma_x^2 = E(x^2) - (E(x))^2$

$E(x^2) = \sigma_x^2 + \bar{x}^2$

3.7.2. Cumulative distribution of two continuous variables

Since it is required to find out the total waiting time a passenger requires for each procedure, mandatory service centers for each procedure are joined. Then it is required to find passengers' total waiting time after going through the frictions when the optional services are placed before the mandatory services. For this purpose, it is important to combine the distributions of passengers' waiting time or that of service time at mandatory service centers for each procedure to find the cumulative waiting time or cumulative service time at mandatory service centers after combining other service centers or frictions.

To find the distributions of waiting times of combined service centers, the formula of mean and the variance of combining two independent continuous random variables (Bandara and Wirasinghe, 1989) were used.

Waiting time or service time at one mandatory service center or one friction is considered as a first stochastically independent continuous random variable (X) and that of another mandatory service center or another friction is considered as a second stochastically independent continuous random variable (Y). If these two service centers are joined, then P = X Y.

Let X and Y be two random variables with moment generating functions $M(t_1)$ and $M(t_2)$ respectively. Let P = X Y.
If X and Y are stochastically independent, the moment generation function for the joint distribution $M(t_1,t_2)$ is

$M(t_1, t_2) = M(t_1) \cdot M(t_2)$

That is,

$$M(t_1, t_2) = \int_{-\infty}^{\infty} e^{t1x} f(x)\, dx \cdot \int_{-\infty}^{\infty} e^{t2y} g(y)\, dy$$

$$M'(t_1, t_2) = \int_{-\infty}^{\infty} x\, e^{t1x} f(x)\, dx \cdot \int_{-\infty}^{\infty} y\, e^{t2y} g(y)\, dy$$

$$M''(t_1, t_2) = \int_{-\infty}^{\infty} x^2 e^{t1x} f(x)\, dx \cdot \int_{-\infty}^{\infty} y^2 e^{t2y} g(y)\, dy$$

Then

$$M'(0,0) = E(P) = E(X) \cdot E(Y)$$

$$M''(0,0) = E(P^2) = E(X^2) \cdot E(Y^2)$$

From equation

$$\overline{P} = \overline{XY} - - - - (3.1)$$

$$\sigma_P^2 = E(P^2) - [E(P)]^2$$

$$= E(X^2)E(Y^2) - [E(X)]^2[E(Y)]^2$$

$$= (\sigma_x^2 + \bar{x}^2)(\sigma_y^2 + \bar{y}^2) - \bar{x}^2\bar{y}^2$$

$$\sigma_P^2 = \sigma_x^2\sigma_y^2 + \bar{x}\sigma_y^2 + \bar{y}\sigma_x^2 - - - - (3.2)$$

3.7.3. Cumulative distribution of three continuous variables

Waiting time or service time at one mandatory service center or one friction is considered as a first stochastically independent continuous random variable (X), that of second mandatory service center or another friction is considered as a second stochastically independent continuous random variable (Y) and that of third mandatory service center or another friction is considered as a third stochastically independent continuous random variable (Z). If these three service centers are joined, then $W = X\,Y\,Z$.

Let X, Y and Z be two random variable with moment generating functions $M(t_1)$,$M(t_2)$ and $M(t_3)$ respectively. Let W = X Y Z.

If X, Y and Z are stochastically independent, the moment generation function for the joint distribution $M(t_1, t_2, t_3)$ is

$$M(t_1, t_2, t_3) = M(t_1) \cdot M(t_2) \cdot M(t_3)$$

That is,

$$M(t_1, t_2, t_3) = \int_{-\infty}^{\infty} e^{t1x} f(x)\, dx \cdot \int_{-\infty}^{\infty} e^{t2y} g(y)\, dy \cdot \int_{-\infty}^{\infty} e^{t3z} g(z)\, dz$$

$$M'(t_1, t_2, t_3) = \int_{-\infty}^{\infty} x\, e^{t1x} f(x)\, dx \cdot \int_{-\infty}^{\infty} y\, e^{t2y} g(y)\, dy \cdot \int_{-\infty}^{\infty} z e^{t3z} g(z)\, dz$$

$$M''(t_1, t_2, t_3) = \int_{-\infty}^{\infty} x^2 e^{t1x} f(x)\, dx \cdot \int_{-\infty}^{\infty} y^2 e^{t2y} g(y)\, dy \cdot \int_{-\infty}^{\infty} z^2 e^{t3z} g(z)\, dz$$

Then

$$M'(0,0,0) = E(W) = E(X) \cdot E(Y) \cdot E(Z)$$

$$M''(0,0,0) = E(W^2) = E(X^2) \cdot E(Y^2) \cdot E(Z^2)$$

From equation

$$\overline{W} = \overline{X}\,\overline{Y}\overline{Z} ----(3.3)$$

$$\sigma_w^2 = E(W^2) - [E(W)]^2$$

$$= E(X^2)E(Y^2)E(Z^2) - [E(X)]^2[E(Y)]^2[E(Z)]^2$$

$$= (\sigma_x^2 + \overline{x}^2)(\sigma_y^2 + \overline{y}^2)(\sigma_z^2 + z^2) - \overline{x}^2\overline{y}^2z^2$$

$$\sigma_w^2 = \sigma_x^2\sigma_y^2\sigma_Z^2 + \overline{x}^2\sigma_y^2\sigma_Z^2 + \overline{y}^2\sigma_x^2\sigma_Z^2 + \overline{z}^2\sigma_x^2\sigma_y^2 + \overline{x}^2\overline{y}^2\sigma_Z^2 + \overline{y}^2\overline{z}^2\sigma_x^2 + \overline{x}^2\overline{z}^2 --(3.4)$$

3.8. Hypothesis Testing Techniques

When the frictions such as wash rooms, food cabins, telephone booths and duty free shops are placed in between various places of airport terminal mandatory service centers, the distributions are found with means and standard deviations by using above (3.1), (3.2), (3.3) and (3.4) equations.

It was necessary to find if there was a significant difference between the mean of waiting times at service centers by placing frictions and without placing frictions. If there is no significant difference between the mean for waiting times with placing frictions and without placing frictions, then placing friction between service centers was considered unnecessary. It is also useful to check whether there is a difference between variances of waiting times at service centers by placing frictions and without placing frictions before locating the frictions between service centers.

Welch's t – test, ANOVA and hypothesis testing were used to check significance differences between the means of frictions, that of mandatory service centers and that of combining frictions and mandatory service centers. Levene test, F test and hypothesis testing were used to check the significant differences between the variances of frictions, that of mandatory service centers and that of combining frictions and mandatory service centers.

3.8.1. Welch's t – Test

It is necessary to find if there is a significant difference between the mean of waiting times at service centers by placing frictions and without placing frictions. For this purpose, the collected samples came from different populations with different variances and their sample sizes were different. To suit these conditions, Welch's t-test was considered suitable to find the significant difference.

Welch's t-test or unequal variances t-test is a two-sample location test which is used to test the hypothesis that two populations have equal means. Welch's t-test is more reliable when the two samples have unequal variances and unequal sample sizes.

Assumption of this test is that the two populations have normal distributions and with unequal variances. Welch's t-test is designed for unequal variances, but the assumption of normality is maintained.

Welch's t – test and hypothesis testing for differences between the means are defined as:

1) $\mathrm{H}_0 : \mu_1 - \mu_2 \geq 0$ Vs $\mathrm{H}_1 : \mu_1 - \mu_2 < 0$

2) $\mathrm{H}_0 : \mu_1 - \mu_2 \leq 0$ Vs $\mathrm{H}_1 : \mu_1 - \mu_2 > 0$

3) $\mathrm{H}_0 : \mu_1 - \mu_2 = 0$ Vs $\mathrm{H}_1 : \mu_1 - \mu_2 \neq 0$

If the data from population with unknown variances and population variances are unequal, then the test statistic is $U = \frac{(\bar{X}-\bar{Y})-(\mu_1-\mu_2)}{\sqrt{\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2}}} \sim t_v.$

$$U_{cal} = \frac{(\bar{X}-\bar{Y})-0}{\sqrt{\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2}}}$$

where $\bar{X}$, S_1^2 and n_1 are the 1st sample mean, sample variance and sample size and $\bar{Y}$,S_2^2 and n_2 are the 2nd sample mean, sample variance and sample size respectively. The degrees of freedom v associated with this variance estimate is approximated using the Welch–Satterthwaite equation:

Where $v = \frac{(\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2})^2}{\frac{(s_1^2/n_1)^2}{n_1-1}+\frac{(s_2^2/n_2)^2}{n_2-1}}$

When v is large, standard normal critical values can be used.

Let U_{cal} be the calculated value of the test statistic (U) under H_0.

Decision Rules are

1) Reject H_0 if $U_{cal} \leq -t_{v,\alpha}$

2) Reject H_0 if $U_{cal} \geq t_{v,\alpha}$

3) Reject H_0 if $U_{cal} \leq -t_{v,\alpha/2}$ or $U_{cal} \geq t_{v,\alpha/2}$

Once t and v have been calculated, these statistics can be used together with the t distribution to test whether the two population mean equal assumption (using a two-tailed test) or the alternative hypothesis that one of the population means is greater than or equal to the other (using a one-tailed test). The approximate degree of freedom is rounded down to the nearest integer.

3.8.2. F Test

It is useful to check whether there is a difference between variances of waiting times at service centers by placing frictions and without placing frictions before locating the frictions between service centers. F-test can be used for this purpose.

F-test is used to test whether the variances of two populations are equal. This test can be a two-tailed test or a one-tailed test. The two-tailed test is for alternative where the difference is not equal. The one-tailed version is tested in only one direction, ie the variance from the first population is greater or less than the second population variance. The choice is up to the question.

The F hypothesis test is defined as:

H0 :$\sigma_1 = \sigma_2$

H1 :$\sigma_1 < \sigma_2$ for a lower one-tailed test

H1 :$\sigma_1 > \sigma_2$ for an upper one-tailed test

H1 :$\sigma_1 \neq \sigma_2$ for a two-tailed test

Test Statistic

F = S_1 / S_2; where S_1 and S_2 and are the sample variances. The more this ratio deviates from 1, the stronger the evidence for unequal population variances.

Critical Region

The hypothesis that the two variances are equal is rejected if

$F \leq F_{\alpha,\ N_1-1,\ N_2-1}$

Where $F_{\alpha,\ N_1-1,\ N_2-1}$ is the critical value of the F distribution with N_1-1 and N_2-1 degrees of freedom and a significance level of α.

3.8.3. Levene's Test for Equality of Variances

Before combining mandatory service centers and frictions, it is necessary to check whether the variances of waiting times are equal or not. Further, if one friction is replaced with another friction, it is necessary to check the equality of variances of waiting times. If the variances are equal, there is no problem for the replacement. If the variances are unequal, some conditions (will be discussed in next chapter) have been considered for the replacement. To suit this purpose, Levene's test can be used. This test comes under ANOVA Test of Homogeneity of Variances.

Levene's test is used to test whether the k samples had the same variance. The process of equal variance between samples is called homogeneity of variance. Some statistical tests, such as analysis of variance, assume that the variances are equal between groups or samples. The Levene's test can be used to verify this hypothesis.

$H_0 : \sigma^2_1 = \sigma^2_2 = \ldots = \sigma^2_k$

$H_1 : \sigma^2_i \neq \sigma^2_j$ for at least one pair (i,j)

Given a variable Y with sample of size N divided into k subgroups, where N_i is the sample size of the i^{th} subgroup, the Levene test statistic is defined as:

$$W = \frac{(N-k)}{(k-1)} \frac{\sum_{i=1}^{k} N_i (\overline{Z_{i.}} - \overline{Z}_{..})^2}{\sum_{i=1}^{k} \sum_{j=1}^{N_i} (Z_{ij} - \overline{Z_{i.}})^2}$$

$$Z_{ij} = \left| Y_{ij} - \overline{Y}_{i.} \right|$$

where $\overline{Y}_{i.}$ - mean of the i^{th} subgroup

$\overline{Z_{i.}}$ - group means of the $\boldsymbol{Z_{ij}}$

$\overline{Z}_{..}$ - overall mean of the $\boldsymbol{Z_{ij}}$

The Levene test rejects the hypothesis that the variances are equal if $W > F_{\alpha, k-1, N-k}$ where $F_{\alpha, k-1, N-k}$ is the upper critical value of the F distribution with k-1 and N-k degrees of freedom at a significance level of α.

3.8.4. ANOVA Test of Homogeneity of Variances

It is necessary to combine all mandatory service centers in the entire arrival or departure procedure and frictions to find the total waiting time of a passenger in arrival or departure procedure by placing one or two frictions before the mandatory service centers. Before starting to combine, it is required to check the equality of differences of mean waiting times of all mandatory service centers with friction by taking each and every mean waiting time together. Not only mean waiting times, it is also necessary to test for a difference in all variance waiting times of mandatory service centers with frictions in entire procedures. ANOVA test, considered the best, was used for this purpose.

The technique of testing the difference between two or more independent means is an extension of two independent samples, which applies when there are two independent comparison groups. The ANOVA technique applies to situations where there are two or more independent groups. The analysis of variance was used to compare the mean of the comparison groups. However, because there are more than two groups, the calculation of test statistics is more involved. Test statistics must consider the sample size, sample mean, and sample standard deviation in each comparison group.

In general, analysis of variance is used in three ways: one-way analysis of variance, two-way analysis of variance, and N-way multivariate analysis of variance. One-way analysis of variance refers to the number of independent variables, not the number of categories in each variable. One-way analysis of variance has only one independent variable. Two-way analysis of variance refers to analysis of variance using two independent variables. Two-way analysis of variance can be used to test the interaction between two independent variables. The interactions show that the differences between all categories of independent variables are inconsistent. N-way ANOVA can be used for many independent variables.

Testing of the Assumptions

The population in which samples are drawn should be normally distributed.

The sample cases should be independent of each other.

The variance among the groups should be approximately equal.

The advantage of the ANOVA F-test is that no need to pre-specify which treatments are to be compared and no need to adjust for making multiple comparisons. The disadvantage of the ANOVA F-test is that if the null hypothesis is rejected, it is unable to find which treatments can be said to be significantly different from the others. To avoid that disadvantage, Post Hoc test in ANOVA such as Tukey HSD test can be applied.

The test is defined as:

H0 : $\mu_1 = \mu_2 = \mu_3 \ldots = \mu_k$

H1 : $\mu_i \neq \mu_j$ for at least one pair (i, j)

Given a variable Y with sample of size N divided into k subgroups, where N_i is the sample size of the i^{th} subgroup.

The formula for the one-way ANOVA F-test statistic is

$$F = \frac{\sum_{i=1}^{K} n_i(\overline{Y_i} - \overline{Y})^2/(K-1)}{\sum_{i=1}^{K}\sum_{j=1}^{n_i}(Y_{ij} - \overline{Y_{ij}})^2/(N-K)}$$

where $\overline{Y_i}$ - sample mean in the i^{th} group

n_i - number of observations in the i^{th} group

$\overline{Y}$-overall mean of the data

K - number of groups

Y_{ij} - j^{th} observation in the i^{th} out of K groups

N - overall sample size

This F statistic follows the F-distribution of K-1, N-K degrees of freedom under the null hypothesis. If the variability between groups is large relative to intra-group variability, this statistic will be large, and if the population mean of these groups all have the same value, this is unlikely to happen.

The null hypothesis is rejected if $F > F_{\alpha,\, k-1,\, N-k}$, where $F_{\alpha,\, k-1,\, N-k}$ is the upper critical value of the F distribution with k-1and N-k degrees of freedom at a significance level of α.

The Tukey HSD Test

The Tukey HSD test is a post hoc test in ANOVA. It applies for comparing the differences between means of values rather than comparing pairs of values. The value of the Tukey test is given by taking the absolute value of the differences between pairs of means and dividing it by the standard error of the mean.

3.9. Queuing Theory Technique

Analytical solutions for placing frictions before the mandatory service centers for entire procedures were found by using above mentioned techniques, now it was necessary to verify the results by using simulation models. To get the simulation models, queuing theory was applied.

Customer traffic from a limited/unlimited crowd to a service facility forms a queue due to a lack of ability to provide services to all at once. In the absence of a perfect balance between service facilities and customers, service facilities or customer arrivals require waiting time.

A queuing system can be completely described by
(i) Arrival pattern
(ii) Service pattern
(iii) Queue discipline
(iv) Customer's behavior

The basic multi-server model includes a separate wait line and a service facility, and multiple independent servers. One example of a multi-server system is an airline ticket and check-in counter, where passengers line up on a single line and wait for one of several agents to serve. Here, one of the most common disciplines mentioned below can be used.

(i) First come first served (FCFS)

(ii) First in first out (FIFO)

(iii) Last in first out (LIFO)

(iv) Selection for service in random order (SIRO)

For this study, first come first served (FCFS) discipline is used and queuing theory formula is as shown below.

$$P(W > 0) = \frac{\rho^S\left(\frac{1-\rho}{1-\rho^{N+1}}\right)}{S!(1-\rho)} \quad \text{Where } \rho = \frac{\lambda}{\mu}$$

λ - Mean Arrival rate

μ - Mean Service rate

ρ - Traffic intensity

S - Number of counters

N - Maximum number of passengers coming for the service

$P(W > 0)$ - Probability that there will be some one waiting

3.10. Summary

This Chapter is about the theory and the methodology towards the flexible model for landside use in airport terminals. The first step in the direction towards the flexible model was collection of data. For the purpose, data was collected from the Bandaranaike International Airport, Sri Lanka (BIA). The data collected, used service times at all mandatory service centers (immigration counters, baggage stations in arrival procedure and check-in counters, ticketing counters, immigration counters departure procedure) and frictions (washrooms, food cabins, shops, internet access) and these data helped find the waiting times at relevant centers. Collected data was first sorted by removing outliers. The next step was finding the distributions of service times and waiting times at service centers and frictions. Probability plot, Empirical CDF, Histogram, Anderson darling test, Chi-Square Goodness of Fit Test were used for the purpose. Some of the distributions found were Normal, Weibull and Log-normal. Then it was necessary to convert all the non-normal distributions to normal distribution to find cumulative distributions of waiting times and service times at mandatory service centers. The conversion was done at the time of generating functions. After the cumulative distributions were found, it was essential to find significances between their parameters (mean waiting times as well as variance waiting times). Hypothesis Testing Techniques, Welch's t – test, F test, Levene Test for Equality of Variances and ANOVA Test of Homogeneity of Variance are some of that tests used in this connection. Finally, queuing theory was used to find the analytical models to minimize passenger movements with both arrival and departure procedures including gates and these models were verified with the Monte-Carlo simulation.

4. MODEL DEVELOPMENT

4.1. Introduction

Arrival and waiting patterns of passengers at different mandatory service centers such as ticket counters, immigration, baggage claim and security checks, could vary, depending on the location and the operation strategy of the terminal. Sometimes, some mandatory service centers are crowded and some are not. Passengers have to wait much more time at the queues when the service center is crowded. This situation arises because the arrival, service and departure rates of the service centers seem to be considerably different from one another. If the departure rate is really high for the first mandatory service center and service rate is quite low for the second mandatory service center, then there is a likely need for a queue to be created at the second service center.

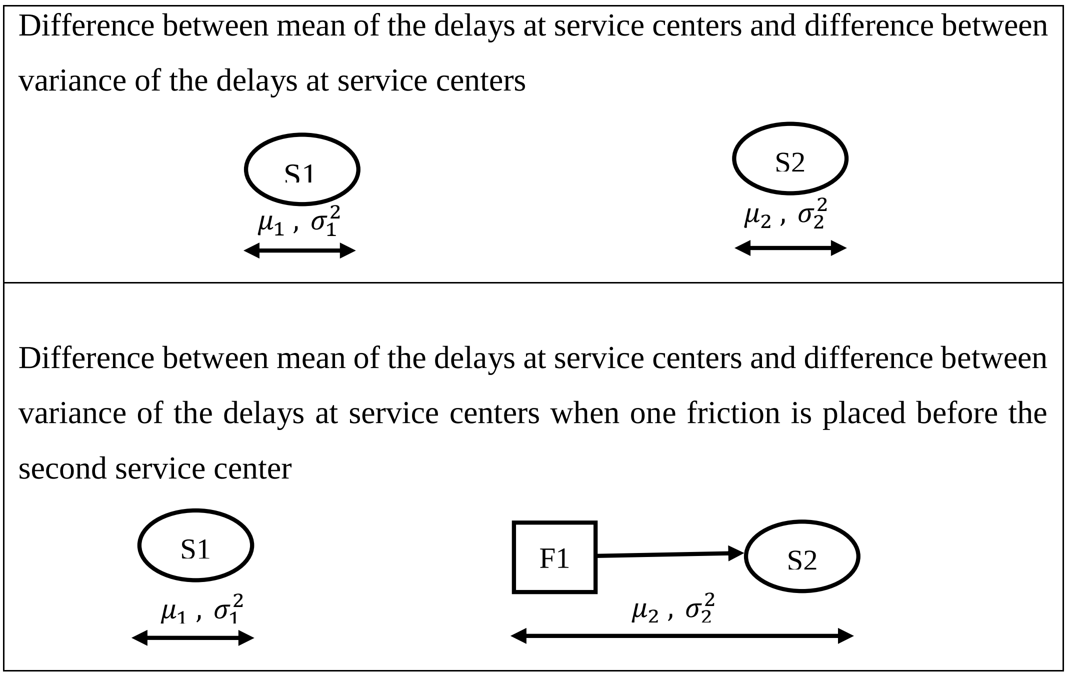
Therefore, to absorb unnecessary waiting, frictions such as shops, washrooms, food cabins and telephone booths can be introduced in such places. It is possible to change the arrival rate at the service center downstream by introducing a friction. If the friction is placed before the second mandatory service center, the arrival rate of passengers to the second service center will be reduced. If so, unnecessary waiting can decrease, can increase further or there will be no difference. When the departure rate of the first service center is greater than the service rate of the second service center and a friction is placed before the service center, the likely unnecessary waiting can be decreased somewhat. When the departure rate of the first service center is less than the service rate of the second service center and a friction is placed before the service center, the likely unnecessary waiting can be further increased. When the departure rate of the first service center is equal to the service rate of the second service center and a friction is placed before the service center, there will be no difference or can be increased too. If the departure rate of the first service center is greater than the service rate of the second service center, a friction can be allowed before the service center or may even be not. Therefore, minimizing walking distances, waiting times and delays at critical service centers within the terminal such as ticket counters, immigration, baggage claim and security checks and optimally placing of other services such as shops, washrooms, food cabins and telephone booths could improve the passenger throughput so that there will be no significant increase in total time spent. The walking time between two mandatory service centers was not considered since it is fixed even if the frictions are placed or not in between service centers. The frictions which have been placed between the mandatory services centers depend on the arrival rate, service rate and departure rate of passengers at mandatory service centers, means and variances of the waiting time at the frictions. The percentages of passengers going through the frictions should also be considered when placing frictions.

Irrespective of the friction arrangement for a given terminal size, there will be a geometry that will be optimum with respect to passenger waiting. Quantitative methodology is used to select a suitable terminal configuration with frictions for a pier-type airport terminal. Three pier-type airport terminal configurations with frictions are used to select a suitable terminal configuration that minimizes the passengers' delays at gates by placing proper frictions in between gates. While the first and second configurations have two piers with n/2 gates and three piers with n/3 gates in each, the third configuration has three piers holding an unequal number of gates. Passenger waiting time at a terminal depends on several factors: arrival, service and departure behaviors of mandatory service centers, the manner of placing frictions in between mandatory service centers, number of gates, the manner of placing frictions (washroom, food cabin, shops, etc.) in-between gates, percentage of passengers going through the different frictions, processing time for frictions and gates, number of piers and gate spacing. Probability of passengers' arrival at frictions, total passenger arrival rate to the piers and arrival rates and service rates of the frictions are considered before placing proper frictions in between the gates at the piers.

4.2. Placing frictions before the mandatory service centers

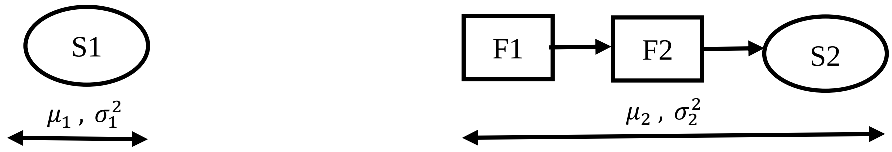
The steps described below were considered to check whether there is a significance difference between the mean of the delay and that of variance of the delay of placing frictions before the mandatory service centers with their parameters to minimize the waiting time at mandatory service centers.

First, the difference between means of the delays at two mandatory service centers and differences between variances of delays at two mandatory service centers were found. Then one friction was placed before the mandatory service centers and again the difference between mean of the delays at mandatory service centers and difference between variance of delays at mandatory service centers were found. After that, two frictions were placed before the mandatory service centers and again the difference between mean of the delays at mandatory service centers and difference between variance of delays at mandatory service centers were found. Positions of mandatory service centers cannot be changed and they are fixed as shown in figure 4.1 (Saparamadu and Bandara, 2018).

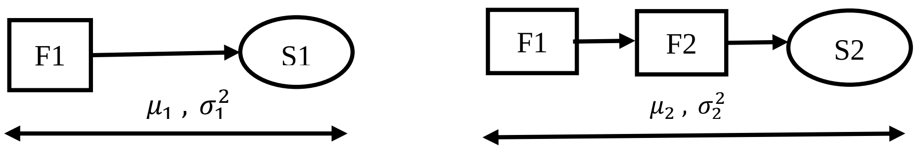


Difference between mean of the delays at service centers and difference between variance of the delays at service centers when one friction is placed before both service centers

Difference between mean of the delays at service centers and difference between variance of the delays at service centers when two frictions are placed before the second service center



Difference between mean of the delays at service centers and difference between variance of the delays at service centers when one friction is placed before the first service center and another friction is placed before the second service center



Difference between mean of the delays at service centers and difference between variance of the delays at service centers when two frictions are placed before the both service centers

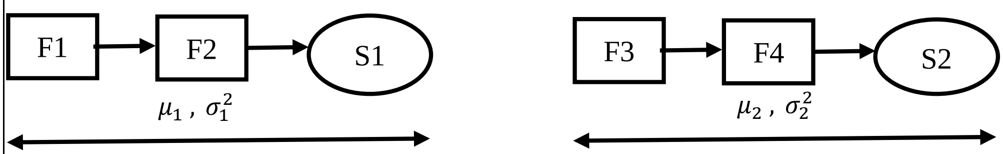


Figure 4. 1: Differences of means of the delays and that of variances of the delays at service centers

The hypotheses below are checked for means (μ_i) and variances (σ_i^2) of the delays at service centers, when one friction and two frictions are placed before the service center in the above steps.

Hypothesizes for mean

1) $H_0 : \mu_1 = \mu_2$ Vs $H_1 : \mu_1 > \mu_2$
2) $H_0 : \mu_1 = \mu_2$ Vs $H_1 : \mu_1 < \mu_2$
3) $H_0 : \mu_1 = \mu_2$ Vs $H_1 : \mu_1 \neq \mu_2$

Hypothesizes for variances

1) $H_0 : \sigma_1^2 = \sigma_2^2$ Vs $H_1 : \sigma_1^2 > \sigma_2^2$
2) $H_0 : \sigma_1^2 = \sigma_2^2$ Vs $H_1 : \sigma_1^2 < \sigma_2^2$
3) $H_0 : \sigma_1^2 = \sigma_2^2$ Vs $H_1 : \sigma_1^2 \neq \sigma_2^2$

By applying the above hypothesis tests for the steps mentioned in figure 4.1, the conditions for placing the frictions before the mandatory service centers could be found as follows.

Table 4. 1: Decision for placing friction before the mandatory service centers

Decision for Mean	Decision for Variance	Decision for friction
$\mu_1 = \mu_2$	$\sigma_1^2 = \sigma_2^2$	Optional
	$\sigma_1^2 > \sigma_2^2$	Allowed
	$\sigma_1^2 < \sigma_2^2$	Disallowed
$\mu_1 > \mu_2$	$\sigma_1^2 = \sigma_2^2$	Allowed
	$\sigma_1^2 > \sigma_2^2$	Allowed
	$\sigma_1^2 < \sigma_2^2$	Optional (*)
$\mu_1 < \mu_2$	$\sigma_1^2 = \sigma_2^2$	Disallowed
	$\sigma_1^2 > \sigma_2^2$	Disallowed
	$\sigma_1^2 < \sigma_2^2$	Disallowed

Optional - The friction / frictions can either be placed or cannot be placed before the mandatory service center.
Allowed - The friction / frictions can be placed before the mandatory service center.
Disallowed - The friction / frictions cannot be placed before the mandatory service center.

(*) Placing friction depends on the difference between μ_1 and μ_2 and difference between σ_1^2 and σ_2^2.

4.3. Queuing Technique for determining delays

According to the criteria described in section 4.2, frictions which can be allowed before the mandatory service centers for the arrival and departure procedure could be found. The next step was determining delays with respect to mandatory service centers and placing of frictions for arrival and departure procedures. For that, queuing theory is used.

First, the base case, i.e only the mandatory service centers without frictions, was considered to find the waiting time of passengers. Waiting time of mandatory service center can be calculated as follows (Lee, 1966, Newell, 1971).

$$P(WT_{Si} > 0) = \frac{(\rho_i)^{S_i}\left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right)}{S_i!(1-\rho_i)} \qquad \text{where} \qquad \rho_i = \frac{\lambda_i}{\gamma_i}$$

$P(WT_{Si} > 0)$ – Probability of having waiting at service center *i*
λi - Arrival rate of passengers at service center *i*
γ_i- Service rate of passengers at service center *i*
Si - Number of counters in service center *i*
Ni - Maximum number of passengers coming to service center *i*
ρ_i - Ratio of arrival rate to service rate in service center *i*
First, only the mandatory service centers without frictions were considered to find the total waiting time of the passengers.

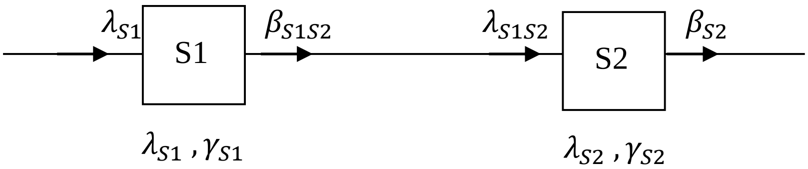


Figure 4. 2: Mandatory service centers without frictions

λ_{S1} - Arrival rate of passengers at service center 1

β_{S1S2} – Departure rate of passengers from service center 1 to service center 2

γ_{S1}- Service rate of passengers at service center 1

λ_{S1S2} - Arrival rate of passengers to service center 2 from service center 1

β_{S2} – Departure rate of passengers from service center 2

λ_{S2} - Arrival rate of passengers at service center 2

γ_{S2}- Service rate of passengers at service center 2

$$\beta_{S1S2} = \lambda_{S1S2}$$

Second, one friction was placed between the mandatory service centers to find the total waiting time of passengers.

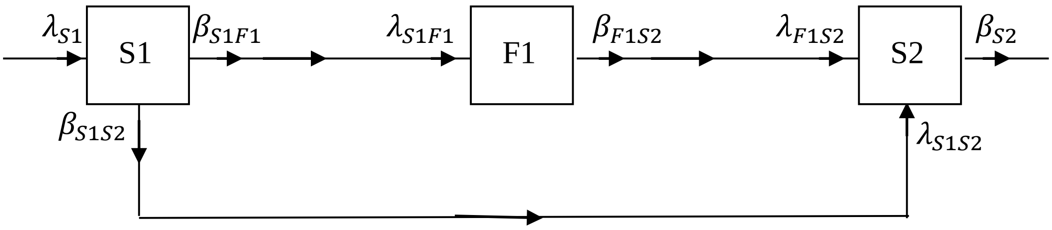


Figure 4. 3: Mandatory service centers with one friction

λ_{S1} - Arrival rate of passengers at service center 1

β_{S1F1} – Departure rate of passengers from service center 1 to friction 1

β_{S1S2} – Departure rate of passengers from service center 1 to service center 2

γ_{S1}- Service rate of passengers at service center 1

λ_{S1F1} - Arrival rate of passengers to friction 1 from service center 1

β_{F1S2} – Departure rate of passengers from friction 1 to service center 2

λ_{F1} - Arrival rate of passengers at friction 1

γ_{F1}- Service rate of passengers at friction 1

λ_{F1S2} - Arrival rate of passengers to service center 2 from friction 1

λ_{S1S2} - Arrival rate of passengers to service center 2 from service center 1

β_{S2} – Departure rate of passengers from service center 2

γ_{S2}- Service rate of passengers at service center 2

λ_{S2} - Arrival rate of passengers at service center 2

P - The probability of passengers who are going from service center 1 to friction 1

$\beta_{S1F1} = \lambda_{S1F1}$

$\beta_{S1S2} = \lambda_{S1S2}$

$\beta_{F1S2} = \lambda_{F1S2}$

$\lambda_{F1} = \lambda_{S1F1}$

When one friction is placed before the mandatory service center, new arrival rates at the service centers were calculated as shown below.

$\lambda_{F1} = P\,\lambda_{S1}$

$\lambda_{S2} = P\,\lambda_{F1} + (1 - P)\lambda_{S1}$

Waiting time of the process at service center 1 +

Waiting time of the process at service center 2 >

Waiting time of the process at (service center 1 + friction 1 + service center 2)

P(Waiting time of the process at service center 1) +

P(Waiting time of the process at service center 2) >

P(Waiting time of the process at (service center 1 + friction 1 + service center 2))

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) > P(WT_{S1+F1+S2} > 0)$$

Third, two frictions were placed between the mandatory service centers.

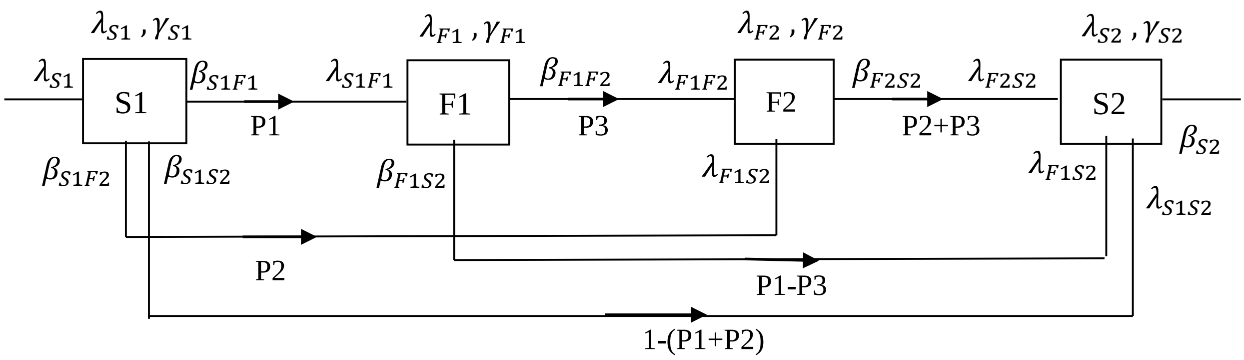


Figure 4. 4: Mandatory service centers with two frictions

λ_{S1} - Arrival rate of passengers at service center 1

β_{S1F1} – Departure rate of passengers from service center 1 to friction 1

β_{S1F2} – Departure rate of passengers from service center 1 to friction 2

β_{S1S2} – Departure rate of passengers from service center 1 to service center 2

γ_{S1}- Service rate of passengers at service center 1

λ_{S1F1} - Arrival rate of passengers to friction 1 from service center 1

β_{F1S2} – Departure rate of passengers from friction 1 to service center 2

β_{F1F2} – Departure rate of passengers from friction 1 to friction 2

λ_{F1} - Arrival rate of passengers at friction 1

γ_{F1}- Service rate of passengers at friction1

λ_{F1F2} - Arrival rate of passengers to friction 1 from friction 2

β_{F1S2} – Departure rate of passengers from friction 1 to service center 2

β_{F2S2} – Departure rate of passengers from friction 2 to service center 2

λ_{F2} - Arrival rate of passengers at friction 2

γ_{F2}- Service rate of passengers at friction2

λ_{F2S2} - Arrival rate of passengers to friction 2 from service center 2

λ_{F1S2} - Arrival rate of passengers to friction 1 from service center 2

λ_{S1S2} - Arrival rate of passengers to service center 1 from service center 2

β_{S2} – Departure rate of passengers from service center 2

λ_{S2} - Arrival rate of passengers at service center 2

γ_{S2}- Service rate of passengers at service center 2

P1 - Probability of passengers who are going from service center 1 to friction 1

P2 - Probability of passengers who are going from service center 1 to friction 2

P3 - Probability of passengers who are going from friction 1 to friction 2

$\beta_{S1F1} = \lambda_{S1F1}$

$\beta_{S1S2} = \lambda_{S1S2}$

$\beta_{S1F2} = \lambda_{S1F2}$

$\beta_{F1S2} = \lambda_{F1S2}$

$\beta_{F1F2} = \lambda_{F1F2}$

$\beta_{F2S2} = \lambda_{F2S2}$

Once the two frictions were placed before the mandatory service center, arrival rates at the service center were changed as shown below.

$\lambda_{F1} = P_1\lambda_{S1}$

$\lambda_{F2} = P_3\lambda_{F1} + P_2\lambda_{S1}$

$\lambda_2 = (P_2 + P_3)\,\lambda_{F2} + (P_1 - P_3)\lambda_{F1} + (1 - P_1 - P_2)\lambda_{S1}$

$P(WT_{S1} > 0) + P(WT_{S2} > 0) > P(WT_{S1+F1+F2+S2} > 0)$

4.3.1. Frictions placed for arrival procedure

Arrival procedure was next considered to place frictions between service centers. The layout below shows service centers without placing frictions.

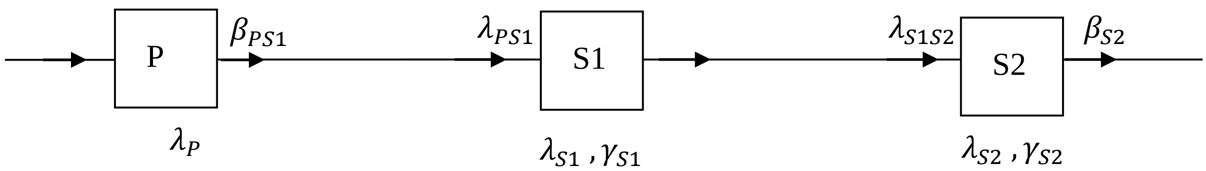


Figure 4. 5: Mandatory service centers without frictions in arrival procedure

λ_{P} - Arrival rate of passengers who get down from the flight

β_{PS1} – Departure rate of passengers from flight to service center 1

λ_{S1} - Arrival rate of passengers at service center 1

γ_{S1}- Service rate of passengers at service center 1

λ_{PS1} - Arrival rate of passengers to service center 1 from the flight

β_{S1S2} – Departure rate of passengers from service center 1 to service center 2

λ_{S2} - Arrival rate of passengers at service center 2

γ_{S2}- Service rate of passengers at service center 2

λ_{S1S2} - Arrival rate of passengers to service center 2 from service center 1

β_{S2} – Departure rate of passengers from service center 2

$\beta_{PS1} = \lambda_{PS1}$ $\qquad\qquad$ $\beta_{S1S2} = \lambda_{S1S2}$

One friction was placed in between pier and service center 1 and another friction was placed in between service center 1 and service center 2.

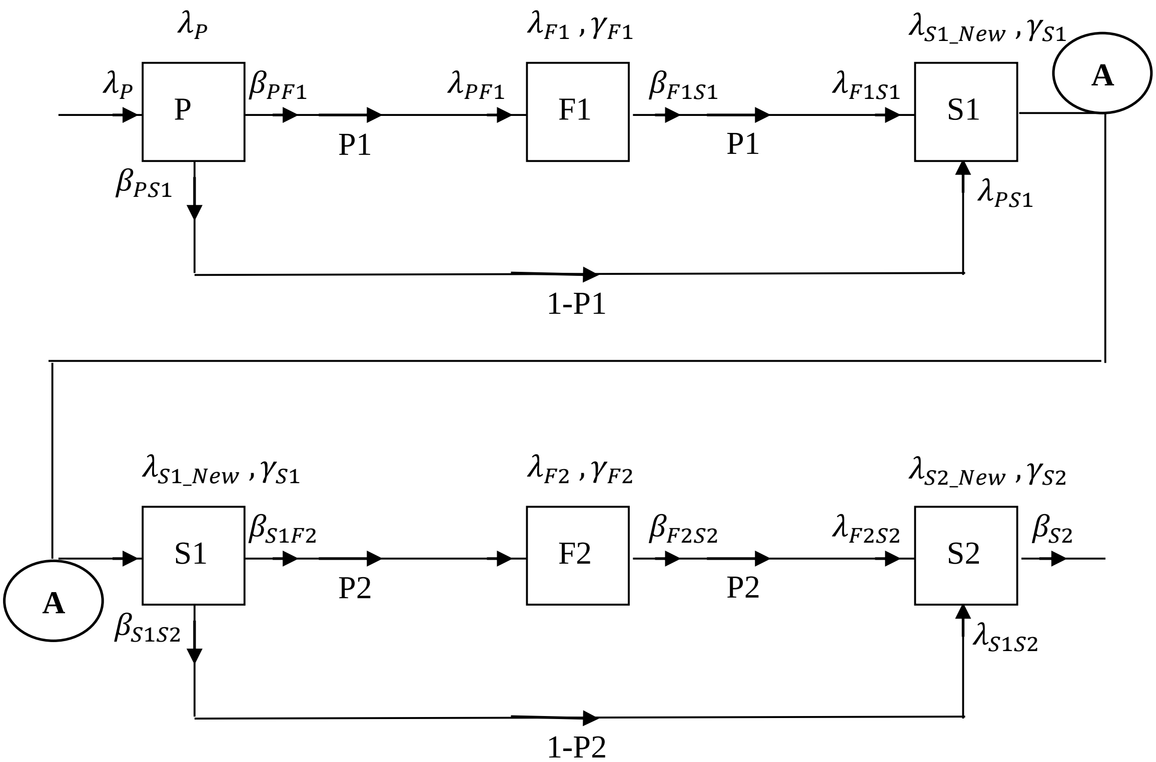


Figure 4. 6: One friction placed before each mandatory service center in arrival procedure

λ_P - Arrival rate of passengers who get down from the flight

β_{PF1} – Departure rate of passengers from flight to friction 1

β_{PS1} – Departure rate of passengers from flight to service center 1

λ_{PF1} - Arrival rate of passengers to friction 1 from the flight

β_{F1S1} – Departure rate of passengers from friction 1 to service center 1

λ_{F1} - Arrival rate of passengers at friction 1

γ_{F1}- Service rate of passengers at friction 1

λ_{F1S1} - Arrival rate of passengers to service center 1from friction 1

λ_{PS1} - Arrival rate of passengers to service center 1from the flight

β_{S1F2} – Departure rate of passengers from service center 1 to friction 2

β_{S1S2} – Departure rate of passengers from service center 1 to service center 2

λ_{S1_New} - Arrival rate of passengers at service center 1

γ_{S1}- Service rate of passengers at service center 1

λ_{S1F2} - Arrival rate of passengers to service center 1 from friction 2

β_{F2S2} – Departure rate of passengers from friction 2 to service center 2

λ_{F2} - Arrival rate of passengers at friction 2

γ_{F2}- Service rate of passengers at friction 2

λ_{F2S2} - Arrival rate of passengers to service center 2 from friction 2

λ_{S1S2} - Arrival rate of passengers to service center 2 from service center 1

β_{S2} – Departure rate of passengers from service center 2

γ_{S2_New}- Service rate of passengers at service center 2

λ_{S2} - Arrival rate of passengers at service center 2

P1 - The probability of passengers who are going from flight to friction 1

P2 - The probability of passengers who are going from service center 1 to friction 2

$\beta_{PF1} = \lambda_{PF1}$ $\quad\quad\quad$ $\beta_{PS1} = \lambda_{PS1}$

$\beta_{F1S1} = \lambda_{F1S1}$ $\quad\quad\quad$ $\beta_{S1F2} = \lambda_{S1F2}$

$\beta_{F2S2} = \lambda_{F2S2}$ $\quad\quad\quad$ $\beta_{S1S2} = \lambda_{S1S2}$

$\lambda_{F1} = \lambda_{PF1}$ $\quad\quad\quad$ $\lambda_{F2} = \lambda_{S1F2}$

$$\lambda_{S1\_New} = P_1\lambda_{F1} + (1 - P_1)\,\lambda_p$$

$$\lambda_{S2\_New} = P_2\lambda_{F2} + (1 - P_2)\,\lambda_{S1}$$

$$\rho_1 = \frac{\lambda_{S1}}{\gamma_{S1}} \qquad \rho_2 = \frac{\lambda_{S2}}{\gamma_{S2}} \qquad \rho_{1\_New} = \frac{\lambda_{S1\_New}}{\gamma_{S1}} \qquad \rho_{2\_New} = \frac{\lambda_{S2\_New}}{\gamma_{S2}}$$

Decision

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) > P\left(WT_{S1\_New} > 0\right) + P\left(WT_{S2\_New} > 0\right)$$

$$\frac{(\rho_1)^{S_1}\left(\frac{1-\rho_1}{1-\rho_1^{N1+1}}\right)}{S_1!\,(1-\rho_1)} + \frac{(\rho_2)^{S_2}\left(\frac{1-\rho_2}{1-\rho_2^{N2+1}}\right)}{S_2!\,(1-\rho_2)} > \frac{(\rho_{1\_New})^{S_1}\left(\frac{1-\rho_{1\_New}}{1-\rho_{1\_New}^{N1+1}}\right)}{S_1!\,(1-\rho_{1\_New})} + \frac{(\rho_{2\_New})^{S_2}\left(\frac{1-\rho_{2\_New}}{1-\rho_{2\_New}^{N2+1}}\right)}{S_2!\,(1-\rho_{2\_New})}$$

Two frictions were placed in between pier and service center 1 and another two frictions were placed in between service center 1 and service center 2.

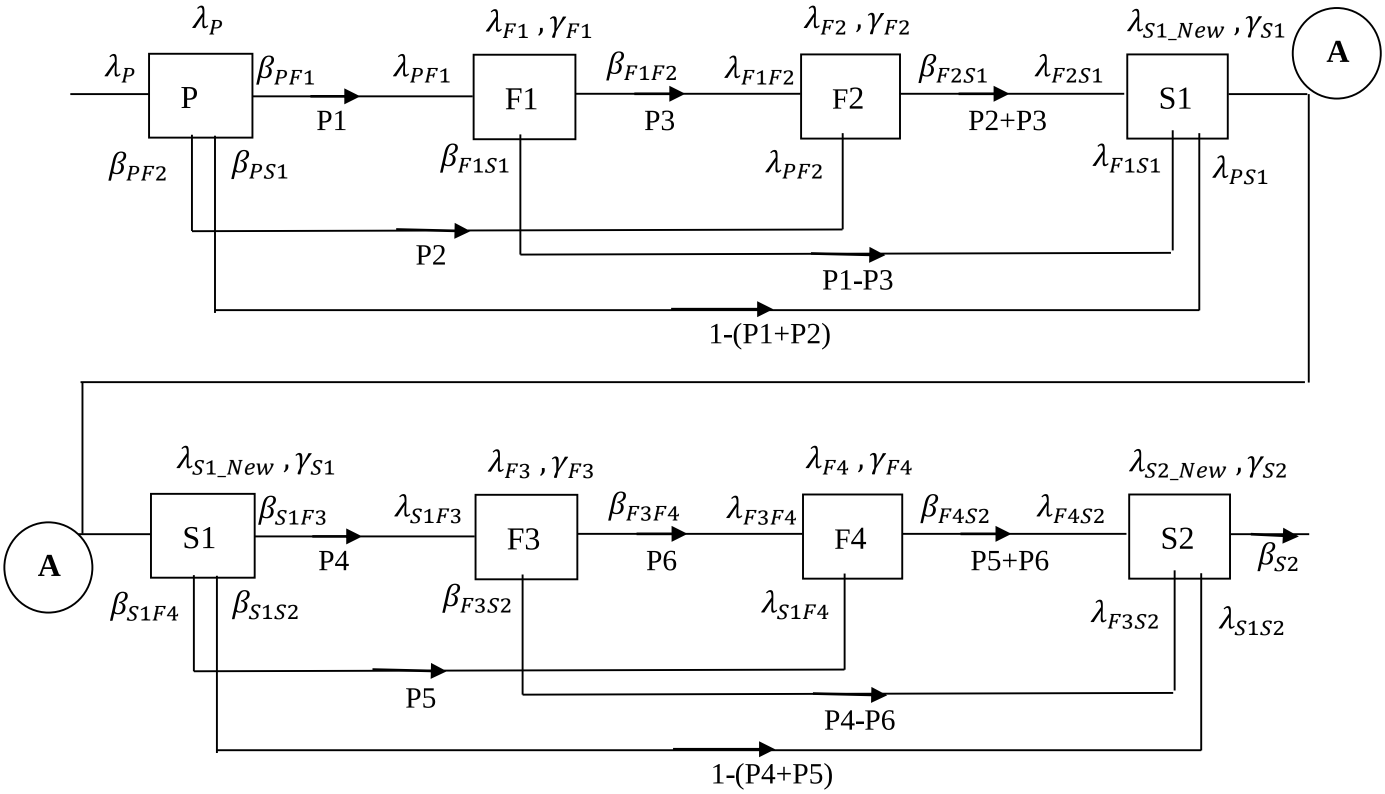


Figure 4. 7: Two frictions placed before each mandatory service center in arrival procedure

λ_P - Arrival rate of passengers who get down from the flight

β_{PF1} – Departure rate of passengers from flight to friction 1

β_{PF2} – Departure rate of passengers from flight to friction 2

β_{PS1} – Departure rate of passengers from flight to service center 1

λ_{PF1} - Arrival rate of passengers to friction 1 from the flight

β_{F1S1} – Departure rate of passengers from friction 1 to service center 1

β_{F1F2} – Departure rate of passengers from friction 1 to friction 2

λ_{F1} - Arrival rate of passengers at friction 1

γ_{F1}- Service rate of passengers at friction 1

λ_{F1F2} - Arrival rate of passengers to friction 2 from friction 1

λ_{PF2} - Arrival rate of passengers to friction 2 from the flight

β_{F2S1} – Departure rate of passengers from friction 2 to service center 1

λ_{F2} - Arrival rate of passengers at friction 2

γ_{F2}- Service rate of passengers at friction 2

λ_{F1S1} - Arrival rate of passengers to service center 1 from friction 1

λ_{F2S1} - Arrival rate of passengers to service center 1 from friction 2

λ_{PS1} - Arrival rate of passengers to service center 1 from the flight

β_{S1F3} – Departure rate of passengers from service center 1 to friction 3

β_{S1F4} – Departure rate of passengers from service center 1 to friction 4

β_{S1S2} – Departure rate of passengers from service center 1 to service center 2

λ_{S1_New} - Arrival rate of passengers at service center 1

γ_{S1}- Service rate of passengers at service center 1

λ_{S1F3} - Arrival rate of passengers to service center 1 from friction 3

β_{F3S2} – Departure rate of passengers from friction 3 to service center 2

β_{F3F4} – Departure rate of passengers from friction 3 to service center 4

λ_{F3} - Arrival rate of passengers at friction 3

γ_{F3}- Service rate of passengers at friction 3

λ_{F3F4} - Arrival rate of passengers to friction 4 from friction 3

λ_{S1F4} - Arrival rate of passengers to friction 4 from service center 1

β_{F4S2} – Departure rate of passengers from friction 4 to service center 2

λ_{F4} - Arrival rate of passengers at friction 4

γ_{F4}- Service rate of passengers at friction 4

λ_{F4S2} - Arrival rate of passengers to service center 2 from friction 4

λ_{F3S2} - Arrival rate of passengers to service center 2 from friction 3

λ_{S1S2} - Arrival rate of passengers to service center 2 from service center 1

β_{S2} – Departure rate of passengers from service center 2

γ_{S2_New}- Service rate of passengers at service center 2

λ_{S2} - Arrival rate of passengers at service center 2

P1 = Probability of passengers who are going from flight to friction 1

P2 = Probability of passengers who are going from flight to friction 2

P3 = Probability of passengers who are going from friction 1 to friction 2

P4 = Probability of passengers who are going from service center 1 to friction 3

P5 = Probability of passengers who are going from service center 1 to friction 4

P6 = Probability of passengers who are going from friction 3 to friction 4

$$\beta_{PF1} = \lambda_{PF1} \qquad \beta_{S1F4} = \lambda_{S1F4}$$
$$\beta_{PF2} = \lambda_{PF2} \qquad \beta_{S1F3} = \lambda_{S1F3}$$
$$\beta_{PS1} = \lambda_{PS1} \qquad \beta_{S1S2} = \lambda_{S1S2}$$
$$\beta_{F1S1} = \lambda_{F1S1} \qquad \beta_{F3S2} = \lambda_{F3S2}$$
$$\beta_{F1F2} = \lambda_{F1F2} \qquad \beta_{F3F4} = \lambda_{F3F4}$$
$$\beta_{F2S1} = \lambda_{F2S1} \qquad \beta_{F4S2} = \lambda_{F4S2}$$

$$\lambda_{F1} = P_1\lambda_p$$
$$\lambda_{F2} = P_3\lambda_{F1} + P_2\lambda_p$$
$$\lambda_{S1\_New} = (P_2 + P_3)\lambda_{F2} + (P_1 - P_3)\,\lambda_{F1} + (1 - P_1 - P_2)\lambda_p$$
$$\lambda_{F3} = P_4\lambda_{S1\_New}$$
$$\lambda_{F4} = P_6\lambda_{F3} + P_5\lambda_{S1\_New}$$
$$\lambda_{2\_New} = (P_5 + P_6)\lambda_{F4} + (P_4 - P_6)\,\lambda_{F3} + (1 - P_4 - P_6)\lambda_{S1\_New}$$

$$\rho_1 = \frac{\lambda_{S1}}{\gamma_{S1}} \qquad \rho_2 = \frac{\lambda_{S2}}{\gamma_{S2}} \qquad \rho_{1\_New} = \frac{\lambda_{S1\_New}}{\gamma_{S1}} \qquad \rho_{2\_New} = \frac{\lambda_{S2\_New}}{\mu_{S2}}$$

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) > P\big(WT_{S1\_New} > 0\big) + P\big(WT_{S2\_New} > 0\big)$$

$$\frac{(\rho_1)^{S_1}\left(\frac{1-\rho_1}{1-\rho_1^{N1+1}}\right)}{S_1!\,(1-\rho_1)} + \frac{(\rho_2)^{S_2}\left(\frac{1-\rho_2}{1-\rho_2^{N2+1}}\right)}{S_2!\,(1-\rho_2)} > \frac{(\rho_{1\_New})^{S_1}\left(\frac{1-\rho_{1\_New}}{1-\rho_{1\_New}^{N1+1}}\right)}{S_1!\,(1-\rho_{1\_New})} + \frac{(\rho_{2\_New})^{S_2}\left(\frac{1-\rho_{2\_New}}{1-\rho_{2\_New}^{N2+1}}\right)}{S_2!\,(1-\rho_{2\_New})}$$

4.3.2. Frictions placed for departure procedure

Departure procedure was considered to place frictions between service centers.

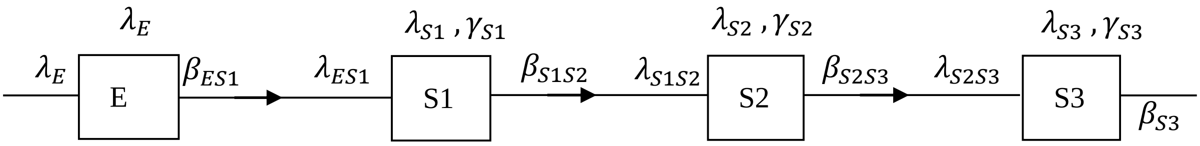


Figure 4. 8: Mandatory service centers without frictions in departure procedure

λ_E - Arrival rate of passengers at the entrance

β_{ES1} – Departure rate of passengers from entrance to service center 1

λ_{S1} - Arrival rate of passengers at service center 1

γ_{S1}- Service rate of passengers at service center 1

λ_{ES1} - Arrival rate of passengers to service center 1 from the entrance

β_{S1S2} – Departure rate of passengers from service center 1 to service center 2

λ_{S2} - Arrival rate of passengers at service center2

γ_{S2}- Service rate of passengers at service center 2

λ_{S1S2} - Arrival rate of passengers to service center 2 from service center 1

β_{S2S3} – Departure rate of passengers from service center 2 to service center 3

λ_{S3} - Arrival rate of passengers at service center3

γ_{S3}- Service rate of passengers at service center 3

λ_{S2S3} - Arrival rate of passengers to service center 3 from service center 2

β_{S3} – Departure rate of passengers from service center 3

One friction was placed in between entrance and service center 1, another friction was placed in between service center 1 and service center 2 and yet another friction was placed in between service center 2 and service center 3.

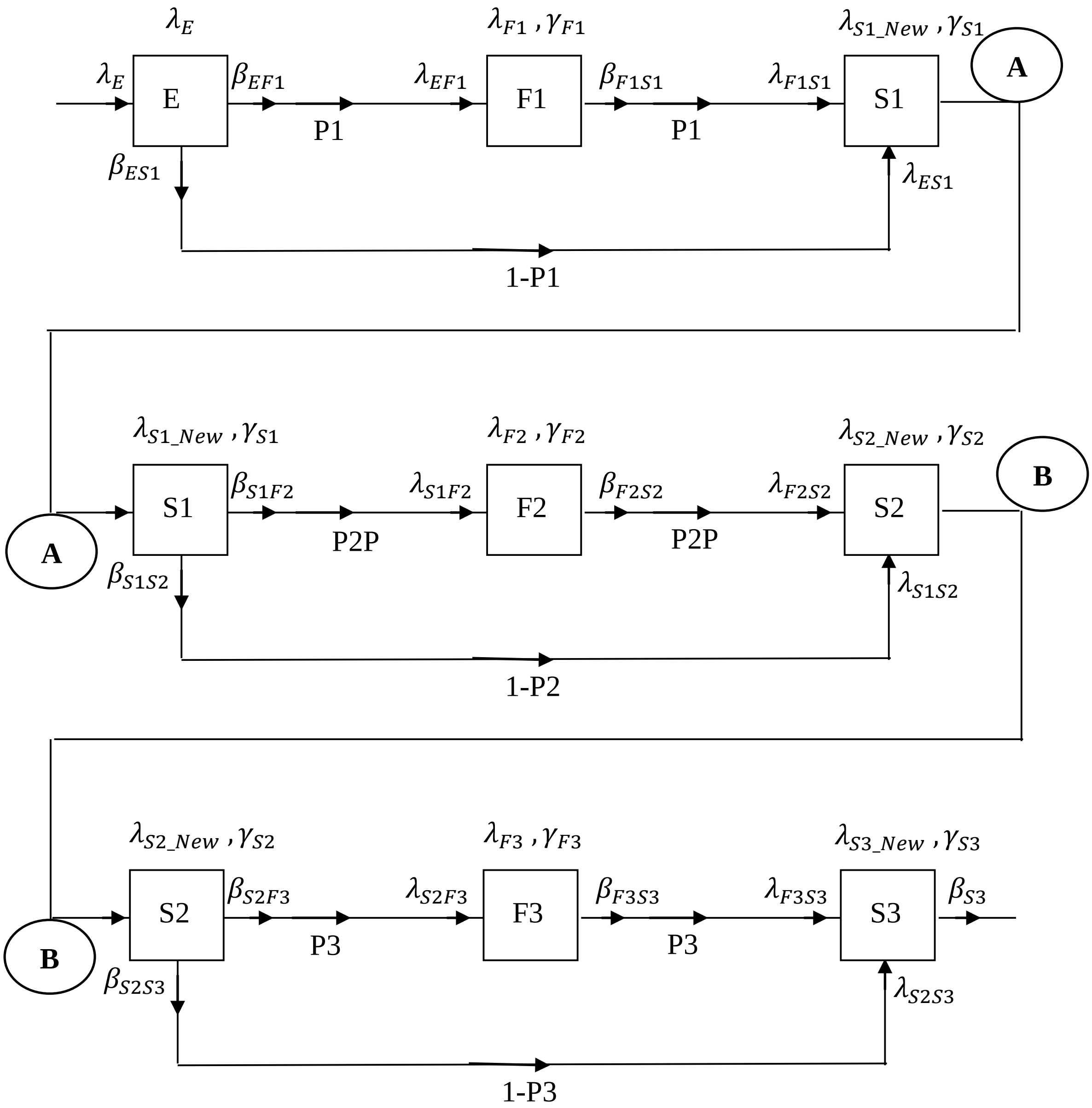


Figure 4. 9: One friction placed before each mandatory service center in departure procedure

λ_E - Arrival rate of passengers at the entrance

β_{EF1} – Departure rate of passengers from entrance to friction 1

β_{ES1} – Departure rate of passengers from entrance to service center 1

λ_{EF1} - Arrival rate of passengers to friction 1 from the entrance

β_{F1S1} – Departure rate of passengers from friction 1 to service center 1

λ_{F1} - Arrival rate of passengers at friction 1

γ_{F1}- Service rate of passengers at friction 1

λ_{F1S1} - Arrival rate of passengers to service center 1 from friction 1

λ_{ES1} - Arrival rate of passengers to service center 1 from the entrance

β_{S1F2} – Departure rate of passengers from service center 1 to friction 2

β_{S1S2} – Departure rate of passengers from service center 1 to service center 2

λ_{S1_New} - Arrival rate of passengers at service center 1

γ_{S1}- Service rate of passengers at service center 1

λ_{S1F2} - Arrival rate of passengers to friction 2 from service center 1

β_{F2S2} – Departure rate of passengers from friction 2 to service center 2

λ_{F2} - Arrival rate of passengers at friction 2

γ_{F2}- Service rate of passengers at friction 2

λ_{F2S2} - Arrival rate of passengers to service center 2 from friction 2

λ_{S1S2} - Arrival rate of passengers to service center 2 from service center 1

β_{S2F3} – Departure rate of passengers from service center 2 to friction 3

β_{S2S3} – Departure rate of passengers from service center 2 to service center 3

λ_{S2_New} - Arrival rate of passengers at service center 2

γ_{S2}- Service rate of passengers at service center 2

λ_{S2F3} - Arrival rate of passengers to friction 3 from service center 2

β_{F3S3} – Departure rate of passengers from friction 3 to service center 3

λ_{F3} - Arrival rate of passengers at friction 3

γ_{F3}- Service rate of passengers at friction 3

λ_{F3S3} - Arrival rate of passengers to service center 3 from friction 3

λ_{S2S3} - Arrival rate of passengers to service center 3 from service center 2

β_{S3} – Departure rate of passengers from service center 3

λ_{S3_New} - Arrival rate of passengers at service center 3

γ_{S3}- Service rate of passengers at service center 3

P1 = Probability of passengers who are going from entrance to friction 1

P2 = Probability of passengers who are going from service center 1 to friction 2

P3 = Probability of passengers who are going from service center 2 to friction 3

$\beta_{EF1} = \lambda_{EF1}$

$\beta_{ES1} = \lambda_{ES1}$

$\beta_{F1S1} = \lambda_{F1S1}$

$\beta_{S1F2} = \lambda_{S1F2}$

$\beta_{S1S2} = \lambda_{S1S2}$

$\beta_{F2S2} = \lambda_{F2S2}$

$\beta_{S1F3} = \lambda_{S1F3}$

$\beta_{S2S3} = \lambda_{S2S3}$

$\beta_{F3S3} = \lambda_{F3S3}$

$\lambda_{F1} = P_1\lambda_E$

$\lambda_{S1\_New} = P_1\lambda_{F1} + (1 - P_1)\lambda_E$

$\lambda_{F2} = P_2\lambda_{S1\_New}$

$\lambda_{S2\_New} = P_2\lambda_{F2} + (1 - P_2)\lambda_{S1\_New}$

$\lambda_{F3} = P_3\lambda_{S2\_New}$

$\lambda_{S3\_New} = P_3\lambda_{F3} + (1 - P_3)\lambda_{S2\_New}$

$$\rho_1 = \frac{\lambda_{S1}}{\gamma_{S1}} \qquad \rho_2 = \frac{\lambda_{S2}}{\gamma_{S2}} \qquad \rho_3 = \frac{\lambda_{S3}}{\gamma_{S3}} \qquad \rho_{1_{New}} = \frac{\lambda_{S1_{New}}}{\gamma_{S1}}$$

$$\rho_{S2_{New}} = \frac{\lambda_{S2\_New}}{\gamma_{S2}} \qquad \rho_{3\_New} = \frac{\lambda_{S3\_New}}{\gamma_{S3}}$$

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) + P(WT_{S3} > 0) > P\big(WT_{S1\_New} > 0\big) + P\big(WT_{S2\_New} > 0\big) + P\big(WT_{S3\_New} > 0\big)$$

$$\frac{(\rho_1)^{S_1}(\frac{1-\rho_1}{1-\rho_1^{N1+1}})}{S_1!\,(1-\rho_1)} + \frac{(\rho_2)^{S_2}(\frac{1-\rho_2}{1-\rho_2^{N2+1}})}{S_2!\,(1-\rho_2)} + \frac{(\rho_3)^{S_3}(\frac{1-\rho_3}{1-\rho_3^{N3+1}})}{S_3!\,(1-\rho_3)} > \frac{(\rho_{1\_New})^{S_1}(\frac{1-\rho_{1\_New}}{1-\rho_{1\_New}^{N1+1}})}{S_1!\,(1-\rho_{1\_New})} + \frac{(\rho_{2\_New})^{S_2}(\frac{1-\rho_{2\_New}}{1-\rho_{2\_New}^{N2+1}})}{S_2!\,(1-\rho_{2\_New})} + \frac{(\rho_{3\_New})^{S_3}(\frac{1-\rho_{3\_New}}{1-\rho_{3\_New}^{N3+1}})}{S_3!\,(1-\rho_{3\_New})}$$

Two frictions were placed in between entrance and service center 1, another two frictions were placed in between service center 1 and service center 2 and yet another two frictions were placed in between service center 2 and service center 3.

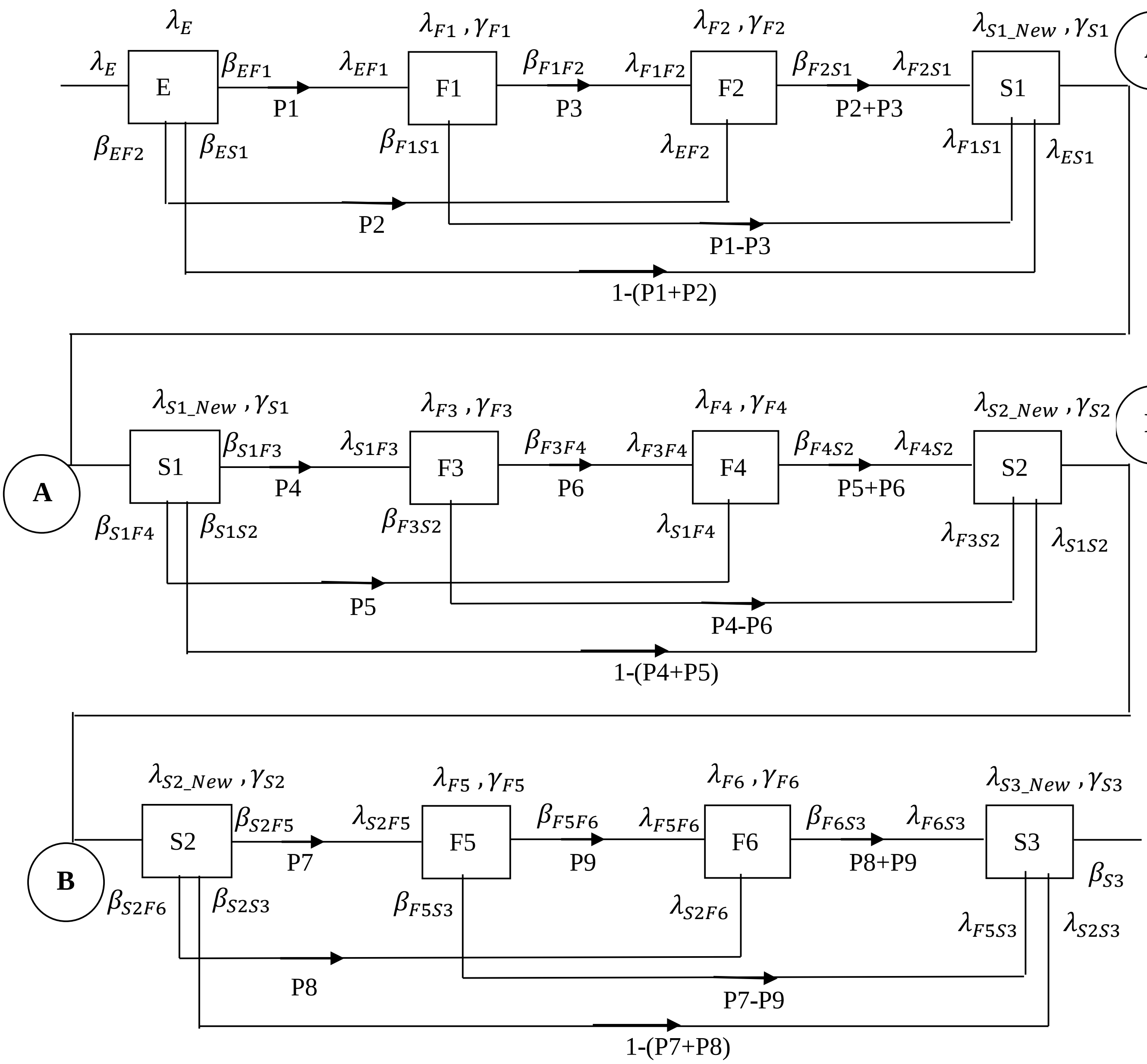


Figure 4. 10: Two frictions placed before each mandatory service center in departure procedure

λ_{E} - Arrival rate of passengers at the entrance

β_{EF1} – Departure rate of passengers from entrance to friction 1

β_{EF2} – Departure rate of passengers from entrance to friction 2

β_{ES1} – Departure rate of passengers from entrance to service center 1

λ_{EF1} - Arrival rate of passengers to friction 1 from the entrance

β_{F1F2} – Departure rate of passengers from friction 1 to friction 2

β_{F1S1} – Departure rate of passengers from friction 1 to service center 1

λ_{F1} - Arrival rate of passengers at friction 1

γ_{F1}- Service rate of passengers at friction 1

λ_{F1F2} - Arrival rate of passengers to friction 2 from friction 1

λ_{EF2} - Arrival rate of passengers to friction 2 from the entrance

β_{F2S1} – Departure rate of passengers from friction 2 to service center 1

λ_{F2} - Arrival rate of passengers at friction 2

γ_{F2}- Service rate of passengers at friction 2

λ_{F1S1} - Arrival rate of passengers to service center 1 from friction 1

λ_{F2S1} - Arrival rate of passengers to service center 1 from friction 2

λ_{ES1} - Arrival rate of passengers to service center 1 from the entrance

β_{S1F3} – Departure rate of passengers from service center 1 to friction 3

β_{S1F4} – Departure rate of passengers from service center 1 to friction 4

β_{S1S2} – Departure rate of passengers from service center 1 to service center 2

λ_{S1_New} - Arrival rate of passengers at service center 1

γ_{S1}- Service rate of passengers at service center 1

λ_{S1F3} - Arrival rate of passengers to friction 3 from service center 1

β_{F3F4} – Departure rate of passengers from friction 3 to friction 4

β_{F3S2} – Departure rate of passengers from friction 3 to service center 2

λ_{F3} - Arrival rate of passengers at friction 3

γ_{F3}- Service rate of passengers at friction 3

λ_{F3F4} - Arrival rate of passengers to friction 4 from friction 3

λ_{S1F4} - Arrival rate of passengers to friction 4 from service center 1

β_{F4S2} – Departure rate of passengers from friction 4 to service center 2

λ_{F4} - Arrival rate of passengers at friction 4

γ_{F4}- Service rate of passengers at friction 4

λ_{F4S2} - Arrival rate of passengers to service center 2 from friction 4

λ_{F3S2} - Arrival rate of passengers to service center 2 from friction 3

λ_{S1S2} - Arrival rate of passengers to service center 2 from service center 1

β_{S2F5} – Departure rate of passengers from service center 2 to friction 5

β_{S2F6} – Departure rate of passengers from service center 2 to friction 6

β_{S2S3} – Departure rate of passengers from service center 2 to service center 3

λ_{S2_New} - Arrival rate of passengers at service center 2

γ_{S2}- Service rate of passengers at service center 2

λ_{S2F5} - Arrival rate of passengers to friction 5 from service center 2

β_{F5F6} – Departure rate of passengers from friction 5 to friction 6

β_{F5S3} – Departure rate of passengers from friction 5 to service center 3

λ_{F5} - Arrival rate of passengers at friction 5

γ_{F5}- Service rate of passengers at friction 5

λ_{F5F6} - Arrival rate of passengers to friction 6 from friction 5

λ_{S2F6} - Arrival rate of passengers to friction 6 from service center 2

β_{F6S3} – Departure rate of passengers from friction 6 to service center 3

λ_{F6} - Arrival rate of passengers at friction 6

γ_{F6}- Service rate of passengers at friction 6

λ_{F6S3} - Arrival rate of passengers to service center 3 from friction 6

λ_{F5S3} - Arrival rate of passengers to service center 3 from friction 5

λ_{S2S3} - Arrival rate of passengers to service center 3 from service center 2

β_{S3} – Departure rate of passengers from service center 3

λ_{S3_New} - Arrival rate of passengers at service center 3

γ_{S3}- Service rate of passengers at service center 3

P1 = Probability of passengers who are going from entrance to friction 1

P2 = Probability of passengers who are going from entrance to friction 2

P3 = Probability of passengers who are going from friction 1 to friction 2

P4 = Probability of passengers who are going from service center 1 to friction 3

P5 = Probability of passengers who are going from service center 1 to friction 4

P6 = Probability of passengers who are going from friction 3 to friction 4

P7 = Probability of passengers who are going from service center 2 to friction 5

P8 = Probability of passengers who are going from service center 2 to friction 6

P9 = Probability of passengers who are going from friction 5 to friction 6

$\beta_{EF1} = \lambda_{EF1}$

$\beta_{EF2} = \lambda_{EF2}$

$\beta_{ES1} = \lambda_{ES1}$

$\beta_{F1S1} = \lambda_{F1S1}$

$\beta_{F1F2} = \lambda_{F1F2}$

$\beta_{F2S1} = \lambda_{F2S1}$

$\beta_{S1F4} = \lambda_{S1F4}$

$\beta_{S1F3} = \lambda_{S1F3}$

$\beta_{S1S2} = \lambda_{S1S2}$

$\beta_{F3S2} = \lambda_{F3S2}$

$\beta_{F3F4} = \lambda_{F3F4}$

$\beta_{F4S2} = \lambda_{F4S2}$

$\beta_{S2F6} = \lambda_{S2F6}$

$\beta_{S2F5} = \lambda_{S2F5}$

$\beta_{S2S3} = \lambda_{S2S3}$

$\beta_{F5S3} = \lambda_{F5S3}$

$\beta_{F5F6} = \lambda_{F5F6}$

$\beta_{F6S3} = \lambda_{F6S3}$

$\lambda_{F1} = P_1\lambda_E$

$\lambda_{F2} = P_3\lambda_{F1} + P_2\lambda_E$

$\lambda_{S1\_New} = (P_2 + P_3)\lambda_{F2} + (P_1 - P_3)\lambda_{F1} + (1 - P_1 - P_2)\lambda_E$

$\lambda_{F3} = P_4\lambda_{S1\_New}$

$\lambda_{F4} = P_6\lambda_{F3} + P_5\lambda_{S1\_New}$

$\lambda_{S2\_New} = (P_5 + P_6)\lambda_{F4} + (P_4 - P_6)\lambda_{F3} + (1 - P_4 - P_5)\lambda_{S1\_New}$

$\lambda_{F5} = P_7\lambda_{S2\_New}$

$\lambda_{F6} = P_9\lambda_{F5} + P_8\lambda_{S2\_New}$

$\lambda_{S3\_New} = (P_8 + P_9)\lambda_{F6} + (P_7 - P_9)\lambda_{F5} + (1 - P_7 - P_8)\lambda_{S2\_New}$

$\rho_1 = \frac{\lambda_{S1}}{\gamma_{S1}}$ $\rho_2 = \frac{\lambda_{S2}}{\gamma_{S2}}$ $\rho_3 = \frac{\lambda_{S3}}{\gamma_{S3}}$ $\rho_{1_{New}} = \frac{\lambda_{S1_{New}}}{\gamma_{S1}}$

$\rho_{2_{New}} = \frac{\lambda_{S2_{New}}}{\gamma_{S2}}$ $\rho_{3\_New} = \frac{\lambda_{S3\_New}}{\gamma_{S3}}$

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) + P(WT_{S3} > 0) > P(WT_{S1\_New} > 0) + P(WT_{S2\_New} > 0) + P(WT_{S3\_New} > 0)$$

$$\frac{(\rho_1)^{S_1}(\frac{1-\rho_1}{1-\rho_1^{N1+1}})}{S_1!\,(1-\rho_1)}+\frac{(\rho_2)^{S_2}(\frac{1-\rho_2}{1-\rho_2^{N2+1}})}{S_2!\,(1-\rho_2)}+\frac{(\rho_3)^{S_3}(\frac{1-\rho_3}{1-\rho_3^{N3+1}})}{S_3!\,(1-\rho_3)}$$

$$>\frac{(\rho_{1\_New})^{S_1}(\frac{1-\rho_{1\_New}}{1-\rho_{1\_New}^{N1+1}})}{S_1!\,(1-\rho_{1\_New})}+\frac{(\rho_{2\_New})^{S_2}(\frac{1-\rho_{2\_New}}{1-\rho_{2\_New}^{N2+1}})}{S_2!\,(1-\rho_{2\_New})}$$

$$+\frac{(\rho_{3\_New})^{S_2}(\frac{1-\rho_{3\_New}}{1-\rho_{3\_New}^{N3+1}})}{S_3!\,(1-\rho_{3\_New})}$$

4.4. Frictions placed before the gates

Consider the single pier terminal configuration with n number of gates without any frictions (Figure 4.11). The probability of passengers going to gate *n* is *Pn*. Once passengers entered the pier, it was assumed they would not come back to the terminal building. This analysis was done under the assumption that the gates are equally distributed (Saparamadu and Bandara, 2017).

Queuing theory was used to find the waiting time of the passenger. Here, only the processing time at gates and frictions were considered for the model. The probability of having waiting time for gate or friction was calculated using the queuing theory as shown below.

$$P(WT_{Gi}>0)=\left.{(\rho_i)^{S_i}(\frac{1-\rho_i}{1-\rho_i^{Ni+1}})}\middle/{S_i!\,(1-\rho_i)}\right. \quad ; \quad \rho_i=\frac{\lambda_i}{\gamma_i}$$

$P\ (WT_{Gi}>0)$ - Probability of passengers’ waiting time at the gate *i*

S_i – Number of servers at the gate *i*

N_i – Maximum number of passengers coming to the gate *i*

λ_i – Arrival rate of passengers at the gate *i*

γ_i – Service rate of passengers at the gate *i*

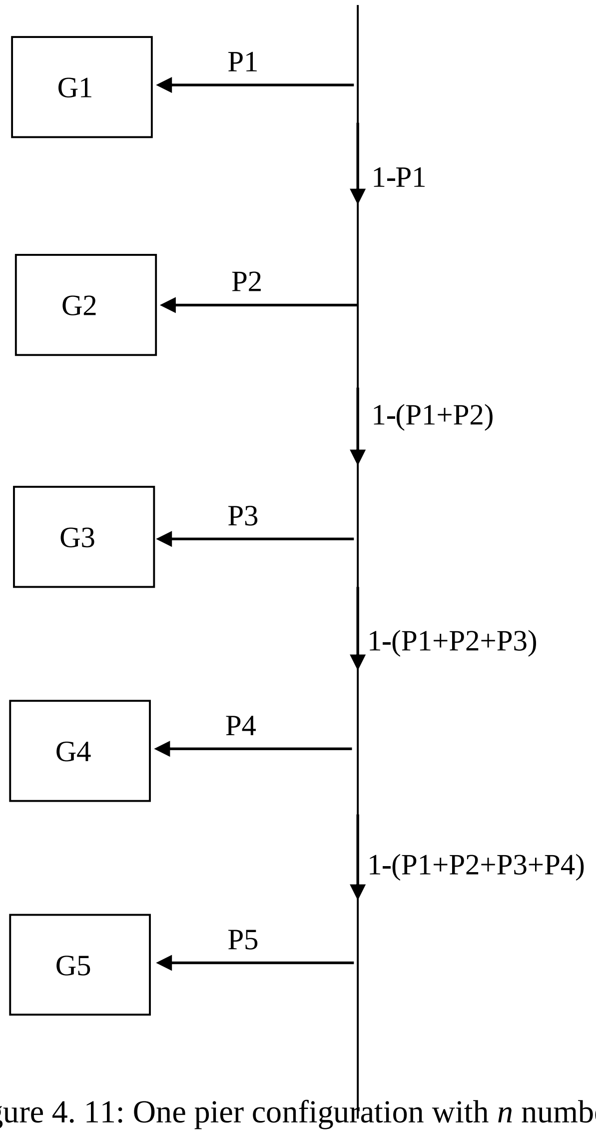


Figure 4. 11: One pier configuration with *n* number of gates

$$\sum_{i=1}^{n} P_i = 1$$

The probability of average waiting time at a gate for the passenger came to be the probability of average waiting time of n gates.

Average waiting time of a gate is

$$\frac{\sum_{i=1}^{n} P(WT_{G1} > 0)}{n} = \frac{\sum_{i=1}^{n} {(\rho_i)^{S_i}(\frac{1-\rho_i}{1-\rho_i^{Ni+1}})} \Big/ {S_i!\,(1-\rho_i)}}{n}$$

Place the m frictions in between the gates. Then the passengers can be moved to gates through frictions (Figure 4.12).

The following notations are used to find the waiting times at gates and frictions.

aj = Probability of being the passenger arrival to friction j

bj = Probability of being the passenger arrival to gate j

cij = Probability of being the passenger arrival from frictioni to gate j

dij = Probability of being the passenger arrival from frictioni to friction j

pj = Probability of being the total passenger arrival at gate j

λ = Passenger arrival rate to the pier

λ_{Fj} = Passenger arrival rate at friction j

λ_{Gj} = Passenger arrival rate at gate j

β_{FiGj}= Departure rate of passengers from friction i to gate j

λ_{FiGj} = Arrival rate of passengers to gate j from friction i

β_{FiFj} = Departure rate of passengers from friction i to friction j

λ_{FiFj} = Arrival rate of passengers to friction j from friction i

For frictions $\lambda_{Fj} = a_j\lambda + \sum_{i=1}^{j-1} d_{ij}\, \lambda_{Fi}$

For gates $\lambda_{Gj} = b_j\lambda + \sum_{i=1}^{j} c_{ij}\lambda_{Fj}$

Probability for gates $P_j = b_j + \sum_{i=1}^{j} c_{ij}$

$\beta_{FiGj} = \lambda_{FiGj}$

$\beta_{FiFj} = \lambda_{FiFj}$

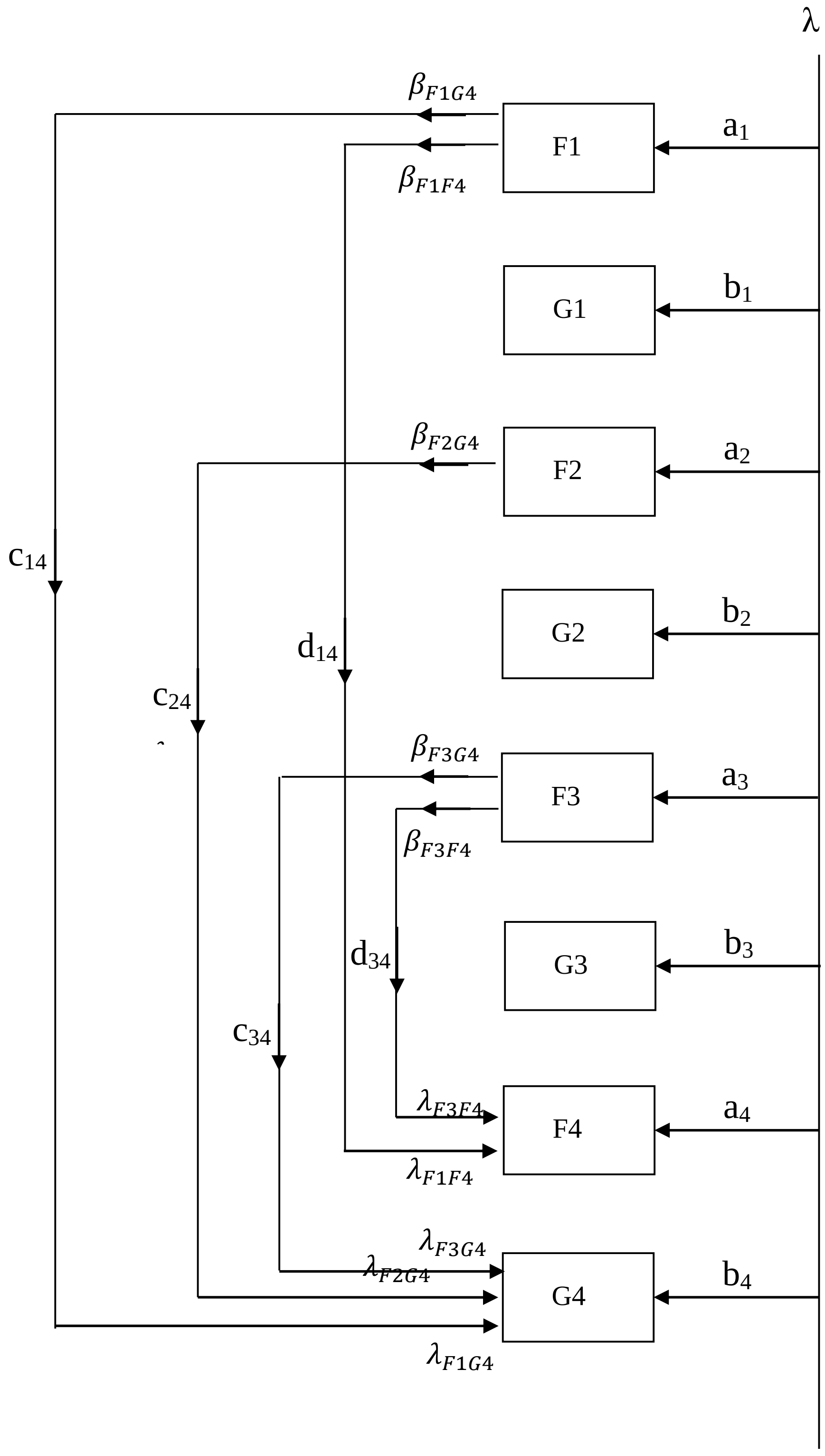


Figure 4. 12: One pier configuration with n number of gates and m number of frictions

$$\sum_{j=1}^{n} P_j = 1$$

$$b_j = P_j - \sum_{i=1}^{j} c_{ij}$$

$$a_j + \sum_{i=1}^{j-1} d_{ij} = \sum_{i=j}^{n} c_{ji} + \sum_{i=j+1}^{n} d_{ji}$$

If the average waiting time at gates with placing frictions in between was less than that of gates without placing frictions, those frictions were allowed to place:

Average waiting time of n gates with placing m frictions <
Average waiting time of n gates without placing frictions

P(Average waiting time of n gates after placing m fictions) <
P(Average waiting time of n gates without placing frictions)

$$\frac{\sum_{i=1}^{n} \left. (\rho_i)^{S_i} \left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right) \middle/ S_i!\,(1-\rho_i) \right.}{n} + \frac{\sum_{i=1}^{m} \left. (\rho_i)^{S_i} \left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right) \middle/ S_i!\,(1-\rho_i) \right.}{m}$$

$$< \frac{\sum_{i=1}^{n} \left. (\rho_i)^{S_i} \left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right) \middle/ S_i!\,(1-\rho_i) \right.}{n}$$

Once the conditions for placing frictions in between gates were found, several terminal configurations were selected to find out the optimum.

Figure 4.13 shows the layout of placing gates and frictions in one pier.

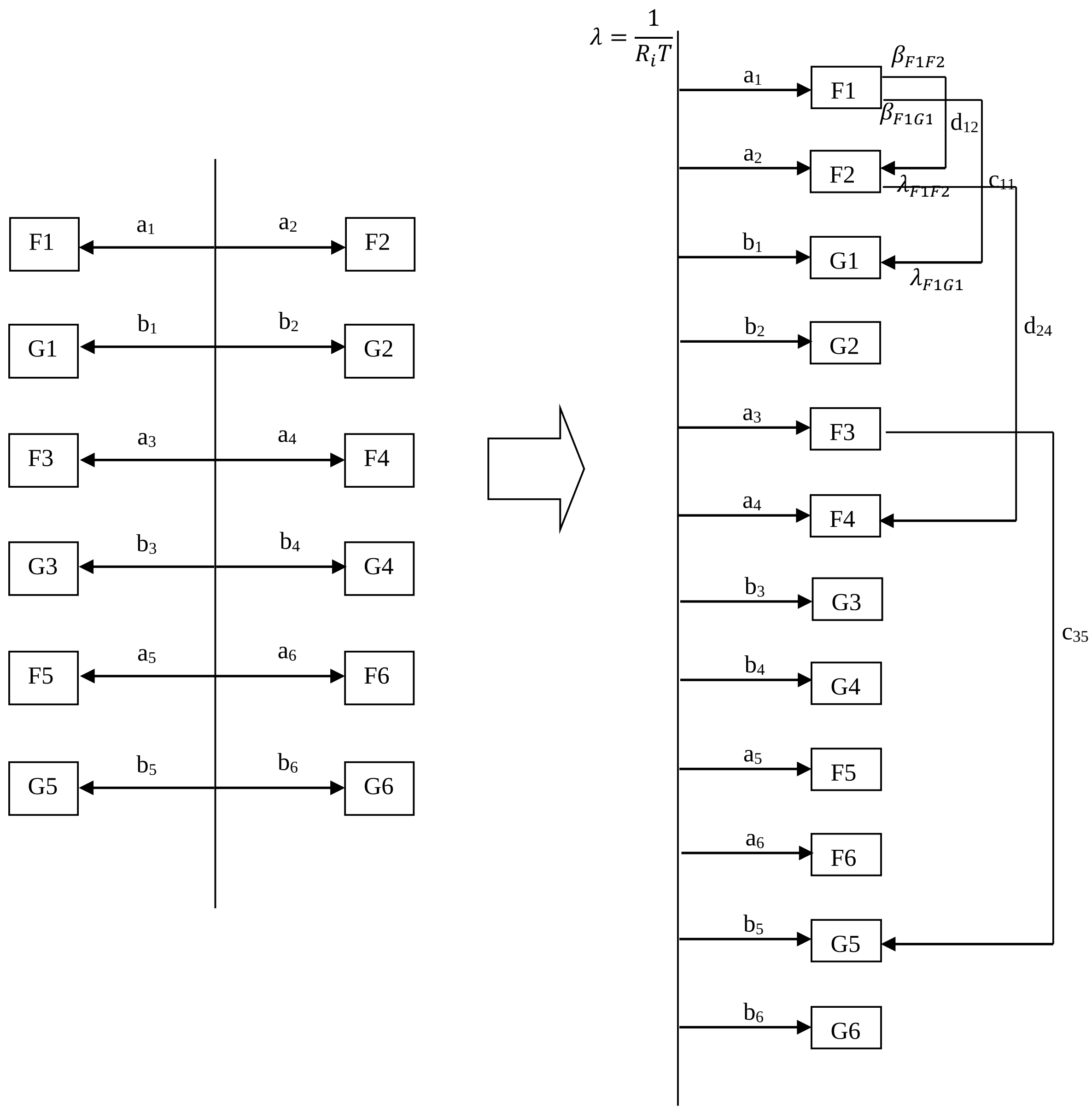


Figure 4. 13: The original layout and considered layout of the one pier

a_j = Probability of passenger arrivals to friction *j*

b_j = Probability of passenger arrivals to gate *j*

c_{ij} = Probability of passenger arrivals from friction *i* to gate *j*

d_{ij} = Probability of passenger arrivals from friction *i* to friction *j*

λ = Passenger arrival rate to the pier

P_j = Probability of passenger arrivals for gate j

Ri= Probability of passenger arrivals for pier *i*

R_iT = Number of passenger arrivals for pier i

T = Total number of passengers

λ_{Fj} = Passenger arrival rate at friction j

λ_{Gj} = Passenger arrival rate at gate j

β_{FiGj}= Departure rate of passengers from friction i to gate j

λ_{FiGj} = Arrival rate of passengers to gate j from friction i

β_{FiFj} = Departure rate of passengers from friction i to friction j

λ_{FiFj} = Arrival rate of passengers to friction j from friction i

For frictions $\lambda_{Fj} = a_j\lambda + \sum_{i=1}^{j-1} d_{ij}\lambda_{Fi}$

For gates $\lambda_{Gj} = b_j\lambda + \sum_{i=1}^{j} c_{ij}\lambda_{Fj}$

$\beta_{FiGj} = \lambda_{FiGj}$

$\beta_{FiFj} = \lambda_{FiFj}$

Probability for gates

$$P_j = b_j + \sum_{i=1}^{j+1} c_{ij} \quad (j = 1,3,5,\dots, Odd\ no.\ gates)$$

$$P_j = b_j + \sum_{i=1}^{j} c_{ij} \quad (j = 2,4,6,\dots, Even\ no.\ gates)$$

$$\sum_{i=1}^{n} P_i = 1 \sum_{i=1}^{n} R_i = 1\ \lambda_i = \frac{1}{R_iT} \qquad T = \sum_{i=1}^{n} R_iT$$

$$a_j + \sum_{i=1}^{j-1} d_{ij} = \sum_{i=j}^{n} c_{ji} + \sum_{i=j+1}^{n} d_{ji} \qquad b_j = P_j - \sum_{i=1}^{j} c_{ij}$$

4.5. Terminal Comparison

The first terminal configuration taken was for two piers with n/2 gates for each (Figure 4.14). Then average waiting times of a passenger at pier 1, that of a passenger at pier 2 and entire terminal were found by using queuing theory formula.

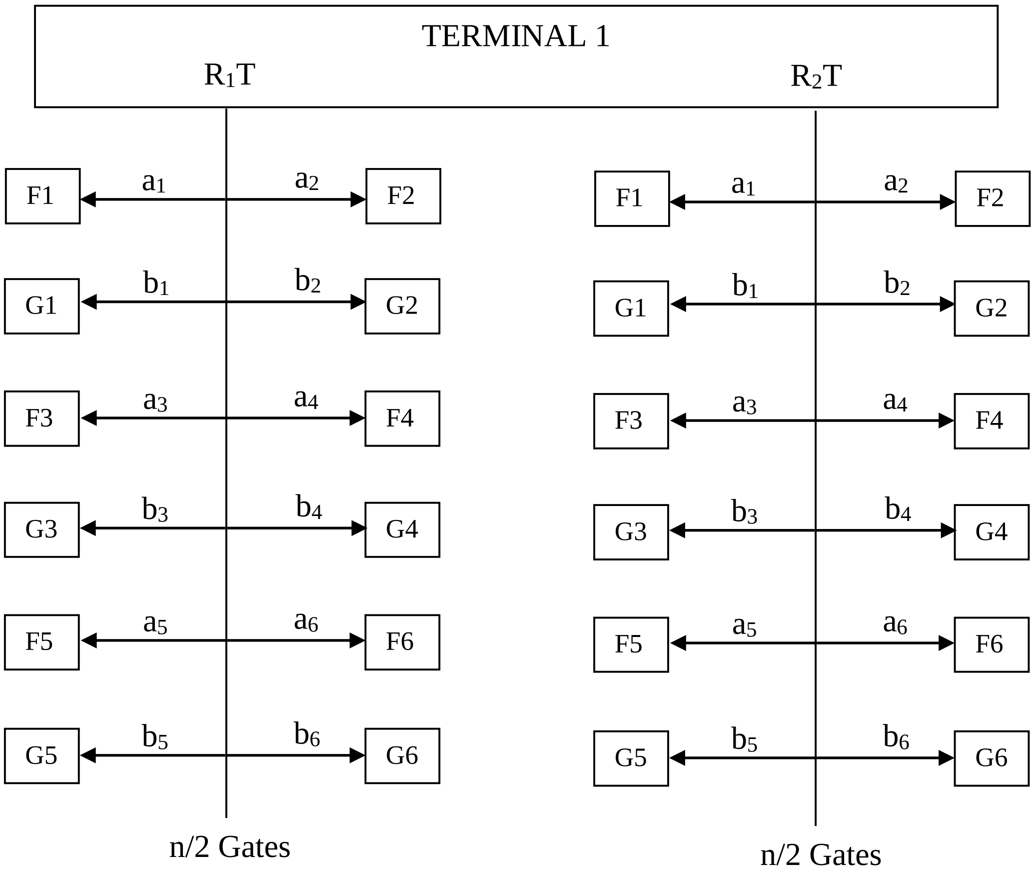


Figure 4. 14: Terminal configuration of two piers with n/2 gates for each

Total average waiting time of a passenger at pier 1

$$T_1 = \frac{\sum_{i=1}^{n/2} {(\rho_i)^{S_i}\left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right)} \Big/ {S_i!\,(1-\rho_i)}}{(n/2)}$$

Total average waiting time of a passenger at pier 2

$$T_2 = \frac{\sum_{i=1}^{n/2} \frac{(\rho_i)^{S_i}\left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right)}{S_i!\,(1-\rho_i)}}{(n/2)}$$

Total average waiting time of a passenger at Terminal 1

$$TAW\ 1 = \frac{(n/2)T_1 + (n/2)T_2}{(n/2) + (n/2)} = \frac{T_1 + T_2}{2}$$

Next terminal configuration was taken for three piers with n/3 gates for each and the average waiting times of a passenger at pier 1, that of at pier 2, pier 3 and entire terminal were found (Figure 4.15).

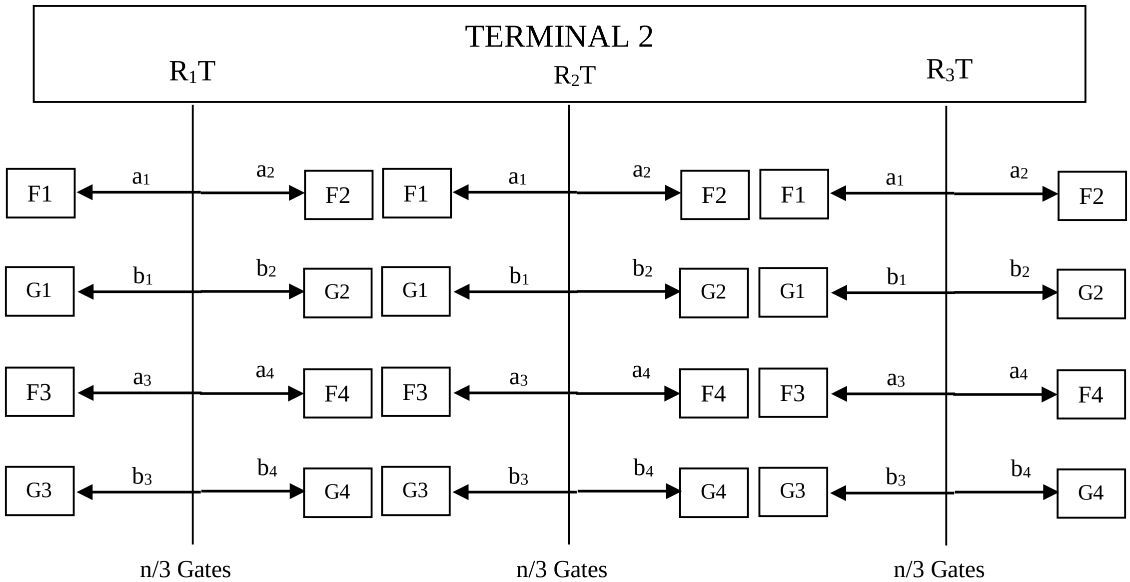


Figure 4. 15: Terminal configuration of three piers with n/3 gates for each

Total average waiting time of a passenger at pier 1

$$T_1 = \frac{\sum_{i=1}^{n/3} \frac{(\rho_i)^{S_i}\left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right)}{S_i!\,(1-\rho_i)}}{(n/3)}$$

Total average waiting time of a passenger at pier 2

$$T_2 = \frac{\sum_{i=1}^{n/3} {(\rho_i)^{S_i}(\frac{1-\rho_i}{1-\rho_i^{Ni+1}})}/{S_i!\,(1-\rho_i)}}{(n/3)}$$

Total average waiting time of a passenger at pier 3

$$T_3 = \frac{\sum_{i=1}^{n/3} {(\rho_i)^{S_i}(\frac{1-\rho_i}{1-\rho_i^{Ni+1}})}/{S_i!\,(1-\rho_i)}}{(n/3)}$$

Total average waiting time of a passenger at Terminal 2

$$TAW\ 2 = \frac{({}^{n}/_{3})T_1 + ({}^{n}/_{3})T_2 + ({}^{n}/_{3})T_3}{({}^{n}/_{3}) + ({}^{n}/_{3}) + ({}^{n}/_{3})} = \frac{T_1 + T_2 + T_3}{3}$$

Bandara (1990) and Bandara and Wirasinghe (1992), with their research, determined optimal terminal geometry as taking three piers with two equal length piers and one lengthy pier. Therefore, one of the terminals was selected using this view. So the last terminal configuration is taken for three piers with n1, n2 and n3 gates (Figure 4.16).

Here, $n_1 + n_2 + n_3 = n$ where $n_1 = n_3 = \frac{n-n_2}{2}$

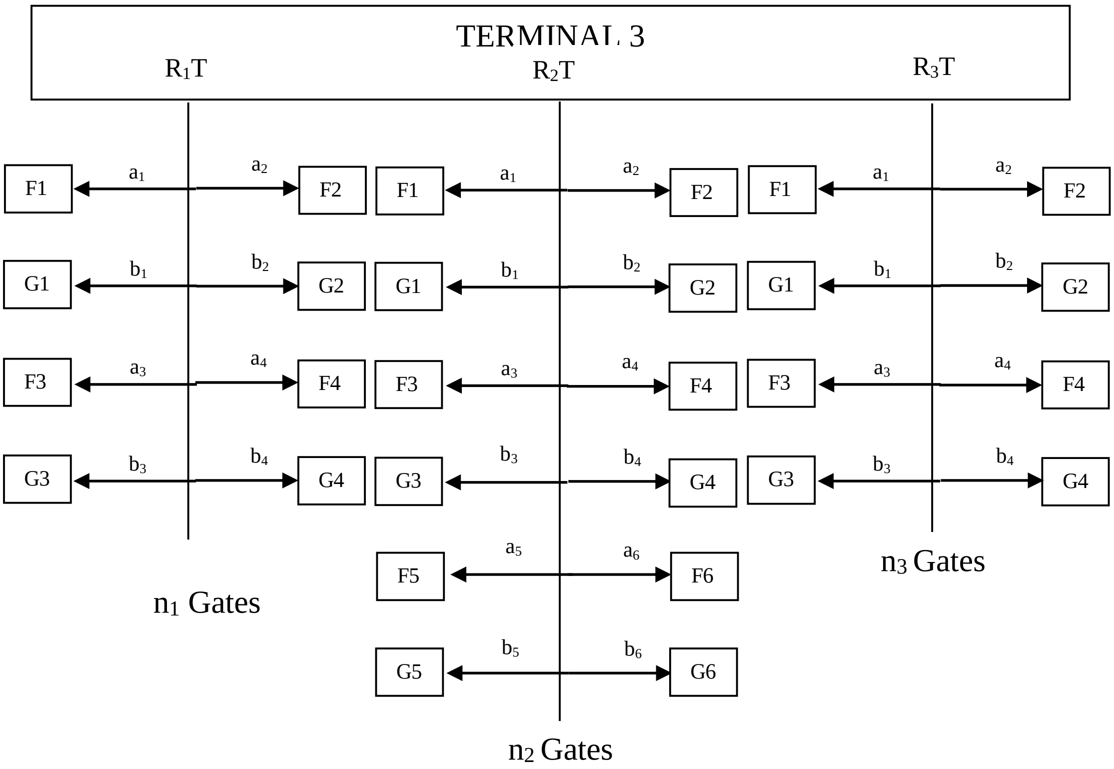


Figure 4. 16: Terminal configuration of three piers with different number of gates for each

Then the average waiting times of a passenger at pier 1, at pier 2, pier 3 and the entire terminal were found.

Total average waiting time of a passenger at pier 1

$$T_1 = \frac{\sum_{i=1}^{n1} \left. (\rho_i)^{S_i} \left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right) \middle/ S_i!\,(1-\rho_i) \right.}{n_1}$$

Total average waiting time of a passenger at pier 2

$$T_2 = \frac{\sum_{i=1}^{n2} \left. (\rho_i)^{S_i} \left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right) \middle/ S_i!\,(1-\rho_i) \right.}{n_2}$$

Total average waiting time of a passenger at pier 3

$$T_3 = \frac{\sum_{i=1}^{n3} {(\rho_i)^{S_i} (\frac{1-\rho_i}{1-\rho_i^{Ni+1}})} \Big/ {S_i! \, (1-\rho_i)}}{n_3}$$

Total average waiting time of a passenger at Terminal 3

$$TAW\ 3 = \frac{(n_1)T_1 + (n_2)T_2 + (n_3)T_3}{n_1 + n_2 + n_3}$$

By comparing TAW 1, TAW 2 and TAW 3 values, the optimum terminal configuration can be found by taking the minimum value from the above total average waiting times at terminals.

4.6. Summary

Several tests like: Welch t-test, hypothesis testing, ANOVA test, F test and Levene test were used to identify locations for proper frictions between mandatory and service centers. With terminal configuration, it was also necessary for proper frictions to be accommodated before the gates as this could help minimize passenger delays. Several steps described within the chapter helped check the significant differences between the distributions of placing frictions before mandatory service centers and their parameters. Queuing theory helped with the distributions of locations for proper frictions before the gates. Comparing them with terminal configurations, it was possible to determine optimal terminal configuration.

5. SIMULATION AND OPTIMIZATION

5.1. Introduction

This chapter is about collection of data and analyzing collected data for frictions and mandatory service centers to determine optimum positions of frictions between service centers to minimize passenger delays. Analytical models were found to identify optimum positions of frictions between service centers to minimize passenger delays. The solutions were then verified by using simulation models.

Analytical models help to find optimum places for frictions which can be placed before the mandatory service centers. Different alternatives by replacing one friction from another friction also help find the optimum result using analytical models. Simulation models helped to get the detailed information and verify the analytical solutions regarding optimum places for frictions which can be located before the service centers.

It cannot be forgotten that placing frictions in between gates depends on factors such as the probability of arrivals of passengers to the frictions, probability of arrivals of passengers from one friction to another friction, total passenger arrival rate to the pier and arrival rates and service rates at the frictions. It has also to be remembered that a model for an optimum terminal configuration depends on several other important factors such as the number of piers, the number of gates in each pier, number of frictions in each pier, the manner of placing frictions in between gates, percentage of passengers going through the different frictions, the distributions and parameters (mean and variance) of frictions, processing time for frictions and gates, number of piers and gate spacing, which minimize the mean mandatory walking distance of arriving, departing, and transferring passengers within the terminal.

5.2. Gathering Data

The data regarding passengers' service time and waiting time at each mandatory service center in arrival and departure procedures and passengers' waiting time at frictions were collected from the Bandaranaike International Airport (BIA).

5.2.1. Service time data at immigration counters in arrival procedure

As each passenger joined the queue of an immigration counter and when he started to get the service from the counter, the time was set to start and it stopped after the passenger left that counter. The waiting time of the passenger in that particular counter was taken in this manner. To measure waiting time and service time at immigration counters, 10 - 15 passengers were selected at a time. It was assumed that all of them got into the queue at the same time. The service time for individual passengers in the selected group was measured. The passengers' waiting times at each counter was calculated by getting cumulative service time. Table 5.1 explains the way to calculate waiting time by getting at the cumulative service time. It is assumed that waiting time of the first passenger in a particular service center is zero.

Table 5. 1: Service time and waiting time at Immigration counter in arrival procedure

Passenger	Service Time (Seconds)	Waiting Time (Seconds)
1	S_1	$W_1 = 0$
2	S_2	$W_2 = W_1 + S_1$
3	S_3	$W_3 = W_2 + S_2$
.	.	.
i - 1	S_{i-1}	$W_{i-1} = W_{i-2} + S_{i-2}$
i	S_i	$W_i = W_{i-1} + S_{i-1}$
.	.	.
n	S_n	$W_n = W_{n-1} + S_{n-1}$

Service time and waiting time of all the mandatory service centers in arrival and departure procedures were measured by using the above mentioned method.

The waiting time of the passenger in mandatory service centers of check-in counters, ticketing counters and immigration counters depend on the numbers of counters at these service centers. For baggage station this will depend on the size of the belt and total number of passengers at the belt.

It is known that the outlier is sometimes due to incorrectly entered or measured data. If the dataset has outliers, it affects both results and assumptions. So it is needed to find any outlier of the dataset before starting the analysis. To find out the outliers of each dataset box plots were used. Once outliers were considered and completed they were removed from the dataset and the dataset without outliers were considered for further analysis.

5.3. Distributions of service times and waiting times of mandatory service centers

The second step was to find the distributions of service times and waiting times of mandatory services.

The cumulative waiting time of all mandatory service centers in each procedure is essential towards finding the waiting time of the entire procedures of arrival and departure. The distributions of the waiting time at each service center are necessary to find the cumulative waiting time of the service centers. So after removing outliers, the rest of the data of data set was used to find the distributions. For the purpose, histograms and probability plots were used. Once the distribution was found, Anderson Darling test was used to verify the distribution.

The Anderson-Darling test is done by using hypothesis and hypothesis are defined as:
H0 : The data follow a specified distribution
H1 : The data do not follow the specified distribution

The critical values for the Anderson-Darling test are dependent on the specific distribution with that being tested.

Since the population mean and variance are unknown and taking 0.05 level as significance, Anderson Darling value (AD value) 0.787 is considered for the research (Stephens, 1976).

Data of service time at Immigration counters at arrival procedure is used to get the histogram and probability plot first.

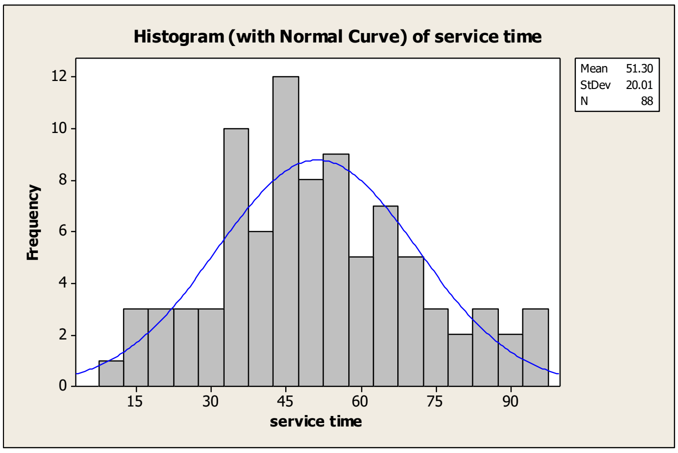


Figure 5. 1: Histogram of the data of waiting time at Immigration counters

The histogram of waiting time at Immigration counters tends to show a normal distribution with mean 51.3 seconds and standard deviation 20.0 seconds.

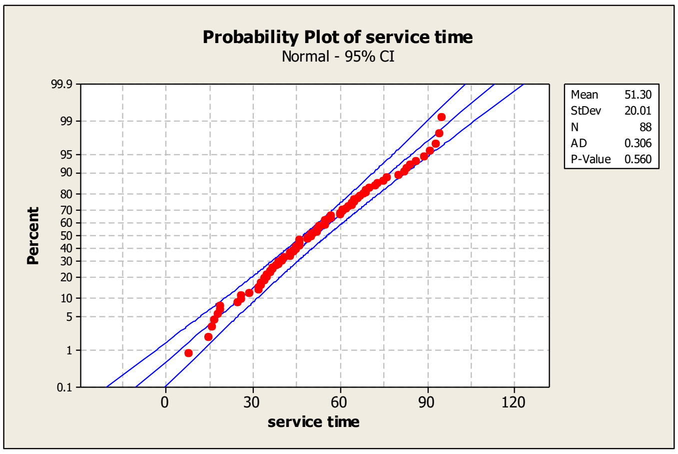


Figure 5. 2: Probability Plot of the data of waiting time at Immigration counters

Figure 5.2 shows a probability plot of waiting time at immigration counters as under 95% confidence interval. It follows the normal distribution with mean 51.3 seconds and standard deviation 20.0 seconds. Anderson Darling goodness of fit test, a test of fit for distributions, was used to detect most departures from normality. The Anderson Darling value (AD value) of above probability plot 0.306 is less than 0.787, and P value 0.56 of above probability plot is greater than 0.05 concludes the distribution of service time at immigration counters in arrival procedure tends towards normal distribution.

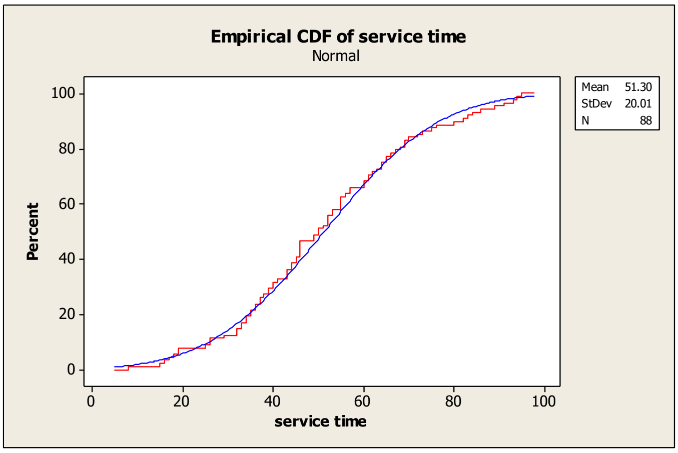


Figure 5. 3: Empirical Cumulative Distribution Function of the data of waiting time at Immigration counters

Cumulative distribution function of normal distribution is S shaped function and figure 5.3 helps to verify the above fitted distribution (normal distribution) for waiting time at immigration counters in arrival procedure in advance.

After removing outliers from all data sets of service time and waiting time at check-in counters, ticketing counters, immigration counters and baggage stations in arrival and departure procedures by using box plots, the distributions of above mentioned data sets was started.

By applying Anderson-Darling test, the distributions of waiting time and service time of check-in counters, ticketing counters, immigration counters and baggage stations were found and verified.

Table 5. 2: Distributions of waiting and service time of mandatory service centers at BIA

	Departure Procedure					
Service Center	Waiting Time			Service time		
	Distribution	Mean (Seconds)	Std. Dev. (Seconds)	Distribution	Mean (Seconds)	Std. Dev. (Seconds)
Entrance check-in	Weibull	742	464	Log-normal	179	101
Ticketing counter	Normal	120	68			
Immigration counter	Normal	396	230	Log-normal	53	26
	Arrival Procedure					
Immigration counters	Weibull	358	200	Normal	51	20
Baggage Stations	Normal	542	370	Log-normal	81	36

Passengers have to wait for longer times at entrance check-in than at other counters. The standard deviation of the entrance check-in is also high. Passengers' waiting time at the entrance check-in is high because the service time at this counter is comparably high (Average waiting time and standard deviation of entrance check-in is higher than that of other all counters).

After doing the analysis for distributions of waiting time and service time at each mandatory service center in arrival and departure procedures separately, Normal, Weibull and Log-Normal distributions were identified and those are shown above in Table 5.2.

This was necessary to connect the mandatory service centers in entire procedures of arrival and departure counters. At the same time, it was required to position the frictions in between mandatory service centers. Therefore, finding the distributions of cumulative service times and waiting times is essential. This required a combination of the distributions of service times / waiting times of mandatory service centers as well as those of frictions. To find the parameters for distributions of cumulative service times / waiting times analytically, it is needed to convert all the distributions into one type of distribution. Then the next step was to transform all the distributions of service times and waiting times to normal distribution.

5.4. Transform other distributions to Normal distribution

Weibull and Log-normal distributions are highly skewed. Analysis of finding cumulative service times and waiting times required that data are normally distributed. This is because normal distribution has special properties which are used to derive the distributions of cumulative service times and waiting times.

5.4.1. Transformation of Weibull distribution to Normal distribution

Waiting time at immigration counters in arrival procedure and waiting time at check-in counters in departure procedure followed a Weibull distribution.

Let X = Waiting time at immigration counters in arrival procedure / waiting time at check-in counters in departure procedure

$X \sim Weibull\ (\lambda\,, k)$ Where λ is a scale parameter and k is a shape parameter and $\lambda\,, k\ > 0$.

The distribution of waiting time at entrance check-in in departure procedure is Weibull distribution and its probability plot is as below.

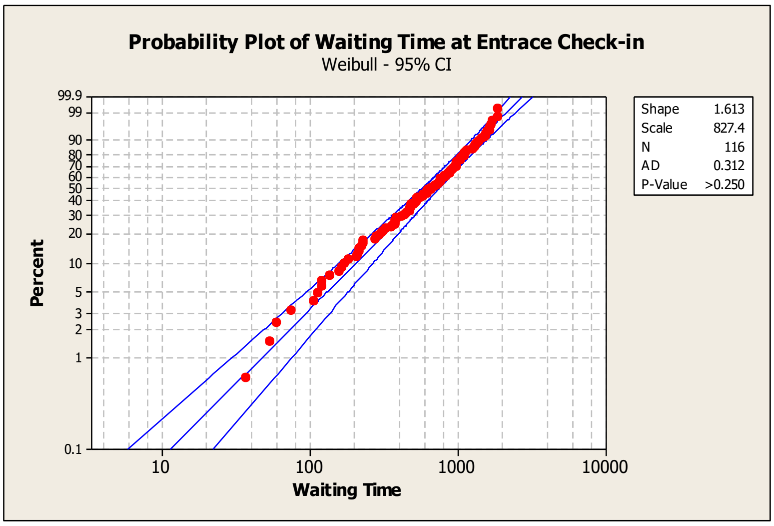


Figure 5. 4: Probability Plot of the data of waiting time at entrance check-in counters in departure procedure before the transformation

By taking the transformation of $Y = X^{(1/2)}$, Y tends to normal distribution with mean μ and variance σ^2.

$Y \sim Normal\ (\mu, \sigma^2)$

By applying the transformation of $Y = X^{(1/2)}$ for waiting time check-in counters in departure procedure, it follows the Normal distribution as follows.

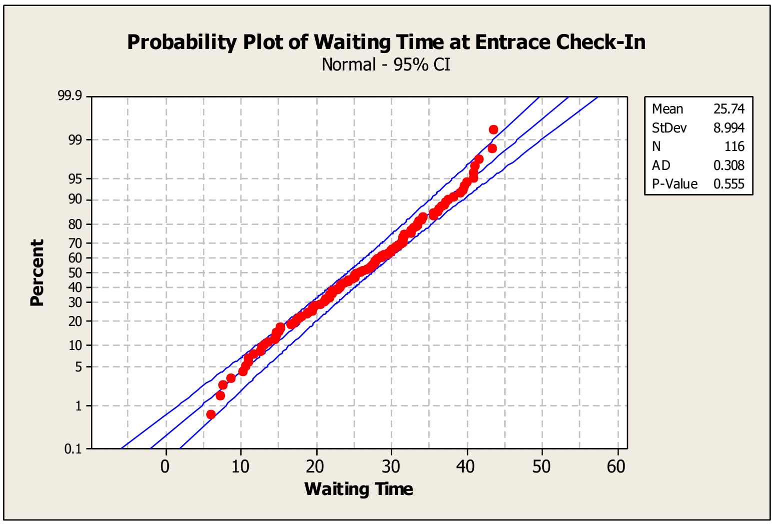


Figure 5. 5: Probability Plot of the data of waiting time at Entrance Check-in counters in departure procedure after the transformation

By using the above transformation, all Weibull distributions were transformed to normal distribution.

5.4.2. Transformation of Log-Normal distribution to Normal distribution

Service time at baggage stations in arrival procedure and service time at check-in counters and immigration counters in departure procedure followed a log-normal distribution.

Let X = Service time at baggage stations in arrival procedure / service time at check-in counters in departure procedure / service time at immigration counters in departure procedure

$X \sim Log - Normal\ (M, S^2)$Where M is a mean and S^2 is a variance of log-normal distribution.

The distribution of service time at entrance check-in in departure procedure is Log-Normal distribution and its probability plot is as shown below.

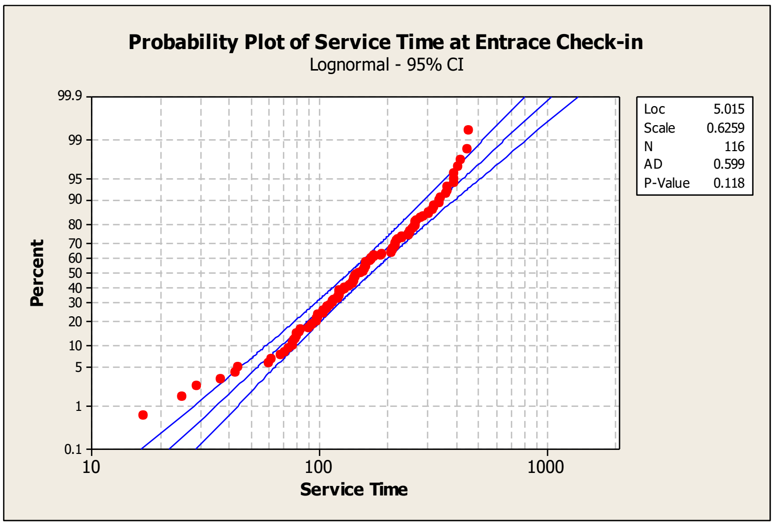


Figure 5. 6: Probability Plot of the data of service time at Entrance Check-in counters in departure procedure before the transformation

By taking the transformation of $Y = LN(X)$, Y tends to normal distribution with mean μ and variance σ^2.

$Y \sim Normal\ (\mu, \sigma^2)$

By applying the transformation of $Y = LN(X)$ for service time at check-in counters in departure procedure, it follows the Normal distribution as follows.

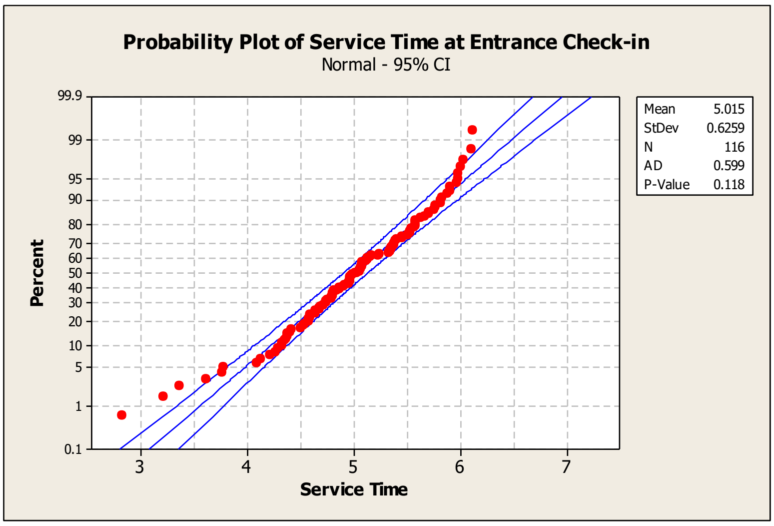


Figure 5. 7: Probability Plot of the data of service time at Entrance Check-in counters in departure procedure after the transformation

By using above mentioned transformation, every log-normal distribution is transformed to normal distribution.

The distribution of service time at immigration counters in departure procedure followed the Log-normal distribution originally. By applying the transformation of LN(X) for the data set it tends to lean towards Normal distribution.

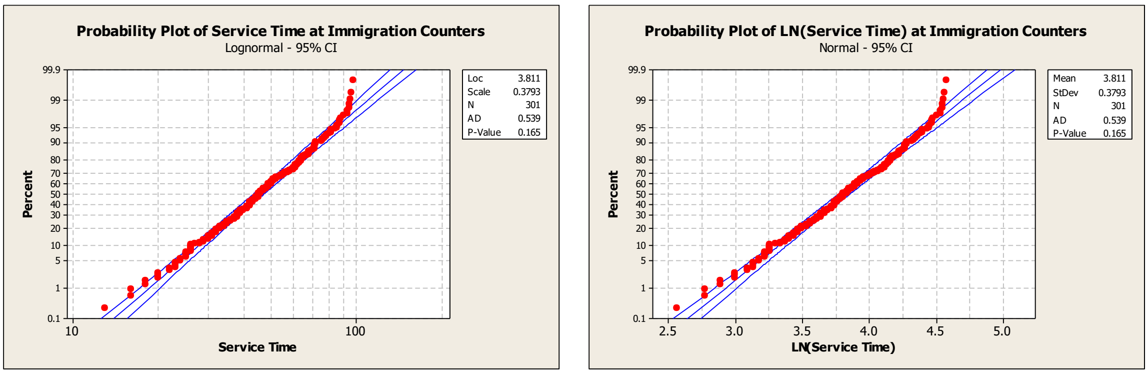


Figure 5. 8: Probability Plots of the data of service time at Immigration counters in departure procedure before and after the transformation

In the same manner the distribution of waiting time at immigration counters in arrival procedure follows the Weibull distribution and after affecting the transformation of Square root of X for the records it tends to show Normal distribution and basically the distribution of service time at immigration counters follows the Log-normal distribution and after getting the transformation of LN(X) for data set it goes to Normal distribution.

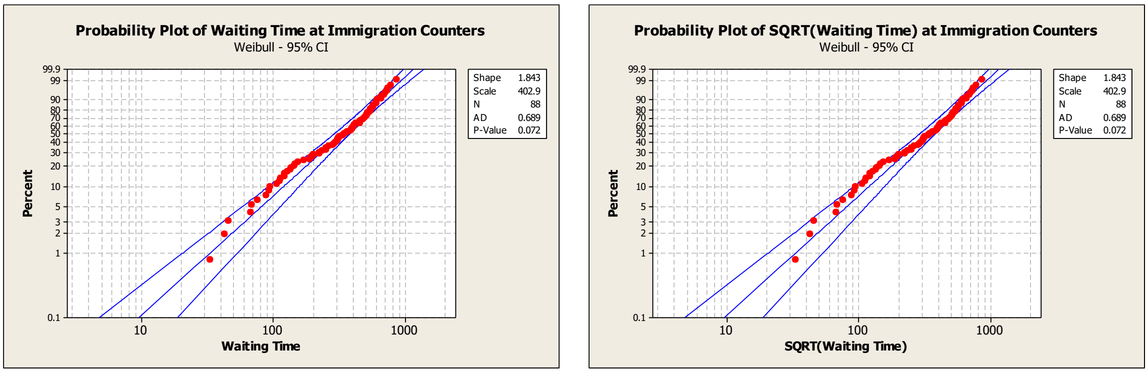


Figure 5. 9: Probability Plots of the data of waiting time at Immigration counters in arrival procedure before and after the transformation

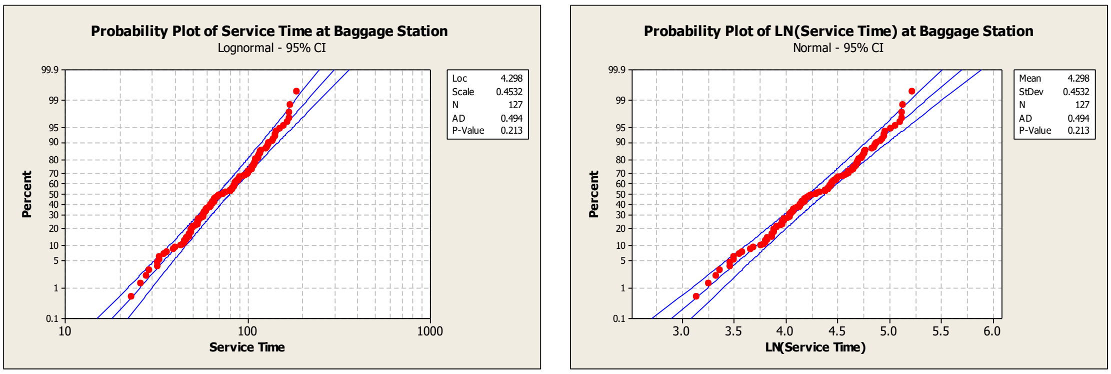


Figure 5. 10: Probability Plots of the data of service time at baggage station in arrival procedure before and after the transformation

5.5. Parameters for Cumulative Distributions

According to the objective, placing frictions between mandatory service centers to minimize the passengers' delay is one of the most important tasks in this research. This requires the findings of the distributions of waiting time of entire arrival and departure procedures, placing frictions between the service centers.

It is needed to find the cumulative mean and variance for combining two and three independent continuous random variables analytically. Because, once the frictions are placed before the mandatory service centers in arrival and departure procedures, it is required to calculate the cumulative mean of the waiting times / service times and cumulative variance of the waiting times / service times for the entire procedures.

First, one friction was placed before the mandatory service center and the mean of the waiting times / service times and variance of the waiting times / service times were calculated. Then, two frictions are placed before the mandatory service center and the mean of the waiting times / service times and variance of the waiting times / service times were calculated. For this purpose, below mentioned equations (5.1), (5.2), (5.3) and (5.4) were used (Bandara and Wirasinghe, 1989).

For a continuous random variable X,

Mean $E(x) = \bar{x}$

Variance $V(X) = \sigma_x^2$

For continuous random variables X and Y,

Let $P = X\,Y$

Mean $\bar{P} = \bar{x}\bar{y}$ --------------- (5.1)

Variance $\sigma_P^2 = \sigma_x^2\sigma_y^2 + \bar{x}^2\sigma_y^2 + \bar{y}^2\sigma_x^2$ -------------- (5.2)

For continuous random variables X, Y and Z,

Let $W = X\,Y\,Z$

Mean $\bar{w} = \bar{x}\bar{y}\,\bar{z}$ ------------- (5.3)

Variance

$\sigma_w^2 = \sigma_x^2\sigma_y^2\sigma_z^2 + \bar{x}^2\sigma_y^2\sigma_z^2 + \bar{y}^2\sigma_x^2\sigma_z^2 + \bar{z}^2\sigma_x^2\sigma_y^2 + \bar{x}^2\bar{y}^2\sigma_z^2 + \bar{y}^2\bar{z}^2\sigma_x^2 + \bar{x}^2\bar{z}^2\sigma_y^2$-(5.4)

5.6. Placing frictions before the mandatory service centers

The data of service times at frictions such as wash rooms, shops, food cabins, internet access, etc. were collected by using sample surveys and the distributions of waiting times at frictions were found. The table below shows the distributions of waiting times with their relevant parameters.

Table 5. 3: The distributions of frictions with means and variances

Friction	Mean (Seconds)	Std. Dev. (Seconds)	Distribution
Wash Rooms	180	300	Normal
shops	1500	2100	Normal
Food cabins	1800	1800	Normal
Internet Access	300	300	Normal

When the frictions such as wash rooms, food cabins, internet access and shops were placed in between various places of airport terminal mandatory service centers, the distributions were found with means and standard deviations by using above (5.1), (5.2), (5.3) and (5.4) equations.

Distributions of complete waiting times of two service centers with parameters were found using above (5.1), (5.2), (5.3) and (5.4) equations for arrival and departure procedures.
Eg: Distribution of complete waiting time of immigration counters and baggage claims

In the same manner distributions of complete waiting times of a service center and a friction with parameters were found using the same (5.1), (5.2), (5.3) and (5.4) equations.
Eg: Distribution of complete waiting time of wash rooms and immigration counters

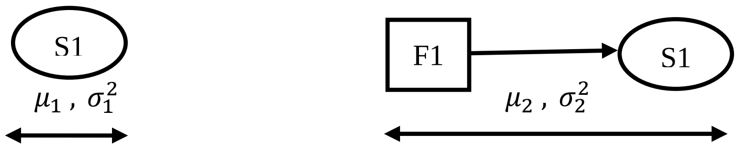
To find the optimal terminal configuration, it is required to minimize waiting times in the queues at the mandatory service centers in arrival (security checks, ticketing counters and immigration counters) and departure procedures (immigration counters and baggage claims). For that, it is good to place frictions (food cabins, shops, internet access, washroom and charging points) in between mandatory service centers.

Before placing frictions, it is needed to check whether it is accepted or not to place frictions before the mandatory service centers. For this purpose, Welch's t – test, ANOVA and hypothesis testing, Levene test and F test were used to identify proper frictions which can be placed before the mandatory service centers. Welch's t – test, ANOVA and hypothesis testing were used to check the differences between the means of frictions, that of mandatory service centers and that of combining frictions and mandatory service centers. Levene test, F test and hypothesis testing were used to check the differences between the variances of frictions, that of mandatory service centers and that of combining frictions and mandatory service centers.

The steps detailed below were considered to check the differences between the distributions of placing frictions before the mandatory service centers with their parameters. Since the service times at mandatory service centers without frictions and that of mandatory service centers with frictions are not changed, only waiting times at service centers were considered to get the means and variances.

First, the differences between mean of the waiting times at service centers and the differences between variances of the waiting times at service centers were found. Then a friction was placed before the service center and again the difference between mean of the waiting times and that of variance of the waiting times were found. If the mean and variance of the waiting times at service center with the friction are greater than that of only the service center, the friction is not allowed to be placed before the service center. This process is done by taking only the service center, one friction with the service center and two frictions with the service center as follows.

(1) Difference between mean of the waiting times at service centers and difference between variance of the waiting times at service centers when one friction is placed before the second service center



Mean waiting time at immigration counters and mean waiting time at immigration counters through wash rooms in arrival procedure were analyzed by using Welch t-test and hypothesis testing.

$\mathrm{H}_0 : \mu_{Immigration} - \mu_{Immigration+Wash\,rooms} = 0$ Vs

$\mathrm{H}_1 : \mu_{Immigration} - \mu_{Immigration+Wash\,rooms} > 0$

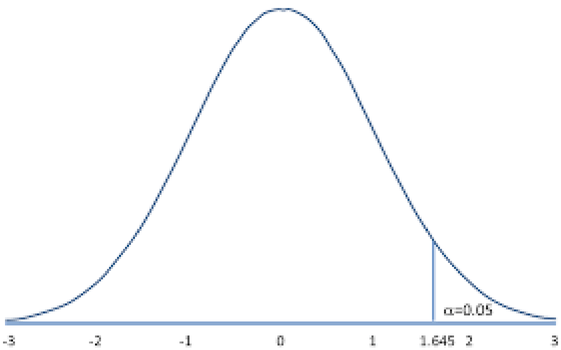
	N	Mean	St. Dev.	SE Mean
Imm_wait	88	358	200	21
Imm+Wash	88	253	210	22

Difference = mu (Imm_wait) - mu (Imm+Wash)

Estimate for difference: 105.250

95% lower bound for difference: 54.143

T-Test of difference = 0 (vs>): T-Value = 3.41 P-Value = 0.000 DF = 173



$\text{P value} = 0.000 < 0.05 = \alpha$

H_0 is rejected at 0.05 level of significance.

$\mu_{Imm} > \mu_{Imm+Wash}$

Therefore, there is an enough evidence to conclude that mean waiting time at immigration counters is greater than that of washrooms through immigration counters at 0.05 level of significance.

Standard deviation of waiting time at immigration counters and standard deviation of waiting time at immigration counters through wash rooms in arrival procedure were analyzed by using hypothesis testing and F test.

σ_1 : standard deviation of Immigration

σ_2 : standard deviation of Immigration + Washrooms

H_0: $\sigma_1 / \sigma_2 = 1$

H_1: $\sigma_1 / \sigma_2 \neq 1$

Significance level $\alpha = 0.05$

Ratio of Standard Deviations

Estimated Ratio	95% CI for Ratio using F
0.955272	(0.773, 1.180)

F method was used. This method is accurate for normal data only.

Method	Test Statistic	DF1	DF2	P-Value
F	0.91	87	87	0.670

0.670 = P-value > α = 0.05

H_0 is not rejected under 0.05 level of significance.

$\sigma_1 = \sigma_2$

Therefore, there is an enough evidence to conclude that variance waiting time at immigration counters is equal to that of immigration counters through washrooms 0.05 level of significance.

According to the above results, considering the conditions for mean waiting time and variance waiting time, mean waiting time at immigration counters is greater than that of immigration counters through washrooms and variance waiting time at immigration counters is equal to that of immigration counters through washrooms, allowing washrooms to be placed before the immigration counters.

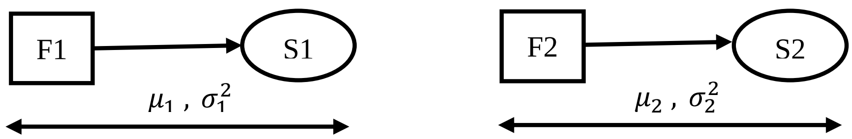
By applying Welch t-test, hypothesis testing and F test for all the mandatory service centers in arrival and departure procedures (check-in, ticketing, immigration, baggage station), the proper frictions (washrooms, shops, food cabins, internet access) which can be placed before the mandatory service centers can be found and it is shown below. The decisions were taken by using the criteria which is described in Table 4.1.

Table 5. 4: The proper frictions which can be placed before the mandatory service centers in arrival and departure procedures

Friction	Arrival		Departure		
	Immigration Counters	Baggage Station	Check-in Counters	Ticketing Counters	Immigration Counters
Wash rooms	√	√	√	√	√
Shops	√	x	√	x	x
Food cabins	√	x	√	√	x
Internet access	√	√	√	√	√

It is needed to check whether it can be minimized the queue delays by placing one friction before the first service center and another friction before the second service center.

2) Difference between mean of the waiting times at service centers and difference between variance of the delays at service centers when one friction is placed before both service centers



Waiting time at immigration counters through one friction and waiting time at baggage station through another friction in arrival procedure were analyzed by using hypothesis testing, two sample t test and F test (Appendix A) and below conclusions can be taken by using the criteria described in Table 4.1.

Table 5. 5: The status of placing frictions before the mandatory service centers in arrival procedures

	Immigration	Baggage Station	Decision for Mean	Decision for Variance	Decision for placing friction
Friction	Shops	Washrooms	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
		Shops	$\mu_1 = \mu_2$	$\sigma_1^2 = \sigma_2^2$	Optional
		Food cabins	$\mu_1 = \mu_2$	$\sigma_1^2 = \sigma_2^2$	Optional
		Internet access	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed

That means, placing shops before the immigration counters and placing washrooms before the baggage station can be allowed. At the same time, it is optional (either can be placed or cannot be placed) to place shops before the immigration counters and place food cabins before the baggage stations.

By taking all frictions and mandatory service centers in arrival procedure, entire analysis was done and was summarized as shown below.

Table 5. 6: The status of placing frictions before the mandatory service centers in arrival procedures

	Immigration	Baggage Station	Decision for Mean	Decision for Variance	Decision for placing friction
Friction	Washrooms	Washrooms	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Shops	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Food cabins	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Internet access	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
Friction	Shops	Washrooms	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
		Shops	$\mu_1 = \mu_2$	$\sigma_1^2 = \sigma_2^2$	Optional
		Food cabins	$\mu_1 = \mu_2$	$\sigma_1^2 = \sigma_2^2$	Optional
		Internet access	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
Friction	Food cabins	Washrooms	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
		Shops	$\mu_1 = \mu_2$	$\sigma_1^2 = \sigma_2^2$	Optional
		Food cabins	$\mu_1 = \mu_2$	$\sigma_1^2 = \sigma_2^2$	Optional
		Internet access	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
Friction	Internet access	Washrooms	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Shops	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Food cabins	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Internet access	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed

By taking all frictions and mandatory service centers in departure procedure, entire analysis was done and is as summarized below.

Table 5. 7: The status of placing frictions before the mandatory service centers in departure procedures

	Check-in Counters	Ticking Counters	Decision for Mean	Decision for Variance	Decision for placing friction
Friction	Washrooms	Washrooms	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
		Shops	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Food cabins	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Internet access	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
Friction	Shops	Washrooms	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
		Shops	$\mu_1 < \mu_2$	$\sigma_1^2 = \sigma_2^2$	Disallowed
		Food cabins	$\mu_1 < \mu_2$	$\sigma_1^2 = \sigma_2^2$	Disallowed
		Internet access	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
Friction	Food cabins	Washrooms	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
		Shops	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Food cabins	$\mu_1 < \mu_2$	$\sigma_1^2 = \sigma_2^2$	Disallowed
		Internet access	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
Friction	Internet access	Washrooms	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
		Shops	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Food cabins	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Internet access	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed

Table 5. 8: The status of placing frictions before the mandatory service centers in departure procedures

	Ticking Counters	Immigration Counters	Decision for Mean	Decision for Variance	Decision for placing friction
Friction	Washrooms	Washrooms	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Shops	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Food cabins	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Internet access	$\mu_1 < \mu_2$	$\sigma_1^2 = \sigma_2^2$	Disallowed
Friction	Shops	Washrooms	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
		Shops	$\mu_1 > \mu_2$	$\sigma_1^2 = \sigma_2^2$	Allowed
		Food cabins	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
		Internet access	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
Friction	Food cabins	Washrooms	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
		Shops	$\mu_1 = \mu_2$	$\sigma_1^2 = \sigma_2^2$	Optional
		Food cabins	$\mu_1 = \mu_2$	$\sigma_1^2 = \sigma_2^2$	Optional
		Internet access	$\mu_1 > \mu_2$	$\sigma_1^2 > \sigma_2^2$	Allowed
Friction	Internet access	Washrooms	$\mu_1 = \mu_2$	$\sigma_1^2 = \sigma_2^2$	Optional
		Shops	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Food cabins	$\mu_1 < \mu_2$	$\sigma_1^2 < \sigma_2^2$	Disallowed
		Internet access	$\mu_1 = \mu_2$	$\sigma_1^2 = \sigma_2^2$	Optional

3) Difference between mean of the waiting time at service center and difference between variance of the waiting time at service center when two frictions are placed before the service center

Waiting time at immigration counters and that of immigration counters through two frictions in arrival procedure were analyzed by using hypothesis testing, One Way ANOVA, Post Hoc test, two sample t test and F test (Appendix B).

Homogeneous subset under Tukey HSD in Post Hoc Test shows the waiting times which have same means since their significance values are greater than 0.05. Therefore, it can be summarized as different means and equal means of waiting times.

Different mean waiting time groups

Immigration + Washrooms + Shops $\neq$ Immigration + Washrooms + Internet Access
Immigration + Washrooms + Shops $\neq$ Immigration + Shops + Food cabins
Immigration + Washrooms + Food cabins $\neq$ Immigration + Washrooms + Internet Access
Immigration + Washrooms + Food cabins $\neq$ Immigration + Shops + Food cabins
Immigration + Washrooms + Internet Access $\neq$ Immigration + Shops + Food cabins
Immigration + Washrooms + Internet Access $\neq$ Immigration + Shops + Internet Access Immigration + Washrooms + Internet Access s $\neq$ Immigration + Food cabins + Internet Access
Immigration + Shops + Food cabins $\neq$ Immigration + Shops + Internet Access
Immigration + Shops + Food cabins $\neq$ Immigration + Food cabins + Internet Access

Equal mean waiting time groups

Immigration + Washrooms + Shops = Immigration + Washrooms + Food cabins
Immigration + Washrooms + Shops = Immigration + Shops + Internet Access
Immigration + Washrooms + Shops = Immigration + Food cabins + Internet Access
Immigration + Washrooms + Food cabins = Immigration + Shops + Internet Access
Immigration + Washrooms + Food cabins = Immigration + Food cabins + Internet Access
Immigration + Shops + Internet Access = Immigration + Food cabins + Internet Access

So, washrooms and shops instead of washrooms and food cabins can be placed before the immigration counters in arrival procedure since mean waiting time at immigration counters through washrooms and shops is same as that of at immigration counters through washrooms and food cabins. Likewise, shops and internet access can be placed instead of food cabins and internet access before the immigration counters by considering mean waiting times.

It is needed to check the differences of variance waiting time at immigration counter through above mentioned frictions which have equal mean waiting times by using confidence intervals and Levene test (Appendix C).

According to the results of differences of variance waiting times, the groups which have equal variance waiting times can be identified.

Immigration + Washrooms + Shops = Immigration + Washrooms + Food cabins
Immigration + Washrooms + Shops = Immigration + Shops + Internet Access
Immigration + Washrooms + Shops = Immigration + Food cabins + Internet Access
Immigration + Washrooms + Food cabins = Immigration + Shops + Internet Access
Immigration + Washrooms + Food cabins = Immigration + Food cabins + Internet Access
Immigration + Shops + Internet Access = Immigration + Food cabins + Internet Access

Since (immigration + washrooms + shops) and (immigration + washrooms + food cabins) have the same means and the same variances, washrooms and shops can be placed instead of washrooms and food cabins before the immigration counters and vice versa in arrival procedure.

By finding the mean and variance waiting time at mandatory service center by going through two different frictions and going through another two different frictions and comparing the differences of means and variances of waiting times of the above two cases the suitable two different frictions that can be placed together before the mandatory service centers to minimize the passengers delay can be identified.

After applying the above concept for all mandatory service centers in arrival and departure procedures, the most suitable replaceable two different frictions before the all mandatory service centers can be found and they are as shown below.

Immigration + Washrooms + Shops = Immigration + Washrooms + Food cabins
Immigration + Washrooms + Shops = Immigration + Shops + Internet Access
Immigration + Washrooms + Shops = Immigration + Food cabins + Internet Access
Immigration + Washrooms + Food cabins = Immigration + Shops + Internet Access
Immigration + Washrooms + Food cabins = Immigration + Food cabins + Internet Access
Immigration + Shops + Internet Access = Immigration + Food cabins + Internet Access

5.7. Monte Carlo Simulation Verification

Analytical solutions for finding the proper places for frictions which can be placed before the mandatory service centers can be found by using above techniques. If the parameters of waiting time distributions (means and variances) of mandatory service centers and frictions are changed, the fixing place for frictions will be changed. This change can be easily verified through simulation analysis. Monte Carlo simulation method was used for the purpose.

It was done under several steps. The first step was generating data for mandatory service centers as well as frictions according to the parameters of distributions which have been already found earlier. For that, 95% and 99.7% confidence intervals for mean waiting time were taken.

Table 5. 9: Confidence Intervals for mean waiting time of the mandatory service centers in arrival and departure procedures

Service Center	Waiting time (Seconds)		95% CI (Seconds)		99.7% CI (Seconds)	
	Mean	Std. Dev.	m-2*sd	m+2*sd	m-3*sd	m+3*sd
Arrival Procedure						
Immigration	358.5	200.3	-42.1	759.1	-242.4	959.4
Baggage Station	541.9	369.9	-197.9	1281.7	-567.8	1651.6
Departure Procedure						
Check-in	742.6	464.1	-185.6	1670.8	-649.7	2134.9
Ticketing	172.5	61.34	49.82	295.18	-11.52	356.52
Immigration	396	230.1	-64.2	856.2	-294.3	1086.3
Frictions						
Washrooms	180	300	-420	780	-720	1080
Shops	1500	2100	-2700	5700	-4800	7800
Food cabins	1800	1800	-1800	5400	-3600	7200
Internet Access	300	300	-300	900	-600	1200

Because of the more reliability, 99.7% confidence interval for mean waiting time was considered. Even though, the lower bound of the confidence interval is a negative value, the time counting will be started on 0, since the time is always positive.

Service Center	Mean	Std. Dev.	m-3*sd	m+3*sd	n
Immigration	358.5	200.3	0	959.4	2000

Waiting time at immigration counters in arrival procedure tends to be a normal distribution and using cumulative probability, number of passengers was calculated for waiting time intervals as follows.

Table 5. 10: Waiting time Intervals for mean waiting time at Immigration counters in arrival procedures

Waiting Time (Seconds)	Cumulative Probability	Waiting Time interval (Seconds)	Probability	No of Passengers	Coded Value
200	0.214381	0 - 200	0.214381	429	1
400	0.582069	201 - 400	0.367688	735	2
600	0.886032	401 - 600	0.303963	608	3
800	0.986245	601 - 800	0.100213	200	4
1000	0.999319	801 - 1000	0.013075	28	5
				2000	

According to the above table, cumulative probabilities were calculated by using below function.

=NORMDIST(x, mean, standard deviation, cumulative)

Then the probabilities for waiting time intervals were calculated. From that, the number of passengers was calculated. Finally waiting time intervals were coded using the below mentioned function as per the table 5.10.

=IF(Waiting Time Value<200,1,IF(Waiting Time Value <400,2,IF(Waiting Time Value <600,3,IF(Waiting Time Value <800,4,5))))

By using the cumulative probability, data for waiting time at immigration counters were generated by using the code of =NORMINV(probability, mean, standard deviation).

Table 5. 11: Generated data for mean waiting time at Immigration counters in arrival procedures

Cumulative Probability	Generated Data	Coded Value
0.227975	209.1696	2
0.373359	293.8092	2
0.051595	32.09453	1
0.300122	253.533	2
0.418307	317.1927	2
0.277069	240.0081	2
0.13884	141.065	1
0.566208	391.8954	2
0.486173	351.5562	2
0.371159	292.6445	2
0.103277	105.5014	1
0.102397	104.5172	1
0.990079	825.0662	5
0.292728	249.2501	2
0.757608	498.4353	3
0.237957	215.7085	2
0.258412	228.6558	2
0.897572	612.4476	4
0.923586	644.8521	4
0.091893	92.26392	1
0.80217	528.6341	3

Mean	SD
364.3045	190.641094

	Mean	SD
1	366.3629	192.038
2	363.475	190.293
3	366.376	191.9442
4	364.6449	189.5024
5	365.4265	190.0189
6	360.5759	189.6188
7	364.963	190.9988
8	364.017	187.4281
9	363.2012	190.9802
10	367.3171	190.8444
11	362.9034	187.4397
12	364.7769	187.07
13	365.3327	189.7035
14	362.9983	187.2067
15	367.4555	190.161
16	365.1803	188.986
17	364.089	191.6298
18	364.5891	189.4283
19	363.328	189.7855
20	363.5652	188.5935
21	365.1811	189.3045
22	361.6786	189.0072
23	362.1495	189.1984
24	366.9266	188.9527
25	364.967	188.428

Then 2000 data were generated and it includes 0 - 200 data 429, 201 - 400 data 735, etc...

This 2000 bunch of data were generated from time to time and mean and standard deviation were found at each and every time. Finally, the averages of the means and standard deviations were calculated.

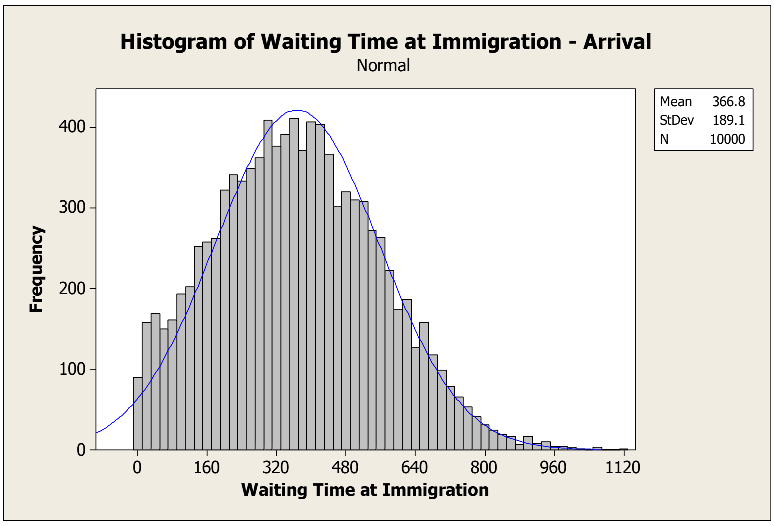


Figure 5. 11: Histogram of the data of waiting time at Immigration counters in arrival procedure

The waiting times at mandatory service centers for arrival and departure procedures and frictions were generated by using the above method.

5.7.1. One friction placed before the mandatory service center in arrival procedure

The arrival procedure was considered to place frictions between service centers. The layout below shows service centers without placing frictions.

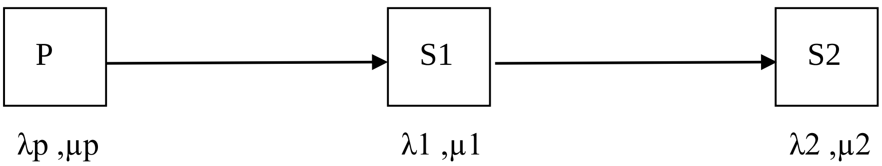


Figure 5. 12: Layout of service centers without placing frictions in arrival procedure

λp – Arrival rate of the pier

μp – Service rate of the pier

λ1 – Arrival rate of immigration counters

μ1 – Service rate of immigration counters

λ2 – Arrival rate of baggage station

μ2 – Service rate of baggage station

S1 - Number of counters in immigration counters

S2 - Number of counters in baggage station

N1 - Maximum number of passengers coming to immigration counters

N2 - Maximum number of passengers coming to baggage station

$\mathrm{P}(\mathrm{WT}_{S1} > 0)$ - Probability of having waiting time at immigration counters without placing friction

$\mathrm{P}(\mathrm{WT}_{S2} > 0)$ - Probability of having waiting time at baggage station without placing friction

Total waiting time in arrival procedure without placing frictions before the mandatory service centers was calculated as follows.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) = \frac{(\rho_1)^{S_1}\left(\frac{1-\rho_1}{1-\rho_1^{N1+1}}\right)}{S_1!\,(1-\rho_1)} + \frac{(\rho_2)^{S_2}\left(\frac{1-\rho_2}{1-\rho_2^{N2+1}}\right)}{S_2!\,(1-\rho_2)}$$

$$\rho_1 = \frac{\lambda_1}{\mu_1} \qquad \rho_2 = \frac{\lambda_2}{\mu_2}$$

$$\lambda_1 = \frac{1}{\mu_{1A}} \qquad \mu_1 = \frac{1}{\mu_{1S}} \qquad \lambda_2 = \frac{1}{\mu_{2A}} \qquad \mu_2 = \frac{1}{\mu_{2S}}$$

One friction was placed in between pier and immigration counters and another friction was placed in between immigration counters and baggage station.

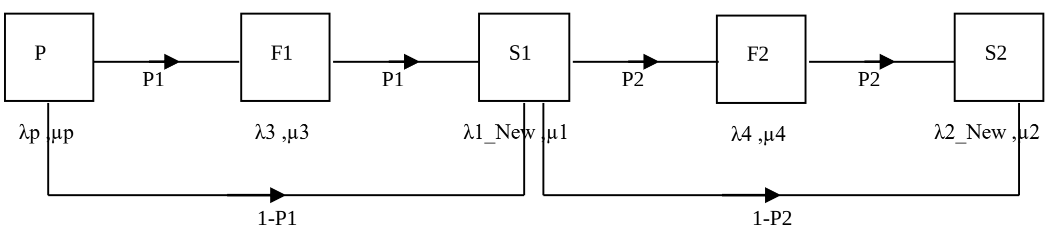


Figure 5. 13: Layout of service centers with placing one friction in arrival procedure

λp – Arrival rate of the pier

μp – Service rate of the pier

$\lambda 1\_New$ – Arrival rate of immigration counters

$\mu 1$ – Service rate of immigration counters

$\lambda 2\_New$ – Arrival rate of baggage station

$\mu 2$ – Service rate of baggage station

$\lambda 3$ – Arrival rate of friction 1

$\mu 3$ – Service rate of friction 1

$\lambda 4$ – Arrival rate of friction 2

$\mu 4$ – Service rate of friction 2

S1 - Number of counters in immigration counters

S2 - Number of counters in baggage station

N1 - Maximum number of passengers coming to immigration counters

N2 - Maximum number of passengers coming to baggage station

p1 - Probability of passengers who are going from pier to friction 1

p2 - Probability of passengers who are going from immigration counters to friction 2

$\mathrm{P}\left(\mathrm{WT}_{\mathrm{S1\_New}} > 0\right)$ - Probability of having waiting time at immigration counters after placing one friction

$\mathrm{P}\left(\mathrm{WT}_{\mathrm{S2\_New}} > 0\right)$ - Probability of having waiting time at baggage station after placing one friction

$$\lambda_{1\_New} = P_1\lambda_3 + (1 - P_1)\,\lambda_p$$

$$\lambda_{2\_New} = P_2\lambda_4 + (1 - P_2)\,\lambda_{1\_New}$$

$$\rho_1 = \frac{\lambda_1}{\mu_1} \qquad \rho_2 = \frac{\lambda_2}{\mu_2} \qquad \rho_{1\_New} = \frac{\lambda_{1\_New}}{\mu_1} \qquad \rho_{2\_New} = \frac{\lambda_{2\_New}}{\mu_2}$$

$$\lambda_1 = \frac{1}{\mu_{1A}} \qquad \mu_1 = \frac{1}{\mu_{1S}} \qquad \lambda_2 = \frac{1}{\mu_{2A}} \qquad \mu_2 = \frac{1}{\mu_{2S}} \qquad \lambda_3 = \frac{1}{\mu_{3A}} \qquad \lambda_4 = \frac{1}{\mu_{4A}}$$

$$\lambda_p = \frac{1}{\mu_{PA}}$$

Total waiting time in arrival procedure with placing one friction before the mandatory service centers was calculated by using the formula shown below.

$$P\left(WT_{S1_{New}} > 0\right) + P\left(WT_{S2_{New}} > 0\right) = \frac{\left(\rho_{1_{New}}\right)^{S_1}\left(\frac{1-\rho_{1_{New}}}{1-\rho_{1_{New}}^{N1+1}}\right)}{S_1!\left(1-\rho_{1_{New}}\right)} + \frac{\left(\rho_{2_{New}}\right)^{S_2}\left(\frac{1-\rho_{2_{New}}}{1-\rho_{2_{New}}^{N2+1}}\right)}{S_2!\left(1-\rho_{2_{New}}\right)}$$

Decision for placing one friction before the mandatory service centers is mentioned below.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) > P\left(WT_{S1\_New} > 0\right) + P\left(WT_{S2\_New} > 0\right)$$

$$\frac{(\rho_1)^{S_1}\left(\frac{1-\rho_1}{1-\rho_1^{N1+1}}\right)}{S_1!\,(1-\rho_1)} + \frac{(\rho_2)^{S_2}\left(\frac{1-\rho_2}{1-\rho_2^{N2+1}}\right)}{S_2!\,(1-\rho_2)} > \frac{(\rho_{1\_New})^{S_1}\left(\frac{1-\rho_{1\_New}}{1-\rho_{1\_New}^{N1+1}}\right)}{S_1!\,(1-\rho_{1\_New})} + \frac{(\rho_{2\_New})^{S_2}\left(\frac{1-\rho_{2\_New}}{1-\rho_{2\_New}^{N2+1}}\right)}{S_2!\,(1-\rho_{2\_New})}$$

Data are fed for following variables.

μ_{1A} - Mean of waiting time at immigration counters

μ_{1S} - Mean of service time at immigration counters

μ_{2A} - Mean of waiting time at baggage station

μ_{2S} - Mean of service time at baggage station

μ_{3A} - Mean of waiting time at friction 1

μ_{4A} - Mean of waiting time at friction 2

μ_{PA} - Mean of waiting time at pier

λp – Arrival rate of the pier

μp – Service rate of the pier

$\lambda 1$ – Arrival rate of immigration counters

$\mu 1$ – Service rate of immigration counters

$\lambda 2$ – Arrival rate of baggage station

$\mu 2$ – Service rate of baggage station

$\lambda 3$ – Arrival rate of friction 1

$\mu 3$ – Service rate of friction 1

$\lambda 4$ – Arrival rate of friction 2

$\mu 4$ – Service rate of friction 2

S1 - Number of counters in immigration counters

S2 - Number of counters in baggage station

N1 - Maximum number of passengers coming to immigration counters

N2 - Maximum number of passengers coming to baggage station

p1 - Probability of passengers who are going from pier to friction 1

p2 - Probability of passengers who are going from immigration counters to friction 2

Once the data were fed for the above variables, below mentioned new variables were calculated by using the above variables.

$\lambda 1$_New – Arrival rate of immigration counters

$\lambda 2$_New – Arrival rate of baggage station

ρ_1 - Ratio of arrival rate to service rate at immigration counters without placing friction

ρ_2 - Ratio of arrival rate to service rate at baggage station without placing friction

ρ_{1_New} - Ratio of arrival rate to service rate at immigration counters with placing friction

ρ_{2_New} - Ratio of arrival rate to service rate at baggage station with placing friction

$\mathrm{P}(\mathrm{WT}_{S1} > 0)$ - Probability of having waiting time at immigration counters without placing friction

$\mathrm{P}(\mathrm{WT}_{S2} > 0)$ - Probability of having waiting time at baggage station without placing friction

$\mathrm{P}(\mathrm{WT}_{S1\_New} > 0)$ - Probability of having waiting time at immigration counters after placing one friction

$\mathrm{P}(\mathrm{WT}_{S2\_New} > 0)$ - Probability of having waiting time at baggage station after placing one friction

After getting above values, the decision was taken by using below formula.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) > P(WT_{S1\_New} > 0) + P(WT_{S2\_New} > 0)$$

If the values feeding the variables are changed, the calculated values of new variables will be changed. According to the calculated values for variables of $\mathrm{P(WT_{S1} > 0)}$, $\mathrm{P(WT_{S2} > 0)}$, $\mathrm{P\left(WT_{S1\_New} > 0\right)}$ and $\mathrm{P\left(WT_{S2\_New} > 0\right)}$, the decision was taken to suit the conditions shown below.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) > P\left(WT_{S1\_New} > 0\right) + \ P\left(WT_{S2\_New} > 0\right)$$

i.e, if this condition is satisfied, that frictions can be placed before the mandatory service centers.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) > P\left(WT_{S1\_New} > 0\right) + \ P\left(WT_{S2\_New} > 0\right)$$

i.e, if the conditions do not satisfy, such frictions cannot be placed before the mandatory service centers.

For example, washrooms placed before the immigration counters and shops placed before the baggage station were considered as one combination. Changing the values of parameters (means and variances) of frictions, decisions can be made regarding which parameter values can be placed before the mandatory service centers. At the same time, the values of the parameters for mandatory services also need to be changed. Then, the frictions have to be changed and the same process repeated again and again. Finally, the best frictions to be placed before the mandatory service centers can be found with this method and using different frictions with different parametric values.

If it is decided to place the friction before the mandatory service center, it can change the values of parameters.

5.7.2. One friction placed before the mandatory service center in departure procedure

The departure procedure is considered to place frictions between service centers.

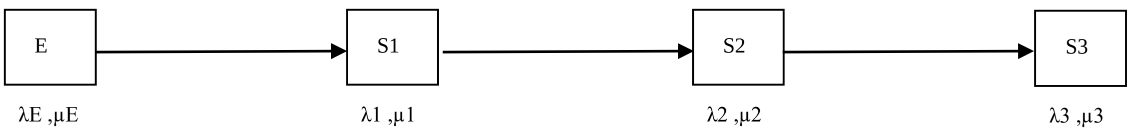


Figure 5. 14: Layout of service centers without placing frictions in departure procedure

λE – Arrival rate of the entrance

μE– Service rate of the entrance

λ1 – Arrival rate of check-in counters

μ1 – Service rate of check-in counters

λ2 – Arrival rate of ticketing counters

μ2 – Service rate of ticketing counters

λ3 – Arrival rate of immigration counters

μ3 – Service rate of immigration counters

S1 - Number of counters in check-in counters

S2 - Number of counters in ticketing counters

S3 - Number of counters in immigration counters

N1 - Maximum number of passengers coming to check-in counters

N2 - Maximum number of passengers coming to ticketing counters

N3 - Maximum number of passengers coming to immigration counters

$\mathrm{P}(\mathrm{WT}_{S1} > 0)$ - Probability of having waiting time at check-in counters without placing friction

$\mathrm{P}(\mathrm{WT}_{S2} > 0)$ - Probability of having waiting time at ticketing counters without placing friction

$\mathrm{P}(\mathrm{WT}_{S3} > 0)$ - Probability of having waiting time at immigration counters without placing friction

$$\rho_1 = \frac{\lambda_1}{\mu_1} \qquad \rho_2 = \frac{\lambda_2}{\mu_2} \qquad \rho_3 = \frac{\lambda_3}{\mu_3}$$

$$\lambda_1 = \frac{1}{\mu_{1A}} \qquad \mu_1 = \frac{1}{\mu_{1S}} \qquad \lambda_2 = \frac{1}{\mu_{2A}} \qquad \mu_2 = \frac{1}{\mu_{2S}} \qquad \lambda_3 = \frac{1}{\mu_{3A}} \qquad \mu_3 = \frac{1}{\mu_{3S}}$$

Total waiting time in departure procedure without placing frictions before the mandatory service centers is calculated as follows.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) + P(WT_{S3} > 0)$$
$$= \frac{(\rho_1)^{S_1}(\frac{1-\rho_1}{1-\rho_1^{N1+1}})}{S_1!\,(1-\rho_1)} + \frac{(\rho_2)^{S_2}(\frac{1-\rho_2}{1-\rho_2^{N2+1}})}{S_2!\,(1-\rho_2)} + \frac{(\rho_3)^{S_3}(\frac{1-\rho_3}{1-\rho_3^{N3+1}})}{S_3!\,(1-\rho_3)}$$

One friction is placed in between entrance and checking counters, one friction is placed in between checking counters and ticketing counters and another friction is placed in between ticketing counters and immigration counters.

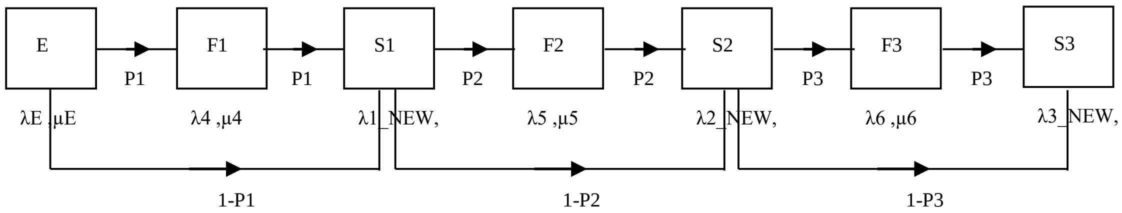


Figure 5. 15: Layout of service centers with placing one friction in departure procedure

λE – Arrival rate of the entrance

μE – Service rate of the entrance

$\lambda 1\_New$ – Arrival rate of check-in counters

$\mu 1$ – Service rate of check-in counters

$\lambda 2\_New$ – Arrival rate of ticketing counters

$\mu 2$ – Service rate of ticketing counters

$\lambda 3\_New$ – Arrival rate of immigration counters

$\mu 3$ – Service rate of immigration counters

$\lambda 4$ – Arrival rate of friction 1

$\mu 4$ – Service rate of friction 1

$\lambda 5$ – Arrival rate of friction 2

$\mu 5$ – Service rate of friction 2

$\lambda 6$ – Arrival rate of friction 3

$\mu 6$ – Service rate of friction 3

S1 - Number of counters in check-in counters

S2 - Number of counters in ticketing counters

S3 - Number of counters in immigration counters

N1 - Maximum number of passengers coming to check-in counters

N2 - Maximum number of passengers coming to ticketing counters

N3 - Maximum number of passengers coming to immigration counters

p1 - Probability of passengers who are going from entrance to friction 1 p2 - Probability of passengers who are going from check-in counters to friction 2

p3 - Probability of passengers who are going from ticketing counters to friction 3

$\mathrm{P}\left(\mathrm{WT}_{\mathrm{S1\_New}} > 0\right)$ - Probability of having waiting time at check-in counters with placing friction

$\mathrm{P}\left(\mathrm{WT}_{\mathrm{S2\_New}} > 0\right)$ - Probability of having waiting time at ticketing counters with placing friction

$\mathrm{P}\left(\mathrm{WT}_{\mathrm{S3\_New}} > 0\right)$ - Probability of having waiting time at immigration counters with placing friction

$$\lambda_4 = P_1 \lambda_E$$
$$\lambda_{1\_New} = P_1 \lambda_4 + (1 - P_1)\,\lambda_E$$
$$\lambda_5 = P_2 \lambda_{1\_New}$$
$$\lambda_{2\_New} = P_2 \lambda_5 + (1 - P_2)\lambda_{1\_New}$$
$$\lambda_6 = P_3 \lambda_{2\_New}$$
$$\lambda_{3\_New} = P_3 \lambda_6 + (1 - P_3)\lambda_{2\_New}$$

$$\rho_1 = \frac{\lambda_1}{\mu_1} \qquad \rho_2 = \frac{\lambda_2}{\mu_2} \qquad \rho_3 = \frac{\lambda_3}{\mu_3} \qquad \rho_{1_{New}} = \frac{\lambda_{1_{New}}}{\mu_1} \qquad \rho_{2_{New}} = \frac{\lambda_{2_{New}}}{\mu_2}$$
$$\rho_{3\_New} = \frac{\lambda_{3\_New}}{\mu_3}$$
$$\lambda_1 = \frac{1}{\mu_{1A}} \qquad \mu_1 = \frac{1}{\mu_{1S}} \qquad \lambda_2 = \frac{1}{\mu_{2A}} \qquad \mu_2 = \frac{1}{\mu_{2S}} \qquad \lambda_3 = \frac{1}{\mu_{3A}} \qquad \mu_3 = \frac{1}{\mu_{3S}}$$
$$\lambda_E = \frac{1}{\mu_{EA}} \qquad \lambda_4 = \frac{1}{\mu_{4A}} \qquad \lambda_5 = \frac{1}{\mu_{5A}} \qquad \lambda_6 = \frac{1}{\mu_{6A}}$$

Total waiting time in departure procedure with placing one friction before the mandatory service centers is calculated by using below formula.

$$P\big(WT_{S1\_New} > 0\big) + P\big(WT_{S2\_New} > 0\big) + P\big(WT_{S3\_New} > 0\big) = \frac{(\rho_{1\_New})^{S_1}\left(\frac{1-\rho_{1\_New}}{1-\rho_{1\_New}^{N1+1}}\right)}{S_1!\,(1-\rho_{1\_New})} + \frac{(\rho_{2\_New})^{S_2}\left(\frac{1-\rho_{2\_New}}{1-\rho_{2\_New}^{N2+1}}\right)}{S_2!\,(1-\rho_{2\_New})} + \frac{(\rho_{3\_New})^{S_3}\left(\frac{1-\rho_{3\_New}}{1-\rho_{3\_New}^{N3+1}}\right)}{S_3!\,(1-\rho_{3\_New})}$$

Decision for placing one friction before the mandatory service centers is mentioned below.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) + P(WT_{S3} > 0) > P\big(WT_{S1\_New} > 0\big) + P\big(WT_{S2\_New} > 0\big) + P\big(WT_{S3\_New} > 0\big)$$

$$\frac{(\rho_1)^{S_1}\left(\frac{1-\rho_1}{1-\rho_1^{N1+1}}\right)}{S_1!\,(1-\rho_1)} + \frac{(\rho_2)^{S_2}\left(\frac{1-\rho_2}{1-\rho_2^{N2+1}}\right)}{S_2!\,(1-\rho_2)} + \frac{(\rho_3)^{S_3}\left(\frac{1-\rho_3}{1-\rho_3^{N3+1}}\right)}{S_3!\,(1-\rho_3)} > \frac{(\rho_{1\_New})^{S_1}\left(\frac{1-\rho_{1\_New}}{1-\rho_{1\_New}^{N1+1}}\right)}{S_1!\,(1-\rho_{1\_New})} + \frac{(\rho_{2\_New})^{S_2}\left(\frac{1-\rho_{2\_New}}{1-\rho_{2\_New}^{N2+1}}\right)}{S_2!\,(1-\rho_{2\_New})} + \frac{(\rho_{3\_New})^{S_3}\left(\frac{1-\rho_{3\_New}}{1-\rho_{3\_New}^{N3+1}}\right)}{S_3!\,(1-\rho_{3\_New})}$$

Data are fed for following variables.

μ_{1A} - Mean of waiting time at check-in counters

μ_{1S} - Mean of service time at check-in counters

μ_{2A} - Mean of waiting time at ticketing counters

μ_{2S} - Mean of service time at ticketing counters

μ_{3A} - Mean of waiting time at immigration counters

μ_{3S} - Mean of service time at immigration counters

μ_{EA} - Mean of waiting time at entrance

μ_{4A} - Mean of waiting time at friction 1

μ_{5A} - Mean of waiting time at friction 2

μ_{6A} - Mean of waiting time at friction 3

λE – Arrival rate of the entrance

μE– Service rate of the entrance

$\lambda 1$ – Arrival rate of check-in counters

$\mu 1$ – Service rate of check-in counters

$\lambda 2$ – Arrival rate of ticketing counters

$\mu 2$ – Service rate of ticketing counters

$\lambda 3$ – Arrival rate of immigration counters

$\mu 3$ – Service rate of immigration counters

S1 - Number of counters in check-in counters

S2 - Number of counters in ticketing counters

S3 - Number of counters in immigration counters

N1 - Maximum number of passengers coming to check-in counters

N2 - Maximum number of passengers coming to ticketing counters

N3 - Maximum number of passengers coming to immigration counters

$\lambda 4$ – Arrival rate of friction 1

$\mu 4$ – Service rate of friction 1

$\lambda 5$ – Arrival rate of friction 2

$\mu 5$ – Service rate of friction 2

$\lambda 6$ – Arrival rate of friction 3

$\mu 6$ – Service rate of friction 3

p1 - Probability of passengers who are going from entrance to friction 1

p2 - Probability of passengers who are going from check-in counters to friction 2

p3 - Probability of passengers who are going from ticketing counters to friction 3

Once the data were fed for the above variables, below mentioned new variables were calculated by using the above variables.

$\lambda 1\_New$ – Arrival rate of check-in counters

$\lambda 2\_New$ – Arrival rate of ticketing counters

$\lambda 3\_New$ – Arrival rate of immigration counters

ρ_1 - Ratio of arrival rate to service rate at check-in counters without placing friction

ρ_2 - Ratio of arrival rate to service rate at ticketing counters without placing friction

ρ_3 - Ratio of arrival rate to service rate at immigration counters without placing friction

ρ_{1_New} - Ratio of arrival rate to service rate at check-in counters with placing friction

ρ_{2_New} - Ratio of arrival rate to service rate at ticketing counters with placing friction

ρ_{3_New} - Ratio of arrival rate to service rate at immigration counters with placing friction

$P(WT_{S1} > 0)$ - Probability of having waiting time at check-in counters without placing friction

$P(WT_{S2} > 0)$ - Probability of having waiting time at ticketing counters without placing friction

$P(WT_{S3} > 0)$ - Probability of having waiting time at immigration counters without placing friction

$P(WT_{S1\_New} > 0)$ - Probability of having waiting time at check-in counters with placing friction

$P(WT_{S2\_New} > 0)$ - Probability of having waiting time at ticketing counters with placing friction

$P(WT_{S3\_New} > 0)$ - Probability of having waiting time at immigration counters with placing friction

After getting the above values, the decision was taken by using the formula below.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) + P(WT_{S3} > 0) > P(WT_{S1\_New} > 0) + P(WT_{S2\_New} > 0) + P(WT_{S3\_New} > 0)$$

If the values feeding the variables are changed, the calculated values of new variables will be changed. According to the calculated values for variables of $P(WT_{S1} > 0)$, $P(WT_{S2} > 0)$, $P(WT_{S3} > 0)$, $P(WT_{S1\_New} > 0)$, $P(WT_{S2\_New} > 0)$ and $P(WT_{S3\_New} > 0)$, the decision is taken under the condition of using different frictions.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) + P(WT_{S3} > 0) > P(WT_{S1\_New} > 0) + P(WT_{S2\_New} > 0) + P(WT_{S3\_New} > 0)$$

i.e, if this condition is satisfied, that frictions can be placed before the mandatory service centers.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) + P(WT_{S3} > 0) > P\left(WT_{S1\_New} > 0\right) + P\left(WT_{S2\_New} > 0\right) + P\left(WT_{S3\_New} > 0\right)$$

i.e, if this condition is not satisfied, that frictions cannot be placed before the mandatory service centers.

For example, washrooms are placed before the check-in counters, internet accesses are placed before the ticketing counters and food cabins are placed before the immigration counters. This was considered as one combination. By changing the values of parameters (means and variances) of frictions, decisions can be taken regarding which frictions with which parameter values can be placed before the mandatory service centers. At the same time, it has to change the values of the parameters for mandatory services also. Then, the frictions have to be changed and the same process repeated again and again. Finally, best frictions which can be placed before the mandatory service centers can be found with this method by using different frictions with different parametric values.

If it is decided to place the friction before the mandatory service center, it can change the values of parameters.

5.7.3. Two frictions placed before the mandatory service center in arrival procedure

An arrival procedure is considered to place two frictions between service centers. Two frictions are placed in between pier and immigration counters and another two frictions are placed in between immigration counters and baggage station.

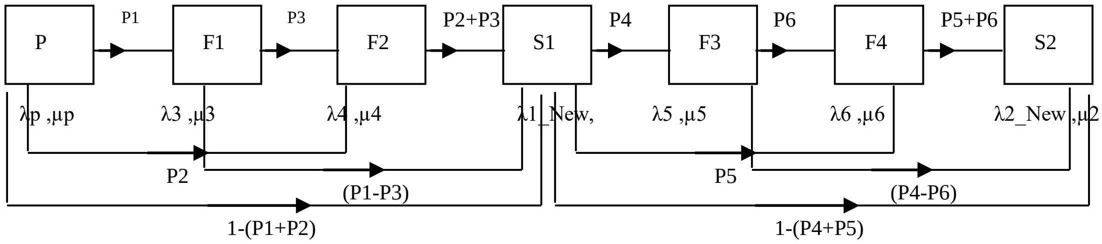


Figure 5. 16: Layout of service centers with placing two frictions in arrival procedure

λp – Arrival rate of the pier

μp – Service rate of the pier

λ1_New – Arrival rate of immigration counters

μ1 – Service rate of immigration counters

λ2_New – Arrival rate of baggage station

μ2 – Service rate of baggage station

λ3 – Arrival rate of friction 1

μ3 – Service rate of friction 1

λ4 – Arrival rate of friction 2

μ4 – Service rate of friction 2

λ5 – Arrival rate of friction 3

μ5 – Service rate of friction 3

λ6 – Arrival rate of friction 4

μ6 – Service rate of friction 4

S1 - Number of counters in immigration counters

S2 - Number of counters in baggage station

N1 - Maximum number of passengers coming to immigration counters

N2 - Maximum number of passengers coming to baggage station

p1 = Probability of passengers who are going from pier to friction 1

p2 = Probability of passengers who are going from pier to friction 2

p3 = Probability of passengers who are going from friction 1 to friction 2

p4 = Probability of passengers who are going from immigration counters to friction 3

p5 = Probability of passengers who are going from immigration counters to friction 4

p6 = Probability of passengers who are going from friction 3 to friction 4

$\mathrm{P}(\mathrm{WT}_{\mathrm{S1\_New}} > 0)$ - Probability of having waiting time at immigration counters with placing friction

$\mathrm{P}(\mathrm{WT}_{\mathrm{S2\_New}} > 0)$ - Probability of having waiting time at baggage station with placing friction

$$\lambda_3 = P_1 \lambda_p$$

$$\lambda_4 = P_3 \lambda_3 + P_2 \lambda_p$$

$$\lambda_{1\_New} = (P_2 + P_3)\lambda_4 + (P_1 - P_3)\lambda_3 + (1 - (P_1 + P_2))\lambda_p$$

$$\lambda_5 = P_4 \lambda_{1\_New}$$

$$\lambda_6 = P_6 \lambda_5 + P_5 \lambda_{1\_New}$$

$$\lambda_{2\_New} = (P_5 + P_6)\lambda_6 + (P_4 - P_6)\lambda_5 + (1 - (P_4 + P_6))\lambda_{1\_New}$$

$$\rho_1 = \frac{\lambda_1}{\mu_1} \qquad \rho_2 = \frac{\lambda_2}{\mu_2} \qquad \rho_{1_{New}} = \frac{\lambda_{1_{New}}}{\mu_1} \qquad \rho_{2_{New}} = \frac{\lambda_{2_{New}}}{\mu_2}$$

$$\lambda_1 = \frac{1}{\mu_{1A}} \qquad \mu_1 = \frac{1}{\mu_{1S}} \qquad \lambda_2 = \frac{1}{\mu_{2A}} \qquad \mu_2 = \frac{1}{\mu_{2S}}$$

$$\lambda_P = \frac{1}{\mu_{PA}} \qquad \lambda_3 = \frac{1}{\mu_{3A}} \qquad \lambda_4 = \frac{1}{\mu_{4A}} \qquad \lambda_5 = \frac{1}{\mu_{5A}} \qquad \lambda_6 = \frac{1}{\mu_{6A}}$$

Total waiting time in arrival procedure with placing two frictions before the mandatory service centers is calculated by using the formula below.

$$P(WT_{S1\_New} > 0) + P(WT_{S2\_New} > 0) = \frac{(\rho_{1\_New})^{S_1}\left(\frac{1-\rho_{1\_New}}{1-\rho_{1\_New}^{N1+1}}\right)}{S_1!\,(1 - \rho_{1\_New})} + \frac{(\rho_{2\_New})^{S_2}\left(\frac{1-\rho_{2\_New}}{1-\rho_{2\_New}^{N2+1}}\right)}{S_2!\,(1 - \rho_{2\_New})}$$

Decision for placing two frictions before the mandatory service centers is as follows.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) > P(WT_{S1\_New} > 0) + P(WT_{S2\_New} > 0)$$

$$\frac{(\rho_1)^{S_1}(\frac{1-\rho_1}{1-\rho_1^{N1+1}})}{S_1!\,(1-\rho_1)}+\frac{(\rho_2)^{S_2}(\frac{1-\rho_2}{1-\rho_2^{N2+1}})}{S_2!\,(1-\rho_2)}>\frac{(\rho_{1\_New})^{S_1}(\frac{1-\rho_{1\_New}}{1-\rho_{1\_New}^{N1+1}})}{S_1!\,(1-\rho_{1\_New})}+\frac{(\rho_{2\_New})^{S_2}(\frac{1-\rho_{2\_New}}{1-\rho_{2\_New}^{N2+1}})}{S_2!\,(1-\rho_{2\_New})}$$

Data are fed for following variables.

μ_{1A} - Mean of waiting time at immigration counters

μ_{1S} - Mean of service time at immigration counters

μ_{2A} - Mean of waiting time at baggage station

μ_{2S} - Mean of service time at baggage station

μ_{EA} - Mean of waiting time at pier

μ_{3A} - Mean of waiting time at friction 1

μ_{4A} - Mean of waiting time at friction 2

μ_{5A} - Mean of waiting time at friction 3

μ_{6A} - Mean of waiting time at friction 4

λP – Arrival rate of the pier

μE– Service rate of the pier

λ1 – Arrival rate of immigration counters

μ1 – Service rate of immigration counters

λ2 – Arrival rate of baggage station

μ2 – Service rate of baggage station

S1 - Number of counters in immigration counters

S2 - Number of counters in baggage station

N1 - Maximum number of passengers coming to immigration counters

N2 - Maximum number of passengers coming to baggage station

λ3 – Arrival rate of friction 1

μ3 – Service rate of friction 1

λ4 – Arrival rate of friction 2

μ4 – Service rate of friction 2

λ5 – Arrival rate of friction 3

μ5 – Service rate of friction 3

λ6 – Arrival rate of friction 4

$\mu6$ – Service rate of friction 4

p1 = Probability of passengers who are going from pier to friction 1

p2 = Probability of passengers who are going from pier to friction 2

p3 = Probability of passengers who are going from friction 1 to friction 2

p4 = Probability of passengers who are going from immigration counters to friction 3

p5 = Probability of passengers who are going from immigration counters to friction 4

p6 = Probability of passengers who are going from friction 3 to friction 4

Once the data were fed for the above variables, new variables shown below were calculated by using the above variables.

$\lambda1$_New – Arrival rate of immigration counters

$\lambda2$_New – Arrival rate of baggage station

ρ_1 - Ratio of arrival rate to service rate at immigration counters without placing friction

ρ_2 - Ratio of arrival rate to service rate at baggage station without placing friction

ρ_{1_New} - Ratio of arrival rate to service rate at immigration counters with placing friction

ρ_{2_New} - Ratio of arrival rate to service rate at baggage station with placing friction

$P(WT_{S1} > 0)$ - Probability of having waiting time at immigration counters without placing friction

$P(WT_{S2} > 0)$ - Probability of having waiting time at baggage station without placing friction

$P\left(WT_{S1\_New} > 0\right)$ - Probability of having waiting time at immigration counters with placing friction

$P\left(WT_{S2\_New} > 0\right)$ - Probability of having waiting time at baggage station with placing friction

After getting above values, the decision was taken by using below formula.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) > P\left(WT_{S1\_New} > 0\right) + P\left(WT_{S2\_New} > 0\right)$$

If the values which are feeding for the variables are changed, the calculated values of new variables will be changed. According to the calculated values for variables of $\mathrm{P}(\mathrm{WT}_{\mathrm{S1}} > 0)$, $\mathrm{P}(\mathrm{WT}_{\mathrm{S2}} > 0)$, $\mathrm{P}\big(\mathrm{WT}_{\mathrm{S1\_New}} > 0\big)$ and $\mathrm{P}\big(\mathrm{WT}_{\mathrm{S2\_New}} > 0\big)$, the decision is taken under the condition of using different frictions.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) \ > P\big(WT_{S1\_New} > 0\big) + \ P\big(WT_{S2\_New} > 0\big)$$

i.e, if this condition is satisfied, that frictions can be placed before the mandatory service centers.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) \ > P\big(WT_{S1\_New} > 0\big) + \ P\big(WT_{S2\_New} > 0\big)$$

i.e, if this condition is not satisfied, that frictions cannot be placed before the mandatory service centers.

For example, washrooms and shops are placed before the immigration counters and washrooms and internet accesses are placed before the baggage station, considered as one combination and by changing the values of parameters (means and variances) of frictions, decisions can be taken regarding which frictions with which parameter values can be placed before the mandatory service centers. At the same time, the values of the parameters for mandatory services have also to be changed. Frictions have to be changed and the same process repeated again and again. Finally, best frictions which can be placed before the mandatory service centers can be found by following this method using different frictions with different parametric values.

5.7.4. Two frictions placed before the mandatory service center in departure procedure

Two frictions were placed in between entrance and check-in counters, another two frictions were placed in between check-in counters and ticketing counters and yet another two frictions were placed in between ticketing counters and immigration counters.

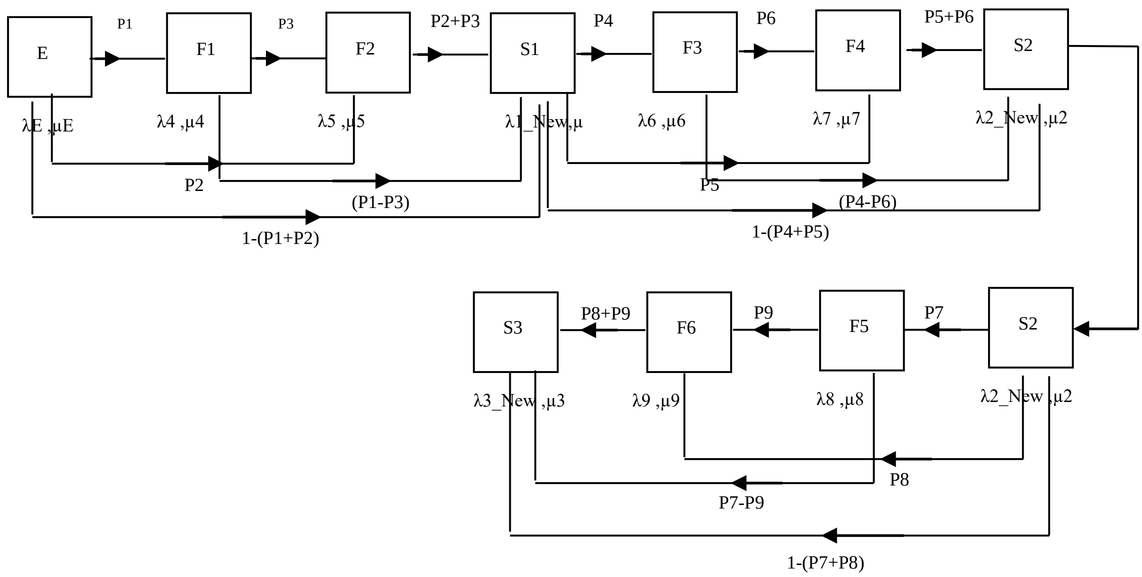


Figure 5. 17: Layout of service centers with placing two frictions in departure procedure

λE – Arrival rate of the entrance

μE – Service rate of the entrance

λ1_New – Arrival rate of check-in counters

μ1 – Service rate of check-in counters

λ2_New – Arrival rate of ticketing counters

μ2 – Service rate of ticketing counters

λ3_New – Arrival rate of immigration counters

μ3 – Service rate of immigration counters

λ4 – Arrival rate of friction 1

μ4 – Service rate of friction 1

λ5 – Arrival rate of friction 2

μ5 – Service rate of friction 2

λ6 – Arrival rate of friction 3

μ6 – Service rate of friction 3

λ7 – Arrival rate of friction 4

μ7 – Service rate of friction 4

λ8 – Arrival rate of friction 5

μ8 – Service rate of friction 5

$\lambda 9$ – Arrival rate of friction 6

$\mu 9$ – Service rate of friction 6

S1 - Number of counters in check-in counters

S2 - Number of counters in ticketing counters

S3 - Number of counters in immigration counters

N1 - Maximum number of passengers coming to check-in counters

N2 - Maximum number of passengers coming to ticketing counters

N3 - Maximum number of passengers coming to immigration counters

p1 = Probability of passengers who are going from entrance to friction 1

p2 = Probability of passengers who are going from entrance to friction 2

p3 = Probability of passengers who are going from friction 1 to friction 2

p4 = Probability of passengers who are going from check-in counters to friction 3

p5 = Probability of passengers who are going from check-in counters to friction 4

p6 = Probability of passengers who are going from friction 3 to friction 4

p7 = Probability of passengers who are going from ticketing counters to friction 5

p8 = Probability of passengers who are going from ticketing counters to friction 6

p9 = Probability of passengers who are going from friction 5 to friction 6

$$\lambda_4 = P_1 \lambda_E$$

$$\lambda_5 = P_3 \lambda_4 + P_2 \lambda_E$$

$$\lambda_{1\_New} = (P_2 + P_3)\lambda_5 + (P_1 - P_3)\lambda_4 + (1 - (P_1 + P_2))\lambda_E$$

$$\lambda_6 = P_4 \lambda_{1\_New}$$

$$\lambda_7 = P_6 \lambda_6 + P_5 \lambda_{1\_New}$$

$$\lambda_{2\_New} = (P_5 + P_6)\lambda_7 + (P_4 - P_6)\lambda_6 + (1 - (P_4 + P_5))\lambda_{1\_New}$$

$$\lambda_8 = P_7 \lambda_{2\_New}$$

$$\lambda_9 = P_9 \lambda_8 + P_8 \lambda_{2\_New}$$

$$\lambda_{3\_New} = (P_8 + P_9)\lambda_9 + (P_7 - P_9)\lambda_8 + (1 - (P_7 + P_8))\lambda_{2\_New}$$

$$\rho_1 = \frac{\lambda_1}{\mu_1} \qquad \rho_2 = \frac{\lambda_2}{\mu_2} \qquad \rho_3 = \frac{\lambda_3}{\mu_3} \qquad \rho_{1_{New}} = \frac{\lambda_{1_{New}}}{\mu_1} \qquad \rho_{2_{New}} = \frac{\lambda_{2_{New}}}{\mu_2}$$

$$\rho_{3\_New} = \frac{\lambda_{3\_New}}{\mu_3}$$

$$\lambda_1 = \frac{1}{\mu_{1A}} \quad \mu_1 = \frac{1}{\mu_{1S}} \quad \lambda_2 = \frac{1}{\mu_{2A}} \quad \mu_2 = \frac{1}{\mu_{2S}} \quad \lambda_3 = \frac{1}{\mu_{3A}} \quad \mu_3 = \frac{1}{\mu_{3S}}$$

$$\lambda_E = \frac{1}{\mu_{EA}} \quad \lambda_4 = \frac{1}{\mu_{4A}} \quad \lambda_5 = \frac{1}{\mu_{5A}} \quad \lambda_6 = \frac{1}{\mu_{6A}} \quad \lambda_7 = \frac{1}{\mu_{7A}} \quad \lambda_8 = \frac{1}{\mu_{8A}}$$

$$\lambda_9 = \frac{1}{\mu_{9A}}$$

Total waiting time in departure procedure with placing two frictions before the mandatory service centers is calculated by using below formula.

$$P\left(WT_{S1\_New} > 0\right) + P\left(WT_{S2\_New} > 0\right) + P\left(WT_{S3\_New} > 0\right) = \frac{(\rho_{1\_New})^{S_1}\left(\frac{1-\rho_{1\_New}}{1-\rho_{1\_New}^{N1+1}}\right)}{S_1!\,(1-\rho_{1\_New})} + \frac{(\rho_{2\_New})^{S_2}\left(\frac{1-\rho_{2\_New}}{1-\rho_{2\_New}^{N2+1}}\right)}{S_2!\,(1-\rho_{2\_New})} + \frac{(\rho_{3\_New})^{S_2}\left(\frac{1-\rho_{3\_New}}{1-\rho_{3\_New}^{N3+1}}\right)}{S_3!\,(1-\rho_{3\_New})}$$

Decision for placing two frictions before the mandatory service centers is as follows.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) + P(WT_{S3} > 0) > P\left(WT_{S1\_New} > 0\right) + P\left(WT_{S2\_New} > 0\right) + P\left(WT_{S3\_New} > 0\right)$$

$$\frac{(\rho_1)^{S_1}\left(\frac{1-\rho_1}{1-\rho_1^{N1+1}}\right)}{S_1!\,(1-\rho_1)} + \frac{(\rho_2)^{S_2}\left(\frac{1-\rho_2}{1-\rho_2^{N2+1}}\right)}{S_2!\,(1-\rho_2)} + \frac{(\rho_3)^{S_3}\left(\frac{1-\rho_3}{1-\rho_3^{N3+1}}\right)}{S_3!\,(1-\rho_3)} > \frac{(\rho_{1\_New})^{S_1}\left(\frac{1-\rho_{1\_New}}{1-\rho_{1\_New}^{N1+1}}\right)}{S_1!\,(1-\rho_{1\_New})} + \frac{(\rho_{2\_New})^{S_2}\left(\frac{1-\rho_{2\_New}}{1-\rho_{2\_New}^{N2+1}}\right)}{S_2!\,(1-\rho_{2\_New})} + \frac{(\rho_{3\_New})^{S_3}\left(\frac{1-\rho_{3\_New}}{1-\rho_{3\_New}^{N3+1}}\right)}{S_3!\,(1-\rho_{3\_New})}$$

Data are fed for following variables.

μ_{1A} - Mean of waiting time at check-in counters

μ_{1S} - Mean of service time at check-in counters

μ_{2A} - Mean of waiting time at ticketing counters

μ_{2S} - Mean of service time at ticketing counters

μ_{3A} - Mean of waiting time at immigration counters

μ_{3S} - Mean of service time at immigration counters

μ_{EA} - Mean of waiting time at entrance

μ_{4A} - Mean of waiting time at friction 1

μ_{5A} - Mean of waiting time at friction 2

μ_{6A} - Mean of waiting time at friction 3

μ_{7A} - Mean of waiting time at friction 4

μ_{8A} - Mean of waiting time at friction 5

μ_{9A} - Mean of waiting time at friction 6

λE – Arrival rate of the entrance

μE– Service rate of the entrance

$\lambda 1$ – Arrival rate of check-in counters

$\mu 1$ – Service rate of check-in counters

$\lambda 2$ – Arrival rate of ticketing counters

$\mu 2$ – Service rate of ticketing counters

$\lambda 3$ – Arrival rate of immigration counters

$\mu 3$ – Service rate of immigration counters

S1 - Number of counters in check-in counters

S2 - Number of counters in ticketing counters

S3 - Number of counters in immigration counters

N1 - Maximum number of passengers coming to check-in counters

N2 - Maximum number of passengers coming to ticketing counters

N3 - Maximum number of passengers coming to immigration counters

$\lambda 4$ – Arrival rate of friction 1

$\mu 4$ – Service rate of friction 1

$\lambda 5$ – Arrival rate of friction 2

$\mu 5$ – Service rate of friction 2

$\lambda 6$ – Arrival rate of friction 3

$\mu 6$ – Service rate of friction 3

$\lambda 7$ – Arrival rate of friction 4

$\mu 7$ – Service rate of friction 4

$\lambda 8$ – Arrival rate of friction 5

$\mu 8$ – Service rate of friction 5

$\lambda 9$ – Arrival rate of friction 6

$\mu 9$ – Service rate of friction 6

p1 = Probability of passengers who are going from entrance to friction 1

p2 = Probability of passengers who are going from entrance to friction 2

p3 = Probability of passengers who are going from friction 1 to friction 2

p4 = Probability of passengers who are going from check-in counters to friction 3

p5 = Probability of passengers who are going from check-in counters to friction 4

p6 = Probability of passengers who are going from friction 3 to friction 4

p7 = Probability of passengers who are going from ticketing counters to friction 5

p8 = Probability of passengers who are going from ticketing counters to friction 6

p9 = Probability of passengers who are going from friction 5 to friction 6

Once the data were fed for the above variables, below mentioned new variables were calculated by using the above variables.

$\lambda 1\_New$ – Arrival rate of check-in counters

$\lambda 2\_New$ – Arrival rate of ticketing counters

$\lambda 3\_New$ – Arrival rate of immigration counters

ρ_1 - Ratio of arrival rate to service rate at check-in counters without placing friction

ρ_2 - Ratio of arrival rate to service rate at ticketing counters without placing friction

ρ_3 - Ratio of arrival rate to service rate at immigration counters without placing friction

ρ_{1_New} - Ratio of arrival rate to service rate at check-in counters with placing two frictions

ρ_{2_New} - Ratio of arrival rate to service rate at ticketing counters with placing two frictions

ρ_{3_New} - Ratio of arrival rate to service rate at immigration counters with placing two frictions

$P(WT_{S1} > 0)$ - Probability of having waiting time at check-in counters without placing friction

$P(WT_{S2} > 0)$ - Probability of having waiting time at ticketing counters without placing friction

$P(WT_{S3} > 0)$ - Probability of having waiting time at immigration counters without placing friction

$P(WT_{S1\_New} > 0)$ - Probability of having waiting time at check-in counters with placing two frictions

$P(WT_{S2\_New} > 0)$ - Probability of having waiting time at ticketing counters with placing two frictions

$P(WT_{S3\_New} > 0)$ - Probability of having waiting time at immigration counters with placing two frictions

After getting above values, the decision was taken by using below formula.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) + P(WT_{S3} > 0) > P(WT_{S1\_New} > 0) + P(WT_{S2\_New} > 0) + P(WT_{S3\_New} > 0)$$

If the values which are feeding for the variables are changed, the calculated values of new variables will be changed. According to the calculated values for variables of $P(WT_{S1} > 0)$, $P(WT_{S2} > 0)$, $P(WT_{S3} > 0)$, $P(WT_{S1\_New} > 0)$, $P(WT_{S2\_New} > 0)$ and $P(WT_{S3\_New} > 0)$, the decision is taken under the condition of using different frictions.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) + P(WT_{S3} > 0) > P(WT_{S1\_New} > 0) + P(WT_{S2\_New} > 0) + P(WT_{S3\_New} > 0)$$

i.e, if this condition is satisfied, that frictions can be placed before the mandatory service centers.

$$P(WT_{S1} > 0) + P(WT_{S2} > 0) + P(WT_{S3} > 0) > P(WT_{S1\_New} > 0) + P(WT_{S2\_New} > 0) + P(WT_{S3\_New} > 0)$$

i.e, if this condition is not satisfied, that frictions cannot be placed before the mandatory service centers.

Changing the values of parameters (means and variances) of frictions, can help decide which frictions with which parameter values can be placed before the mandatory service centers. At the same time, the values of the parameters for mandatory services also have to be changed. Frictions have to be changed and the same process repeated again and again. Finally, best frictions which can be placed before the mandatory service centers can be found by doing this method using different frictions with different parametric values. If it is decided to place the friction before the mandatory service center, it can change the values of parameters.

5.8. Frictions placed before the gates

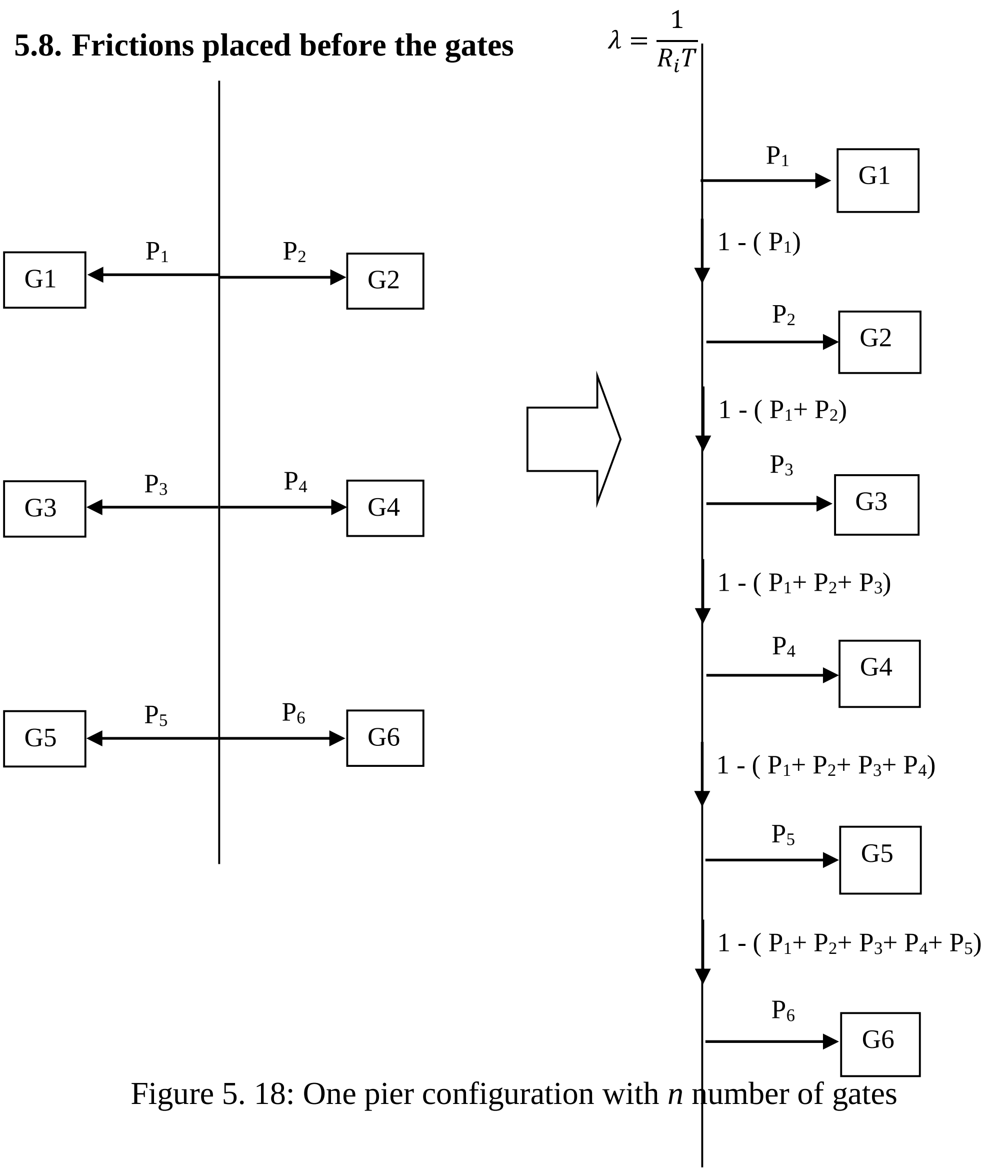


Figure 5. 18: One pier configuration with *n* number of gates

S_k – Number of servers at the gate k

N_k – Maximum number of passengers coming to the gate k

λ_k – Arrival rate of the gate k

μ_k – Service rate of the gate i

$P\ (WT_{Gk} > 0)$ - Probability of waiting time at the gate k without placing frictions

Pi - Probability of passengers going to gate i

$$P(WT_{Gk} > 0) = {(\rho_k)^{S_k}(\frac{1-\rho_k}{1-\rho_k^{Nk+1}})} \Big/ {S_k!\,(1-\rho_k)} \quad ; \quad \rho_k = \frac{\lambda_k}{\mu_k}$$

$$\sum_{i=1}^{n} P_i = 1$$

The probability of average waiting time at a gate for the passenger is the probability of average waiting time of n gates.

Average waiting time of a gate is

$$\frac{\sum_{i=1}^{n} P(WT_{Gk} > 0)}{n} = \frac{\sum_{k=1}^{n} {(\rho_k)^{S_k}(\frac{1-\rho_k}{1-\rho_k^{Nk+1}})} \Big/ {S_k!\,(1-\rho_k)}}{n}$$

Place the m frictions in between the gates. Then the passengers can be moved to gates through frictions (Figure 5.19).

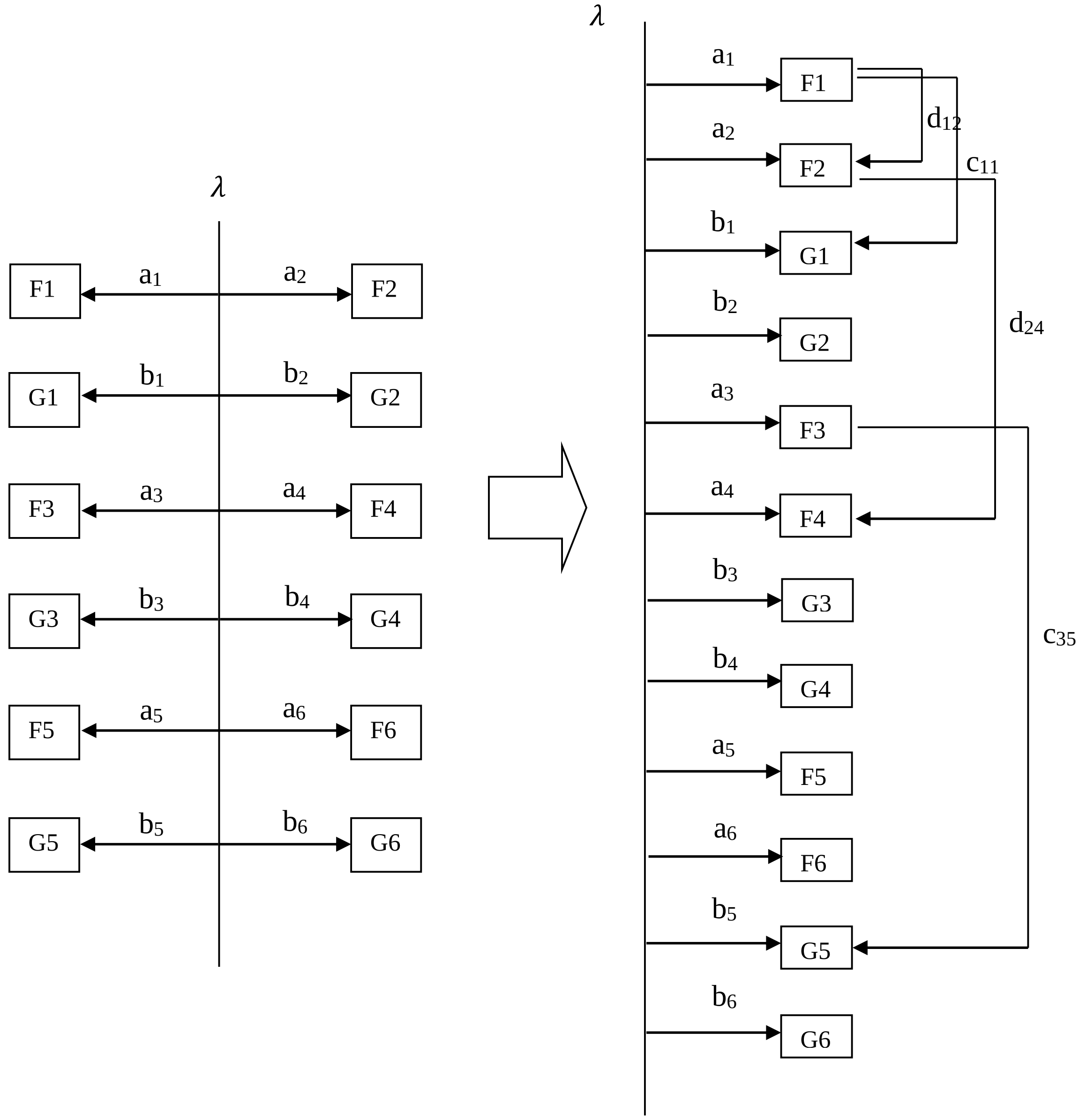


Figure 5. 19: One pier configuration with n number of gates and m number of frictions

a_j = Probability of passenger arrivals to friction *j*

b_j = Probability of passenger arrivals to gate *j*

c_{ij} = Probability of passenger arrivals from friction *i* to gate *j*

d_{ij} = Probability of passenger arrivals from friction *i* to friction *j*

λ = Total passenger arrival rate to the pier

P_j = Probability of passenger arrivals for gate *j*

S_i – Number of servers at the gate *i*

N_i – Maximum number of passengers coming to the gate i

λ_{Gi} – Arrival rate of the gate i after placing friction

μ_{Gi} – Service rate of the gate i after placing friction

S_j – Number of servers at the friction j

N_j – Maximum number of passengers coming to the friction j

λ_{Fj} – Arrival rate of the friction j after placing friction

μ_{Fj} – Service rate of the friction j after placing friction

$P\ (WT_{Gi} > 0)$ - Probability of waiting time at the gate i after placing friction

$P\ (WT_{Fj} > 0)$ - Probability of waiting time at the friction j

For frictions $\lambda_{Fj} = a_j\lambda + \sum_{i=1}^{j-1} d_{ij}\lambda_{Fi}$

For gates $\lambda_{Gj} = b_j\lambda + \sum_{i=1}^{j} c_{ij}\lambda_{Fj}$

Probability for gates

$$P_j = b_j + \sum_{i=1}^{j+1} c_{ij} \ \ (j = 1,3,5,\dots, Odd\ no.\ gates)$$

$$P_j = b_j + \sum_{i=1}^{j} c_{ij} \quad (j = 2,4,6,\dots, Even\ no.gates)$$

$$\sum_{i=1}^{n} P_i = 1$$

$$a_j + \sum_{i=1}^{j-1} d_{ij} = \sum_{i=j}^{n} c_{ji} + \sum_{i=j+1}^{n} d_{ji} \qquad b_j = P_j - \sum_{i=1}^{j} c_{ij}$$

Average waiting time of n gates with placing m frictions

$$\frac{\sum_{i=1}^{n} P(WT_{Gi} > 0)}{n} + \frac{\sum_{j=1}^{n} P\big(WT_{Fj} > 0\big)}{m}$$

$$= \frac{\sum_{i=1}^{n} {(\rho_i)^{S_i}\left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right)} \Big/ {S_i!\,(1-\rho_i)}}{n} + \frac{\sum_{j=1}^{m} {(\rho_j)^{S_j}\left(\frac{1-\rho_j}{1-\rho_j^{Nj+1}}\right)} \Big/ {S_j!\,\big(1-\rho_j\big)}}{m}$$

If the average waiting time at gates with placing frictions in between is less than that of gates without placing frictions, those frictions are allowed to place before the gates.

Average waiting time of n gates with placing m frictions <
Average waiting time of n gates without placing frictions

P(Average waiting time of n gates after placing m fictions) <
P(Average waiting time of n gates without placing frictions)

$$\frac{\sum_{i=1}^{n} \left. (\rho_i)^{S_i}\left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right) \middle/ S_i!\,(1-\rho_i) \right.}{n} + \frac{\sum_{j=1}^{m} \left. (\rho_j)^{S_j}\left(\frac{1-\rho_j}{1-\rho_j^{Nj+1}}\right) \middle/ S_j!\,(1-\rho_j) \right.}{m}$$

$$< \frac{\sum_{k=1}^{n} \left. (\rho_k)^{S_k}\left(\frac{1-\rho_k}{1-\rho_k^{Nk+1}}\right) \middle/ S_k!\,(1-\rho_k) \right.}{n}$$

According to that model, data are fed for following variables.

μ_{iA} - Mean of waiting time at gate *i*

μ_{iS} - Mean of service time at gate *i*

μ_{jA} - Mean of waiting time at friction *j*

μ_{jS} - Mean of service time at friction *j*

λ - Total passenger arrival rate to the pier

P_i - Probability of passenger arrivals for gate *i*

S_i – Number of servers at the gate *i*

N_i – Maximum number of passengers coming to the gate *i*

λ_{Gi} – Arrival rate of the gate *i*

μ_{Gi} – Service rate of the gate *i*

S_j – Number of servers at the friction *j*

N_j – Maximum number of passengers coming to the friction *j*

λ_{Fj} – Arrival rate of the friction *j*

μ_{Fj} – Service rate of the friction *j*

a_j - Probability of passenger arrivals to friction *j*

b_j - Probability of passenger arrivals to gate *j*

c_{ij} - Probability of passenger arrivals from friction *i* to gate *j*

d_{ij} - Probability of passenger arrivals from friction *i* to friction *j*

Once the data were fed for the above variables, below mentioned new variables were calculated by using the above variables.

New arrival rates for gates and frictions

ρ_i - Ratio of arrival rate to service rate at gate *i*

ρ_j - Ratio of arrival rate to service rate at friction *j*

$P\ (WT_{Gi} > 0)$ - Probability of waiting time at the gate *i* after placing friction

$P\ (WT_{Fj} > 0)$ - Probability of waiting time at the friction *j*

After getting above values, the decision was taken by using below formula.

$$\frac{\sum_{i=1}^{n} P(WT_{Gi} > 0)}{n} + \frac{\sum_{j=1}^{m} P\left(WT_{Fj} > 0\right)}{m} < \frac{\sum_{k=1}^{n} P(WT_{Gk} > 0)}{n}$$

If the values which are feeding for the variables are changed, the calculated values of new variables will be changed. According to the calculated values for variables of $\mathrm{P}(\mathrm{WT}_{\mathrm{Gi}} > 0)$ and $\mathrm{P}\left(\mathrm{WT}_{\mathrm{Fj}} > 0\right)$, the decision is taken under the condition of using different frictions.

$$\frac{\sum_{i=1}^{n} P(WT_{Gi}>0)}{n} + \frac{\sum_{j=1}^{m} P\left(WT_{Fj}>0\right)}{m} < \frac{\sum_{k=1}^{n} P(WT_{Gk}>0)}{n}$$

i.e, if this condition is satisfied, that frictions can be placed before the mandatory service centers.

$$\frac{\sum_{i=1}^{n} P(WT_{Gi}>0)}{n} + \frac{\sum_{j=1}^{m} P\left(WT_{Fj}>0\right)}{m} > \frac{\sum_{k=1}^{n} P(WT_{Gk}>0)}{n}$$

i.e, if this condition is not satisfied, that frictions cannot be placed before the mandatory service centers.

If the parameters of frictions (mean and variance of waiting time at frictions) will change, the place of frictions will be changed.

If we want to place some frictions in between gates, we can change the parameters of frictions (mean and variance of waiting time at frictions) according to that.

Once the conditions for placing frictions in between gates are found, several terminal configurations are selected to find out the optimum.

5.9. Terminal Comparison

The first terminal configuration is taken for two piers with n/2 gates for each (Figure 5.20). So 6 gates for each pier for the model have to be taken.

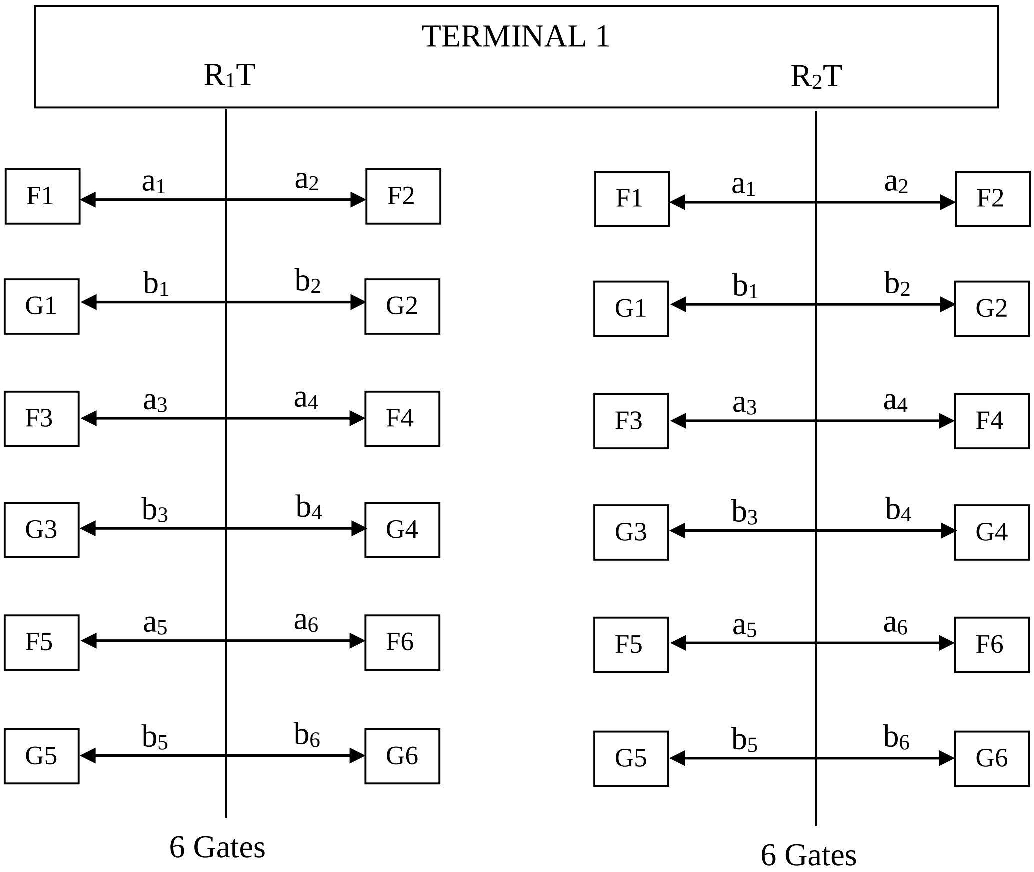


Figure 5. 20: Terminal configuration of two piers with 6 gates for each

Then average waiting times of a passenger at pier 1, that of at pier 2 and the entire terminal were found by using queuing theory formula.

Total average waiting time of a passenger at pier 1

$$T_1 = \frac{\sum_{i=1}^{6} \frac{(\rho_i)^{S_i}\left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right)}{S_i!\,(1-\rho_i)}}{6}$$

Total average waiting time of a passenger at pier 2

$$T_2 = \frac{\sum_{i=1}^{6} \frac{(\rho_i)^{S_i}\left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right)}{S_i!\,(1-\rho_i)}}{6}$$

Total average waiting time of a passenger at Terminal 1

$$TAW\ 1 = \frac{6 \times T_1 + 6 \times T_2}{6+6} = \frac{T_1 + T_2}{2}$$

The next terminal configuration taken for three piers was with n/3 gates for each and the average waiting times of a passenger at pier 1, that of at pier 2, pier 3 and entire terminal were found. The terminal of 3 piers with 4 gates for each was taken as a model (Figure 5.21).

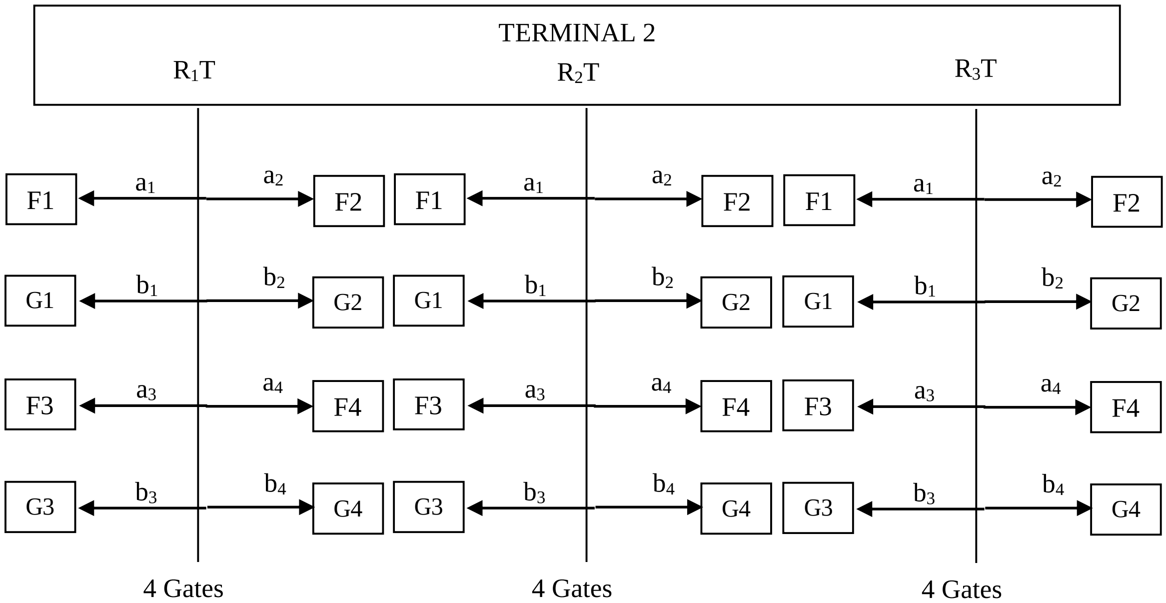


Figure 5. 21: Terminal configuration of three piers with 4 gates for each

Total average waiting time of a passenger at pier 1

$$T_1 = \frac{\sum_{i=1}^{4} \frac{(\rho_i)^{S_i}(\frac{1-\rho_i}{1-\rho_i^{Ni+1}})}{S_i!\,(1-\rho_i)}}{4}$$

Total average waiting time of a passenger at pier 2

$$T_2 = \frac{\sum_{i=1}^{4} \frac{(\rho_i)^{S_i}(\frac{1-\rho_i}{1-\rho_i^{Ni+1}})}{S_i!\,(1-\rho_i)}}{4}$$

Total average waiting time of a passenger at pier 3

$$T_3 = \frac{\sum_{i=1}^{4} \frac{(\rho_i)^{S_i}(\frac{1-\rho_i}{1-\rho_i^{Ni+1}})}{S_i!\,(1-\rho_i)}}{4}$$

Total average waiting time of a passenger at Terminal 2

$$TAW\ 2 = \frac{4 \times T_1 + 4 \times T_2 + 4 \times T_3}{4+4+4} = \frac{T_1 + T_2 + T_3}{3}$$

Bandara (1990) and Bandara and Wirasinghe (1992), with their research, determined optimal terminal geometry as taking three piers with two equal length piers and one lengthy pier.

Therefore, one of the terminals was selected using this view. So the last terminal configuration is taken for three piers with n1, n2 and n3 gates.

So, $n_1 + n_2 + n_3 = n$ Where $n_1 = n_3 = \frac{n-n_2}{2}$

For the model it has to be taken 3 piers with 4, 6, 4 gates respectively (Figure 5.22).

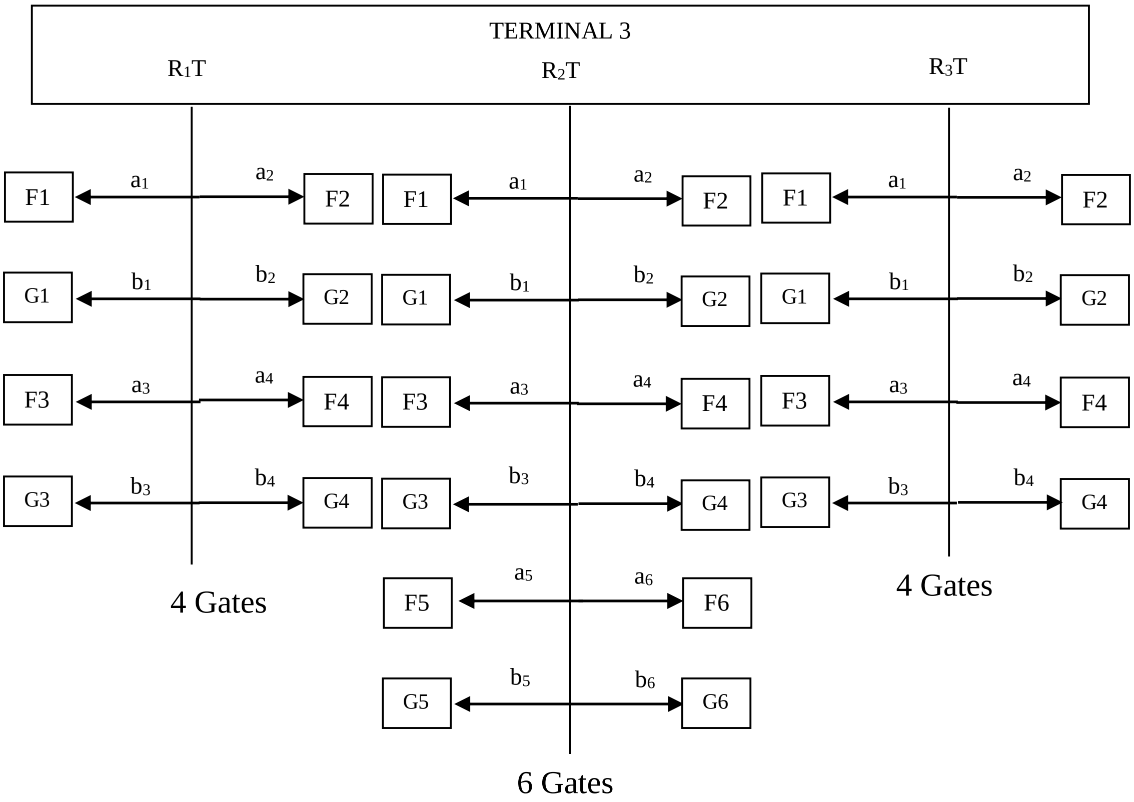


Figure 5. 22: Terminal configuration of three piers with different number of gates for each

Then the average waiting times of a passenger at pier 1, at pier 2, pier 3 and the entire terminal were found.

Total average waiting time of a passenger at pier 1

$$T_1 = \frac{\sum_{i=1}^{4} \left. (\rho_i)^{S_i}\left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right) \middle/ S_i!\,(1-\rho_i) \right.}{4}$$

Total average waiting time of a passenger at pier 2

$$T_2 = \frac{\sum_{i=1}^{6} \left. (\rho_i)^{S_i}\left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right) \middle/ S_i!\,(1-\rho_i) \right.}{6}$$

Total average waiting time of a passenger at pier 3

$$T_3 = \frac{\sum_{i=1}^{4} {}^{(\rho_i)^{S_i}\left(\frac{1-\rho_i}{1-\rho_i^{Ni+1}}\right)}\Big/{}_{S_i!\,(1-\rho_i)}}{4}$$

Total average waiting time of a passenger at Terminal 3

$$TAW\ 3 = \frac{4 \times T_1 + 6 \times T_2 + 4 \times T_3}{4 + 6 + 4}$$

According to that model, data were fed for the following variables.

μ_{iA} - Mean of waiting time at gate *i*

μ_{iS} - Mean of service time at gate *i*

μ_{jA} - Mean of waiting time at friction *j*

μ_{jS} - Mean of service time at friction *j*

λ - Total passenger arrival rate to the pier

P_i - Probability of passenger arrivals for gate *i*

S_i - Number of servers at the gate *i*

N_i - Maximum number of passengers coming to the gate *i*

λ_{Gi} - Arrival rate of the gate *i*

μ_{Gi} - Service rate of the gate *i*

S_j - Number of servers at the friction *j*

N_j - Maximum number of passengers coming to the friction *j*

λ_{Fj} - Arrival rate of the friction *j*

μ_{Fj} - Service rate of the friction *j*

a_j - Probability of passenger arrivals to friction *j*

b_j - Probability of passenger arrivals to gate *j*

c_{ij} - Probability of passenger arrivals from friction *i* to gate *j*

d_{ij} - Probability of passenger arrivals from friction *i* to friction *j*

T - Total number of passengers coming to the terminal

Ri - Passenger Proportion out of total passengers who are coming to the pier *i*

Once the data were fed for the above variables, new variables mentioned below were calculated by using the above variables.

New arrival rates for gates and frictions

ρ_i - Ratio of arrival rate to service rate at gate *i*

ρ_j - Ratio of arrival rate to service rate at friction *j*

P ($WT_{Gi} > 0$) - Probability of waiting time at the gate *i* after placing friction

P ($WT_{Fj} > 0$) - Probability of waiting time at the friction *j*

Ti - Average of the Probability of waiting time at pier *i*

TAWi - Total Average of the Probability of waiting time at the terminal *i*

$$TAW\ 1 = \frac{T_1 + T_2}{2}$$

$$TAW\ 2 = \frac{T_1 + T_2 + T_3}{3}$$

$$TAW\ 3 = \frac{4 \times T_1 + 6 \times T_2 + 4 \times T_3}{4 + 6 + 4}$$

By comparing TAW 1, TAW 2 and TAW 3 values according to the above models, the optimum terminal configuration can be found by taking the minimum value from above total average waiting times at terminals.

By putting different set of values for parameters (variables), TAW 1, TAW 2 and TAW 3 were calculated several times. It revealed that TAW 3 value was always less than the other two values. Therefore, it can be concluded that the third terminal which has middle longer pier is taken as an optimum terminal configuration (Saparamadu and Bandara, 2017).

5.10. Summary

The mean waiting time and variances of wasted time (parameters) help identify optimum positions for frictions before the mandatory service centers. If the parameters of optional services and mandatory services change, the positions for frictions also get changed. It is also likely that some passengers would use the optional services before proceeding to the mandatory services centres. This number going through the frictions, however small, should also be considered percentage-wise to determine the optimum positions of frictions between service centers. Further, placing frictions in between mandatory service centers depends on factors such as probability of arrivals of passengers to the frictions, probability of arrivals of passengers from one friction to another friction, total passenger arrival rate to the service centers and arrival rates and service rates of the frictions, as well. An analysis of data related to frictions and mandatory service centers led to analytical solutions for optimum positions of frictions between service centers to minimize passenger delays. These solutions were later verified by using simulation models. Analytical models help with initial solutions to placing frictions before mandatory service centres and handling different alternatives whereas, simulation models help with detailed information to help verify analytical solutions with optimum placements for the location of frictions before the service centers. Many factors contribute towards placing frictions in between gates, some of which are: the probability of arrivals of passengers to the frictions, probability of arrivals of passengers from one friction to another friction, total passenger arrival rate to the pier and arrival rates and service rates of the frictions. The model for an optimum terminal configuration depends on important factors such as: the number of piers, the number of gates in each pier, number of frictions in each pier, the manner of placing frictions in between gates, percentage of passengers going through the different frictions, the distributions and parameters of frictions, processing time for frictions and gates, number of piers and gate spacing. These factors help minimize the mean mandatory walking distance of passenger arrivals, departures, and transfers within the terminal. The third terminal with three piers including a longer middle pier proved to be the optimal terminal configuration to minimize passenger waiting time.

6. DISCUSSION AND CONCLUSION

6.1. Discussion

Airport terminals need to focus on several matters related to service centres if they wish to improve passenger movements. In this connection, a major task is to reduce waiting times and delays. Delays in airports, occur at critical service centres like: ticket counters, immigration, baggage claims and security checks as well as other optimal centres like: shops, washrooms, food cabins and Internet accesses. Since location and the opening strategy of different airport terminals vary, the arrival and waiting patterns of passengers also could vary. Frictions with services related to shops, washroom etc., placed between mandatory service centres could contribute towards cutting down on waiting times.

Available literature highlights several simulation and analytical models to minimize walking distance through airport terminals minimizing waiting times at ticket counters, check-in gates, baggage stations and security checks at airports. In the initial stages these analytical models are helpful towards planning, besides, they can also deal with different alternatives as simulation models contribute much towards verifying analytical results.

There were some analytical models providing formulae to determine the numbers of counters and likely space required for passengers waiting in queues especially with the mandatory services at airport terminals. Included were the capacity and delays associated. There have been simulation models to consider walking distances and waiting time between mandatory service centers and the location of the service centers fail to measure up to expectations. A model to determine the terminal configuration considering all factors mentioned above has not been found yet. Further, the existing models can be applied in one airport or one part of the airport only and they cannot be applied in other airports or other parts of the airport. Taking into consideration the drawbacks with existing analytical and simulation models to suit airport terminals, an attempt was made to derive a suitable model acceptable for use in any section of any airport terminal. This attempt towards a flexible model for use went through stringent tests to meet likely weaknesses or further drawbacks. A likely suitable model was developed. It contains the common features at all airport terminals and is capable of describing any terminal configuration. An advantage with the proposed model is that it can be modified to suit any airport terminal.

Waiting times in the queues at the mandatory service centers in arrival (security checks, ticketing counters and immigration counters) and departure procedures (immigration counters and baggage claims) are necessary for optimal terminal configuration. To minimize long waiting in queues it is possible to use some services such as food cabins, shops, internet access, washroom and charging points in between mandatory service centers. Identification of proper frictions (optional services) to be placed in between mandatory service centers is important as sometimes placing other services (frictions) may increase overall waiting time. Using the Welch t-test, hypothesis testing, ANOVA test, F test and Levene's test, it was possible to check whether the differences of mean waiting times and that of variance of waiting times at mandatory service centers with placing frictions and without placing frictions are significant. Then, it was required to find out the appropriate locations to place frictions before the mandatory service centers, so that helps to minimize passenger delays.

It is observed that passengers either use or do not use these frictions before proceeding to the mandatory services area. Therefore, it is necessary to consider this fact regarding passenger use of frictions as regards placement of frictions before service centres. In addition, the placement of frictions in between mandatory service centres also requires consideration regarding factors like: probability of passenger arrival to the frictions, the likelihood of passengers reaching one friction from another friction, total number of passenger arrivals to service centres and arrival rates and service rates of frictions. Accordingly, going on pre-determined predictions regarding waiting times and service times, allocations for proper placement of frictions were found.

Placing frictions before the mandatory service centers mainly depends on the means and variances (parameters) of the frictions and that of mandatory service centers. If the mean waiting time of mandatory service center without friction is less than the mean waiting time of mandatory service center with friction, it is not allowed to place the friction before the mandatory service center. At the same time, even the mean waiting times at mandatory service center without friction and with friction are equal, the variance of the waiting time at mandatory service center without friction is less than that of with friction, again placing friction before the mandatory service center is not allowed. Then the research was extended to find the placement of suitable frictions before the mandatory service centers in a proper manner to suit arrival and departure whole procedures to minimize passenger delays by using queueing theory.

Once the criteria for selecting appropriate frictions were found, it was used to compare different terminal configurations considering walking distance as well. In terminal configurations, gate assignment needs to be considered for the purpose of minimizing passenger delays. Consequently, the optimal terminal layout by placing suitable frictions before the gates had to be found so that passengers' waiting times can be minimized. This research considered three pier type terminal configurations to find out the optimal terminal configuration. The first terminal configuration was taken for two piers with n/2 gates for each and the second one was taken for three piers with n/3 gates in each. The terminal which had three piers including a longer middle pier was taken as the third terminal configuration.

In terminal configuration, probability of passenger arrivals to the frictions, the likelihood of passengers arriving from one friction to another, total passenger arrival rate to the pier and arrival rates and service rates of the frictions are some factors to help determine placement of frictions in between gates. Important factors for consideration towards development of model for an optimum terminal configuration include, among others: the number of piers with the number of gates in each pier, number of frictions in each pier, the pattern of placing frictions in between gates, percentage of passengers using different frictions, the distributions and parameters (mean and variance) of frictions, processing time for frictions and gates, number of piers and gate spacing. They contribute towards reducing the mean mandatory walking distance of arrivals, departures and transfers within a terminal. The terminal with three piers consisting of a longer middle pier appears to be the optimal terminal configuration to minimize passenger waiting time, as passengers' waiting time values of terminal configurations show. All analytical solutions were verified through simulation models by using queueing theory.

If the mean and variance of waiting time at a friction changes, the place of the friction gets changed. If the mean and variance of waiting time at a mandatory service center changes, a friction to be placed will also be changed. If a particular friction is required for placement in between gates, the parameters of friction (mean and variance of waiting time at frictions) need to change accordingly.

Finally, the results of this research can be applied to any service center and any gate of any airport to minimize waiting time of passengers. Passengers are most likely to welcome the move to prevent loss of valuable time.

6.2. Conclusion

Travel by air, though more expensive, is to minimize on time spent on the journey. However, it is unfortunate that such passengers be expected to spend valuable time at airport terminals for clearance to board a flight. Inconvenience of moving through airport terminals waiting long in queues, researchers have made attempts towards suitable models for the purpose. Yet, with developing technology and continuous developments at airports to meet the needs of increasing numbers of air passengers, the models developed have not had much of an impact towards helping passengers with shorter time at terminals. In such a background, the proposed model, apparently, is a better development. Anyhow, it may not meet with all the requirements of future airport terminals due to technology developments or airport expansions as described above. Hence, it is timely to think of further developments to the suggested model as what matters in the end will be passenger comfort.

6.3. Future Work

According to the BIA case study done for this research, only few frictions were considered towards optimizing passengers' waiting times. However, in airports, various types of frictions and many numbers of frictions can be placed before the service centers as well as the gates to minimize passengers' waiting time at the airport. Even though, three terminal types were used in this research to check the optimal terminal configuration, this can be extended to more terminal configurations with more piers and other configurations as well.

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Appendix A

Analysis of waiting time at immigration counters through one friction and waiting time at baggage station through another friction in arrival procedure

(i) Two-Sample T-Test and CI: Imm_Shop, Bag_Wash

Method

μ_1: mean of Imm_Shop

μ_2: mean of Bag_Wash

Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Imm_Shop	88	2128	1504	160
Bag_Wash	127	386	302	27

Estimation for Difference

Difference	95% Lower Bound for Difference
1742	1471

Test

Null hypothesis	H_0: $\mu_1 - \mu_2 = 0$
Alternative hypothesis	H_1: $\mu_1 - \mu_2 > 0$

T-Value	DF	P-Value
10.71	91	0.000

$P - Value = 0.000 < 0.05 = \alpha$

H_0 is rejected under 0.05 level of significance.

So, there is enough evidence to conclude that the mean waiting time of immigration+shop is greater than that of baggage+washrooms under 0.05 level of significance.

(ii) Test and CI for Two Variances: Imm_Shop, Bag_Wash

Method

σ_1: standard deviation of Imm_Shop

σ_2: standard deviation of Bag_Wash

Ratio: σ_1/σ_2

F method was used. This method is accurate for normal data only.

Descriptive Statistics

Variable	N	StDev	Variance	95% Lower Bound for σ
Imm_Shop	88	1504.361	2263100.877	1339.255
Bag_Wash	127	302.327	91401.686	274.180

Ratio of Standard Deviations

Estimated Ratio	95% Lower Bound for Ratio using F
4.97594	4.240

Test

Null hypothesis	H_0: $\sigma_1 / \sigma_2 = 1$
Alternative hypothesis	H_1: $\sigma_1 / \sigma_2 > 1$
Significance level	$\alpha = 0.05$

Method	Test Statistic	DF1	DF2	P-Value
F	24.76	87	126	0.000

$P - Value = 0.000 < 0.05 = \alpha$

H_0 is rejected under 0.05 level of significance.

So, there is enough evidence to conclude that the variance waiting time of immigration+shop is greater than that of baggage+washrooms under 0.05 level of significance.

(iii) Two-Sample T-Test and CI: Imm_Shop, Bag_Shop

Method

μ_1: mean of Imm_Shop

μ_2: mean of Bag_Shop

Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Imm_Shop	88	2128	1504	160
Bag_Shop	127	1862	1381	123

Estimation for Difference

Difference	95% CI for Difference
266	(-132, 664)

Test

Null hypothesis	H_0: $\mu_1 - \mu_2 = 0$
Alternative hypothesis	H_1: $\mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
1.32	176	0.189

$$P - Value = 0.189 > 0.05 = \alpha$$

H_0 is not rejected under 0.05 level of significance.

So, there is enough evidence to conclude that the mean waiting time of immigration+shop is equal to that of baggage+shop under 0.05 level of significance

(iv) Test and CI for Two Variances: Imm_Shop, Bag_Shop

Method

σ_1: standard deviation of Imm_Shop

σ_2: standard deviation of Bag_Shop

Ratio: σ_1/σ_2

F method was used. This method is accurate for normal data only.

Descriptive Statistics

Variable	N	StDev	Variance	95% CI for σ
Imm_Shop	88	1504.361	2263100.877	(1310.217, 1766.581)
Bag_Shop	127	1380.921	1906943.360	(1229.439, 1575.315)

Ratio of Standard Deviations

Estimated Ratio	95% CI for Ratio using F
1.08939	(0.900, 1.328)

Test

Null hypothesis	H_0: $\sigma_1 / \sigma_2 = 1$
Alternative hypothesis	H_1: $\sigma_1 / \sigma_2 \neq 1$
Significance level	$\alpha = 0.05$

Method	Test Statistic	DF1	DF2	P-Value
F	1.19	87	126	0.377

$P - Value = 0.377 > 0.05 = \alpha$

H_0 is not rejected under 0.05 level of significance.

So, there is enough evidence to conclude that the variance waiting time of immigration+shop is equal to that of baggage+shop under 0.05 level of significance

(v) Two-Sample T-Test and CI: Imm_Shop, Bag_Food

Method

μ_1: mean of Imm_Shop

μ_2: mean of Bag_Food

Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Imm_Shop	88	2128	1504	160
Bag_Food	127	1831	1274	113

Estimation for Difference

Difference	95% CI for Difference
297	(-90, 684)

Test

Null hypothesis	H_0: $\mu_1 - \mu_2 = 0$
Alternative hypothesis	H_1: $\mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
1.51	166	0.132

$P - Value = 0.132 > 0.05 = \alpha$

H_0 is not rejected under 0.05 level of significance.

So, there is enough evidence to conclude that the mean waiting time of immigration+shop is equal to that of baggage+food under 0.05 level of significance.

(vi) Test and CI for Two Variances: Imm_Shop, Bag_Food

Method

σ_1: standard deviation of Imm_Shop

σ_2: standard deviation of Bag_Food

Ratio: σ_1/σ_2

F method was used. This method is accurate for normal data only.

Descriptive Statistics

Variable	N	StDev	Variance	95% CI for σ
Imm_Shop	88	1504.361	2263100.877	(1310.217, 1766.581)
Bag_Food	127	1274.483	1624305.751	(1134.676, 1453.893)

Ratio of Standard Deviations

Estimated Ratio	95% CI for Ratio using F
1.18037	(0.975, 1.439)

Test

Null hypothesis	H_0: $\sigma_1 / \sigma_2 = 1$
Alternative hypothesis	H_1: $\sigma_1 / \sigma_2 \neq 1$
Significance level	$\alpha = 0.05$

Method	Test Statistic	DF1	DF2	P-Value
F	1.39	87	126	0.088

$P - Value = 0.088 > 0.05 = \alpha$

H_0 is not rejected under 0.05 level of significance.

So, there is enough evidence to conclude that the mean waiting time of immigration+shop is equal to that of baggage+food under 0.05 level of significance.

(vii) Two-Sample T-Test and CI: Imm_Shop, Bag_Tele

μ_1: mean of Imm_Shop

μ_2: mean of Bag_Tele

Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Imm_Shop	88	2128	1504	160
Bag_Tele	127	346	281	25

Estimation for Difference

Difference	95% Lower Bound for Difference
1782	1512

Test

Null hypothesis $H_0: \mu_1 - \mu_2 = 0$

Alternative hypothesis $H_1: \mu_1 - \mu_2 > 0$

T-Value	DF	P-Value
10.98	91	0.000

$P - Value = 0.000 < 0.05 = \alpha$

H_0 is rejected under 0.05 level of significance.

So, there is enough evidence to conclude that the mean waiting time of immigration+shop is greater than that of baggage+internet access under 0.05 level of significance.

(viii) Test and CI for Two Variances: Imm_Shop, Bag_Tele

Method

σ_1: standard deviation of Imm_Shop

σ_2: standard deviation of Bag_Tele

Ratio: σ_1/σ_2

F method was used. This method is accurate for normal data only.

Descriptive Statistics

Variable	N	StDev	Variance	95% Lower Bound for σ
Imm_Shop	88	1504.361	2263100.877	1339.255
Bag_Tele	127	281.180	79062.360	255.002

Ratio of Standard Deviations

Estimated Ratio	95% Lower Bound for Ratio using F
5.35016	4.559

Test

Null hypothesis	H_0: $\sigma_1 / \sigma_2 = 1$
Alternative hypothesis	H_1: $\sigma_1 / \sigma_2 > 1$
Significance level	$\alpha = 0.05$

Method	Test Statistic	DF1	DF2	P-Value
F	28.62	87	126	0.000

$P - Value = 0.000 < 0.05 = \alpha$

H_0 is rejected under 0.05 level of significance. So, there is enough evidence to conclude that the variance waiting time of immigration+shop is greater than that of baggage+internet access under 0.05 level of significance.

Appendix B

Analysis of waiting time at immigration counters and that of immigration counters through two frictions in arrival procedure

Oneway

ANOVA

Waiting Time

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	672880161.636	5	134576032.327	66.383	.000
Within Groups	1058240482.295	522	2027280.617		
Total	1731120643.932	527			

Post Hoc Tests

Multiple Comparisons

Dependent Variable: Waiting Time

Tukey HSD

(I) Friction	(J) Friction	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	219.864	214.650	.910	-394.11	833.83
	3	1965.057*	214.650	.000	1351.09	2579.03
	4	-1929.057*	214.650	.000	-2543.03	-1315.09
	5	-112.727	214.650	.995	-726.70	501.24
	6	118.341	214.650	.994	-495.63	732.31
2	1	-219.864	214.650	.910	-833.83	394.11

	3	1745.193*	214.650	.000	1131.22	2359.16
	4	-2148.920*	214.650	.000	-2762.89	-1534.95
	5	-332.591	214.650	.632	-946.56	281.38
	6	-101.523	214.650	.997	-715.49	512.45
3	1	-1965.057*	214.650	.000	-2579.03	-1351.09
	2	-1745.193*	214.650	.000	-2359.16	-1131.22
	4	-3894.114*	214.650	.000	-4508.08	-3280.14
	5	-2077.784*	214.650	.000	-2691.76	-1463.81
	6	-1846.716*	214.650	.000	-2460.69	-1232.74
4	1	1929.057*	214.650	.000	1315.09	2543.03
	2	2148.920*	214.650	.000	1534.95	2762.89
	3	3894.114*	214.650	.000	3280.14	4508.08
	5	1816.330*	214.650	.000	1202.36	2430.30
	6	2047.398*	214.650	.000	1433.43	2661.37
5	1	112.727	214.650	.995	-501.24	726.70
	2	332.591	214.650	.632	-281.38	946.56
	3	2077.784*	214.650	.000	1463.81	2691.76
	4	-1816.330*	214.650	.000	-2430.30	-1202.36
	6	231.068	214.650	.891	-382.90	845.04
6	1	-118.341	214.650	.994	-732.31	495.63
	2	101.523	214.650	.997	-512.45	715.49
	3	1846.716*	214.650	.000	1232.74	2460.69
	4	-2047.398*	214.650	.000	-2661.37	-1433.43
	5	-231.068	214.650	.891	-845.04	382.90

*. The mean difference is significant at the 0.05 level.

Homogeneous Subsets

Waiting Time

Tukey HSD

Friction	N	Subset for alpha = 0.05		
		1	2	3
3	88	458.28		
2	88		2203.48	
6	88		2305.00	
1	88		2423.34	
5	88		2536.07	
4	88			4352.40
Sig.		1.000	.632	1.000

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 88.000.

Appendix C

Analysis of differences of variance waiting time at immigration counter through frictions

(i) Test and CI for Two Variances: Im-Wa-Sh, Im-Wa-Fo

Method

σ_1: standard deviation of Im-Wa-Sh

σ_2: standard deviation of Im-Wa-Fo

Ratio: σ_1/σ_2

F method was used. This method is accurate for normal data only.

Descriptive Statistics

Variable	N	StDev	Variance	95% CI for σ
Im-Wa-Sh	88	1506.902	2270753.630	(1312.430, 1769.565)
Im-Wa-Fo	88	1283.974	1648588.965	(1118.272, 1507.779)

Ratio of Standard Deviations

Estimated Ratio	95% CI for Ratio using F
1.17362	(0.950, 1.450)

Test

Null hypothesis	H_0: $\sigma_1 / \sigma_2 = 1$
Alternative hypothesis	H_1: $\sigma_1 / \sigma_2 \neq 1$
Significance level	$\alpha = 0.05$

Method	Test Statistic	DF1	DF2	P-Value
F	1.38	87	87	0.137

$P - Value = 0.137 > 0.05 = \alpha$

H_0 is not rejected at 0.05 level of significance.

So, there is enough evidence to conclude that the variance waiting time of immigration+washroom+shop is equal to that of immigration+washroom+food at 0.05 level of significance.

(ii) Test and CI for Two Variances: Im-Wa-Sh, Im-Sh-Te

Method

σ_1: standard deviation of Im-Wa-Sh

σ_2: standard deviation of Im-Sh-Te

Ratio: σ_1/σ_2

F method was used. This method is accurate for normal data only.

Descriptive Statistics

Variable	N	StDev	Variance	95% CI for σ
Im-Wa-Sh	88	1506.902	2270753.630	(1312.430, 1769.565)
Im-Sh-Te	88	1492.748	2228296.156	(1300.103, 1752.944)

Ratio of Standard Deviations

Estimated Ratio	95% CI for Ratio using F
1.00948	(0.817, 1.247)

Test

Null hypothesis	H_0: $\sigma_1 / \sigma_2 = 1$
Alternative hypothesis	H_1: $\sigma_1 / \sigma_2 \neq 1$
Significance level	$\alpha = 0.05$

Method	Test Statistic	DF1	DF2	P-Value
F	1.02	87	87	0.930

$P - Value = 0.930 > 0.05 = \alpha$

H_0 is not rejected at 0.05 level of significance.

So, there is enough evidence to conclude that the variance waiting time of immigration+washroom+shop is equal to that of immigration+washroom+internet access at 0.05 level of significance.

(iii) Test and CI for Two Variances: Im-Wa-Sh, Im-Fo-Te

Method

σ_1: standard deviation of Im-Wa-Sh

σ_2: standard deviation of Im-Fo-Te

Ratio: σ_1/σ_2

F method was used. This method is accurate for normal data only.

Descriptive Statistics

Variable	N	StDev	Variance	95% CI for σ
Im-Wa-Sh	88	1506.902	2270753.630	(1312.430, 1769.565)
Im-Fo-Te	88	1288.165	1659369.402	(1121.922, 1512.701)

Ratio of Standard Deviations

Estimated Ratio	95% CI for Ratio using F
1.16980	(0.947, 1.445)

Test

Null hypothesis H_0: $\sigma_1 / \sigma_2 = 1$

Alternative hypothesis H_1: $\sigma_1 / \sigma_2 \neq 1$

Significance level	$\alpha = 0.05$

Method	Test	DF1	DF2	P-Value
F	1.37	87	87	0.145

$P - Value = 0.145 > 0.05 = \alpha$

H_0 is not rejected at 0.05 level of significance.

So, there is enough evidence to conclude that the variance waiting time of immigration+washroom+shop is equal to that of immigration+food+internet access at 0.05 level of significance.

(iv) Test and CI for Two Variances: Im-Wa-Fo, Im-Sh-Te

Method

σ_1: standard deviation of Im-Wa-Fo

σ_2: standard deviation of Im-Sh-Te

Ratio: σ_1/σ_2

F method was used. This method is accurate for normal data only.

Descriptive Statistics

Variable	N	StDev	Variance	95% CI for σ
Im-Wa-Fo	88	1283.974	1648588.965	(1118.272, 1507.779)
Im-Sh-Te	88	1492.748	2228296.156	(1300.103, 1752.944)

Ratio of Standard Deviations

Estimated Ratio	95% CI for Ratio using F
0.860141	(0.696, 1.063)

Test

Null hypothesis	$H_0: \sigma_1 / \sigma_2 = 1$
Alternative hypothesis	$H_1: \sigma_1 / \sigma_2 \neq 1$

Significance level α = 0.05

Method	Test Statistic	DF1	DF2	P-Value
F	0.74	87	87	0.162

$P - Value = 0.162 > 0.05 = \alpha$

H_0 is not rejected at 0.05 level of significance.

So, there is enough evidence to conclude that the variance waiting time of immigration+washroom+food is equal to that of immigration+shop+internet access at 0.05 level of significance.

(v) Test and CI for Two Variances: Im-Wa-Fo, Im-Fo-Te

Method

σ_1: standard deviation of Im-Wa-Fo

σ_2: standard deviation of Im-Fo-Te

Ratio: σ_1/σ_2

F method was used. This method is accurate for normal data only.

Descriptive Statistics

Variable	N	StDev	Variance	95% CI for σ
Im-Wa-Fo	88	1283.974	1648588.965	(1118.272, 1507.779)
Im-Fo-Te	88	1288.165	1659369.402	(1121.922, 1512.701)

Ratio of Standard Deviations

Estimated Ratio	95% CI for Ratio using F
0.996746	(0.807, 1.232)

Test

Null hypothesis	H_0: $\sigma_1 / \sigma_2 = 1$
Alternative hypothesis	H_1: $\sigma_1 / \sigma_2 \neq 1$
Significance level	$\alpha = 0.05$

Method	Test Statistic	DF1	DF2	P-Value
F	0.99	87	87	0.976

$P - Value = 0.976 > 0.05 = \alpha$

H_0 is not rejected at 0.05 level of significance.

So, there is enough evidence to conclude that the variance waiting time of immigration+washroom+food is equal to that of immigration+food+internet access at 0.05 level of significance.

(vi) Test and CI for Two Variances: Im-Sh-Te, Im-Fo-Te

Method

σ_1: standard deviation of Im-Sh-Te

σ_2: standard deviation of Im-Fo-Te

Ratio: σ_1/σ_2

F method was used. This method is accurate for normal data only.

Descriptive Statistics

Variable	N	StDev	Variance	95% CI for σ
Im-Sh-Te	88	1492.748	2228296.156	(1300.103, 1752.944)
Im-Fo-Te	88	1288.165	1659369.402	(1121.922, 1512.701)

Ratio of Standard Deviations

Estimated Ratio	95% CI for Ratio using F
1.15882	(0.938, 1.432)

Test

Null hypothesis	H_0: $\sigma_1 / \sigma_2 = 1$
Alternative hypothesis	H_1: $\sigma_1 / \sigma_2 \neq 1$
Significance level	$\alpha = 0.05$

Method	Test Statistic	DF1	DF2	P-Value
F	1.34	87	87	0.171

$P - Value = 0.171 > 0.05 = \alpha$

H_0 is not rejected at 0.05 level of significance.

So, there is enough evidence to conclude that the variance waiting time of immigration+shop+internet access is equal to that of immigration+food+internet access at 0.05 level of significance.