Utilization of evacuation model for airports using risk based fire safety scenario

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UTILIZATION OF EVACUATION MODEL FOR AIRPORTS

USING RISK BASED FIRE SAFETY SCENARIO

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This report presents the generalized method of designing an airport terminal based on the design peak hour passengers and the risk based fire safety method to identify the high fire risk locations with respect to the occupant evacuation safety.
The evacuation strategies have been modeled in two simulation software tools (Pathfinder and LegionEvac) to compare the total evacuation time. The comparison between the models is discussed based on the total evacuation time. Based on the evacuation time, further evacuation strategies are simulated to study the flow pattern and evacuation problems with respect to airport environment. In the result section, critical factors which affect the airport evacuation and suggestion for optimization is discussed.

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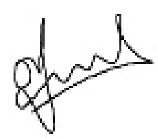

(30-April-2014)

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விமான நிலைய முனைய கட்டிடங்களை முழுவதுமாக காலி செய்யும்பொழுது பாதுகாப்பு கதவின் வழியாக வெளியேறுபவர்களை ஆயும் வெளியேற்று மாதிரிகளை பற்றி இந்த ஆய்வில் கவனம் செலுத்தப்படுகிறது. முனைய வருகை மண்டபம் மற்றும் புறப்பாடு மண்டபம் ஆகிய இடங்களில் ஆபத்து மதிப்பிடின் அடிப்படையில் வழக்கு ஆய்வுகள் மேற்கொள்ளப்பட்டிருக்கிறது. இந்த இரண்டு வழக்குகளிலும், ஒரு புற ஓட்டம் மற்றும் எதிர்புற ஓட்டம் அடிப்படையில் பாதுகாப்பு கதவுகளின் வழியாக வெளியேறும் உத்திகள் பயன்படுத்தப்பட்டுள்ளது.

வடிவமைப்பு உச்ச மணி நேர அடிப்படையில் விமான நிலைய முனையம் வடிவமைக்கும் பொதுவான முறை இந்த அறிக்கையில் விவாதிகப்பட்டுள்ளது. மற்றும் விமான நிலைய உபயோகிப்பவர்களுடைய பாதுகாப்பான வெளியேற்றத்தின் அடிப்படையில் அதிக தீ உருவாக வாய்ப்புள்ள இடங்களை கண்டறியும் ஆபத்து அடிப்படையிலான தீ பாதுகாப்பு முறை விவாதிக்கப்பட்டுள்ளது.

காலி செய்யும் உத்திகளை குறுக்கு ஒப்பீடு செய்வதற்காக இரண்டு வெவ்வேறு உருவகப்படுத்தும் மென்பொருளில் உருவகபடுதப்பட்டு ஆய்வுகள் மேற்கொள்ளப்பட்டது. இரண்டு மாதிரிகளும், மொத்த காலியாகும் நேரம் அடிப்படையில் ஒப்பீடு செய்யப்பட்டன. மொத்த காலியாகும் நேர அடிப்படையில், மேலும் சில காலியாகும் உத்திகள் உருவகப்படுத்தப்பட்டு காலியாகும் பிரச்சினைகள் ஆரயாப்பட்டன. காலியாகும் உத்திகளை பாதிக்கும் முக்கியமான காரணிகள் மற்றும் விமான நிலைய காலியாகும் உத்திகள் மேம்பாடு செய்யும் முறைகளை பற்றி இறுதி பிரிவில் விவாதிக்கப்பட்டுள்ளது.

Table of Contents

List of abbreviations

IATA – International Air Transport Association

IRCC – Inter-Jurisdictional Regulatory Collaboration Committee

FAA – Federal Aviation Administration

LOS – Level of Service

Pax – Passengers

ATO – Airport Ticket Office

CBP – Customs and Borderline Protection (Immigration control)

GST – Goods and Service Tax

PA – Public Address system

CAD – Computer Aided Design

SFPE – Society of Fire Protection Engineers

BSI – British Standard Institution

List of tables and figures

1. Introduction

Airports terminal buildings are built to stimulate economic growth by encouraging tourism and to handle huge capacity of passengers. It is mandatory to have fire safety provisions provided properly to ensure life safety and continuous operation of airports. In fire safety and evacuation point of view, the airport terminal buildings are not to have a fire, and even when a fire occurs, the fire has to be confined without spreading out to limit the number of occupants being affected and the losses incurred [1]. In case of fire situation, the frequent users such as staffs and airport terminal officials can easily recognize the escape route to evacuate. But, for travelers/ passengers/ visitors, who are unfamiliar with the building, would have problem in finding the escape routes.

Security concerns are equally important in the terminals [2], as it poses a threat to national security. So airport management gives more importance to airport security with respect to the fire threat, irrespective of probability of such an event occurring, and the consequence of a lapse in security extend far beyond the facility and its occupants.

In any building, people enter into the area (ingress), move around (circulation movement) and finally leave the area (egress) [3]. In reality, the three types of movement are applicable to airport as well. However these movement types are complicated in airport environments, where security restricts the movement of the users. Due to security features of airport, ingress is closely managed, access is limited, and egress is controlled. As the fire safety and security is interlinked in airports, persons intending to harm in an airport terminal, could use the fire detection/ alarm system as a means to open security doors and gain access to various secured areas in the airport. So, unlike normal buildings, different evacuation methodology has to be implemented in airports to compromise the safety and security of the terminal buildings.

Airports have very distinct features such as very high ceiling, uneven distribution of occupant density & fuel load, security area partition from public area. These are the factors that affect the emergency evacuation process.

In an airport terminal, because of architectural requirements, large areas are allocated to arrival and departure halls. These halls have a ceiling with greater heights and volume, which complicates the design of fire detection and suppression system [1]. As designing fire safety and suppression system for open areas is difficult, it will lead to untenable condition sooner than other places with fire safety.

The occupant density would not be distributed evenly in a terminal building [1], as the retail areas are more crowded than the passenger waiting areas. In departure hall, people tend to go for shopping rather than waiting for the flight in the waiting area. In the arrival hall, the occupant density is high in the immigration clearance, baggage collection area (secured area) and passengers' receiver area (public area). Commonly, the occupant density is high in front of security counters, check-in counters, and passenger waiting hall (waiting area, before boarding an aircraft). In an emergency evacuation situation, it will lead to a queue formation and increase in evacuation time, when all the occupants in high occupant density areas, start to move to the exit for evacuation [5].

The fire load density in the terminal building is not evenly distributed [4], which may lead to a potential fire and in turn leads to emergency situation in airport. Retail areas, festival display areas (such as Christmas tree display) will have more fire load density. So probability of having highly severe fire in the high fire load density area is high.

By considering the occupant behavior, security and building features, the evacuation methodologies has to be distinct for airport environment. However, it is impossible to conduct emergency evacuation exercise in an airport, as it has the following drawbacks,

- Airport is always expected to have a considerable amount of population almost all days irrespective of the time. Hence choosing a time to execute this activity even becomes impossible
- Fire drill causes serious disruption to airport activities. It is costly to operators, airlines and its customers.
- It affects on-time movement of passengers, freight and aircraft which is most important for the financial wellbeing of an airport.
- Evacuation in real-time affects commercial enterprises in airport which are the most important source of revenue.
- Affects airport services and business continuity during and after conducting a fire drill in real time.

These shortfalls can be eliminated by simulating the airport environment in any of the evacuation simulation software. The advantage of simulating the evacuation will avoid the above issues with respect to the real-time evacuation procedure, as well as, it will help to optimize the evacuation strategy based on the simulation results.

As discussed earlier, evacuation in any airport terminal is different from other buildings, as it involves the security constraint in movement and architectural features. Security is a major concern, when the secured area occupants evacuate to the public area or public area evacuate to the secured area. These two areas are divided by security doors. So these security doors have to be restricted in flow direction. However these doors are used by fireman to enter secured area for firefighting/ rescue operation from the public area, when there is any fire at the secured side of a terminal. So it is not possible to let the security door to restrict the evacuation flow in one direction.

1.1 Objectives

This thesis focuses on the issues and problems which may arise in an airport evacuation due to the influence of security and safety in an airport terminal and give possible suggestion to improve the evacuation strategy for airport terminals.

The objective of the thesis is to:

- Develop generic design for airport by studying common airport design methodologies.
- Develop risk based fire scenario to identify high fire risk locations in airport.
- Model and simulate the evacuation using evacuation tools based on the result of fire scenario and evacuation strategies used in airports.
- Study and analyze problems in an airport emergency evacuation based on simulation results and compare between different evacuation strategies.
- Suggest an evacuation strategy for airport terminal buildings.

1.2 Methods

Several airport terminal design and common airport terminal design methodologies used in airport are studied to develop a generalized design for airport terminal. Based on the study result and analysis, generalized features and plan of an airport is developed which will be used as a model for the fire risk assessment and evacuation simulation. Risk based fire scenarios are developed by identifying the potential fire risks in airports. Based on the potential risk scenarios, the worst credible case locations are identified. The identified high risk locations are taken as input to the evacuation simulation. Simulations are designed for the scenario, by considering the safety, security and fireman counter access to fire, which will hinder the evacuation process. Each Scenario will be simulated for the following sub-scenarios

- Evacuation by considering the security of an airport (One way flow, secured area passengers evacuate to outside of the terminal building through public side)
- Evacuation combined with fireman access from public (Prioritized counter flow - Priority to fireman)

Different evacuation strategies are formulated and the sub-scenarios are simulated in simulation software to analyze the common evacuation flow pattern in terminal buildings. The results are studied and analyzed to suggest an optimized solution to airport terminal buildings.

1.3 Delimitations

The research focuses on the generalized plan of an airport, based on the study of different airports. It focuses on the open area fire in an airport's secured area, based on the preliminary fire risk assessment. It does not consider the fire in any utility rooms inside airport, as these areas have very limited access to passengers and visitors, and it is closed most of the time.

Fire risk assessment is carried out to identify high risk locations. As this thesis concentrates on the open space fire, fire can be seen clearly from certain distance, where there is no effect of fire. So it is assumed that occupants avoid those places, which has fire effects to human, during evacuation. Most of the airports do also have smoke control system, which will minimize the toxic effects to the occupants. So the thesis does not account for the fire effects to the occupants.

Airports have its own fire service offices in its boundary. So the intervention of the fireman is assumed to be shorter compared with the fire scenarios in other buildings. As airports are complex buildings, it is assumed that occupants are mostly using the familiar exits for evacuation and in some cases, airport staffs may guide them to the nearest emergency exits to evacuate. During the evacuation some of the airport terminal’s staffs such as retail shop staffs, restaurant staffs, who are not trained to handle fire emergency, may evacuate using the other emergency exits (non-security doors). This research does not consider the evacuation of occupants in the building, who evacuate through non security doors. This research may not be applicable for smaller/domestic airports which have less number of passengers, so that the evacuation is well managed by the operation and maintenance staff in the airport.

2. Airport passenger terminal

Passenger terminal area is the major interface between airfield and rest of the airport. It includes facilities for passenger handling, baggage handling, retail shops, airport maintenance, airport operations and other administration activities. Airport terminals have three major sections; they are curb side, land side and air side. These three parts are functionally divided into three components, such as access interface, processing interface and flight interface [6].

1. Access interface is used as an accessing medium to the airport terminal. In this, passenger transfers from their access mode of travelling to the processing interface of the airport terminal. This interface includes activities like parking, loading/unloading of passengers/luggage and movement of maintenance vehicles and trolleys.
2. In the processing interface, passengers are processed for the starting/ending/continuation of their air journey. The primary activities in this zone are check-in, ticketing, federal inspection services and security.
3. The flight interface is an interface, where passengers transfer from the processing interface to the aircraft. The activity includes, assembly, conveyance to and from the aircraft and aircraft loading/unloading.

The functional activities of the three areas in the airport are depicted in a table below [7].

	Arrival	Departure
Curb side	i. Curb Allocation ii. Transit waiting	i. Curb side check in ii. Curb side allocation
Land side	i. CBP primary ii. Baggage claim iii. CBP secondary iv. Inbound baggage v. Greeter lobbies	i. Check in ii. Passenger screening iii. Baggage screening iv. Well-wisher lobbies
Air side	-N.A-	i. Gates ii. Hold rooms

Table 1 : Airport terminal areas and function

As the thesis focuses on the evacuation of occupants (in case of fire) inside the terminal building, the terminal designing process mainly concentrates on design of the facilities, which are inside the terminal. The design of terminal curb is omitted in the design.

2.1. Overall space approximations

In the preliminary design of the airport terminal, overall size of the terminal can be estimated roughly. The Federal Aviation Administration (FAA) has indicated that, the gross terminal area space requirements between 0.007 m^2 and 0.01m^2 per annual enplaned passengers are reasonable. There is another method which estimates the terminal area as 13 m^2 per design hour passenger [8]. In this method, estimates of the level of peak hour passengers, peak hour aircraft operations and gate positions are obtained from the annual enplanements. The overall size of the airport is also estimated from the number of enplanements [8].

There are Federal Aviation Administration (FAA) standards for approximation of spaces for the facilities inside the terminal. Based on FAA, 55% of terminal space is rentable and 45% is non-rentable [9]. In operations point of view, the terminal area is divided into airline operations area (35 to 40%), airport administration area (15 to 25%), public space (25 to 35%) and utilities/stairways area (10 to 15%) [9]. However the actual area of an individual facility is determined based on the detailed analysis of the performance of the facility.

2.2. Level of service (LOS)

The level of service or quality of service is viewed by users (airlines, passengers and airport operators) based on their own perspectives [10]. Airlines have a perspective of on-time schedule, airport operating costs and profitability. Passengers are more concerned with successfulness of their journey, minimum waiting time in the facilities and maximum convenience. Airport operators are mostly interested in providing modern facilities to the passengers and airlines.

There are ranges for the LOS from LOS A (excellent design) to LOS E (unacceptable design). Much research has been carried out to define the level of service standards [11] [12] [13] [14] [15]. In general, the LOS is associated with the congestion within the terminal building, walking distance, passenger delays, waiting queue lengths and passenger processing time. In order to design an acceptable or optimal solution, the designer must take in to account the perspective of the airport users.

2.3. Departure hall

In the departure hall of the airport, passenger and their well-wishers enter the airport and then the passenger proceeds to their air travel initiation formalities, such as check-in, collection of boarding pass, baggage drop and then enter the secured area of the terminal. In the secured area, passengers complete their immigration formalities, security screening, waiting at the hold rooms and finally enters the aircraft to start their air journey. The typical flow diagram of the departure process is:

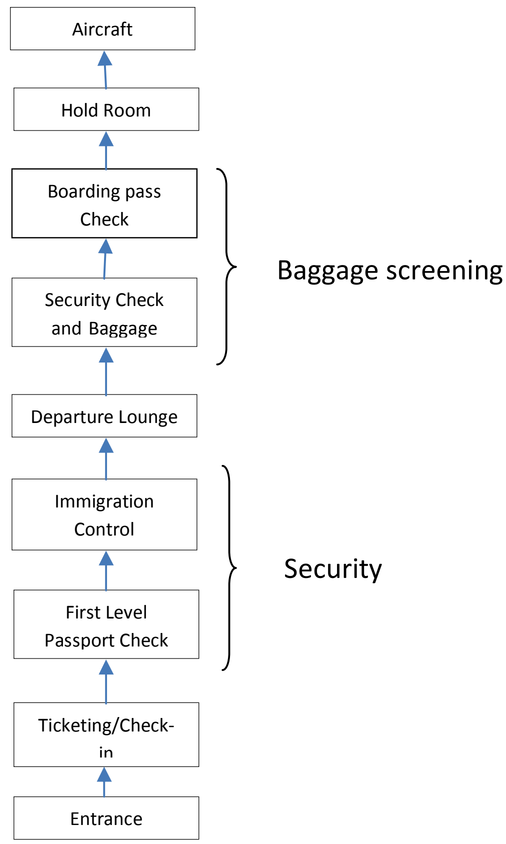

Figure 1: Departure hall flow

As shown in the figure 1, the departure hall of an airport has the following facilities.

i. Check-in/Ticketing
ii. Security
iii. Baggage screening
iv. Hold rooms

2.3.1. Check-in/Ticketing

The departure process is initiated at ticket/check-in counter of the terminal, which is usually referred as Airport Ticket Office (ATO). This is the area, where the airline and passengers make final ticket transactions, and then drops in their baggage for a flight. This area consists of airline check-in counters, airline ticket agent service area, outbound baggage handling device and support office area for the ticketing agents. As shown in figure 2, check-in / ticketing counters are designed with multiple counters in both the sides of the check in row and the center of the check in row is provided with baggage handling conveyor to transport check-in baggage for the further processing and finally load in the aircraft.

The design of check-in/ ticketing counters is based on the number of design hour enplaning passengers, number of airlines, time distribution of passenger arrival time to the ticketing counter, average service time and maximum waiting time targets.

The total number of ticketing counter required can be calculated from the below formula [7]:

$$N_{counter} = \frac{Departing\ Passenger_{Peak\ 30\ min} \times Processing\ time/passenger}{30\ minute\ time\ period + Time_{Desired\ waiting}}$$

$$Space_{counter} = Space/passenger\ (based\ on\ LOS) \times max.Passenger\ in\ Queue$$

The above formulae are used for designing of staffed check-in counter space in the terminal. These can also be used for designing of automated check in kiosks space requirement by multiplying with the percentage of passengers, who are using the kiosk facility. However the final determination of the number of counters is made through consultation with the various airlines to be served and through usage of some analytical models. There are some simulation models available in the market to do efficient space calculation and number of counters available [7] [17].

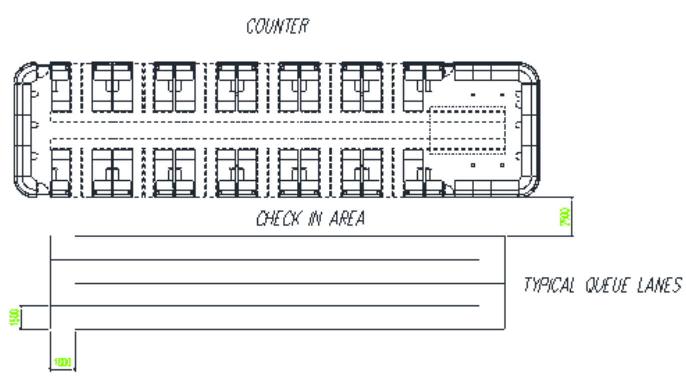

Figure 2: Typical check-in counter queue lanes

2.3.2. Security, baggage screening and hold rooms

Security and baggage screening is the most critical function in an airport, as it is concerned with the safety of the onboard passenger. The security screening area will include check point for identification check, walk through metal detectors and x-ray equipment for hand carrying baggage screening. The location and size of the screening area is based on the passenger volume and consideration to the passenger queuing issues. As observed from most of the airport, in order to increase the LOS and delay in security and baggage screening, screening area is placed inside the hold rooms. So the hold room area is designed in such a way that it caters space for security and baggage screening.

Holding room serves as an assembly area for passengers waiting to board aircraft. It is usually designed and sized to accommodate the number of passengers before the aircraft boarding starts. A conservative design of the hold room is to accommodate about 90% of the enplaning passengers for the particular flight. Holding rooms are sized in such a way that, it has space for passenger queue, seats, and airline processing and exit way for the deplaning passengers. Many larger airports have the baggage screening and security check at the entrance. Then the passenger goes through the boarding pass check and enters into hold room area to wait for the aircraft boarding.

2.4. Arrival hall

In case of the larger airports, there will be different floors for the arrival and departure halls, to increase the level of service of the airport and easier passenger handling. Arrival hall has the following flow sequence of the passengers. So the terminal facilities will be designed to cater for the arrival passenger flow sequence.

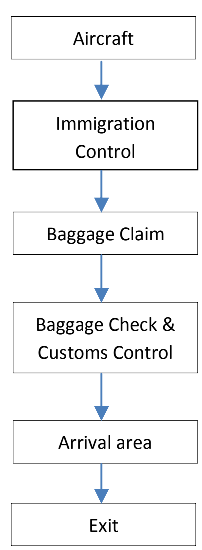

Figure 3: Arrival hall flow

Arrival hall passenger flow starts from the deplaning from the aircraft to the exit from the terminal. Deplaned passenger enters the departure hall from the aircraft and proceeds to arrival hall for the immigration control and baggage claim. The main areas of the arrival hall are immigration control, baggage claim and arrival area. The facilities in the arrival hall are designed based on the designed hour deplaned passenger and the level of service to be followed for the facility. In many of the airports, the level of service for the arrival facility is designed to be LOS A or B. If there are many aircrafts at the peak hour period, there will be a delay in passenger arriving to the claiming unit. So the baggage claiming unit is supposed to be accommodating almost 100% of the number of bags in the aircraft.

2.4.1. Immigration controls

Immigration control is designed based on the number of arriving passengers from several flights at the design hour period. The standard double inspector "piggyback" booth is approximately 4.3m (14 feet) deep with the passenger standing areas on either side. CBP (Customs and border line Protection) requires a minimum distance of 3.5m (11 feet 6 inches) wide for a counter and two passages for passengers [7]. The CBP requires a minimum distance of 2.1m (7 feet) from the booth to the passenger standing queue. The CBP recommends 15.24m (50 feet) and 22.9m (75 feet) of queuing depth for the smaller and larger airport respectively [7]. However the actual depth of the passenger queue is based on the peak number of passengers forecast and the LOS assumed.

2.4.2. Baggage claim

The terminating passengers would be returning to the baggage claim facility to collect their checked-in baggage. Hence, the baggage claim facility should be located in an accessible distance to facilitate the ease of passengers. In case of airports, where the traffic/passenger flow is less, then the checked-in baggage can be placed in a shelf, from which passengers can claim on their return. In case of airports which are more active, mechanical delivery and display equipment can be installed.

The number of claim devices that are required to be installed is determined by the type and the number of aircrafts arrivals in the peak hour, time interval between the aircraft arrivals, the number of terminating passengers, the amount of checked-in baggage and the procedure that is used to move the checked-in baggage between the aircraft and the passenger claiming area. Ideally in real-time, a baggage claim device should not be shared between the flights arriving at the same time frame, as it leads to congestion in the locality to a great extent and also confusion to the passengers. For the effective utilization of the claim devices, the airlines could plan the share the claim devices according to the timing of aircrafts.

Mostly, the delays in baggage claim area may be due to "passenger movement from the aircraft to the claim area is faster". They travel faster from the aircraft to the claim area before the conveyance system can transport the baggage from aircraft to the claim areas. Considering this delay, the baggage claim area must be designed to accommodate waiting passengers and passengers should be able to pick-up their baggage rapidly once it is available in the claim device.

In preliminary studies, great attention should be exhibited in the space existing around a claim device. A free space of 4 to 4.5m (13 to 15 ft.) is recommended near the baggage claim device, for passengers currently claiming their baggage and for the passengers who are waiting to claim, as well as for free movement in the claim area [6]. An additional free space of 4 to 4.5m (13 to 15 ft.) is recommended which can ensure mobility between the claim devices [6].

2.4.3. Corridors

Passenger circulation corridors are available in both arrival and departure hall. Corridors provide circulation for passengers and visitors in departure lounges or in central terminal areas. These area designs should consider the disabled persons during the peak hour of high density flow. Studies [8] [19] [20] [21] showed that a typical 6m wide corridor will have a capacity ranging from 330 to 600 persons per minute. This standard is based upon a width of 0.75m per person and a depth separation of 1.8m between people.

2.5. Terminal design

The generalized airport terminal's facilities and the recommended design considerations are discussed in the previous sections. This chapter deals with the application of above section's design consideration and values to design a generalized airport terminal building.

Terminal facilities are majorly based on the peak hour passenger forecast and the Level of Service provided in the terminal. So it is important to know about the number of passenger departing and arriving during the peak hour period [7]. As it is a generalized design, the peak hour details are assumed to proceed with the design. The design is taken to be an international airport with around 6 million enplanements per year and an equivalent airports peak hour detail is taken for the design. So the arriving and departing passenger in peak hour for an airport which has about 6 million annual enplanement is 1500 and 1900 [22] respectively. These values have been set as the design requirement for the terminal design.

Airport terminals are categorized based on the horizontal and vertical distribution. Level of service, aesthetics, cost effectiveness and minimum space requirements are the important consideration while designing the terminals. In order to reduce the operation cost and improve the passenger control, Pier/Finger concept is used in the design for the horizontal distribution of the terminal. In Pier/Finger concept, terminal building is fully utilized for the passenger control and flight information services and the finger is used for the handling of enplaning and deplaning passengers. So this design is operationally effective while handling the passenger movement in the terminal. In vertical distribution of the terminal concept, two floors terminal is designed for the easy handling of the arrival and departing passenger. Each floor is dedicated for facilities which are meant for either arrival or departure. By using this concept, passenger processing and control is effectively managed in both the floors. Upper floor is dedicated for the departing passenger. So the facilities and passenger service is more for the departing passenger in the upper floor. Lower floor is dedicated for facilities which are for arriving passengers. So the design of terminal is using the pier/finger and two floor terminal concept.

2.5.1. Departure hall

Departure hall layout and exit locations are shown in appendix A4 and A5. Departing passenger's arrival pattern to an airport is not in a uniform manner. In order to design departure hall facilities, the 30 min demand period with a defined maximum waiting time is considered. This is called peak 30 min period in design peak hour period [7]. The peak 30 min is normally of 30% to 50% of the design peak hour [7].

Facility	Design parameter
Peak hour departing passenger	1900
No. of flight in peak hour	6
No. of Piers	2
No. of flights per pier in peak hour	3
Maximum queue waiting time in ticketing	15 min
Check in counter processing time	1 min/ passenger
First level passport check processing speed	3 passengers/ min
No. of immigration control double booths	9
No. of hold rooms per pier	12

Table 2: Departure hall design requirement parameter

2.5.1.1. Check-in/ Ticketing

Based on the assumed departing passenger of 1900, there will be several departures at the particular time. In terminal, each departing airlines has their own check-in rows for their passengers. Check-in process is not consistent over the time period from the check-in opens to the check-in closes. As discussed earlier, the conservative value of 50% of peak hour passenger is assumed to be the departing passenger in peak 30 min period. However, there are certain percentage of passenger will use the other facilities to check-in. It is assumed to be 60% of passengers using the check-in counters.

$$peak\ 30\ min\ originating\ passengers = \%\ using\ the\ facility\ \times \%\ peak\ 30min\ \times Passenger_{Peak\ hour}$$

$$peak\ 30\ min\ originating\ passengers = 0.6\ \times 0.5 \times 1900 = 570\ passengers$$

$$Service\ position_{Required} = \frac{passenger_{peak\ 30\ min}\ \times\ Processing\ time/passenger}{(30\ min\ time\ period + desired\ max.wait)}$$

The terminal is designed to have a check-in counter processing time is 1 min and the maximum queue waiting time for the passengers is 15 min.

$$Service\ position_{Required} = \frac{570\ \times\ 2}{(30 + 15)} \approx 26$$

IATA [23] standards for Level of Service:

IATA Space Standards in m^2		LOS A	B	C	D	E
Check In	Queue w/Few Carts and few passengers with bags	1.7	1.4	1.2	1.1	0.9
	Queue w/Few Carts and 1 to 2 bags per passenger	1.8	1.5	1.3	1.2	1.1
	Queue w/High percentage of passengers with carts	2.3	1.9	1.7	1.6	1.5
	Queue w/ 2 or more bags per passenger and high percentage of cart usage.	2.6	2.3	2	1.9	1.8
Passport Control	Queue	1.4	1.2	1	0.8	0.6
Hold rooms	Waiting Area	1.4	1.2	1	0.8	0.6
Baggage Claim	Retrieval and Peripheral Area	2.6	2	1.7	1.3	1

Table 3: IATA space standards

Based on the IATA [23] LOS, the ranges are from A (Excellent design) to E (unacceptable design). It denotes that LOS C should be the design standard as it is a good service at reasonable cost [7]. Based on the LOS C standard, the space requirement for a passenger in a queue with few carts and 1 to 2 bags is 1.3 m^2. So queuing space required for peak hour departing passenger is:

$$Queuing\ space\ _{Required} = Passenger_{Peak\ 30\ min} \times space/pax\ @\ LOC$$

$$Queuing\ space\ _{Required} = 570\ \times 1.3 \approx 740\ m^2$$

The calculated value is for the total number of departing passengers during the peak 30 min period. However, based on the counter processing time and number of operating counters, the number of passenger in the queue will be based on the normal distribution of departing passengers joining the queue for 30 min. Based on the counter processing time, there are 0.5 passenger/counter processed per minute. The normal distribution of the departing passenger reaching the check-in queue area is given below in figure 4. Based on the figure 4 the peak 30 min originating passenger is 570. The maximum number of passengers in the queue will be calculated based on the passenger joining distribution in the queue and the counter processing time. Based on the required service station calculation, there are 26 required counter positions for peak hour passengers. There are 26 passengers will be processed per minute, based on the counter processing speed. Graph is drawn based on the departing passengers arriving the check in counter during peak hour and counter processing speed, and it is shown in figure 5. Based on the passengers in queue graph, the maximum number of passenger in the peak hour queue is 198.

$$Queuing\ space\ _{Required} = 198\ \times 1.3 \approx 260\ m^2$$

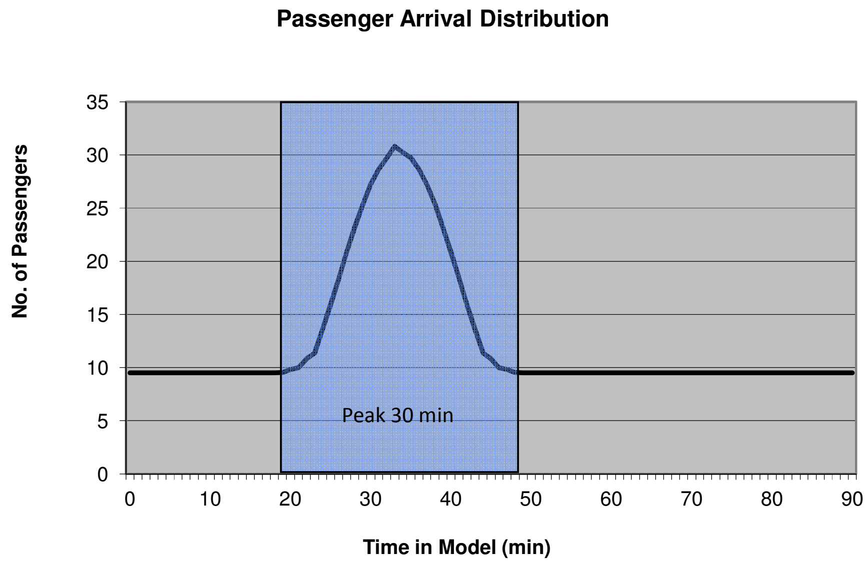

Figure 4: Departing passenger arrival distribution to terminal

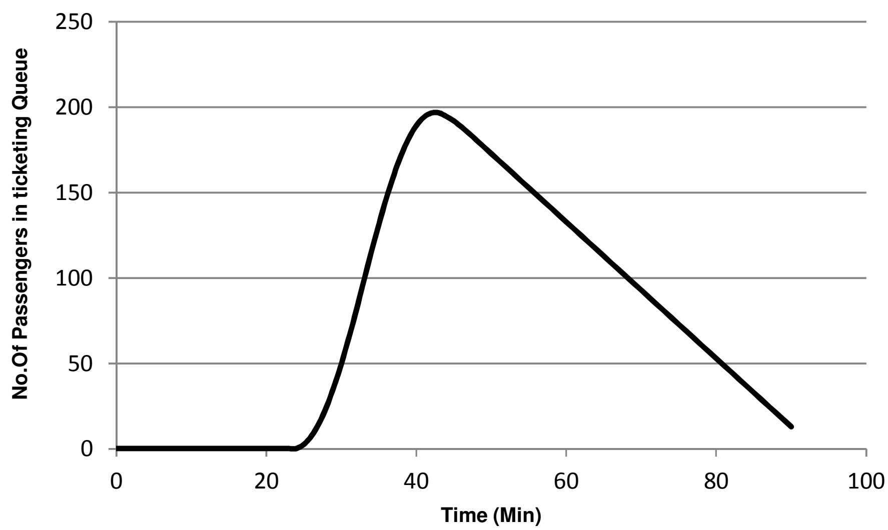

Figure 5: Passengers in check-in/ ticketing queue

The calculated number of counters and space requirement is for the predicted number of peak hour passengers and this is the required minimum for the design. In airport terminals, each departing airlines will have their own check-in rows for the easy processing of their passengers. There are 6 departing airlines in the peak hour based on the set design standard for this terminal. Minimum of six rows of check-in counters are needed for this design. However the subsequent airlines departure in the following hours will not use the same check-in rows. Therefore 12 rows with 12 check-in counters are designed for the terminal. In order to accommodate the future growth of the terminal's annual passengers, check-in rows' queuing area is designed with larger area than the calculated value.

2.5.1.2. Departing immigration check

Departing immigration check demand is based on the processing speed of the check-in facility. As per the figure 5, the arriving passengers to the terminal are consistent till the peak 30 min. So the flow is consistent in the immigration check as well. However there will be queue formation in the immigration check area during the peak 30 min period. As per IATA [23] standard, the processing time for the immigration office counter is 100 passenger/double booth/hour (1.7 passengers/double booth/minute). In order to increase the security inside the terminal, the airport is equipped with first level of passport check-in before the immigration check. The first level of passport check is checking the passport and flight ticket to let the passengers enter into the immigration clearance queue. Based on the experience, this is assumed to be 3 passengers/minute and this is set as one of the design requirement for the terminal.

The supply to the immigration check is controlled by the first level passport check. So the queue formation in the immigration check area is effectively managed by the first level passport check. The design is planned for 9 double booths. The supply is carefully managed by introducing 6 first level checks in front of the doors which lead to the immigration check.

$$Processed\ passenger_{first\ level\ check} = number\ of\ first\ level\ checks\ \times processing\ speed$$

$$Processed\ passenger_{first\ level\ check} = 6\ \times 3 = 18\ passengers/minute$$

$$Processed\ passenger_{immigration} = number\ of\ double\ booths\ \times processing\ speed$$

$$Processed\ passenger_{immigration} = 9\ \times 1.7\ \approx\ 15\ passengers/minute$$

Based on the processing speed difference between the first level check and immigration check, there will be 3 passengers will be added to the immigration queue every minute. This value is then plotted in the graph to study the maximum number of passengers in the immigration queue. By assuming the first level check is almost consistent during the start of the check-in/ticketing open, the queue model is developed and a graph is plotted, which is given below

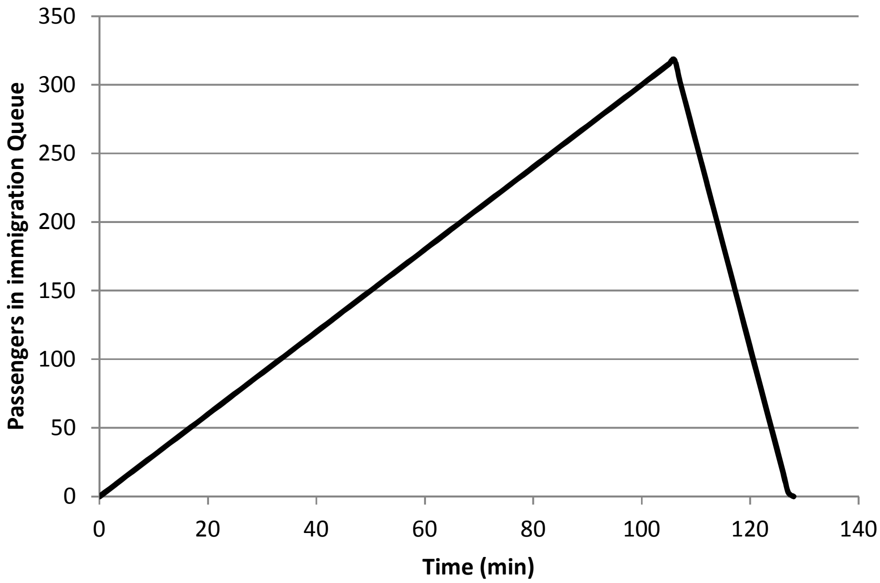

Figure 6: Passengers in departure immigration queue

The maximum number of passengers in the immigration is 318 passengers. Based on IATA [23] LOS C standard, the required space for the passengers in passport control queue is 1 m^2 (table 3). Therefore the required minimum space is 318 square meter for the immigration passport queue. However in the current design, the immigration clearance area has place for an immigrant interview room and office rooms for the immigration officers. So the design is considered for this office room area and it is designed with area which is more than the required minimum.

2.5.1.3. Hold room

As this design is two floor terminal and pier design, the terminal building is solely used for the passenger processing, control and respective facilities and the pier is for the passenger enplaning and deplaning facilities, such as security, baggage screening, hold rooms and waiting area. So the departure hall is filled with duty free shops and retails areas, in order to compensate the arrival hall area.

Piers are designed to have hold rooms and passenger enplaning and deplaning. Based on the annual enplanement design parameter, 24 hold rooms are designed in the terminal.

The design parameter for the hold rooms are 400 passengers per hold room as this hold rooms are for international passengers with larger aircrafts (possibly jumbo aircrafts which has about 400 seats in the aircraft [22]). Based on the hold room space requirement standard [6], the minimum space requirement of 1 square meter to 1.4 square meter is allocated for a passenger. Therefore the hold room size should be 560 square meter for 400 passengers. In order to reduce the passenger handling time in baggage screening and security, hold rooms are equipped with baggage screening machine and Walk through metal detector. So the entrance of the hold room is used for baggage screening and security purpose. The standard space requirement for the two walk through metal detector with 2 baggage screening machine is 8.5m x 10m [7] and these dimensions are allocated in the entrance of the every hold room. The passenger sitting area of the hold room size is designed to be a larger area than the calculated area, in order to compensate the space requirement allocated for telephone booths, internet accessing kiosk and other facilities, which are present inside the hold rooms to improve the passengers' comfort. The design area space for the extra facilities such as telephone booth and internet kiosk is designed with 10% of the calculated value. So the floor area for a hold room is designed with around 600 square meter. The passenger loading bay width is 1.8m, based on standard width range for the passenger loading bay [6].

2.5.2. Arrival hall

The layout of the arrival hall and its facilities are given in appendix A3 and A5. In the design of arrival hall, it is considered that there are 4 flights arriving in the peak hour and the peak hour arriving passenger is 1500. The design parameter for the arrival hall is shown in table 4.

Facility	Design parameter
Peak hour arriving passenger	1500
No. of flight in peak hour	4
No. of Piers	2
No. of flights per pier	2
No. of immigration control double booths per pier	5.5
No. of baggage handling belts per pier	4
No. of Baggage check area per pier	2

Table 4: Arrival hall design requirement parameter

An arrival passenger queue model is developed based on the design parameter and the figure is shown below to identify the maximum number of queuing passengers in the immigration clearance and baggage claim area. As explained earlier, the processing speed of an immigration clearance is 100 passengers/double booth/hour.

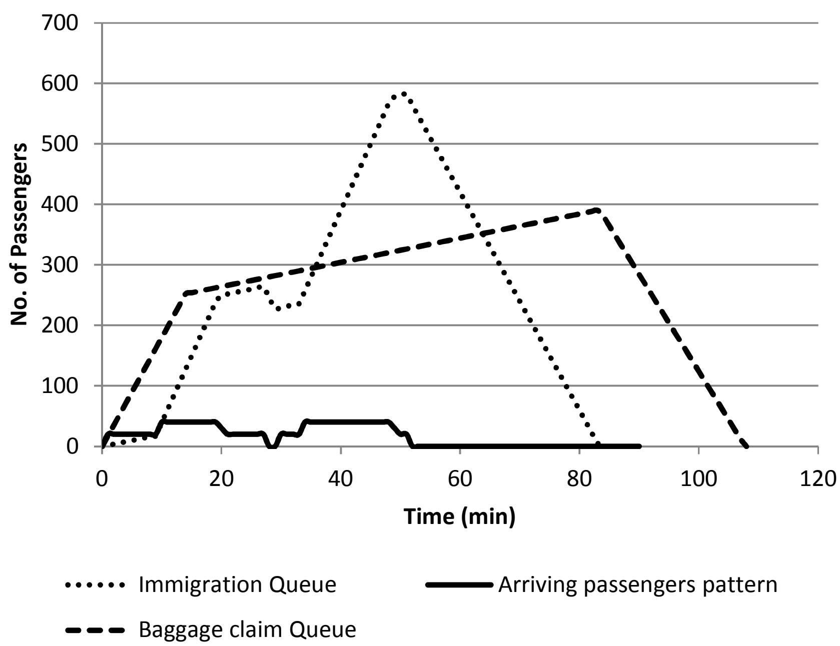

Figure 7: Passenger arrival queue in various facilities

Based on the above figure 7, the maximum passengers in the immigration queue is 582 passengers and the required space is 582 square meter (1 square meter/passenger [23]) based on LOS. The passenger queuing is only about half of the arrival concourse, and the rest of the space is used for the elevators, escalators, offices for immigration officers, utility rooms, etc.

So the design caters for about 40 - 50% extra space for the immigration clearance arrival lobby. So this area is designed with about 1000 square meter, in order to accommodate facilities which are meant for the arriving passengers.

The minimum space requirement for the baggage claiming area is 4.5m [7] obstacle free distance from the edge of the baggage feeding equipment. As per the design, each baggage feeding equipment designed with the distance of 10m and the nearby facilities such as arrival duty free shop area and baggage check area is placed 14 to 15m away from the baggage feeding (5m for the baggage feeding equipment clearance and 10m for the passageway and queuing for the other facility). Baggage checking is placed at exit doors of the secured area. Then the rest of the area is designed for the arrival pubic area of the terminal.

3. Risk based fire safety design

There has been a steadily growing interest towards performance based building codes, since early 1985 [32]. Even though, the performance based approach provides greater flexibility to adapt to the modern architecture and thorough investigation of fire safety, the design team should possess a high level of knowledge, experience and education [33]. As a result of growing need for the performance based design, the Inter-jurisdictional Regulatory Collaboration Committee was formed on 1996. This committee consists of ten of the building regulatory agencies and organizations from several countries, including Australia, Canada, Japan, UK and US. IRCC made an eight tier hierarchy, which illustrates the method of developing fire safety design based on performance based building codes.

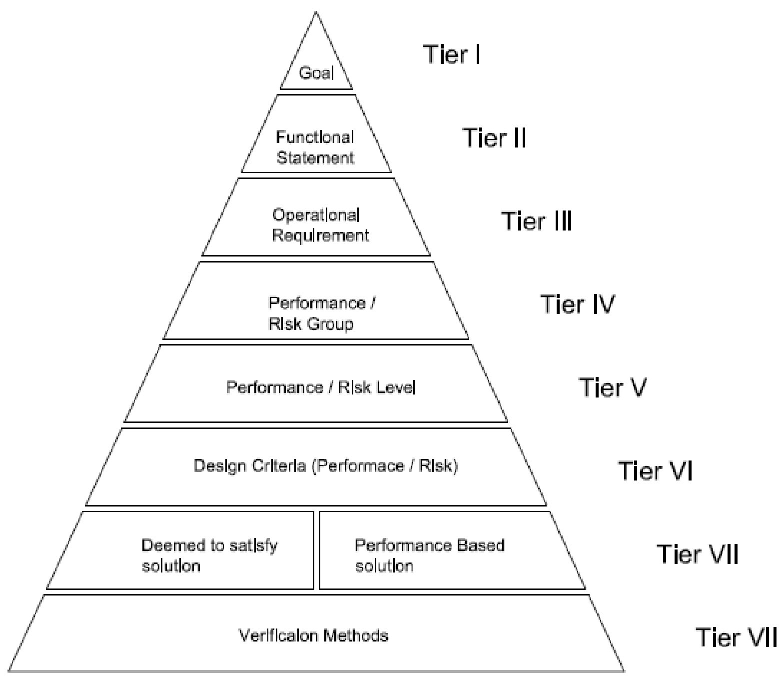

Figure 8: IRCC hierarchy for performance based design

In this hierarchy, the method of developing fire safety design is pictorially explained. The top three tiers (TIER I, II and III) give the qualitative statements (Goal, functional and operational requirement) of performance of a fire safety design [25]. The qualitative statements are then translated as criteria for the design and design assessment. The translations of these are happening in the TIER IV and V. The translated design assessment values are used in the rest of the tiers to develop a fire safety design.

In the IRCC hierarchy, the risk or performance is taken into account when developing a fire safety design. As the Performance based approach has been used for many years, many of the early users of the approach started to work directly in second generation performance based building codes, which is the idea of using risk as a assessing criteria for identifying tolerable building performance [25] [26] [27] [28] [29] [30].

3.1. Fire risk assessment

The design of fire safety system does always have uncertainty in the implementation and none will be 100% effective. For example, the workings of fire alarm system components/ fire suppression system components do not have 100% reliability to detect or suppress fires. Hence, there is always certain level of risk to the occupants and property. The assessment of these levels of risk is done by the fire risk assessment.

There are three methods of carrying out fire risk assessment [35], they are

- Fire risk assessment based on past fire experience
- Qualitative fire risk assessment
- Quantitative fire risk assessment

The first method is based on the past fire experience, which means that fire risk assessment carried out for a building based on the buildings past fire statistics. The second method is based on the subjective judgment of probability of fire hazard/ scenario occurring and consequence of such a fire hazard/scenario. The last method involves numerical quantifications of fire scenario probability and its consequences.

As this thesis focuses on the generalized airport environment, the first method can't be used. The third method is not dealt in this thesis, because there are very limited or less resources available to get the numerical quantifications of the fire scenario probability and its consequences for airport environment. So qualitative fire risk assessment is carried out to identify the worst credible case scenario's location, which is to be used for the evacuation simulation.

3.2. Qualitative fire risk assessment

As the thesis focuses on the occupants' evacuation during fire, fire risk assessment is carried out to find the worst credible case by considering the fire exposure to the occupants and its consequences. The risk may be defined as the function of hazard and exposure [34]. The fire hazard is based on the available combustible items in the particular location as well as additional fire protection measures, which are installed in that location. The exposure to occupants is based on the occupants' characteristics (building familiarity, age, limited mobility and group behavior).

3.3. Risk assessment scenario

As the thesis is about evacuation, life safety is given importance to safely evacuate occupants from the terminal building and study the flow patterns at the security doors, which separates public area from secured area. A big fire with higher fire load, which is away from the exit is given less importance than the small fire with limited fire load, which is near to the exit. Even there is a probability of smaller fire near the exits, it will impact the evacuation at a higher percentage, as it blocks the exit for the evacuation. Risk assessment is carried out based on the above criteria that the scenario accounts for the events that affect the evacuation.

As explained in the design of terminal, the peak hour period is the period when maximum number of occupants are inside the terminal. Evacuation is also affected by the usage of less number of exits by more number of occupants, which will lead to the queue formation and in turn increase the evacuation time to reach a safe place.

3.4. Preliminary risk assessment

Preliminary risk assessment is carried out in the terminal area to identify the potential fire risk inside the terminal based on the facilities which provides services to the passengers and occupants. The result of the preliminary risk assessment is listed in table 5, which is based on the probable initiation of fire in several locations inside the terminal. There are qualitative terms used in the table to describe the occurrence and consequences. The definition of the terms are explained below to understand the terms [35]

- Occurrence level or probability of occurrence
  - Almost certain - expected to occur in many times
  - Likely - probably occur in many times
  - Moderate - Most occur at some times
  - Unlikely - Could occur at some time
  - Rare - May occur in exceptional cases

- Consequence
    - Catastrophic - major fatalities (Death), huge financial loss
    - Major - Extensive injuries, major financial loss
    - Moderate - Medical treatment required, high financial loss
    - Minor - First aid treatment, medium financial loss
    - Insignificant - No injuries, low financial loss
- Risk level
    - Extreme - Require immediate action
    - High - Senior management action required
    - Moderate - Management responsibility required
    - Low - Managed by routine procedures.

S. No	Location	Hazards	Impact	Existing Risk control	Occurrence	Consequence
1	Any one of the terminal facilities room	Electrical panels, Poor electrical installation.	Property damage	Fire detection and suppression system	Unlikely	Moderate
2	Arrival hall restaurant's kitchen	cooking burners, gas supply leak	Physical damage, property damage	Gas leak detection and suppression system.	Moderate	Moderate
3	Baggage screening equipment in arrival hall	Friction in moving parts, electrical and electronic components, overuses.	Physical damage, property damage, blockage of evacuation.	Smoke detection and extraction system.	Moderate	Major
4	Baggage feeding equipment	Frictional mechanical moving parts	Physical damage, property damage and partial blockage of evacuation.	Smoke detection and extraction system.	Moderate	Major
5	Arrival immigration check counter	Electronic equipment, electrical connections, combustible materials	physical damage, Property damage	Smoke detection system	Unlikely	Minor
6	Seasonal display or advertisement board, at immigration check arrival queue area	Electrical and electronic components & combustible materials	Physical damage, property damage, blockage of evacuation route	Smoke detection and extraction system.	Unlikely	Moderate
7	Any one of the airline offices in departure hall	Electronic equipment, electrical connections, combustible materials	Physical damage, Property damage, Partial blockage of emergency exit	Smoke detection system and extraction system	Rare	Minor
8	Any one of the check in/ ticketing counters	Frictional mechanical moving parts, combustible materials and objects, Electrical and electronic components	Physical damage, property damage	Smoke detection system and extraction system	Unlikely	Moderate
9	Any one of the departure immigration check counters	Electronic equipment, electrical connections, combustible materials	Physical damage, property damage and partial blockage of evacuation.	Smoke detection system	Unlikely	Minor
10	Retail shops in departure lounge	Combustible materials and objects, electrical equipment, fire spread.	Physical damage, property damage, blockage of evacuation.	Smoke detection system	Likely	Major
11	Seasonal display and decorations in departure lounge	Electrical and electronic components, combustible materials	Physical damage, property damage, blockage of evacuation.	Smoke detection and suppression system	Likely	Major
12	Any one of the Hold rooms	Moving parts in baggage screening equipment.	Physical damage, property damage	Smoke detection system	Unlikely	Minor

Table 5: Preliminary risk assessment in the terminal facilities

3.5. Risk matrix

Risk matrix is derived from the hazard analysis and consequence analysis [35]. The below figure shows the risk matrix for all the scenarios in the preliminary risk analysis

Probability

Almost certain	High Risk		Extreme Risk		
Likely	Moderate Risk			**10,11**	
Moderate			**2**	**3,4**	
Unlikely		**5,9,12**	**1,6,8**		
Rare	Low Risk	**7**			
	Insignificant	Minor	Moderate	Major	Catastrophic

Consequence

Figure 9: Risk matrix

As shown in the risk matrix, scenarios 3,4,10 and 11 are in the extreme risk zone. However scenarios 3 and 10 are near to the exits which are very familiar to the occupants. As scenarios 3 and 10 block the evacuation exit more than the other two scenarios, scenarios 3 (Case 1) and 10 (case 2) are considered for the simulation.

3.6. Quantification of scenarios

Case 1: Baggage screening equipment in arrival hall

Baggage screening equipment is situated at the arriving passengers exit (as shown in Appendix A3) from the secured area to the public side. This is the final customs check for the arrival passengers. There are four baggage screening equipment for all the arriving passengers. There are six exit doors, which are next to the baggage screening equipment. These exits are basically used by all the arriving passengers to exit to the public area of the terminal and in turn to the road transport to go out of the airport terminal. So in case of fire outbreak in any of the machine, there will be a hindrance to evacuation process, as this facility is situated very close to the exit.

In order to consider the scenario to be worst credible case, there should be maximum number of arrival passengers in the arrival hall. In this fire scenario, when there is maximum number of passengers in arrival hall and less number of exit doors, there will be an increase in evacuation time and it becomes a worst case to be considered for the evacuation analysis.

As discussed in the previous chapter, there is a maximum number of arriving passengers in peak hour and the design parameter for number of arriving passenger is 1500 during peak hour. When the last passenger arrives at the arrival immigration queue, there will be about 600 passengers in the immigration queue in both the sides of the arrival immigration. Approximately 350 passengers are at the baggage claiming unit and rest of them are outside the secured area. The remaining passengers cleared all the arrival formalities and entered arrival public side of the terminal.

In airports, departing passengers reach and wait at the hold room when their flight arrives at the terminal. So it is considered to be all the departing passengers are inside the secured area of the departure hall for Case 1.

Case 2: Retail shops in departure lounge

Retail shops are spread over most areas of the departure secured area just next to the departure passengers' entrance to the departure lounge (as shown in Appendix A4). The retail shop, which is close to the immigration clearance area, is considered for this case. As this retail shop is close to the entrance which leads the passenger to the secured area of the departure hall, the departure hall immigration area's doors are not used for evacuation, when there is a fire in the retail shop.

As explained in the previous case, the worst credible case encounters for the maximum number of occupants present in the departure level of the terminal during the event. So the maximum number of occupants is present in the departure level during the peak hour. The peak hour departing passenger is 1900.

As the arriving passengers use the departure level for deplaning and to go to the arrival hall, the maximum number of passengers will be available when there is deplaning passengers from the aircraft and also departing passengers enters the departure lounge and hold rooms. The arriving aircraft departs about 30 to 45 min from its arrival. As the departure hall is utilized for enplaning and deplaning passengers, the deplaned passengers have to walk in the departure hall to go to the arrival concourse. During the peak hour in the departure hall, there will be certain amount of arriving passengers will be in the departure hall. So they have to be taken in account in the departure hall scenario. The percentage of arriving passengers in the departure hall is based on the interval between different arrival aircraft and the travel distance between the deplaned gate to the arrival concourse. As this design is a generic design and does not have time interval of arriving aircrafts at the terminal, a conservative value of 25% is assumed for the arrival passengers in departure hall during the departure hall peak hour.

Based on the IATA passenger arrival distribution, there are about 90% passengers are processed and enter inside the secured area of the departure hall. The remaining 10% of passengers shall be either in check-in or immigration check area. The distribution of passengers inside the departure hall secured area is assumed that 70% of the passengers are at the hold rooms and remaining 30% are at the retails shop areas.

Location		Case 1	Case 2
Arrival Hall	Immigration queue	600	400
	Baggage claim area	350	300
	Arrival public side	550	450
Departure Hall	Check-In ticketing	0	100
	Immigration clearance	0	100
	departure concourse	570	500 + 350
	Hold rooms	1330	1200

Table 6: Number of passengers in different locations for different cases in the terminal

Airport terminals are also occupied by security officers, immigration officers and visitors. Therefore the numbers of occupants who are non-passengers are added to the table 6 to get the realistic count of people in the terminal. The number of visitors in the arrival hall and departure hall is based on the number of passengers arriving/ departing. Based on a research [53], there are 75% passengers access the airport with zero, 18% with 1 and 7% with two or more accompanying non-fliers. Based on the peak hour passengers, this gives 600 and 750 visitors in arrival and departure hall respectively. Every hold room has about 10 staffs (airline and security officers) for baggage screening and boarding pass checking. Airport maintenance staff is monitoring the airport facilities and attend breakdown calls everywhere in the airport terminal. They are mostly available in the public side halls as well as departure concourse. It is assumed that there are 80 maintenance staff in departure concourse and 20 staffs each in both the pubic side halls in the terminal. The modified table (table 7) gives the exact number of occupants in the terminal, which comprises of passengers, visitors and airport staffs.

Location		Case 1				Case 2			
		Passenger	Staff	Visitor	Total	Passenger	Staff	Visitor	Total
Arrival Hall	Arrival public	550	20	600	1170	450	20	600	1070
	Both arrival concourse/ Immigration	600	10	0	610	400	10	0	410
	Baggage claim	350	10	0	360	300	10	0	310
Departure Hall	Departure public	0	20	300	320	100	50	750	900
	Immigration	0	20	0	20	100	20	0	120
	Concourse	570	80	0	650	850	80	0	930
	Hold room 1	270	10	0	280	200	10	0	210
	Hold room 2	150	10	0	160	170	10	0	180
	Hold room 3	250	10	0	260	230	10	0	240
	Hold room 4	260	10	0	270	200	10	0	210
	Hold room 5	180	10	0	190	180	10	0	190
	Hold room 6	220	10	0	230	220	10	0	230

Table 7: Number of occupants in different facilities in terminal

4. Simulation software

In recent days, evacuation models are widely used in the performance based fire safety design. However choosing an appropriate simulation model for a project is challenging and time consuming. Selection of models are based on four factors [36], they are

- Project requirements
- Background information of the software
- Software model characteristics
- Future considerations

The chosen model has to support to fulfill the project requirements such as the applicability of software for that project environment and project deliverables. Background research/ information about the software gives the in-depth knowledge about the software. Software may be developed by a single person or team of people with different expertise such as mathematics, psychology, etc. There are different kinds of software in the market by the way it is developed. Some software development source codes are available to public and the development and improvement is based on the work done by many researchers (Open source software). There is other software, which is only used by the companies for their personal and consultancy use. In open source software, the understanding of algorithm used in the software is made available and it is easier to get, compared with the software, which are developed by companies. So by knowing the details about the software give better understanding to a user about the software. Validation and verification information about the software gives confidence to a user to use that software.

Software model characteristics deal about the software's algorithms [37]. These algorithms deal with occupants' representation, occupant movement (behavioral/ non-behavioral), evacuation flow (coarse/ fine/ continuous) and types of output (text/ visual). Behavioral models uses the decision making capabilities of occupants along with the movement to the exit (goal) based on their familiarity about the building and available data about the emergency information. Non-behavioral model uses only the movement of the occupants from point to point such as the movement from the evacuation zone to the exit. They do not consider the human behavior aspect of the occupants. Coarse network model represents the building layout as network of nodes and these nodes representing the spaces such as rooms, doors, corridors, etc. Occupants are placed in the nodes, and the movement is from node to node and there is no occupant movement information about the occupants between nodes. In fine network models, the building layout is divided into number of small cells and represented as cell grids. The movements of the occupants are from one cell to another cell and the speed of the occupant is based on the population density specified by the user. Continuous models represents the building layout in coordinate systems, so the location of the occupants is represented by their x and y coordinates. Fine and continuous models are able to simulate the obstacles and barriers in the buildings, which affects the route choice of the evacuees.

Models may also be chosen based on the model's output. There are different types of output available for different models. They are text, visual, maps and graphical representation of outputs. So the selection of model will also be affected by the type of models' output. A project may be planned for long term and further improvements in future. So the selected model will support the project's long-term goal as well as future integration of sub projects in larger scale.

4.1. Selection of software

The above discussed four factors are important when simulation software is to be selected for evacuation simulation. The requirement for designing an airport terminal evacuation starts with the understanding of terminal features and specific requirements with respect to evacuation.

As discussed in earlier chapters, terminal is majorly divided into two areas (secured area, public area). Occupants who are in secured side, either cleared immigration check and waiting for departing from the airport to their travel destination, or arriving passengers who need to clear immigration to enter the city. The security of airport is majorly based on the separation of secured side from the public side. Therefore, both the areas are divided by the security doors, in order not to let each side of the occupants enter the other side. These doors will only be used in the emergency situation. In normal conditions, the doors which are nearer to the immigration check area, are used to enter the secured side of departure hall, whereas, in arrival hall, doors, which are near the baggage check area are used to let the arriving passengers out from the secured side.

Based on the simulation scenarios, there will be a counter-flow situation when there is an emergency in the building. This is due to the firemen and airport emergency team personnel enter the emergency location through security doors. Therefore, there will be a counter-flow condition occurs in the security doors where evacuation of passengers from the secured side to the public and firemen enter secured side from the public side. As this thesis studies the effect of the counter-flow in the security doors, model should be capable of simulating behavioral aspect of the occupants.

Airport terminal is a large and complex building. Designing the terminal layout is another difficult task in the simulation model. If model has functionality to import CAD layout, which will be one of the major selection criteria for model selection. So the selection criteria for the simulation model with respect to airport terminal evacuation simulation are given below:

Factors	Project specific
Project requirements	Counter flow, complex building.
Background information	Extensive range of verification and validation studies for the software.
Model characteristics	Freely available to public to use, fine/ continuous movement, Behavioral/partial behavioral, CAD data input, visual output.
Future considerations	Release of future version

Table 8: Terminal evacuation simulation design requirements

The above factors are considered to select the simulation software. There are three more additional parameters used to further filter the model selection. They are time to prepare simulation model, ease of using the software and familiarity of the software to the researcher. There is much software which satisfies the above selection criteria. However when the additional filtering parameters are applied to the selected results, there are two software filtered out for the thesis. So the chosen software for carrying out the theses are Pathfinder and Legion.

4.2. Pathfinder

Pathfinder is developed by Thunderhead Engineering [39] and it is an agent-based, movement/partial behavior model. It provides two ways to model the evacuation process called SFPE mode and steering mode.

SFPE mode implements the concepts in the SFPE handbook of Fire Protection Engineering [38]. This mode is otherwise known as flow model and is based on calculation of means of capacity of a considered environment.

Steering mode is known as agent-based model [39] (the Reynolds steering behavior model redefined by Amor [43] [44]) which defines, congestion and queuing arises due to model representation of a human process. This model explains as, the occupants move along their intended paths while interacting with the environment and other occupants. In this method, occupants find their lowest cost steering path. Input parameters to the model are delay times, walking speed of occupants and body size, which are assigned through distribution laws. While considering the occupant behavior only collision avoidance is included.

Movements are calculated as discrete time steps. For each step, model updates target points, calculates occupants steering speed and then moves the occupants in their optimal path. Deterministic approach is used to provide facility to assign a specific exit or the next nearest exit to the occupants.

Behavior sequences are used to simulate the evacuation. Behavior can be defined as an ordered sequence of goals, which has to be achieved by each occupant in the simulation. There are mainly two goals used in the software: idle goals and seek goals. In idle goals, occupants should wait in a particular location till the triggering event to occur, whereas seek goals, occupants move directly to waypoint such as room, escalators, elevators or an exit.

Priority parameter is used to give priority to movement of particular type of occupants during an evacuation process. For example, high priority is given to firemen during evacuation for the purpose of fire-fighting and rescue operation. If two occupants with same priority level meet, they will exhibit their own behavior. In this case, the priority will not affect their behavior, whereas two occupants with different priority level, there will be a change in their behavior based on the priority parameter.

4.2.1. Collision handling and response

In SFPE mode, occupants are not allowed to collide with other occupants; however they can still collide with the walls in the layout. For the pre-movement time step, the travel velocity is adjusted to force the occupant to slide any nearby walls. After the adjusted velocity, the occupant is moving with the new velocity and this stage, wall collisions are still possible. So the occupant will simply halt at the earliest collision.

In steering mode, pathfinder uses a combination of steering mechanism and collision handling to control how the occupant move in the model. During collision or obstruction, this mechanism makes the occupant deviate from the path, while still heading to the correct direction towards the goal. Pathfinder's steering system leads the occupant to roughly follow their seek curve and can respond to a changing environment. Wall avoidance behavior and occupant avoidance behavior will help the occupant to move around the obstacles and walls. But they may not always succeed in case of a crowded situation where congestion presents. In this situation, additional two collision handling scenarios are introduced. The first one, in which, two or more occupants collide and another where an occupant collides with the boundary of the navigation mesh. The second, if collision handling algorithm is turned on, the occupant will halt at the earliest collision with either wall or occupants. If it is not turned on, the occupant will only halt at the earliest collision with a wall.

4.2.2. Counter-flow

In terminal there is counter-flow situation arises when there is a firemen enter to the secured side of the airport by security doors. In pathfinder's counter-flow behavior, if an occupant from a room R1 and another occupant from room R2 are trying to pass through a common door for R1 and R2, the flow is controlled and directed by the density of the room. If the density of the R1 is high, the occupant from R1 is allowed to enter into R2, even though the occupant from R2 is in the queue before R1 occupant. If the rooms are too crowded, the two occupants will be exchanged and the delay time placed on the door queue will be the sum of the delay times resulting from the passage of the two occupants.

However there is other functionality in pathfinder which provides priority level in the movement, which may be used in the counter-flow situation to give priority to certain type of occupants. When an occupant encounter another occupant with higher priority level, the low priority occupant will ignore his seek state and instead use the separation state to give way to the higher priority occupant.

4.3. Legion

Legion [40] is a multi-agent pedestrian model. Pedestrian is modeled as two dimensional "entity" with circular body. Pedestrian moves in 2D continuous space with the time step of 0.6sec. The model is capable of handling multiple floors with special objects which can link multiple floors, such as stairs, elevators, ramps and moving walkways.

A movement of an entity towards the target is based on the concept of minimizing the objective cost function and navigation. When Legion calculates the entity movement, it uses minimum cost/ maximum utility as the cornerstone of pedestrian logic. During an entity movement towards the target, entity chooses to have minimum dissatisfaction. Dissatisfaction caused by physical and psychological factors that affects the quality of their journey. There are three factors which contribute to an entity's overall experience of dissatisfaction [40].

- Frustration – having to slow down in congested spaces.
- Inconvenience – the degree to which an entity should divert from its preferred shortest distance.
- Discomfort – the perceived lack of adequate space.

As the vision of entities is bound by angle and distance, entities perception of the neighborhood is imperfect. So they have to predict the future position of their neighbors. As they move, entities learn from recent experience and calculate the weightage of frustration, inconvenience and discomfort. Entities communicate with the neighbors to either avoid or resolve the blockage and collision. Entity profiles are deduced from the entity profiles. They vary with

- Types of pedestrian – Tourists, commuters, runners, stadium users, weekend passengers
- Region – UK, Asia, Europe and China
- Context – indoor, outdoor, escalator, stairs up and down and flat ground.

These parameters include:

- The physical radius of each entity, drawn based on the distribution or sizes [41]
- Preferred free speed, drawn from the distributions of speed measured from the real types of pedestrian in a region for the particular context.
- Personal space – This size is also drawn from the distribution measured on real people. This also depends on an entity's relative speed [42]

Though there are predefined values for the occupants' profiles, the values can be customizable by the users.

4.3.1. Counter-flow

In legion, counter-flow is also handled by the above mentioned cost function. However there are additional parameters available to give priority to the pedestrians. They are entity priority and entity direction. Higher entity priority level pedestrians are able to pass other lower priority level pedestrians. The entity direction is used to specify the movement of the pedestrians when there is a collision or counter-flow. The entity direction can be set to left or right. The entity will move based on the entity direction setting when there is a counter-flow in the simulation.

5. Evacuation design

In order to study the evacuation of an airport terminal, evacuation design is to be carried out to model the simulation of evacuation scenario. Before start to design the model, it is important to understand the building, occupant and fire characteristics with respect to the airport terminal building, which affect the human behavior in fire [45].

5.1. Building characteristics

The response to an emergency situation is dependent upon the location where the occupant is in and the activity in which the occupant is involved. The pre-movement time is highly based on the activity of the occupants. As discussed earlier, there are several facilities in the airport which caters service for the public and passengers. So it is interesting to study about the facility areas and the activities, which affects the pre-movement time.

Most of the occupants in the terminal building are unfamiliar about the building, as the travelers and visitors are not repeated users of the building. So evacuation way finding takes time and affects the overall evacuation time. However, airport terminals have better fire safety management with fire alarm system and voice alarm system to alert the occupants. Terminals are equipped with signage system to navigate the users to the exits. This fire safety management improves the pre-movement time and overall evacuation time. Terminal buildings comes under the category with higher fire safety management, High alarm level (Fire alarm and voice alarm) and High building complexity [46]. Based on the standard [46], the pre-movement time for the airport terminal building is 1.5 to 2 min.

In most of the facilities in airport, passengers will have to wait in the queue. In case of an emergency, they do not want to give up their queue position. Passengers in the pier side may be hesitant to use the exits which are nearer to the hold rooms, as they are leading to the apron side of the terminal. As per passengers understanding, apron side is prohibited to the public and it is only for airline/airport operation and maintenance staff. So passengers tend to move to the terminal side to use the exits, which either they entered in or emergency exits in central terminal area.

As many of the airport passengers are new users to the terminal, terminal building has signage system to let the passengers know the different facilities in the terminal such as signage for gate hold room locations, rest room, restaurant, GST counter, waiting lounge, etc. signage are everywhere in the terminal. So finding an emergency exit signage in between the many facility signage will be difficult during an emergency and sometimes passengers may oversee the emergency route signage.

5.2. Occupant characteristics

In airport terminals, there are many passengers with different characteristics are observed, as many of them are from different countries with different age. The different types of occupants who use the airport terminals are

- Airline passengers
- Escorts, meeters/ visitors
- Airport police/ security personnel (staff)
- Customs officers (staff)
- Retail area personnel (staff)
- Airport maintenance staffs (staff)
- Airline staffs (staff)

In the event of an emergency, most of the occupants act as followers [47] [48] and they have their roles to follow. So the occupants who do not have familiarity of the building act as followers such as airline passengers who are inside the terminal building. Occupants tend to follow their roles in case of emergency [49], such as, airport maintenance personnel try to inform the passengers about the emergency and guide them to the evacuation exit. The passengers may have their own roles and rules during emergencies like father save his family, trip organizers search for their members to gather and evacuate. There are other parameters which will affect the occupant behavior.

- Gender and age
- Knowledge and experience
- Role
- Condition at the time of the event
- Disabilities

In this thesis, the occupant behaviors are modeled in such a way that it influences the evacuation process. Gender of the occupants are categorized by their shoulder width (body size) and it influences the evacuation process when they pass through the security doors. Walking speed is modeled based on the age and disability. The walking speed for the youth is faster than the elder people and the disabled people walks slower compared with other occupants. Knowledge & experience about the fire evacuation and building layout, and, condition at the time of the event (awake, sleep, etc.) determines how occupants react to an emergency event. So the pre-movement time is influenced by these characteristics. Staffs in the airport follow their role and guide the occupants to the nearest exit and this characteristic of the occupants influences the exit choice of the occupants.

5.3. Fire characteristics

Fire characteristics give clues to the occupants to understand the emergency situation and to act based on the situation. There are visual, olfactory and audible clues which give information to the occupants. When a passenger receive a visual clues such as burning flame, smoky environment, the passengers' next action (evacuate/fighting fire) is immediate. So the pre-movement time is affected much by the fire characteristics.

5.4. Egress components

In the terminal, there are several exits at the front side of the terminal which leads the occupants to outside of the terminal and there are two exits at the rear side of the terminal which is mainly used by the airport maintenance staff to enter the apron area, in order to carry out the maintenance services, baggage sorting and baggage handling services. The rear side exits are secured exits where the users of that exit have to go through security checks before entering the apron area. There are security doors provided for the passengers who are in secured side of the terminal to evacuate from the building to the public side and in turn to the outside of the terminal. Staircases are available in the public and secured side of the terminal for evacuation purposes. There are lifts available in the public as well as secured side of the terminal; however these lifts are brought to the lift homing position when there is an emergency in the terminal. Escalators are used in both the area of the terminal (secured & public).

5.4.1. Terminal exits

As explained above, there are two kinds of exits, out of which one is solely used for the airport maintenance staff to access the apron area and the other one is at the front side of the terminal which is used by the passengers to enter and exit from the terminal. The front side exits are the familiar exits almost all the occupants who use the terminal. There are eight exits for each floor. There are actually six main exits/entrances and two small exits/entrances at the corner of the terminal to use mostly by the stair/ lift users, as it is with the stair and lift lobby. The size of the exits is designed in such a way that there is enough space provided to three passengers with trolleys at a time. Based on the LOS standard, it is 1.5m per passengers with trolleys; therefore the exit widths are in the range of 4.5m to 5.0m. So the design chooses 5m for the main exits width. And the smaller exits are mainly used by very few passengers. So the width is provided with one passenger LOS width with some tolerance. The smaller exits are designed with 1.7m. Appendix A3, A4 and A5 shows the exits available in terminal's arrival and departure halls.

5.4.2. Security doors

There are 8 security doors in the arrival hall and 12 security doors in the departure hall. Security doors are with fire rated double swing door. Based on the standard dimension of the fire rated doors, the width of the security doors are 1650mm for each security doors. All the security doors are locked and secured all the time, except those sliding doors with security personnel like the doors which are near to the baggage check area.

The departure hall in the terminal has 6 staircases with security doors, which lead the passengers to the apron side of the terminal. There are 12 staircases with security doors for each pier. These staircases also lead the passengers to the apron side of the terminal.

5.4.3. Escalators

Escalators in the public side are mostly used by the visitors, as the most of the departing passengers will directly arrive to the departure hall. In the secured area, escalators are majorly used by arriving passengers, as these escalators leads to the Immigration check area of the arrival concourse.

5.5. Evacuation strategies

This section presents the different evacuation strategies for airport terminals which are to be investigated by mean of egress modeling. Apart from the base scenarios (no counter-flow and counter-flow), these strategies are used to compare the results to suggest an optimized solution for airport evacuation.

As the airports have its own fire station within its perimeter, the arrival of firemen to the airport terminal is considered to be within 300s. The terminal fire alarm system is equipped with sending signal to fire station directly during the very early stage of detection. The arrival time of firemen to the terminal, their entry through the security door to fire location and the door which they choose to enter, affect the evacuation pattern.

As the airport terminal is a complex building type and has very large floor area, the evacuation from hold rooms at pier side takes longer time to evacuate through the familiar exits, in which the passengers entered. In the design, a concept of fire zone evacuation (zonal evacuation) is studied to understand the suitability of the strategy. Terminal floor levels are divided into terminal building side and pier side. Based on this strategy, a fire in arrival hall will evacuate only people from arrival level floor. Departure level terminal building area is evacuated only when there is a fire in terminal building side. Only a particular zone is evacuated when there is a fire in that zone and rest of the zones will not be affected.

In zonal evacuation, the airport is divided into eight fire zones and they are arrival hall public zone, arrival hall secured zone, arrival level left pier zone, arrival level right pier zone, departure hall public zone, departure hall secured zone, departure hall left pier zone and departure level right pier zone. Based on the risk based fire location (figure 10 and figure 11), the fire comes under the arrival hall secured zone (case 1) and departure hall secured zone (case2). So the evacuation will only be done at the particular two zones and rest will not be affected.

Based on the base scenario, firemen access and zonal evacuation, there are five evacuation strategies investigated to study the influence of the firemen and zonal evacuation. They are

- No firemen counter-flow
- Firemen enters terminal at 180s
- Firemen enters terminal at 120s
- Zonal evacuation
    - Firemen enters through security door to terminal secured area
    - Dedicated firemen access to enter secured area

In order to simulate the firemen entry at the security doors, it is assumed that there are 20 firemen will respond to the terminal, when there is any fire notification to the fire station at the airport.

5.6. Model design

The number of passengers is given in the quantification of scenario section in the earlier chapter and the quantity is modeled in the simulation software. In the model, it is important to specify the walking speed and the body sizes of the occupants. Model takes the unimpeded walking speed; however the speed of the occupants will be varied in the model, based on the population density.

5.6.1. Walking speed

Occupants walking speed [50] and body sizes [51] are based on their age and gender and it is given in table 9. The values given for the body size (shoulder width) and walking speed is considered as uniformly distributed in the simulation.

Occupants	Body size (Shoulder width) (cm)	Age	Walking speed (m/s)		
			Corridors	Stair down	Stair up
Men	40.6 - 49.3	Less than 30	1.11 - 1.85	0.76 - 1.26	0.5 - 0.84
		30 to 50	0.97 - 1.62	0.64 - 1.07	0.47 - 0.79
		Older than 50	0.84 - 1.4	0.5 - 0.84	0.38 - 0.64
		Older than 50 (mobility impaired)	0.64 - 1.06	0.38 - 0.64	0.29 - 0.49
Women	36.6 - 44.96	Less than 30	0.93 - 1.55	0.56 - 0.94	0.47 - 0.79
		30 to 50	0.71 - 1.19	0.49 - 0.81	0.44 - 0.74
		Older than 50	0.56 - 0.94	0.45 - 0.75	0.37 - 0.61
		Older than 50 (mobility impaired)	0.43 - 0.71	0.34 - 0.56	0.28 - 0.46

Table 9: Occupant shoulder width and walking speed profiles

5.6.2. Passenger distribution

The passenger distribution in the terminal is majorly based on the distribution of population in the airport city. Based on the air passengers survey (2006) [53], the percentage of male passengers are 52% and female passengers are 48%. The distribution is further divided by percentage of passengers based on the age [53].

Age	Population percentage
Under 18	1%
18 - 25	13%
26 - 35	24%
36 - 45	24%
46 - 55	20%
Over 55	19%

Table 10: Airport terminal users' population

The number of disabled passengers in a terminal is 132 per month [54]. This gives about 5 disabled passengers per day. However this data had been taken from a survey and the survey result is based on the number of disabled passengers who took the survey. So the number of disabled occupants may be more than 132 for the particular month. Therefore, in the design, a conservative value of 1% is assumed to be disabled passengers during the peak hour. The walking speed for the disabled passengers majorly affect the total evacuation time, as they have difficulty in mobility. The walking speed for the disabled passengers are considered to be same as the walking speed of mobility impaired (Men) in table 9.

The age profile is rearranged to suit to the speed profile's age. An assumption is made to divide the percentage which is in two ranges in the speed profile. For ex, 25-35 is in the less than 30 and 30 - 45 range. This age range is divided into 26 - 30 (5 years range) and 31-35 (5 years range) and the percentage is divided based on the number of year's ratio. In this case, it is half. So 26-30 is 12% and 31-35 is 12%. After get percentage of distribution by age wise, the values are further divided into gender wise based on the data of 52% male and 48% female. The rearranged speed profile based passenger distribution is:

Gender	Age	Distribution
Male	Less than 30	13%
	30 to 50	23%
	Older than 50	15%
Female	Less than 30	12%
	30 to 50	22%
	Older than 50	14%
Disabled		1%
	Total	100%

Table 11: Airport terminal users' population distribution based on age

5.6.3. Pre-movement time

Based on BSI standard, airport terminals comes under the high complex building type with good fire safety management and high level of alarms with voice alarm and PA announcement [46]. Building which comes under this classification has a pre-movement time in the range of 90 to 240 sec [46], based on the fire safety management implemented in the terminal building. However airport is a large building and it is unrealistic to use the same pre-movement time for all the facility locations in the terminal. Therefore some realistic assumptions are made for the pre-movement time for the various facilities and is discussed further.

The occupants' states of the occupants who are in the area where fire occurs are awake and active and they receive fire clues by seeing the smoke or flame from the fire location. So their pre-movement time is much quicker than the other facilities. The fire location is considered to have awake and familiar passengers, and based on the BSI standard [46], the pre-movement time for the occupants for the above criteria is 60sec to 90sec. It is good to assume that the visitors and passengers in the public side of the terminals are awake and familiar about the entrance they came inside the terminal. So the users’ pre-movement time at the public side of the terminal is set from 60sec to 90sec. The rest of the passengers inside the secured side are assumed to be with the pre-movement time specified in BSI standard [46] for transportation buildings (railway, bus station or airport), which is 90 sec to 240 sec. The standard normal distribution of the pre-movement time values are used in the simulation to model the evacuation process.

5.6.4. Exit choice

As there are no much data about the airport evacuation, the exit choices data are taken from its equivalent and occupant category type building. The category type of terminal buildings are "Awake and unfamiliar" and the equivalent is assumed to be the large retail stores which is also in the category type which is same as terminal buildings. In retail stores [52], there are 54.7% (within a range of 19.8% to 71.8%) of occupants uses the familiar exit and 45.3% (within a range of 28.2% to 80.2%) of occupant use emergency exit to evacuate. There was further research on the reasons for using the exits and the results were [52] given in table 12.

Factors	Type	Percent	Range
Exit type	Familiar exit	54.7	19.8 to 71.8
	Emergency exit	45.3	28.2 to 80.2
Reasons for choosing the exit	Familiar exit	19.5	14.6 to 29.7
	Nearest exit	50.1	29.7 to 69.9
	Directed by staff	25.2	13.4 to 32.6
	Followed others	5.2	0.4 to 9.5

Table 12: Exit choice

There are no familiar exits to the passengers who are arriving to the airport as they are totally unfamiliar with the exits available in the airport. The familiar exit to the departing passengers is the one which they used to enter the security side of the terminal, which is through the immigration check. Terminal staffs are in the emergency location to inform and guide the passenger to the nearest emergency exit.

During the fire situation in arrival hall (hatched area in the figure 10), passengers are not able to use the familiar exit which is where the fire is initiated. So there are only 4 exits (circled area in the figure) available for them evacuate from the arrival hall. The exits which are at the stairs lead the passengers to the departure hall to evacuate from there. The immigration officers in the immigration check booths will evacuate from the security door which is next to the stair exit. So most of the passengers from baggage claim and immigration arrival will take the security doors to evacuate. However when there is a situation where queue is forming at the security door, the occupants are directed to staircase either by security staff or by maintenance staff. Based on the evacuation exit choice behavior, 25% of occupants will take the staircase exit to evacuate from the departure hall and the remaining passengers go through the security door to evacuate from the arrival hall.

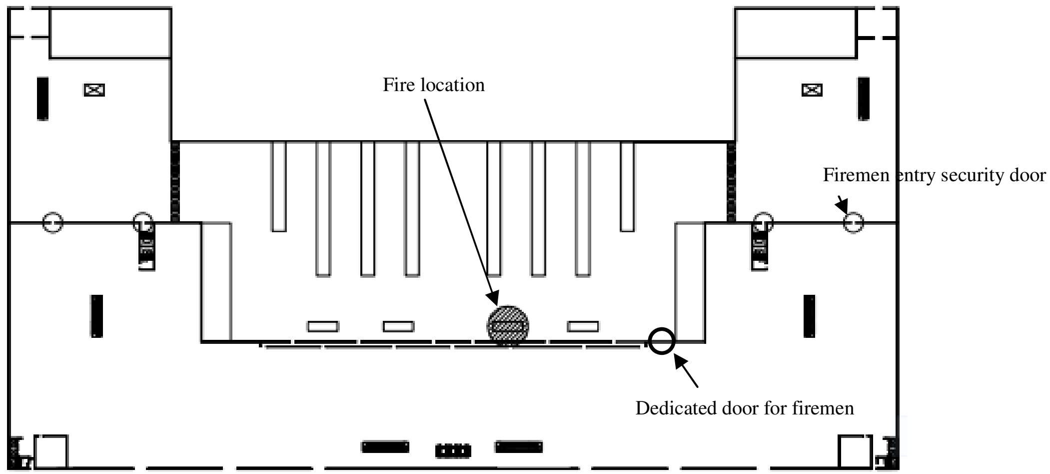

Figure 10: Arrival hall fire location and security doors

The fire location in departure hall is highlighted with hatched circle (Figure 11) and which is in front of the departure immigration clearance area. This is the entry for all the departing passengers to enter the terminal's secured side. So this is the familiar exit to all the departing passengers. There are 8 security door exits which separate the secured and public side (circled in the dividing boundary). As per theories discussed, occupants tend to take familiar exit during emergency; however when the familiar exit is blocked, occupants tend to take the other available exits based on the direction given by the airport staffs or security officers.

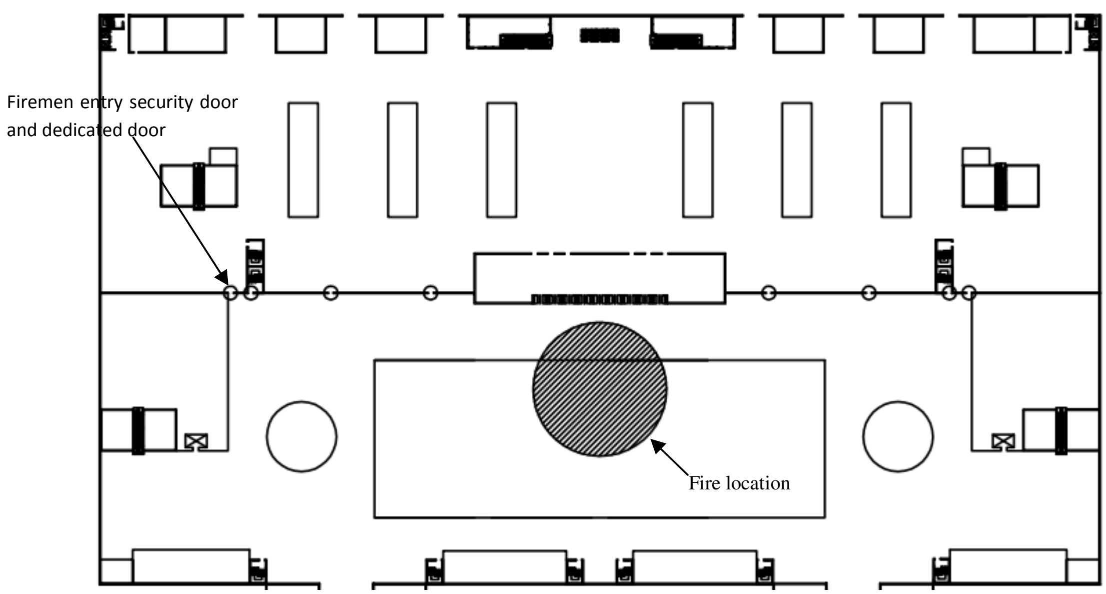

Figure 11: Departure hall fire location and security doors

The exit choice is majorly based on the shortest route in the terminal side. In the pier side, every hold room has stair which leads the occupants to the terminal's apron area. So during evacuation, 25% of hold room occupants will take the stair which is next to the hold room and remaining will travel to the familiar exit. During their travel to the familiar exit, if there are any hold room occupants exit by their nearest stair, 5% (follow others) of travelling passenger will join with them.

5.6.5. Simulation run

In evacuation modeling, there are many stochastic variables used to define the characteristics of the agents, such as pre-evacuation time distributions, unimpeded walking speeds, agent size, etc. So it is necessary to define the number of runs to be simulated to get converged result irrespective of the stochastic variables. A convergence method is introduced to converge the results based on the averaged evacuation time produced by a consecutive number of runs. In this method, the number of simulations of the same scenarios with different agent’s characteristics, dependent on the error of two consecutive averaged evacuation times and also the error of two consecutive standard deviation of evacuation times. The averaged evacuation time error is set as 1% and the standard deviation error is set as 5%. That is, an additional run of a scenario would change the results less than 1% in error and less than 5% error in standard deviation. Based on the convergence method, every scenario is simulated until the 5 consecutive runs which fall below the required criteria.

6. Results

The results of the different scenarios simulated in the evacuation software are presented here. The analysis of the results are divided into two groups and they are

1. Validity of model results - A cross comparison of base scenarios (no counter-flow and counter-flow for arrival and departure hall) for the two different models (Pathfinder and Legion Evac)

2. Relative comparison of strategies - A relative comparison of all the evacuation strategies and this is done by a single evacuation model (Pathfinder)

6.1. Validity of model results

The first group of results is a cross comparison of the total evacuation time between two evacuation models. The base strategies are simulated using both the software to compare the models' algorithm. In particular, sub models, which are employed to simulate the counter-flow, collision handling and prioritized agent movement are compared between two models. The scope is to evaluate the range of variability of the results between the two models with respect to airport environment. In order to compare the total evacuation time between two models, the percentage of total occupants evacuated is plotted against their evacuation time.

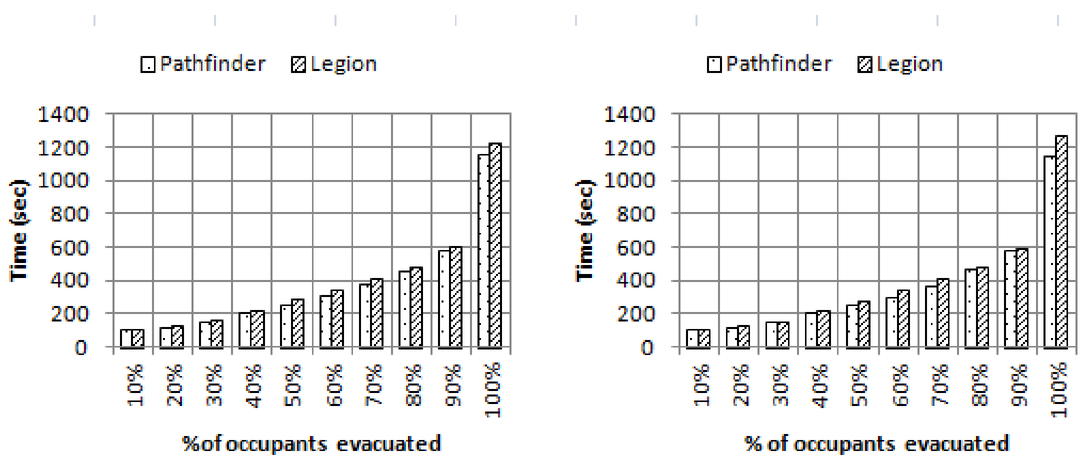

Figure 12: Arrival hall fire scenario evacuation with (left) and without counter-flow (right)

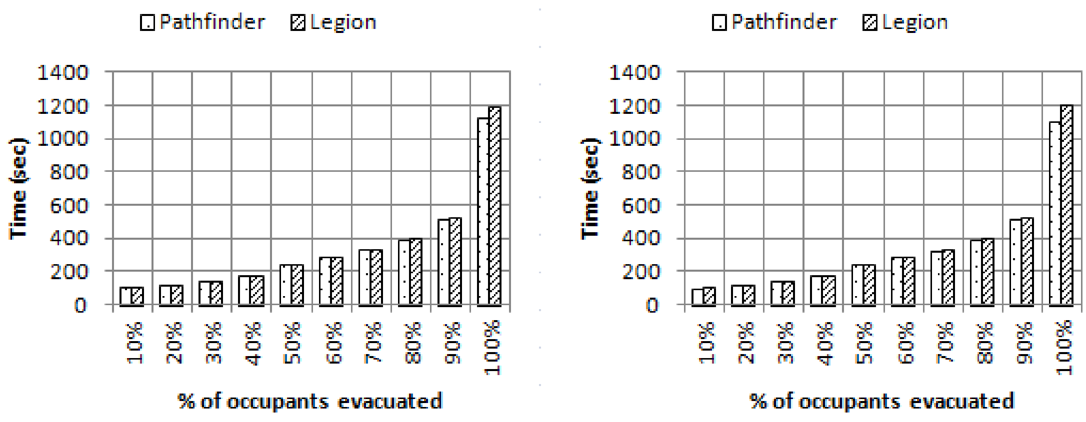

Figure 13: Departure hall fire scenario evacuation with (left) and without counter-flow (right)

In both the simulations, the models have very good fit until the 90% of the occupants' evacuation and only there are small deviations in the last 10% of occupants. Based on the simulation, 90% of the occupants are from the terminal building side as well as the front of the pier side. The last 10% of the occupants are from the rear of the pier side which is far from the terminal exit, and that is why they take long travel time to evacuate. The slight difference in the value is because of the stochastic variables such as walking speed range selection and pre-movement time range selection for the particular simulation. As both the models have almost similar results for the base evacuation strategies, the other strategies are modeled in single evacuation software (Pathfinder) to study the problems and effectiveness of the strategies.

6.2. Relative comparison of strategies

In this section, all the strategies are modeled and simulated in Pathfinder software to analyze the problem in the airport terminal evacuation. Based on the base scenario analysis, the total evacuation time for the no counter-flow and counter-flow does not have much difference for the departure hall as well as arrival hall.

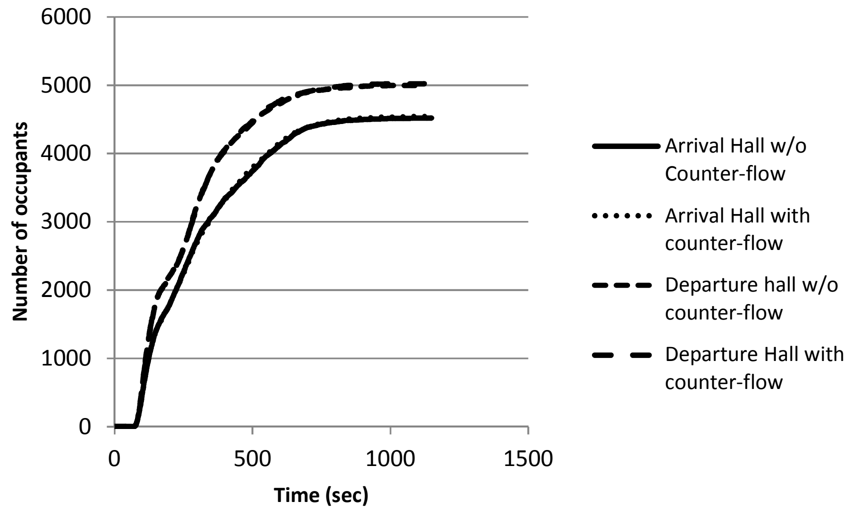

Figure 14: Number of occupants evacuate over time

As shown in the graph, the evacuation patterns (with and without counter-flow) follow the same trend line. So the counter-flow of firemen does not affect the total evacuation time. However the counter-flow affects the security door flow, in which, the firemen enter the security side. Cumulative count of the passengers passing through the security door is plotted over the time to understand the impact of firemen counter-flow at the security door for all the scenarios.

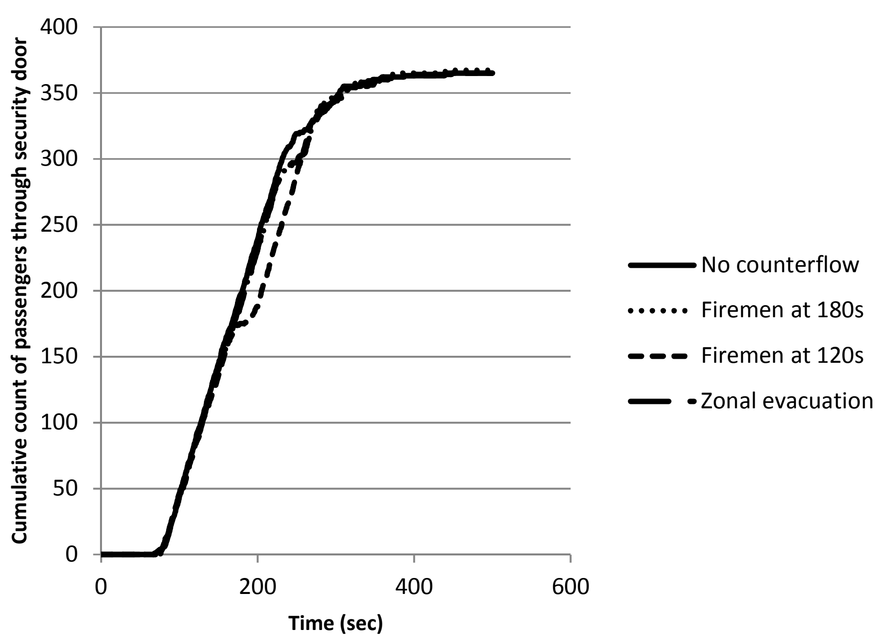

Figure 15: Passenger flow at arrival hall security door

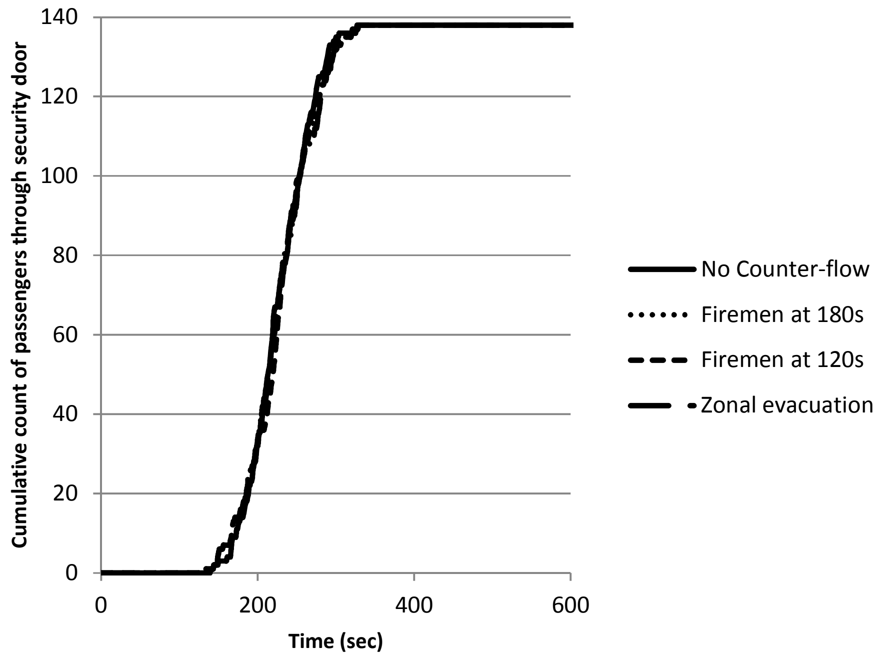

Figure 16: Passenger flow at departure hall security door

As shown in figure 15 and figure 16, the security door passing through time for the passengers are affected slightly at the arrival hall, which is because of the occupant density at the arrival security door. There are about 360 passengers passing through the security door in 200 seconds which gives almost more than a passenger passing through the door every second. The firemen entry, where is a slight deviation from the "No Counter-flow" line, is clearly seen in the arrival hall's graph. In departure hall, the occupant density at the security door is not so high as compared with the arrival hall. There are total of 138 passengers passing through the security door in 200 seconds, which is about 1.5 second for a passenger. That is the reason, the departure curve is not smooth and there is no much influence of the firemen entry at the security door.

In practical situations, all the hold room passengers do not evacuate to the apron side of the terminal, where aircraft is parked. Most of the passengers from hold rooms try to evacuate through the entrance, in which they entered. The walking time of the hold room passengers are compared with the total evacuation time and the graph is given in figure 17.

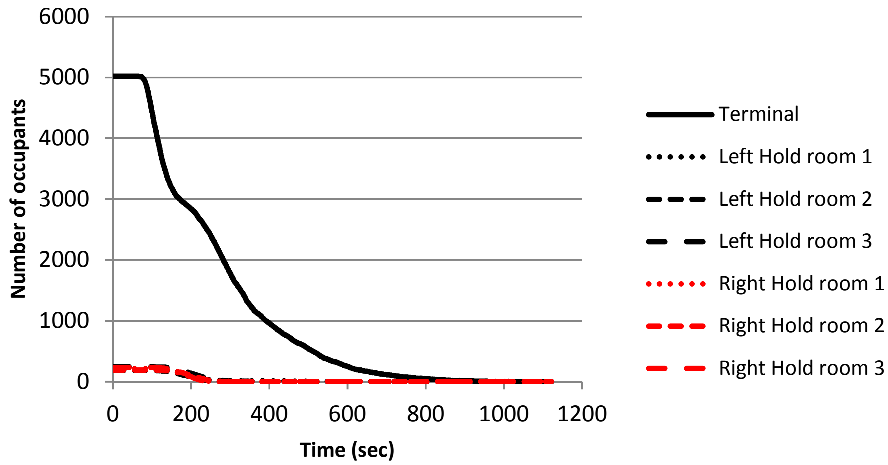

Figure 17: Comparison of total evacuation time and time to leave hold rooms

As shown in the figure 17, the passengers from hold rooms leave the rooms in about 250 seconds and then walk about 800 seconds to evacuate through the exit. In the departure hall fire case, the fire at the entrance of the departure hall's secured area may not affect the passengers in the pier side, unless the fire spread to the pier side.

Airport terminal is separated by different fire zones and zonal evacuation strategy is studied. Airport terminal building and pier side are separated into separate fire zones. Building is divided into public side fire zone and security side fire zone and the pier is separated into left side pier and right side pier/finger fire zones, so that any fire in a fire zone, there will be an evacuation only at that particular fire zone and the rest of the fire zones will not be evacuated. As discussed in simulation strategies section, the fire is at arrival secured zone for arrival floor and departure secured zone in departure floor. So the occupants in the building side are only evacuated during the zonal evacuation. The evacuation zone is arrival concourse, baggage claim and arrival public for the arrival floor fire scenario & departure public and departure concourse for the departure floor fire scenario. As the number of occupants evacuating in zonal evacuation is less than the total terminal evacuation, the time taken for the fire zone occupants evacuation is less than the total evacuation time. The total time taken for the evacuation is given below in the figures (figure 18 and figure 19) for all the evacuation strategies.

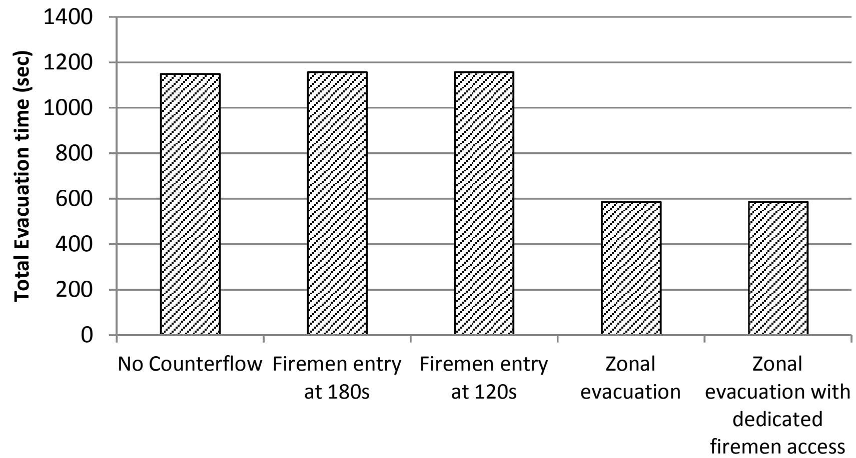

Figure 18: Total evacuation time for different strategies (arrival hall fire)

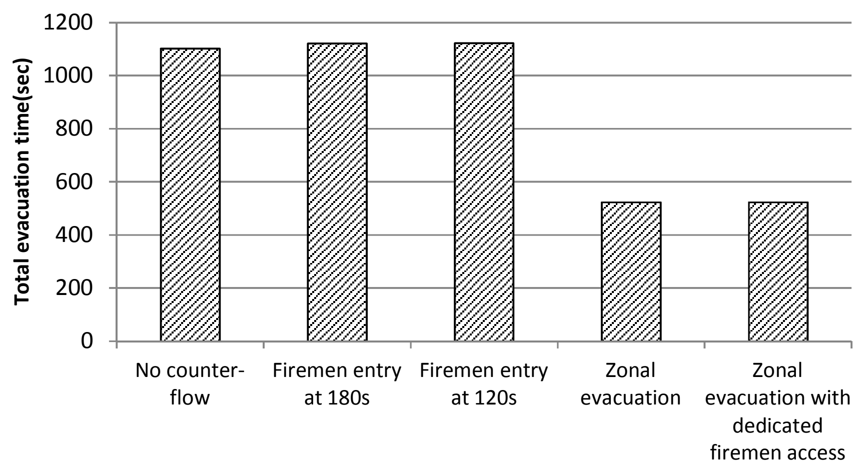

Figure 19: Total evacuation time for different strategies (Departure hall fire)

Based on the result shown on the above graph, irrespective of the time of disturbance (counter-flow) in the passengers' evacuation flow, the total evacuation time remains the same except the zonal evacuation. Even in zonal evacuation, the total time for the evacuation with firemen counter-flow and with dedicated door for firemen access is the same.

6.3. Sensitivity analysis

The evacuation study is based on the experimental data for the pre-movement time, walking speed, number of occupants in the terminal and number of firemen enters the terminal. So the data may have uncertainty in the actual implementation of the data in the evacuation simulation. Sensitivity analysis for the above variables are conducted in the zonal evacuation with dedicated firemen strategy to see how the variables affect the total evacuation time in the simulation. As the pre-movement time and walking speed is standard normal distribution and uniform distribution respectively, the whole distribution is shifted based on the mean value by 20% in high and low side.

Parameter	Range	High (sec)		Low (sec)		Difference (sec)	
		Case 1	Case2	Case1	Case2	Case1	Case2
Number of occupants	±20%	592.8	523.3	582.8	478.8	10.0	44.5
Number of firemen	±50%	588.8	523.3	588.8	523.3	0.0	0.0
Pre-movement time	±20%	603.8	556.3	573.8	490.5	30	65.8
Walking speed	±20%	477.8	454	786.5	653.5	308.7	199.5

Table 13: Sensitivity study parameters

In table 13, the parameters used in the simulation are varied and ran the simulation to see impact of the variables in the total evacuation time. The base total evacuation time is 588.8 sec and 523.3 sec for case1 and case2 respectively. The sensitivity graph is given below

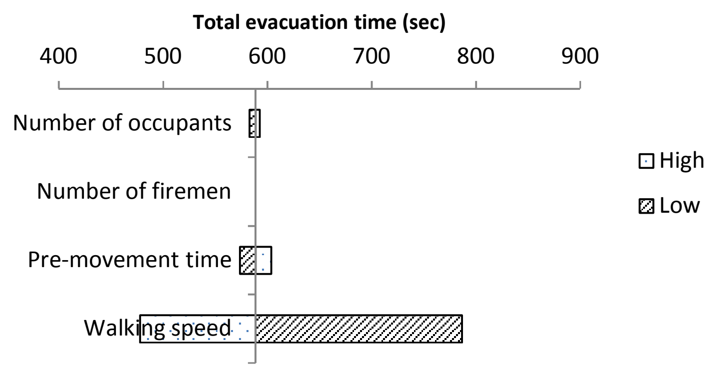

Figure 20: Sensitivity of simulation parameter to arrival hall fire (case1)

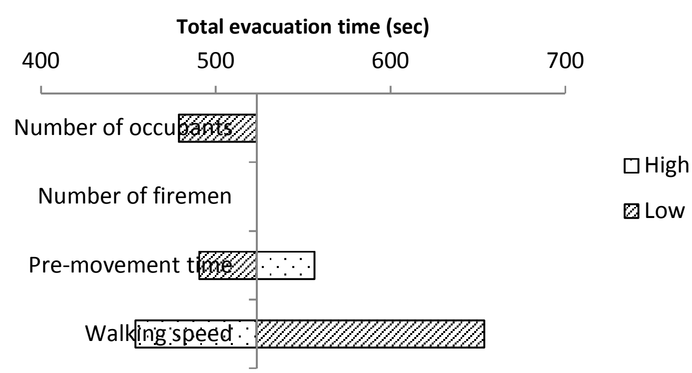

Figure 21: Sensitivity of simulation parameters to departure hall fire (case2)

The studies show that only the walking speed majorly affect the total evacuation time. Number of firemen does not affect the result even it is varied by 50%.

7. Discussions

Airport design for an international terminal with finger/pier model is developed to simulate the evacuation scenarios. Simulation has been done with two egress modeling software Pathfinder and Legion Evac. The total evacuation time for the occupants is compared to understand the range of variability of the results. In order to study the evacuation problems with respect to the airport terminal building, further strategies have been simulated in Pathfinder.

The major part of the evacuation in the airport terminal is through the security doors, as security doors are the dividing part of terminal for secured area and public area. Both models which are used here has a validation against the sub-algorithms used in the simulation such as counter-flow, prioritized agent movement, collision handling and escalator use. Pathfinder has validation against code requirements, fire drills, literature and other models. Legion has validation against code requirements, fire drills, literature on past evacuation experiments and third party validation. Both models have prioritized agent movement, so that some group of agents with high priority can supersede the low priority agents goals. This sub-algorithm is used to model the flow at security doors for the prioritized movement of firemen to reach the fire location against the flow of passengers.

The total evacuation time produced by both the models (Pathfinder and Legion Evac) are almost similar. As discussed earlier, the main sub-algorithms used in the model to simulate the airport scenario are counter-flow, collision handling and prioritized agent movement. These algorithms produced almost similar result for the both the fire scenarios. There are still slight deviation in the total evacuation time. This is because of the stochastic variables used in the simulations and the number of simulation run is simulated to get a converged result with less than 1% error. The simulation result for all the occupants are same except the last 10% of occupants. The last 10% of occupants are from the pier side. As the major difference is only on the last 10% and the rest are similar, the selection of stochastic variables such as speed distribution and pre-movement time distribution plays the role in the results between both the models.

The major concern in airport fire safety is to improve the safety and security. As discussed earlier in the chapters, the security will be affected when there is a fire in an airport. When there is a fire, the security doors will unlock, so that anyone may enter any side of the terminal. Further strategies have been made to analyze the problems in the airport evacuation.

The total evacuation time result shows that there are no major changes in the total evacuation time, even though there is a firemen counter-flow at the security door, which is used for passenger evacuation. However since the flow at the security door is two way, there is a possibility of public side people may enter the security side through security door during fire evacuation or sometimes they may activate the fire system to let the security door unlock and may enter security side intentionally. So further evacuation strategies are studied to identify the impact of firemen counter-flow at the security door and restrict the flow direction security door in one direction by introducing dedicated firemen door.

A study is done on the passenger flow at the security door, at which firemen enters to the security side to understand the impact of firemen counter-flow. The result of the study shows that the impact of the counter-flow is occurred for few seconds and then the flow coincides with the non-counter-flow pattern. There is some impact on security door flow at the time of firemen arrival to the terminal, however this does not affect the total evacuation time for the airport terminal. In arrival floor level, there is queuing of passengers at the security door in the earlier stage of evacuation. However after sometimes the passenger flow is without queuing and the number of passengers passing through the security door is less. That is why the no-counter flow pattern is increasing rapidly till it reaches about 200sec and then the graph is not increasing rapidly. When firemen enter through the security door, it affects the passenger evacuation. However this delay is compensated with the later part of the passenger flow at which no queue at the security door. In departure floor level, the passenger flow at the security door is always free and there is no queuing at the security door. So firemen entry does not really affect the passenger evacuation flow.

The evacuation time for the airport is about 1200 seconds, which is mainly due to major percentage of the passengers from the pier side choose their familiar exit to evacuate from the terminal. As shown in the comparison between the total evacuation time to the time taken for passengers to leave the hold rooms, the passengers from pier side takes about 800 seconds to reach exit which is at the front of the terminal. So fire zone evacuation strategy has been simulated without changing any parameters from the base simulation and only the fire zone is evacuated to study the total evacuation time. As the number of passengers in the particular zone is less than the total number of passengers in the whole terminal, the total evacuation time for the zonal evacuation is less than the total evacuation time for the whole terminal. So the total evacuation time for the zonal evacuation is almost half the time of the base simulation results. Based on the zonal evacuation, both the fire scenarios will come under the security side fire zone of the terminal building. So there is an evacuation only for the passengers at secured side of either the departure hall or the arrival hall with respect to the floor at which the fire is. In normal evacuation strategy, fire in any location will unlock all the security doors in the terminal, however in zonal evacuation, the arrival level security doors will only unlock for arrival hall fire and the same goes for the departure hall. So the number of security doors unlock is fairly reduced in this strategy.

A strategy is studied with dedicated firemen door to let firemen enter secured side and other security doors are set to open only in one direction to let only secured side passengers evacuate during emergency(open from secured side). This will certainly restrict the flow from the public side to the secured side and result in higher security. The result shows that there is almost no impact on the total evacuation time, because of the dedicated firemen door. Based on the sensitivity study, the walking speed is majorly affect the total evacuation time. Even though the zonal evacuation without dedicated firemen door and with dedicated firemen door gives same result for total evacuation, the security breach will majorly be reduced by using the zonal evacuation with dedicated firemen door. In zonal evacuation with dedicated firemen door strategy, the number of security door unlock is reduced and the flow direction restricted to security side to public side and the public side people enter the secured side through any of the isolated security door is highly controlled in this strategy. So safety and security feature of the airport terminal is well maintained in this strategy than the other strategies. So based on the results shown in the earlier section, safety and security aspects of the terminal, the zonal evacuation with dedicated firemen access gives better results on the total evacuation.

8. Conclusions and future research

Based on the simulation results of various strategies, the zonal evacuation with dedicated firemen door gives a better result, however this is for the generalized airport design. In actual airport design, there will be more complex layout in the airport design and finding a suitable position for the dedicated firemen door requires a lot of consideration on the building layout and the fire risk in the terminal building.

This research can be further extended with introducing the fire effect on the simulation to study the impact of smoke, heat and fire in the evacuation. Airport terminal has high level of fire safety management with smoke extraction system, fire alarm system and sprinkler system. The effect of the fire safety systems can be integrated to study the fire and smoke spread in the airport terminal and that can be used in the evacuation simulation. This research can be extended to different size of terminal buildings and also can be extended to different airport terminal configurations such as single floor terminal building, terminal without finger/pier.

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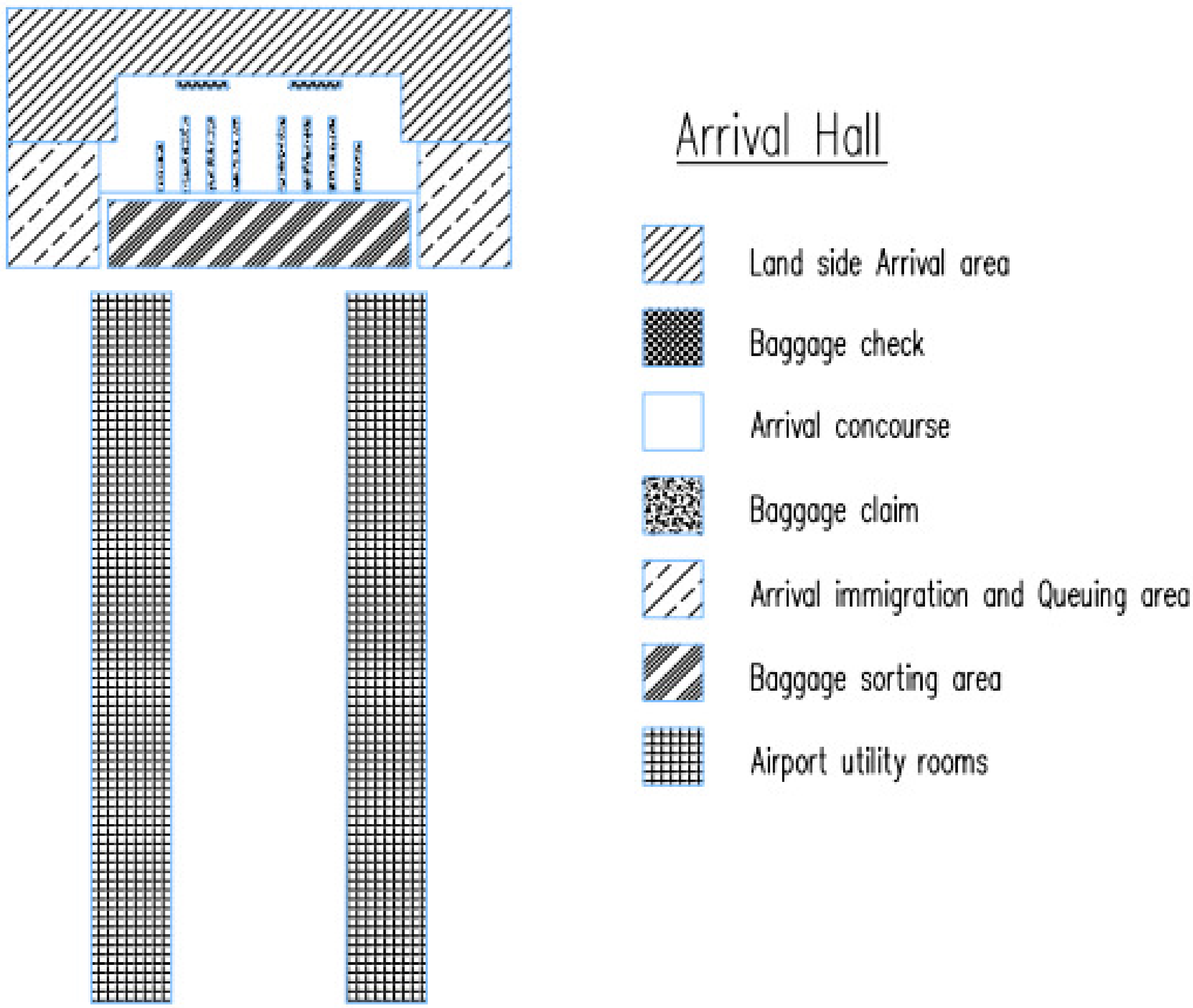
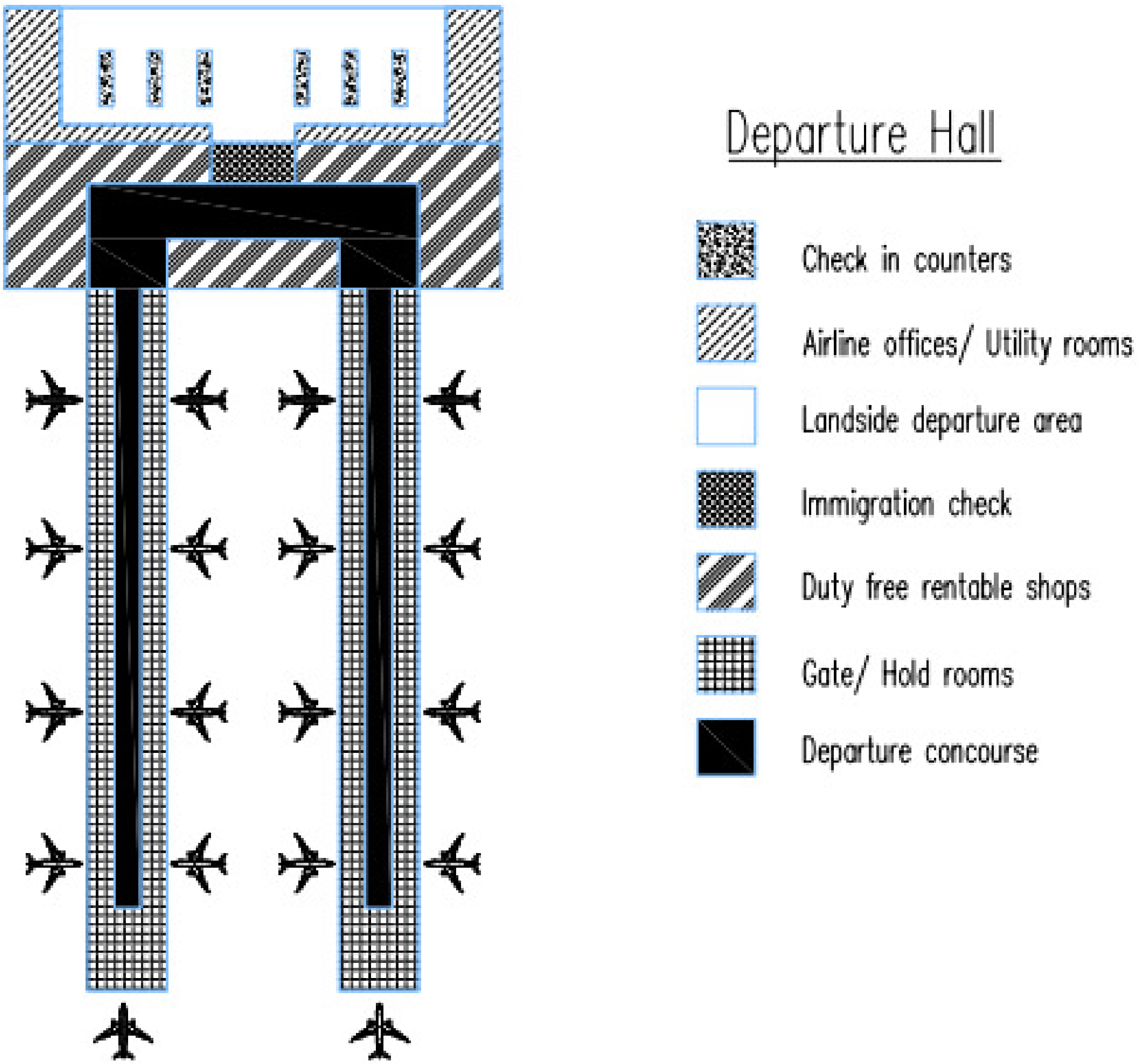
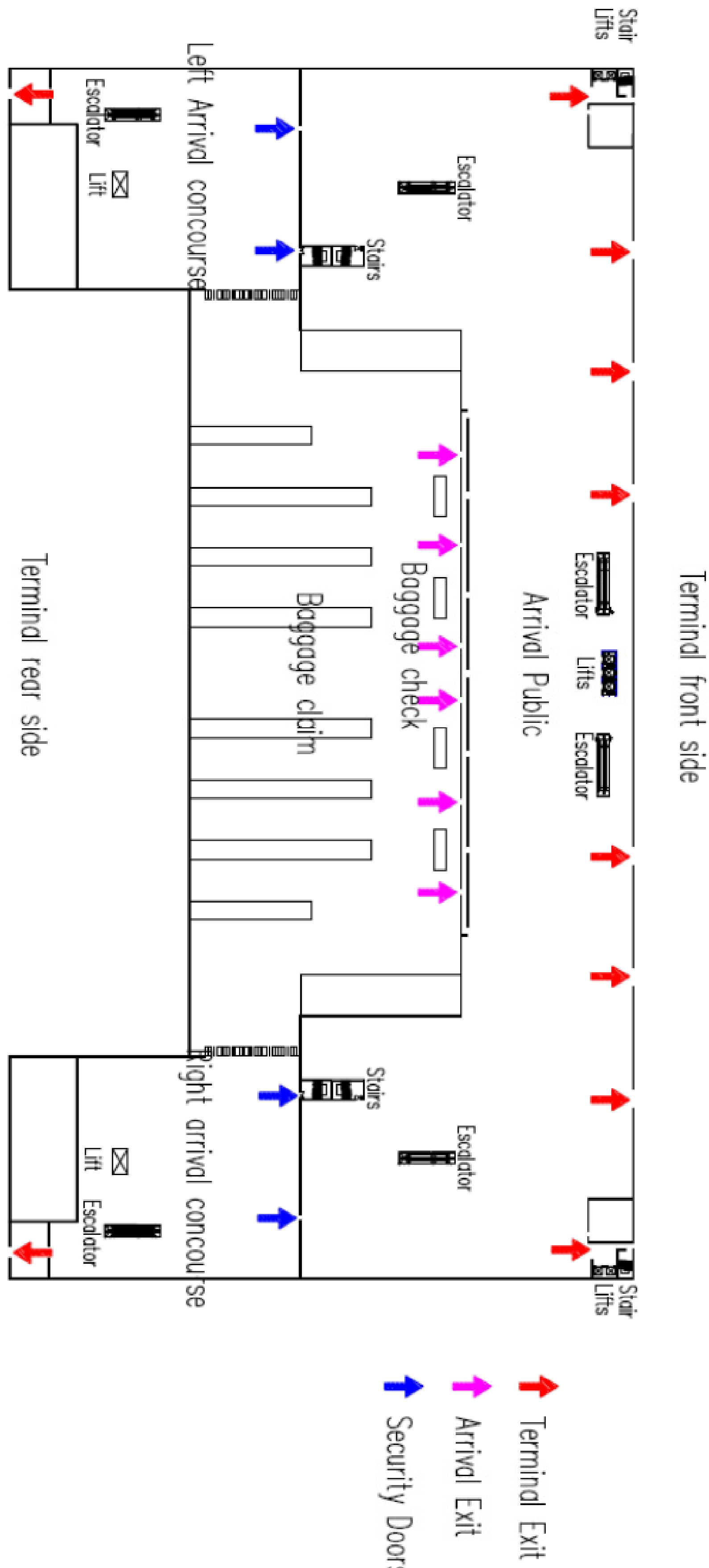
Appendix A1: Arrival hall facilities design



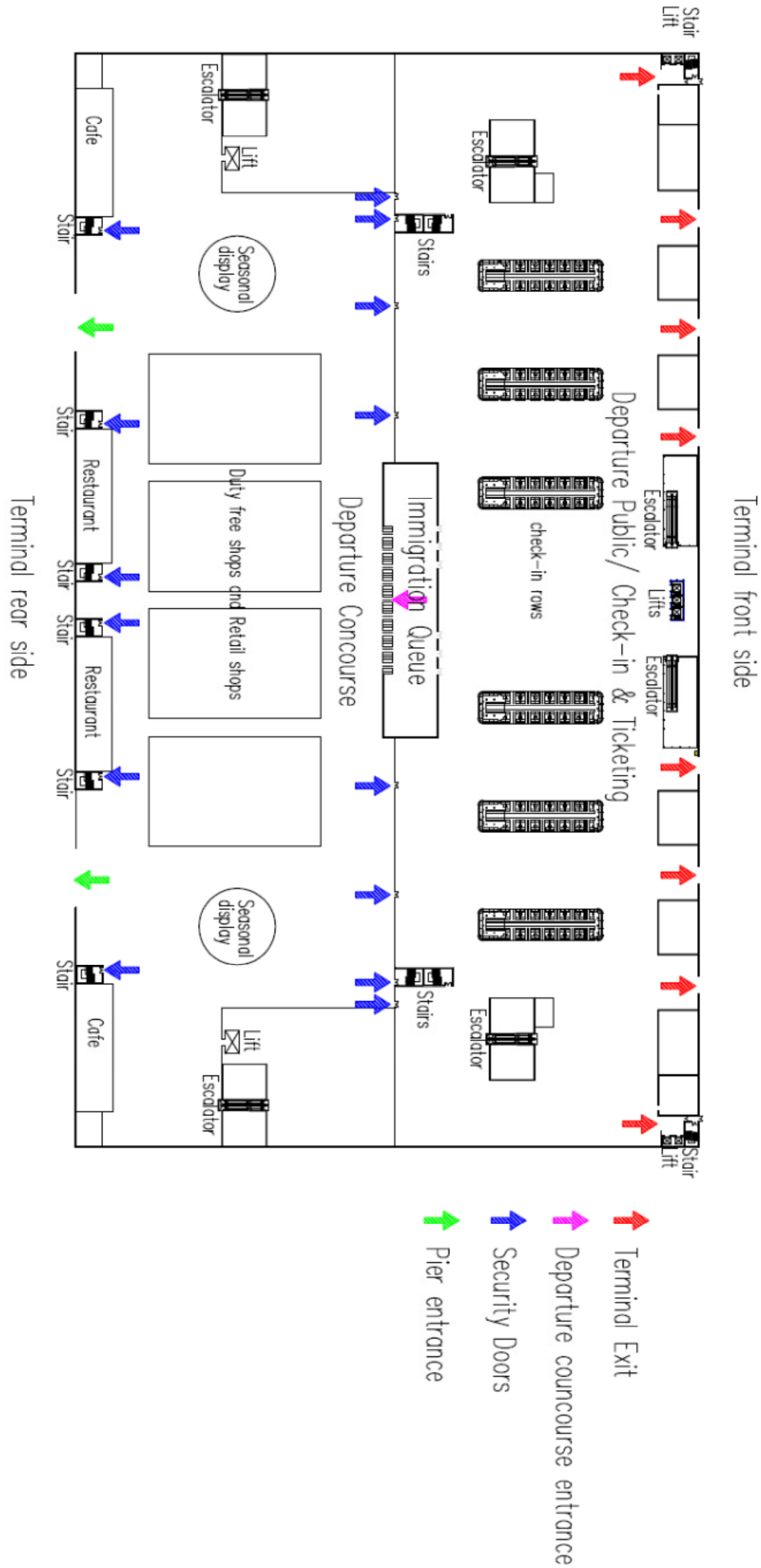
Appendix A2: Departure hall facilities design



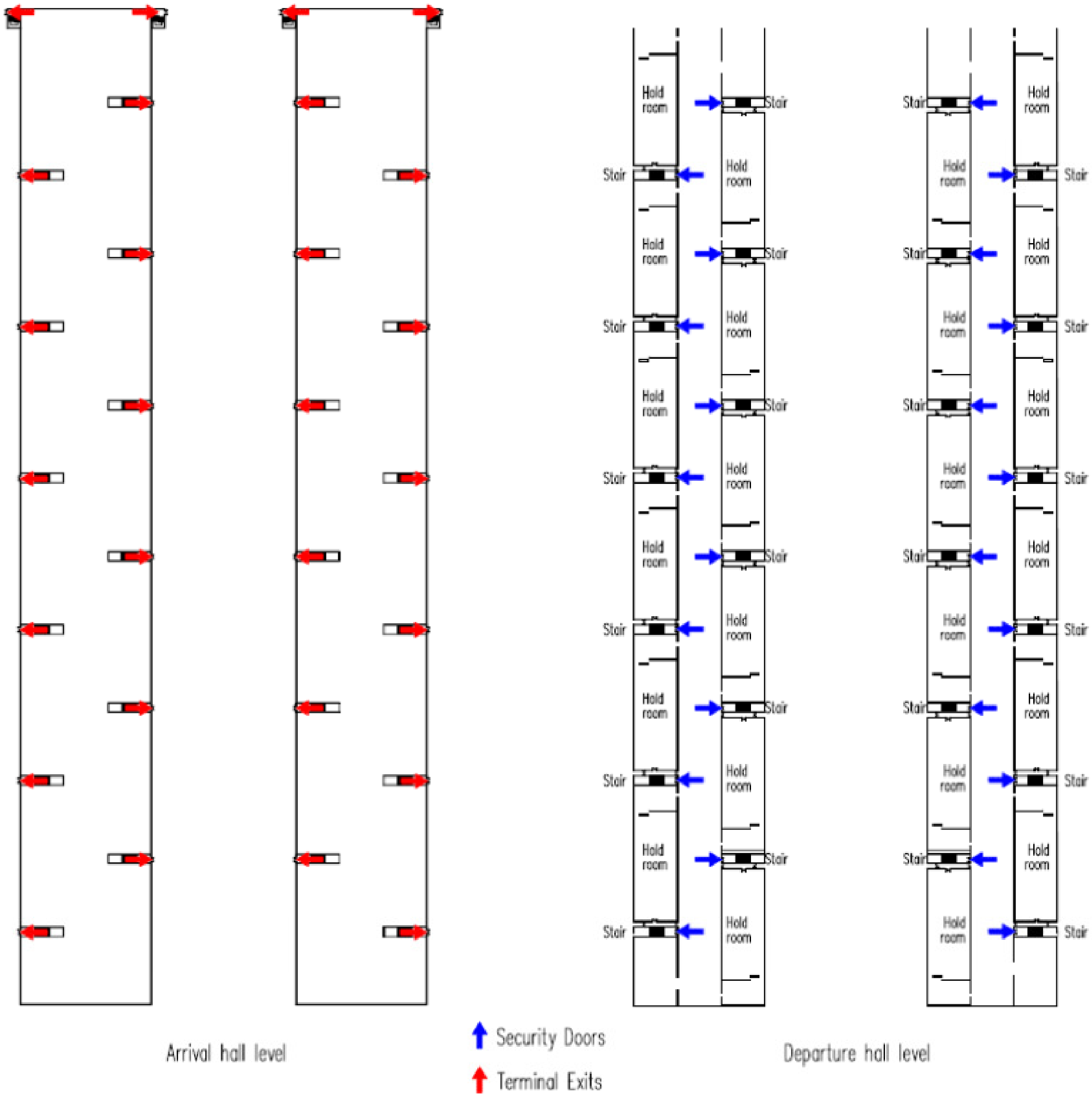
Appendix A3: Arrival hall layout and exits



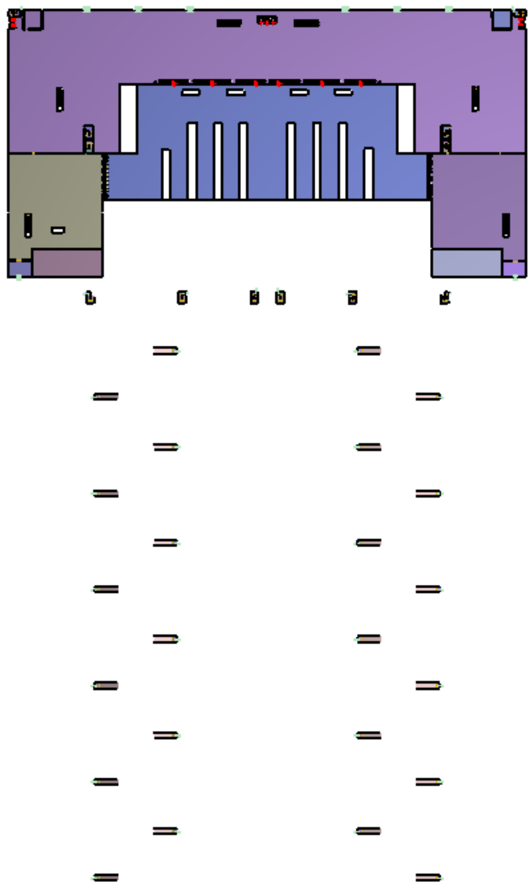
Appendix A4: Departure hall layout and exits

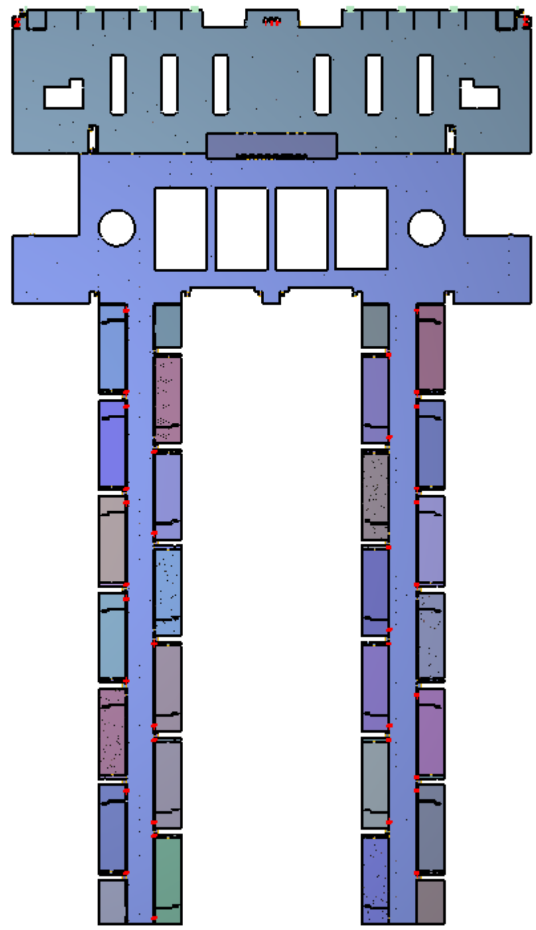


Appendix A5: Arrival and departure hall's pier layout



Appendix A6: Terminal design in Pathfinder





Appendix A7: Terminal design in Legion Evac