UNIVERSITY OF CALGARY

Planning of Airports for the New Large Aircraft

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF CIVIL ENGINEERING

CALGARY, ALBERTA

JUNE, 2001

0-612-64853-2

ABSTRACT

Aircraft manufacturers are developing a new generation of very large aircraft – known as New Large Aircraft – that will supersede any existing ones both in size and seat capacity. The Airbus A380 is scheduled to enter service in 2006 and the Boeing 747X could follow suit soon after.

Due to their larger dimensions and seat capacity, the New Large Aircraft will impact the planning and operation of airports. The design and operation of the airside sytem – comprised of runways, taxiways and aprons – will be highly affected by the New Large Aircraft's unprecedented wingspan, length, height and weight. Its high passenger capacity will affect the passenger terminal, as more passengers and baggage will require processing and accommodation in the check-in, security check, departure lounge, baggage claim, customs and immigration areas. Determining these effects and seeking solutions for those problems comprise the object of this thesis.

Since the airside effects of the New Large Aircraft have been extensively studied by several institutions, this thesis focuses on the issues related to the passenger terminal planning. Five main issues are analysed in more detail: the gate requirement, the terminal configuration, the sizing of the departure lounge, the processing of passengers and the design of the baggage claim area. As the full-scale operation of the New Large Aircraft is still years ahead, this thesis concentrates on developing mathematical models that will help in the early stages of airport planning. Thus an analytical approach is chosen with the use of deterministic models suitable for when important decisions must be made with little data available.

Several separate models are developed to analyse the five issues cited above. It is shown that, with the use of proper operational and structural measures, it is possible to accommodate the New Large Aircraft in an effective, economical manner.

ACKNOWLEDGEMENTS

My deepest gratitude goes to Dr. Wirasinghe for his role as thesis supervisor. His constructive and challenging comments and criticisms, as well as his support and friendship, were fundamental to the success of my research and to the expansion of my knowledge.

I would like to extend my appreciation to the members of my supervisory committee, Dr. Hunt and Dr. Wardell, for their help and suggestions to improve the quality of this work, and to Dr. Ehlers for his help with the probability problems. I am also very grateful to Dr. R. de Neufville from the MIT, for his important, helpful insights that also contributed in part to this thesis. Thanks also to Dr. Morrall and Dr. MacIver for their support, and to all the staff in the Department of Civil Engineering.

Thanks to all of those who somehow contributed to the success of this research, especially Mr. G. Falk and Mr. R. Livesey at the Calgary International Airport, Mr. P. Bianconi at the Vancouver International Airport, Ms. P. McHargue at Los Angeles World Airports, and Airbus Industrie for all the information and data provided.

Many thanks to all of those who contributed to help my family and me adapt to life in Canada. I am especially grateful to the Heinz, Baranoski and Rodrigues families for their invaluable support during our stay in Calgary.

Special thanks to my family and my parents for all the love, patience, encouragement, inspiration and unconditional support provided during all these years.

This research was made possible by CNPq, an agency of the Brazilian government dedicated to scientific and technological development.

To

my wife Solange

and my children

Ana Carolina and Maurício

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CHAPTER 1
INTRODUCTION

1.1 THE NEED FOR NEW LARGE AIRCRAFT

The world demand for air transportation has grown at a very rapid pace in the last several decades. It is predicted to keep growing rapidly over the next several decades. Boeing [2000] forecasts suggest that air travel (in revenue passenger-kilometres) will grow at an average annual rate of 4.8% over the period 2000-2019. Airbus Industrie [2000a] predicts an average annual growth rate of 5.2% for the period 1999-2009 and 4.6% for the period 2009-2019. Airbus also predicts that the average capacity of the world's aircraft fleet will increase from 179 seats in 1999 to 217 seats in 2019. However, air traffic is predicted to remain highly concentrated: as of 1996, 50% of all world wide seat-kilometres were provided on 6% of the routes, flying from or to 2% of the airports [Airbus, 1997].

An ever-growing demand is not new to the air transportation community, which has dealt with it mainly in three ways: 1. increasing airport capacity through construction and expansion of facilities, improvements in air traffic control procedures and technologies, and changes in operational policies; 2. increasing aircraft capacity, i.e. making the aircraft bigger so that it can carry more passengers at a time; 3. increasing flight frequency. The first solution appears to have reached its saturation point, as most airports are constrained by surrounding urban areas, high construction and land acquisition costs, and lack of room for further significant operational changes. Increases in frequency are still possible to subutilised airports, but not to the busiest ones. On the other hand, increases in aircraft size and capacity have not been successfully implemented after the 70's when the Boeing 747 was introduced (Figure 1.1). Now that the air transportation system capacity seems to need a boost, manufacturers are again planning to build aircraft larger than the 747. Such new aircraft developments are known as New Large Aircraft (NLA).

A comparison of Table 1.1 and Table 1.2 shows that the forecasts by the two major aircraft manufacturers, Boeing and Airbus, differ in the number of NLA that will be delivered in the next 20 years. While Airbus predicts that 1,200 aircraft larger than the 747 will be needed, Boeing estimates that only 1,000 aircraft including the 747 and larger will be delivered – leaving a much smaller share for the NLA. This difference in the predictions by the two manufacturers is in how they foresee the growth in air travel being absorbed by the market. Airbus believes in the consolidation of air travel, with a high concentration of traffic in a few selected trunk routes – especially in the Trans-Pacific and Asia-Europe routes. On the other hand, Boeing foresees a greater degree of travel fragmentation, with more point-to-point routes being opened and making use of existing large aircraft. Which prediction is right remains to be seen, and is not within the scope of this work.

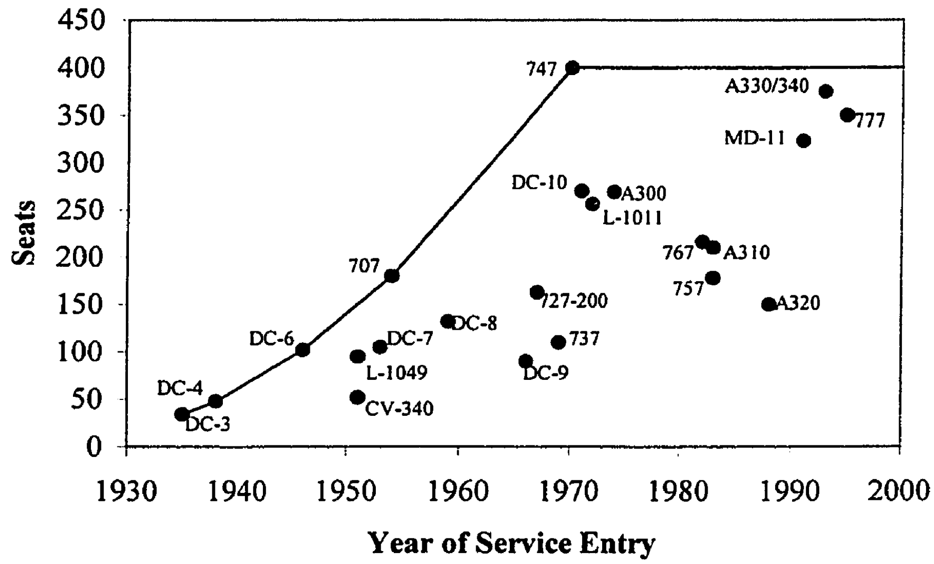


Figure 1.1: Evolution of the aircraft passenger capacity

Table 1.1: Aircraft deliveries 1999-2018 according to Airbus [2000a]

Seat capacity category	Aircraft units
70, 85	692
100, 125, 150, 175	7,570
210, 250	3,046
300, 350, 400	2,118
>400	1,235

Table 1.2: Aircraft deliveries 2000-2019 according to Boeing [2000]

Seat capacity	Aircraft units
Single-aisle	
<91	4,194
91-120	3,051
121-170	6,839
171-240	2,490
Twin-aisle	
230-310	2,314
311-399	2,417
Large (includes 747)	
$\geq$ 400	1,010

Although the increase in aircraft capacity is necessary to overcome ground infrastructure constraints, it is not the only motivation for the NLA. Aircraft operating costs account for most of airline costs. Larger aircraft capacity, if accompanied by technological improvements, will significantly reduce operating costs per passenger. Such technological improvements would include better fuel burn per passenger-km, longer service life, less downtime and lower maintenance costs [Mecham & McKenna, 1994; Shifrin, 1994]. In fact, Airbus [2000b] claims its new developments will have per-passenger operational costs 25% lower than the Boeing 747. Such reduction in costs would certainly appeal to airlines.

1.2 NLA DEVELOPMENTS

Studies to build an NLA date back to the 1970's. However, it was not until the early 1990's that the industry began to push for larger aircraft. Due to a predicted small market for such a big project – development costs are estimated at US$8-10 billion – talks were held between the major aircraft manufacturers to set an international program – titled "Very Large Civil Transport" (VLCT) – that would provide, without competition, the NLA units required by the market [Proctor, 1994a].That idea was abandoned in the mid-1990's and each manufacturer continued with their own projects [FAA, 1998b].

Before its merger with Boeing, McDonnel-Douglas had performed limited work on an NLA design. The four-engine MD-12 could carry up to 570 passengers in a three-class configuration on two decks. The program was halted in the mid-1990's because the company determined that the airlines were not prepared to buy high-capacity aircraft [Smith, 1994], and was abandoned when it was assimilated by Boeing.

Boeing is the producer of the largest aircraft in the world – the Boeing 747, which can carry over 400 passengers in a three-class configuration. A natural development for Boeing would be to produce stretched derivatives of the 747 in order to increase its capacity. In fact, Boeing is currently offering airlines the 747X Stretch, which has a passenger capacity between 504 and 522 passengers [Boeing, 2001]. Plans to build a totally new double-decker have been developed [Boeing, 1994; Proctor, 1994b; Barros & Wirasinghe, 1998b], but have been halted since 1997 for the same reason McDonnell-Douglas halted theirs – a belief that the market will not be strong enough to compensate for the development costs.

Despite the scepticism of Boeing, Airbus is investing heavily in its NLA. Formerly known as the A3XX project, Airbus announced the official launch of the aircraft with the denomination of A380 in December 2000. As of that date, Airbus has firm orders for fifty A380-800s plus forty-two options. The first delivery is expected in 2006. Airbus also plans to build an even larger airliner, the A380-900. An artist's impression of the A380 is shown in Figure 1.2. A comparison of the proposed NLA and existing wide-bodied aircraft is given in Table 1.3.

1.3 IMPORTANCE OF THE NLA TO AIRPORT PLANNING

The expected reduction in operational costs with the NLA does not come without a price. With the possible exception of a few new airports, most existing ones were designed to accommodate the 747 and will have difficulty handling larger aircraft. Operational constraints are expected both on the airside and on the terminal side of the airport. If not properly addressed, those constraints may more than compensate for the gains in aircraft operational costs. Furthermore, they might even prevent NLA's from operating at many airports.

Figure 1.2: Artist's impression of the Airbus A380, formerly known as A3XX [Airbus Industrie, 2001a]

Table 1.3: Comparison of NLA and existing wide-bodied aircraft (NLA in bold letters)

Aircraft	Wingspan (m)	Length (m)	Wheel base (m)	Wheel track (m)	Runway length (m)[a]	Passengers	Maximum takeoff weight (kg)
A340-300	60.3	59.4	23.2	10.7	3,000	262-375	253,511
A340-600	63.5	75.3	32.9	10.7	N/A	380	365,000
777-200	60.9	63.7	25.9	11.0	3,200	305-375	242,670
777-300	60.9	73.8	25.9	11.0	3,350	368	299,370
MD-11	51.8	61.3	24.6	10.7	3,200	323-410	273,287
747-400	64.9	70.4	25.6	11.0	3,353	400	362,871
A380-800	79.8	73.0	N/A	N/A	3,353	555	540,000
A380-900	79.8	79.4	N/A	N/A	N/A	656	540,000
747X Stretch	69.8	79.8	31.5	11.7	N/A	504-522	473,100
Boeing NLA	88.0	85.0	N/A	N/A	N/A	600-800	771,101

[a] Maximum take-off weight, standard day, sea level, no wind, level runway.

Awareness of these compatibility issues brought up by the NLA has increased among the airport industry. In 1994, the Airports Council International – North America (ACI-NA) held a conference on those compatibility issues [ACI-NA, 1994]. Through its global headquarters, ACI has also set up a task force and performed a survey among existing airports around the world to find out how they expected the NLA to impact their facilities. Of the 23 replies, 16 airports anticipated the costs of preparing for the NLA to range from US$20 to US$600 million [Airport World, 1996]. In the fall of 1996, this research at the University of Calgary was initiated with the objective of evaluating the impact of the NLA on airports.

In the U.S., the Federal Aviation Administration (FAA) has set up an NLA Facilitation Group to assess the impact on American airports. The results of that effort so far are two documents listing the NLA-airports compatibility issues [FAA, 1998a, 1998b]. The Facilitation Group has also set up a website to provide sharing of information on the subject [FAA, 2001]. The International Civil Aviation Organisation (ICAO) has also studied the impact of the NLA on the airport airside. Those studies resulted in the updated edition of the Annex 14 to the Chicago Convention – the document that provides international standards for airport design – to account for aircraft lengths and widths of 80 m [ICAO, 1999a].

The impacts of the NLA on airport planning can be divided into two groups: airside and passenger terminal. The airside issues are basically a matter of airfield geometry – the size and separation of taxiways, runways and aprons, which will be affected by the larger dimensions of the NLA – and how it impacts system capacity, as well as the structural design of the airfield pavement. These issues are crucial to the airport system and have been extensively studied by several aviation institutions in the documents referenced above. However, very little has been done on the effects the NLA's higher passenger capacity will have on passenger terminal operations [Barros & Wirasinghe, 1998b; Trani & Venturini, 1999]. Filling that gap is the main objective of this research.

1.4 RESEARCH OUTLINE

This research was started with the objective of determining the effects the New Large Aircraft will have on airport planning and operations. This work focuses on the unaddressed issues related to the compatibility of the NLA and the passenger terminal – the hike in passenger flows within the terminal and the design of the terminal for larger aircraft.

Although this work is concentrated on the passenger terminal, it is recognised that the importance of the airside issues cannot be ignored in a work on airport planning. For that reason, Chapter 2 presents a review of those issues and the solutions that have been proposed by others.

During the development of the research, five main issues related to the compatibility of airport terminals and the NLA were identified and compose the main body of this dissertation. Those issues, listed below, are also consistent with those identified by the FAA [1998a, 1998b]:

- The number of gate positions that are needed for NLA operations: Due to its large dimensions, providing exclusive-use gates for the NLA is very expensive, for it requires the allocation of a great amount of physical space. How to determine the number of gate positions for the NLA and other aircraft types, as well as what can be done to reduce the need for physical space while allowing for a greater number of aircraft to be operated and more flexibility in the design, are addressed in Chapter 3.
- The best terminal configuration for the operation of the NLA in conjunction with smaller aircraft: In a few words, terminal configuration can be described as the way in which a certain number of gate positions is arranged and how passengers access those gates. The most common large terminal configurations are analysed in Chapter 4.
- The design and sizing of the departure lounge (also known as gate lounge): The departure lounge is the buffer where passengers are accommodated prior to boarding the aircraft. As NLA will feature a passenger capacity up to 64% larger than the 747, the need to investigate ways to accommodate those passengers economically and effectively becomes clear. This investigation is done in Chapter 5.

- The processing of NLA passengers and baggage: More passengers means more baggage and higher flows of both within the terminal. The key to improve this process is the use of new technologies that will greatly facilitate the processing and increase the throughputs of the various services involved – including check-in, security check, passenger identification, customs, immigration and baggage handling. Those technologies are reviewed and solutions to improve passenger and baggage servicing are proposed in Chapter 6.
- The design and operation of the baggage claim area: Cited by many passengers as the most unpleasant part of an air trip, baggage claim is expected to become a yet worse problem with the introduction of the NLA, if not resolved. For that reason, Chapter 7 presents a discussion on how to size the baggage claim area, and proposes solutions to its specific use for the NLA.

In order to address the issues listed above, several analytical models were developed to replace or complement those found in the literature, where deemed necessary. Some of those models actually find applications for general airport terminal planning, even if not used for planning for the NLA.

Chapter 8 summarises the work developed in the previous chapters and offers the conclusions.

1.5 METHODOLOGY

Aircraft and passenger flows and service rates present significant variations within the hour, the day, the month, the year and over the years. At times when the arrival rate exceeds the service rate, a queue is formed and delays occur. Queues require storage space; many costs related to loss of productivity and passenger discomfort can be associated with delays. Queues and delays can be reduced with higher service rates; however, this also implies higher costs. Clearly, an optimal balance exists between service rates and queues and delays, such that the sum of the costs involved is minimised.

Simulation techniques have been widely used to model the relationship between the many subsystems that comprise the airport system. Simulation models have the advantage of being easy to explain and understand, capable of dealing with very complex systems, and able to model stochastic variations in detail. On the other hand, to achieve a reasonable level of accuracy, they may require great amounts of detailed information and a great programming effort.

In spite of the timely variations in inflow and service rates, airport systems and subsystems actually see patterns that are repeated every day. Predicting the exact size of the queue and amount of delay at a given time is virtually impossible. However, if arrival and departure curves are plotted for a rush period of several hours as illustrated in Figure 1.3, and this plot is repeated for many days, the patterns become clear, with the variations on the pattern becoming small. Due to the nature of regular air transportation systems, which have a flight schedule that is repeated daily or weekly, the total delay over the years, as well as queues, can be inferred from those patterns. This technique, known as "deterministic queuing theory", is described in detail by Newell [1982].

Deterministic queuing models have the advantages of requiring less information and being easier to implement, relative to their simulation counterparts. Besides, function costs can be more easily determined and minimised with the help of optimisation techniques. In the early stages of airport planning, when little information is available and investment decisions must be made quickly, deterministic queuing models can provide very reasonable results.

Evidently, deterministic queuing theory does not replace simulation; rather, both techniques can complement each other. It has already been said that deterministic models are very useful for early planning; as more detailing becomes necessary, simulation can then be used. In addition, optimisation and other analytical techniques can actually be incorporated in simulation models, making them more powerful with more robust results. The terminal configuration models in Chapter 4, although not involving queuing and delays, also adopt a deterministic approach for the walking distances involved in the choice of the terminal configurations.

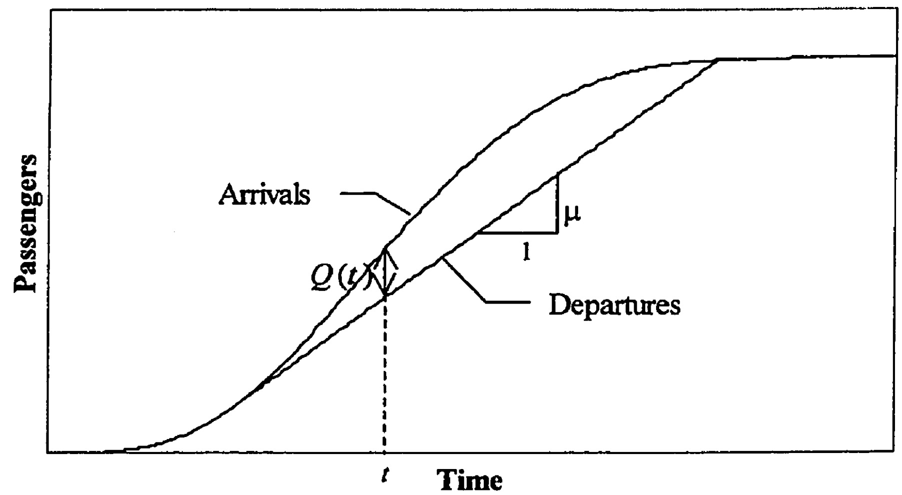


Figure 1.3: Arrival and departure patterns during a rush hour

Two reasons led this work to use deterministic models in most analyses that were performed. First, the NLA entry into operations is still years ahead, therefore little data is available. Second, the models developed in this research are intended for global use in any airport, and aim mainly at formulating and understanding the problems and possible solutions. Simulation models are mainly case-specific and would not meet these requirements. Analytical models are therefore more indicated for this research.

1.5.1 Objective Functions

Public-funded projects, including transportation ones, use funds originating from tax dollars and should provide benefits to the society as a whole. In that sense, the objective function in any public-funded project is usually to maximise a benefit function that represents the difference between benefits and costs to society. The benefits are most times represented by the *consumer surplus* [Heggie, 1972], exemplified in Figure 1.4.

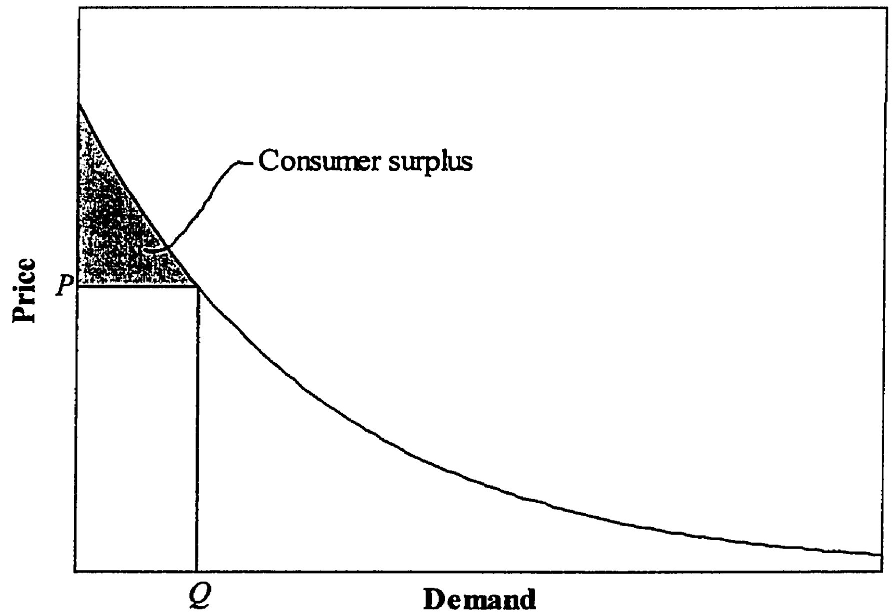


Figure 1.4: Consumer surplus

Even when public funds are not directly involved in the form of tax dollars, a project may have to be designed so as to maximise the benefits to society. That may be the case of many airports in North America, which are now run by non-profit organisations whose goal is to provide air transportation service to the public. In this case, the decision on where to invest money should take into account how much it will cost to passengers and how passengers will benefit from the investment. Maximising the benefit function should therefore be the goal of an airport project.

It should be noted, however, that the models presented in this thesis deal with a somewhat different problem – or the same problem at a different level. Here, we are dealing with the design of specific facilities of the airport. The designers are faced with the challenge of providing enough resources to service a pre-specified demand at a pre-specified level of service. Price-demand curves are very difficult to determine in such studies. In this case, the demand is assumed to be mostly influenced by factors that are external to the facility in question. Such assumption leads us to adopt the objective function used throughout this thesis: the minimisation of the costs involved.

Evidently, minimising costs does not at all mean ignoring passenger comfort. Minimal standards of level of service are included in the constraints of the models, and the objective functions themselves include penalties for passenger inconveniences such as delays and standing. A balance between passenger discomfort and the cost of reducing that discomfort is therefore sought. By minimising the total cost, we provide the best possible use of the funding available while satisfying minimum requirements of level of service.

CHAPTER 2
NLA/AIRSIDE ISSUES

Due to their greater dimensions, NLA will require airfield facilities that are specifically designed for the operation of larger aircraft. Among the areas of airside design that are expected to be affected by the NLA are the runway and taxiway width and shoulders, the separation between runways and taxiways, and the wingtip clearances from objects at taxilanes and parking aprons.

Air transport institutions like ICAO, ACI and the FAA have performed extensive studies on the impact the NLA will have on the design of the airport airside. Of those, the FAA has released a report that explains all the airport design issues that have been identified so far [FAA, 1998b].

Although the solutions for the issues regarding the compatibility of the NLA and the airport airside are out of the scope of this work, those issues are recognised as very important to the airport industry. Some of them, like the clearances at parking aprons, will even influence the planning of the airport passenger terminal. Thus this chapter will present a brief review of the issues that have been identified as the most important to airfield design. This review does not intend to be comprehensive; the reader who is interested in learning more about airfield design for the NLA is referred to FAA [1998b], David [1995] and ACI-NA[1994].

2.1 AIRPORT DESIGN STANDARDS

All airports do not need to accommodate aircraft of all sizes. While large international hubs must handle very large transports, on the other end of the rope very small airfields serving small communities will probably never see aircraft larger than commuters. Therefore, it is rather more economical to choose a *design aircraft* and size the various airfield components for it.

The dimensions of the airfield components, as well as the clearances required between the aircraft, other aircraft and ground obstacles, are obviously dependent on the size of the design aircraft. Besides providing enough room for the aircraft movements, the design of the airfield must also provide extra room to allow for deviations in the normal paths of the aircraft. These measures will give the final dimensions of the airfield facilities.

The FAA and ICAO have both conducted extensive studies on the minimum requirements for airfield design. Those studies resulted in standards to be used in any airport [FAA, 1989; ICAO, 1999a]. In the U.S., the FAA standards are mandatory for airport certification, whereas the ICAO standards are adopted by the majority of aviation authorities elsewhere. Both standards are very similar in nature and attempt to facilitate the process of designing an airfield and certifying it for aircraft operations.

Both the FAA and ICAO standards are based on the size of the largest aircraft that is allowed to operate at the airport. Airports are assigned a reference code, which ultimately determines the types of aircraft that the airport can handle. ICAO's code is composed by a number and a letter. The number designates the runway length available and the letter, the size of the aircraft the airport can handle in terms of wingspan and wheel track. The codes and their correspondent runway lengths and aircraft sizes are shown in Table 2.1. An airport that handles the Boeing 747-400, which has a wingspan of 64.9 m, a wheel track of 11 m and a runway length requirement of 3,353 m, is classified as 4E. Most large airports around the world fall into this classification.

The FAA reference code is slightly different from the ICAO's in that it uses aircraft approach speed instead of runway length requirement for categorisation. The code, shown in Table 2.2, is comprised of a letter for the approach speed category and a roman number for the aeroplane design group. In the 747-400 example, the airport reference code is D-V.

The dimensions of the NLA, shown in Table 1.3, make them fall into ICAO's code F and into FAA's design group VI. Most airports around the world do not meet the standards for those airport reference codes, which means they will either have to upgrade their facilities or operate under severe restrictions when an NLA is on the move. In the next sections, the compatibility of the NLA and airports is discussed in more detail where its impact is of more importance to airport planning.

Table 2.1: ICAO aerodrome reference codes [ICAO, 1999a]

Aerodrome code number	Reference field length (m)	Aerodrome code letter	Wingspan (m)	Outer main gearwheel span (m)
1	<800	A	<15	<4.5
2	800–<1200	B	15–<24	4.5–<6
3	1200–<1800	C	24–<36	6–<9
4	≥1800	D	36–<52	9–<14
		E	52–<65	9–<14
		F	65–<80	14–<16

Table 2.2: FAA airport reference codes [FAA, 1989]

Aircraft approach category	Aircraft approach speed (kn)	Aeroplane design group	Aircraft wingspan (m)
A	<91	I	<15
B	91–<121	II	15–<24
C	121–<141	III	24–<36
D	141–<166	IV	36–<52
E	≥166	V	52–<65
		VI	65–<80

2.2 AIR TRAFFIC CONTROL (ATC)

The main NLA-related issues identified by the FAA [1998a] regarding ATC are:

- ATC separation during final approach, landing and departure.
- ATC distance behind engine thrust.

The first issue relates to the separation between the NLA and trailing aircraft during the final approach, as well as to the effects of wake vortex on adjacent runway/taxiway operations and structures during take-off and landing. Wake vortex is a rotating, helicoidal air stream generated by the tip of an aircraft wing on the move. Such air streams last several minutes and can be extremely dangerous for trailing aircraft, especially light ones. For that reason, a minimum separation is required between two aircraft approaching the same or close parallel runways. Table 2.3 shows minimum separations under instrument flight rules (IFR) conditions, which are more stringent than visual flight rules (VFR). A time separation is also used for consecutive take-off/landing operations on runways. The heavier the aircraft, the stronger the wake vortex and therefore the longer the separation required to trailing aircraft.

Table 2.3: IFR minimum separations on approach (nautical miles) [FAA, 1978]

	Trailing aircraft weight (kg)		
Leading aircraft weight (kg)	<5,625	5,625–135,000	>135,000
<5,625	3.0	3.0	3.0
5,625–135,000	4.0	3.0	3.0
>135,000	6.0	5.0	4.0

NLA are obviously going to be heavier than the existing aircraft, raising the question of whether current standards are sufficient for NLA operations. Airbus has been conducting experiments to determine the wake vortex effects generated by the A380, but has so far not published any conclusions. Airbus claims, however, that the A380 will be able to operate under current separation standards [Airbus, 2001b].

The second issue listed by the FAA affects separations on the ground. NLA will have much more powerful engines that could generate more turbulence behind them, affecting other aircraft as well as ground vehicles. Ultimately, the minimum separation between aircraft on taxiways may have to be increased, reducing airfield capacity.

The possibility of increased separations between NLA and other aircraft may lead some airports to restrain NLA operations to non-peak hours [FAA, 1998a]. Although this may be acceptable as a temporary solution at airports with a low number of NLA operations, it would obviously be impracticable where several NLA operations per day are to occur. In such cases, another solution will be required.

2.3 AIRFIELD GEOMETRIC DESIGN

2.3.1 Runway Length and Width

The runway length requirement depends on various factors, including aircraft weight, engine thrust, runway longitudinal slopes, weather conditions, and runway elevation with respect to sea level. For the purpose of airport planning, aircraft manufacturers publish runway length requirements for each aircraft for a "standard day" – with specific weather conditions defined by the FAA. The FAA [1990a] also provides general guidelines to determine runway lengths for airport design purposes.

All currently proposed NLA designs are being developed for runway length requirements no longer than the 747-400's [FAA, 1998b; Barros & Wirasinghe, 1997, 1998b; Airbus, 2000b]. Therefore, the NLA is not expected to impact airport design in this aspect.

In principle, current runway width standards are enough for NLA operations. FAA standards for runway widths are 45 m for group V and 60 m for group VI aircraft. Clearly, runways that do not meet the standard for group VI will have to be widened. However, depending on the accuracy of the landing system used by the NLA, it may be able to operate on a group V runway. At Los Angeles International Airport, the master plan even suggests modifications in the group VI standards that would reduce the need for modification in existing runways [Graham, 1994; Los Angeles World Airports, 1996].

Runway shoulders and blast pads are also likely to be impacted. Current standards for aircraft group VI require a runway shoulder 12 m wide. However, the NLA's maximum jet blast velocities could extend up to 6 m beyond the runway shoulder [FAA, 1998b]. This effect is shown in Figure 2.1. Such phenomenon could cause soil erosion and harm objects in the vicinity of the runway. It may therefore be necessary to review the standards for runway shoulders.

2.3.2 Runway Clearances

ICAO and the FAA standards establish minimum separation requirements between the centrelines of runways and parallel taxiways. These requirements are set to keep a minimum clearance between the wingtips of two aircraft rolling on the runway and the taxiway. In addition, for IFR conditions the FAA [1989] establishes an inner-transitional object free zone (OFZ), illustrated in Figure 2.2. The objective of the OFZ is to protect aircraft that are landing or taking off, and to protect missed approaches that may require the aircraft to veer in the direction of the taxiway. The inner-transitional part of the OFZ is limited by a 6:1 (horizontal:vertical) plan rising from 60 m away from the runway centreline and starting at an elevation that is determined by a formula based on the airport elevation above sea level.

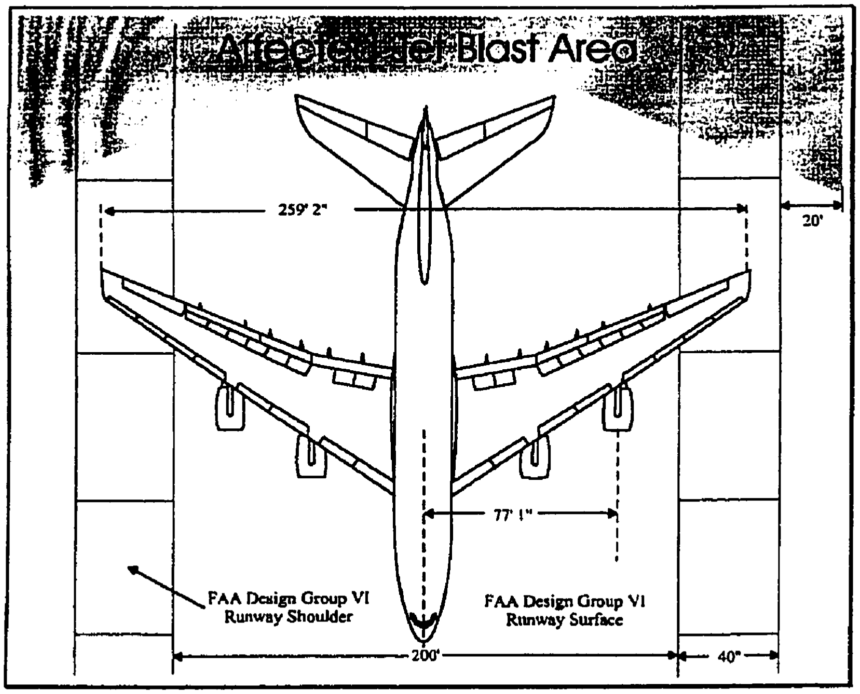


Figure 2.1: Effect of jet blast on runway shoulders [FAA, 1998b]

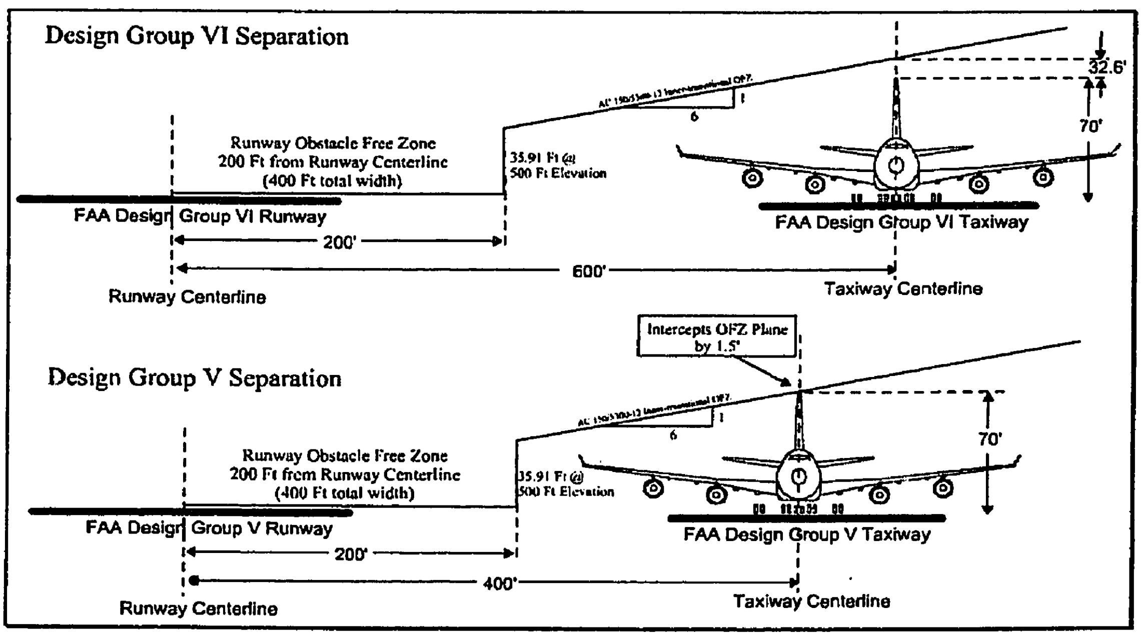


Figure 2.2: Clearance between runway and parallel taxiway [FAA, 1998b]

Runway-to-taxiway separation standards are set such that no aircraft of any sizes will penetrate the OFZ. At sea level, that separation is 120 m and 180 m for design groups V and VI, respectively. In the case of wingtip clearances, it is still possible to operate NLA at airports designed by group V standards, provided that only smaller aircraft be allowed on parallel taxiways or runways and that the path of the NLA be also free of obstacles. However, there is nothing that can be done to prevent certain NLA tail fins to penetrate the OFZ at certain airports compatible with aircraft group V – as shown in Figure 2.2 for a tail fin with a 21 m height. In that case, the only way to allow an NLA to operate would be to shut down the runway until the NLA leaves the parallel taxiway. Such procedure would significantly reduce the airside capacity and would be unthinkable during peak hours and may be impracticable even during non-peak hours. In such cases, NLA may be prevented from operating at those airports altogether, since upgrading to group VI standards is in many cases impossible without significantly reducing the airport capacity.

2.3.3 Taxiway Design

The NLA issues related to taxiway design are similar in nature to the runway issues. Due to its wider wingspan and wheel track, the widths of the taxiway and its shoulders, as well as the separation between parallel taxiways and between a taxiway and objects on the ground, must be enlarged. Table 2.4 shows the FAA's taxiway design standards. Although room for enlarging the width of taxiways is usually not a problem, increasing the separation between taxiway centrelines requires the relocation of one or both taxiways. Fife [1994] presents some propositions to relocate taxiways and runways at New York JFK to make the airside system compatible with group VI standards.

Table 2.4: FAA's taxiway design standards

Aeroplane design group	V	VI
Taxiway width (m)	23	30
Taxiway safety margin (m)	4.5	6

Most large airfields are completely developed and occupied by runways, taxiways and aprons, leaving no room for relocation without a complete rearrangement of the airfield components – exceptions are airports that were planned for larger aircraft, such as Paris

Charles de Gaulle [Chevallier, 1997], Hong Kong Chek Lap Kok and Kuala Lumpur. Such rearrangement is, in most cases, prohibitively expensive. The solution may be in defining specific routes for NLA operations within the airfield, limiting the taxiway realignments and other necessary upgrades to the NLA routes. An example of an NLA route within the airfield is found in the Los Angeles International Airport (LAX) master plan [Los Angeles World Airports, 1996].

The group VI requirements could also be relaxed if a proposition made in the LAX master plan is adopted. The master plan suggests that the separation between taxiway centrelines could be as low as 91.5 m, compared to 99 m by current group VI standards and to 95 m as suggested by the ACI NLA task force. The proposition is based on a study performed by Boeing, which showed that the probability of significant deviations of 747's from taxiway centrelines is very small – a deviation of more than 4.5 m was found to have a probability of occurrence of 10^{-6}. A wingtip contact with a taxiway centrelines separation of 80 m would occur at a rate of one occurrence in a billion encounters. Such relaxation would greatly reduce the costs of adapting existing airports for the NLA [Los Angeles World Airports, 1996].

A specific issue related to taxiways relates to the manoeuvring capability of NLA. Due to its longer wheelbase, turning it at a taxiway-taxiway or taxiway-runway intersection will require a wider pavement to keep the minimum safety distance between the outside edge of the main gear and the pavement edge. A taxiway fillet may be necessary in such cases. Figure 2.3 illustrates this solution.

2.4 MISCELLANEOUS

Many other aspects of the geometric design of the airport airside are to be impacted by the introduction of the NLA. Among those aspects not discussed in this chapter are the sizing of holding bays, bridges and tunnels, culverts, and runway blast pads. The reader is referred to the publications mentioned in the preamble of this chapter for further information.

The planning of an airport for NLA operations must also take into consideration many other aspects. Pavement strength is an issue that is important for an aircraft that is carrying a much greater weight than any existing ones. Although the design of the NLA's main gear is such that the aircraft weight is distributed through a higher number of tires, the real effects on the pavement remain undetermined. Airbus and the FAA have been conducting experiments to figure out those effects, but no final conclusions have been reached yet. This problem is not limited to the NLA, however – the Boeing 777-200's unusual main gear configuration prompted the FAA to issue an advisory circular specifically to address the design of airport pavements for the 777 [FAA, 1995a]. The NLA may end up requiring the same solution.

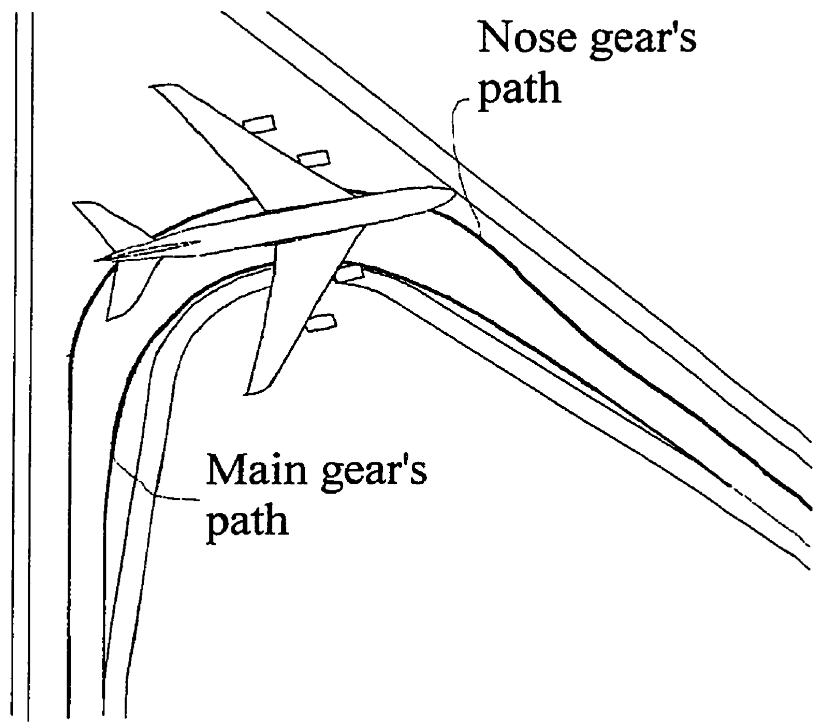


Figure 2.3: Taxiway fillets for aircraft turning

Finally, the NLA will also require a complete re-evaluation of the adequacy of emergency equipment and procedures. Neither the FAA nor ICAO have specific standards for aircraft as large as the A380, for instance. Both organisations do have standards based on the length of the aircraft, but that does not account for the use of a full-length upper deck, featured in the A380 and the Boeing NLA. New-generation supersonic aircraft, although not believed to become operational in the foreseeable future, may present a similar problem. Manufacturers, airlines, airports and air transport organisations around the world are studying this matter and must come up with answers before the first A380 enters service in 2006.

2.5 SUMMARY

The larger dimensions of the NLA will require airports to upgrade all their facilities if the NLA are to operate with no constraints. Such upgrades will evidently be more expensive at older, crowded airports that simply do not have any room left for expansion. A temporary, less expensive solution would be to issue operational constraints for when the NLA is moving – such as closing one taxiway when an NLA is rolling on a close parallel taxiway. This solution, however, may significantly reduce the airside capacity and would be impracticable during peak hours or where a significant number of NLA operations is expected.

Upgrading the airports may not be as bad a solution as it seems. Airbus [2001b] claims the cost of upgrading existing airports to accommodate larger aircraft and their consequent boost in passenger capacity costs, in average, hundreds of millions of dollars, while building new airports would cost billions of dollars. According to this rationale, using larger aircraft is still more economical, even if at the cost of adapting existing infrastructure.

Many issues remain unsolved, however. It is still not clear if current pavement strength evaluation procedures are valid for the NLA, and emergency equipment and procedures most certainly need re-evaluation. The air transport industry is becoming more aware of these problems and solutions are expected within the next few years, before the first NLA's enter service.

One thing is clear for airports where the NLA will operate: planning for the NLA must be done quickly, as it is clear that those aircraft cannot operate at airports that were designed for the 747. Time is of the essence, as the first NLA's are expected to enter service within 5 years.

CHAPTER 3
GATE REQUIREMENT FOR AIRPORT TERMINALS SERVING NLA AND CONVENTIONAL JETS

3.1 INTRODUCTION

The evaluation of the number of gate positions that will be provided for aircraft in an airport terminal is one of the first steps in airport terminal planning. Terminal concept and configuration, apron layout, walking distances, and taxiway distances will all depend on the number of gates [Bandara & Wirasinghe, 1988]. All these variables will ultimately determine the overall cost of the terminal.

Several factors influence the gate requirement. The most important of them are demand characteristics – aircraft mix, arrival rate, and type of operation – gate occupancy time, gate usage policy, construction and maintenance costs, and delay costs.

If the flight schedule for a terminal is known in advance, then the determination of the gate requirement can be done based on that schedule. However, flight schedules are rarely known more than a few months in advance, and are subject to constant changes. If one wishes to plan the terminal for a long term, aircraft arrival rates would provide more reliable estimates. Arrival rates throughout a typical day for different types of aircraft can be estimated based on market projections carried out by airlines and manufacturers [Bandara & Wirasinghe, 1988; Transport Canada, 1982].

The aircraft mix, though a characteristic of demand, will strongly influence both the service rate and the cost of the terminal, as both the gate occupancy times and the size of the gate vary according to the type of aircraft. Conventional jets have a typical turnaround time of 30 to 60 minutes, whereas current wide-bodied aircraft have turnaround times of up to 90 minutes (Boeing 747). The New Large Aircraft (NLA) turnaround time could reach 2 hours, according to Airbus [2000b]. Clearly, the larger the proportion of large aircraft in the mix, the higher the gate requirement. It is important, therefore, to obtain a good estimate of the mix of aircraft that will occur during the planning period.

The cost of a terminal is ultimately the sum of construction and maintenance costs and delay costs. The rate at which aircraft are serviced at the terminal with respect to time is a direct function of the number of gate positions. If this service rate is not able to keep up with demand, delays will occur due to aircraft not finding an available position. However, due to airport demand varying considerably throughout the year, the month, the week and even the day, ensuring zero delay may require a terminal so large that the construction and maintenance costs would overcome the gains obtained by elimination of delays. Clearly, a trade-off must exist between these two costs. In fact, the cost of adapting gates for NLA has been identified as an issue by the New Large Aircraft Facilitation Group [FAA, 1998a].

In addition to its peaking characteristics, the demand for gates usually increases from year to year. This imposes another difficulty to the planning process, as the terminal must be able to service the demand for a long period – usually 5 to 20 years. However, due to interest applied on the amount of funds invested in the terminal, the construction today of a terminal to service a demand level that will only be reached several years ahead may end up being too expensive if the interest rate is beyond a certain threshold. Thus the postponement of as much of the initial investment as possible is suggested when interest rates are high [Heggie, 1972]. This can be done by means of stage construction, where only a part of the final configuration of the terminal is built in the beginning, and the terminal is later expanded as demand increases. That also allows plans to be updated as new information becomes available.

The introduction of NLA adds one more complication to the problem. Due to its size – larger than any existing aircraft – and to its specific features such as the double deck and higher passenger capacity [Airbus, 2000b; Barros & Wirasinghe, 1998b], an NLA may not be able to use gates designed by current standards without operational restrictions such as blocking adjacent positions. In some cases, it may even not be able to use those gates at all. Thus, the NLA will require either the provision of exclusive gates or special arrangements for using regular gates. The choice will depend on the expected NLA arrival rate, the demand for regular gates, and on the time at which peaks will occur for these two different demands. If NLA and conventional jet peaks occur at different times, then it may be possible to have two different terminal configurations via a transformation of gates.

In this chapter, a mathematical model to evaluate the optimal number of gates for an airport terminal with three types of gates will be presented. The model is capable of determining the number of gates that should be provided for each of the three gate types; the amount of space that should be shared by the three different gate types; and how much of the terminal should be built and when. The inputs for the model are expected aircraft arrival rates rather than flight schedules; current unitary costs of construction, gate maintenance and delays imposed to aircraft; and expected interest and demand growth rates. The next sections will discuss the model, its basic concepts and formulations, and its implementation.

3.2 LITERATURE REVIEW

Several works have attempted to determine the number of gate positions for an airport terminal. Analytical models have been developed in an attempt to provide a simple, easy to use tool for early stage planning. With the rapid development of computational resources, simulation models have become more popular, due to their capacity to better model case-specific configurations and situations.

The major drawbacks of simulation models are the costly data input requirement and the fact that they do not provide an optimal solution. Rather, simulation models provide the planner with the ability to model scenarios and to play with them, allowing the planner to get answers to "what-if" questions. Perhaps the most widely used airport simulation model is SIMMOD [FAA, 1990b], which has been used to analyse gate requirements in a number of airports worldwide [Barros & Müller, 1995; Alvarez & Jan, 1997].

Of all analytical models, perhaps the simplest and most widely known is the deterministic model proposed by Horonjeff [Horonjeff & McKelvey, 1994]. The number of gates G is given as a function of the weighted average gate occupancy time T, the design volume of arrivals or departures C, and the gate utilisation factor U:

$$G = \frac{C\,T}{U} \tag{3.1}$$

The utilisation factor U is applied to account for the fact that it is impossible to have all the gates occupied 100% of the time. The value of U depends on several factors: aircraft manoeuvring time, gate utilisation policy, airline schedule and deviations from this schedule, among others. For airports with no restrictions on gate usage – i.e. where all aircraft and all airlines can use all gates – the utilisation factor falls in the interval 0.6-0.8. Values between 0.5-0.6 have been suggested where an exclusive gate usage policy exists, for this policy will prevent certain aircraft from using certain available gates. An accurate estimation of the utilisation factor is not easy, however – especially in the case of a new airport, where the flight schedule is not usually available, and even the gate usage policy may be unknown.

Bandara [1989] and Bandara & Wirasinghe [1988] have identified deficiencies in the above model and proposed a model to determine the number of gates that partially overcomes the problems with the utilisation factor proposed by Horonjeff. In Bandara's model, the number of gates is given by

$$G = R(T + S) \tag{3.2}$$

where R is the aircraft arrival rate; T is the gate occupancy time; and S is the separation time, or the time required between the departure of one aircraft and the arrival of the next. R, T and S are all random variables, which means the number of gates G will also be a random variable. If the mean and variance of R, T and S are known, then the determination of the mean and variance of G is straightforward. If the probability distribution of G is also known, then the number of gates to be provided, g, can be determined such that a chosen level of reliability $1 - \alpha$ is satisfied, i.e.

$$P(G \leq g) = 1 - \alpha \tag{3.3}$$

where α is defined as the percentage of time during which the demand for gates will exceed the number of gates supplied.

Two advantages of Bandara's model over Horonjeff's can be promptly identified. First, the separation time S can be more easily evaluated for the expected aircraft mix, and the model is also less sensitive to S than Horonjeff's model is to U. Second, neither the arrival rate nor the separation time require a schedule to be evaluated. In fact, in the planning stage of a terminal, it is easier to obtain an estimate for the aircraft arrival rate than the flight schedule. If, however, a flight schedule is available, then one could use this schedule to generate the demand for gates, provided that deviation from the schedule is considered.

Hassounah and Steuart [1993] have developed such a model. For a given flight in the schedule, if $t = 0$ at the scheduled arrival time, then $Y(t)$ is defined as a Bernoulli random variable with

$$Y(t) = \begin{cases} 1 & \text{if the aircraft occupies a gate at time } t \\ 0 & \text{otherwise} \end{cases} \tag{3.4}$$

Let A be the arrival lateness with respect to the scheduled arrival time; t_d, the scheduled departure time; and D, the departure lateness with respect to the scheduled departure time. The probability that the aircraft occupies a gate at time t is

$$P[Y(t) = 1] = P[(A \le t) \cap (D + t_d \ge t)] \tag{3.5}$$

i.e. the probability that the aircraft has arrived before time t and will leave after time t.

Data from Toronto's Lester B. Pearson International Airport show that, for flights arriving before their buffer time, arrival lateness and departure lateness can be assumed to be statistically independent. On the other hand, flights arriving after their buffer time have correlated arrival times and departure times. Buffer time is defined as the latest instant at which the aircraft can arrive at the gate and still be able to be completely serviced before its scheduled departure time. Defining B as the event that a flight arrives before its buffer time, and B' as its complement, the probabilities of these events can be written as a function of the cumulative distribution of A:

$$P(B) = P(A \le t_b) = F_A(t_b) \tag{3.6}$$

$$P(B') = 1 - F_A(t_b) \tag{3.7}$$

The probability of the aircraft occupying a gate at time t can then be expressed in terms of those two events:

$$P[Y(t)=1]=P\{[Y(t)=1]\mid B\}P(B)+P\{[Y(t)=1]\mid B'\}P(B') \tag{3.8}$$

Each of the conditional probabilities above can be determined separately. Hassounah and Steuart [1993] showed that the probability that an aircraft occupies a gate at time t given that it has arrived before its buffer time is

$$P\{[Y(t)=1]\mid B\}=\begin{cases}F_{A|B}(t) & \text{for } t<t_b\\ 1 & \text{for } t_b<t<t_d\\ 1-F_{D|B}(t-t_d) & \text{for } t>t_d\end{cases} \tag{3.9}$$

where

$F_{A|B}(t) = F_A(t)/F_A(t_b)$ for $t < t_b$,

$= 1$ for $t > t_b$

and $F_{D|B}(t)$ can be assessed directly from operational data.

In the case of flights arriving after their buffer time, the probability that a gate is occupied by the aircraft at time t is

$$P\{[Y(t)=1]\mid B'\}=\begin{cases}0 & \text{for } t<t_b\\ F_{A|B'}(t)-F_{A+H|B'}(t) & \text{for } t>t_d\end{cases} \tag{3.10}$$

where

H = random variable defined as the actual occupancy time;

$F_{A|B'}(t) = 0$ for $t < t_b$

$=[F_A(t) - F_A(t_b)]/[1- F_A(t_b)]$ for $t > t_b$

and $F_{A+H|B'}(t)$ can be evaluated from operational data.

On a given day, for a given flight i with a scheduled arrival time s_i, the expected value of $Y_i(t)$ is

$$E[Y_i(t)]=P[Y_i(t-s_i)=1]=p_i(t-s_i) \tag{3.11}$$

and the variance of $Y_i(t)$ is

$$\mathrm{Var}[Y_i(t)] = p_i(t - s_i)[1 - p_i(t - s_i)] \tag{3.12}$$

The total demand for aircraft gates at time t on a given day is

$$N(t) = \sum_i Y_i(t) \tag{3.13}$$

The random variable $N(t)$ has an expected value given by

$$E[N(t)] = \sum_i E[Y_i(t)] \tag{3.14}$$

and the variance of $N(t)$ is

$$\mathrm{Var}[N(t)] = \sum_i \mathrm{Var}[Y_i(t)] + \sum_{i \neq j} \mathrm{cov}[Y_i(t), Y_j(t)] \tag{3.15}$$

The models described above all attempt to evaluate the number of gates to be provided such that little or no delay is imposed to aircraft. However, those delays decrease with the number of gates. If a cost can be associated with both delays and gates, it becomes clear that a trade-off must exist between these two costs.

For long-term planning purposes, Bandara & Wirasinghe [1990] have proposed a model that attempts to find the optimal number of gates that minimises the sum of the costs of both providing gates and delays imposed to aircraft. The total cost of the terminal is

$$C = G\,k + W\,d \tag{3.16}$$

where

G = number of gates;

W = total deterministic delay imposed to aircraft;

k = cost of a gate position;

d = cost per unit of delay time.

Both G and W can be expressed as functions of the service rate R. The expression for G is the same as in Equation 3.2. Newell [1982] and Bandara [1989] have developed expressions for the deterministic delay caused by an arrival peak exceeding the service rate with a parabolic and a triangular shape, respectively. Substituting for G and W in Equation

3.16, one can find the optimal service rate that minimises the cost of the terminal, *C*, by setting its first derivative to zero.

As can be seen above, two important aspects in terminal planning have been overlooked by gate requirement models: 1. the effect of both interest and demand increases over the terminal life; and 2. the use of common areas that could be shared by more than one gate. This work will attempt to develop a model that includes these two features.

3.3 UNCONSTRAINED SPACE SHARING MODEL

As the NLA will feature a wider wingspan, NLA gates will also be wider, requiring more terminal airside frontage [Barros & Wirasinghe, 1998b]. Let us assume that there will be three types of gates: conventional jet (CJ) gates, requiring l_C meters of airside frontage per gate; wide-body gates (WB), which require l_W metres of airside frontage each; and NLA gates, with an airside frontage requirement of l_N metres per gate.

If both NLA and WB main peaks occur during the same time period as the CJ main peak, then the determination of both the number of gates and the terminal length is done separately for each gate type, and the total terminal airside frontage will equal the sum of the terminal length requirements for each gate type, i.e.

$$L = l_N G_N + l_W G_W + l_C G_C \tag{3.17}$$

where l_N, l_W and l_C are the terminal airside frontage required by an NLA, a WB and a CJ gates, respectively; and G_N, G_W and G_C are the number of NLA, WB and CJ gates, respectively. In this case, there will be no shared space between the three gate types, and consequently there will be no positions being blocked by the use of others.

In many cases, however, the main arrival peaks for different gate types occur at different times of the day. Figure 3.1 shows arrivals at Los Angeles International Airport. It can be seen that a secondary CJ peak occurs concurrently with the WB main peak, near 12:00 pm, as a portion of the WB passengers are transferring to smaller aircraft to reach their final destinations. The main CJ peak, however, occurs at a different time – around 8 am. For the purpose of this work it will be assumed that NLA peaks will occur simultaneously with WB peaks, as NLA are being designed to operate on routes currently served by WB jets.

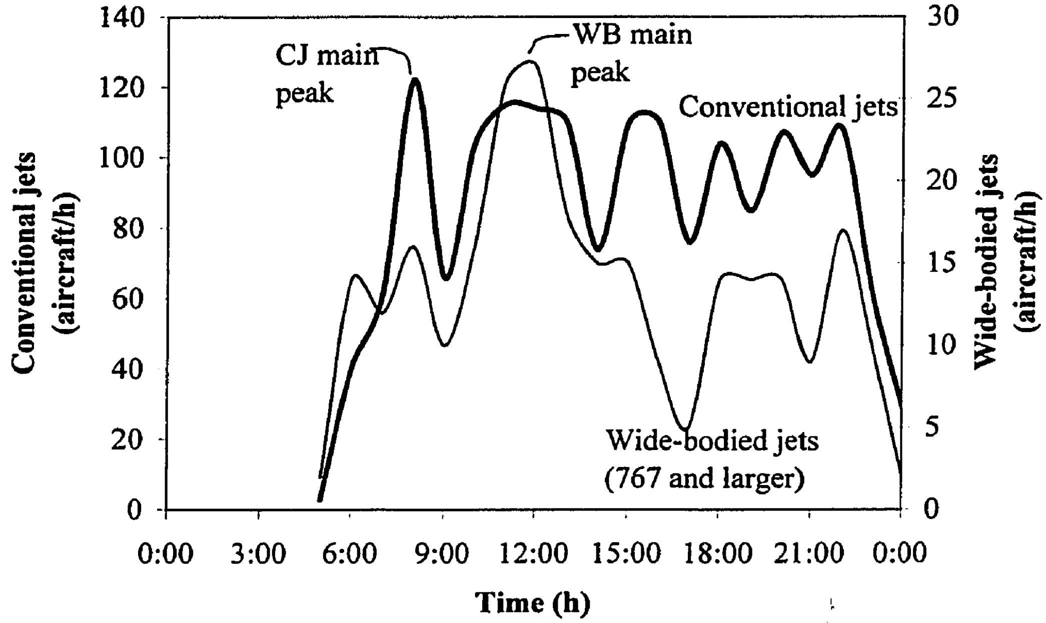


Figure 3.1: Aircraft arrivals on a typical day of January 1999 at Los Angeles International Airport

The number of positions necessary to accommodate the demand for a given gate type will be determined by that type's main peak; however, the number of positions provided during off-peak and secondary-peak periods could be lower. If a number of different gate types could share the same space in a terminal as illustrated in Figure 3.2 and suggested by IATA [1995] and de Neufville and Belin [2001], then that space could be used by CJ gates during CJ main peaks and by NLA/WB gates during NLA/WB main peaks. This space sharing would allow for shorter terminal lengths, but could also result in higher delays if the provided service rate becomes lower than the aircraft arrival rate. Still, the optimal service rates may be such that delays occur, but the cost is compensated by a shorter terminal length, with a lower construction cost.

Figure 3.3 illustrates the use of different gate service rates. In this example, there are two peak periods: the first is an NLA/WB peak with a correspondent secondary CJ peak, since NLA are expected to be used in hub operations, with a large number of NLA passengers transferring to and from CJ's. During this period, the NLA and WB gate service rates would be at their maximum – μ_{N1} and μ_{W1} respectively – while CJ's could be serviced at a rate $\mu_{C1} < \mu_{C2}$. The main CJ peak, however, occurs at a different time, when NLA and WB arrivals are less frequent. Thus, the CJ maximum service rate, μ_{C2}, would occur during this main CJ peak, whereas NLA and WB could then be serviced at a rate $\mu_{N2} < \mu_{N1}$ and $\mu_{W2} < \mu_{W1}$ respectively.

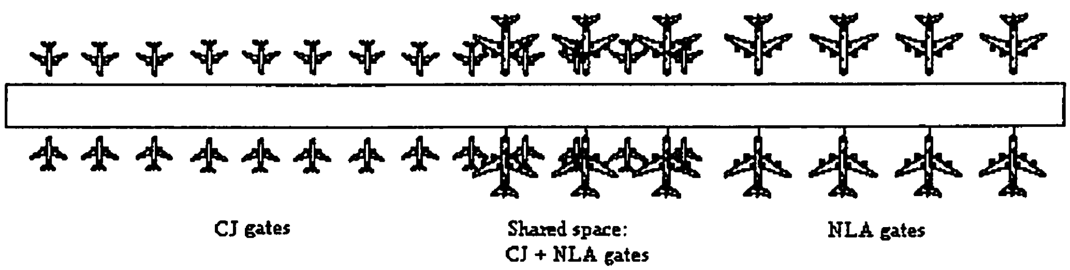


Figure 3.2 - NLA and CJ gates sharing terminal space

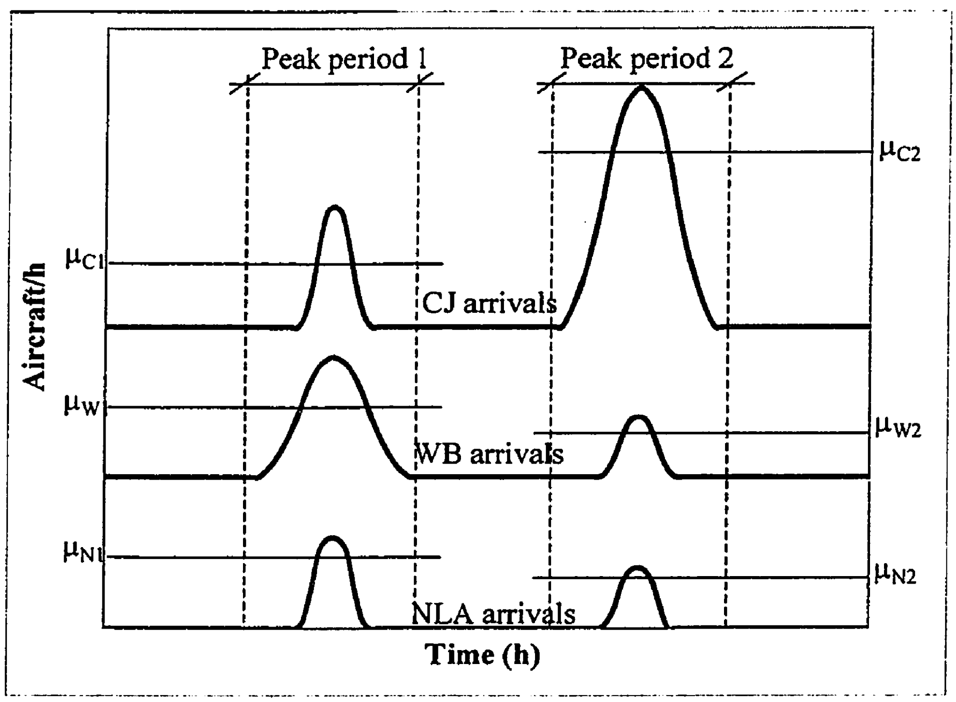


Figure 3.3: Different service rates for different arrival peaks on one day

The number of *available* gates for a given aircraft type i during the peak period j, AG_{ij}, can be evaluated using the Bandara equation [Bandara & Wirasinghe, 1988]

$$AG_{ij} = \mu_{ij}(T_i + S_i) \tag{3.18}$$

where

T_i = the average gate occupancy time of aircraft type i;

S_i = the average time separation required between two consecutive gate occupancies to allow for aircraft manoeuvring;

i = {C for CJ, W for WB, N for NLA};

j = peak period = {1, 2}.

Let us define G_i as the number of *existing* gates for a given aircraft type i – regardless of whether they are available or not. G_i will be the number of gates available during the most demanding period peak for that aircraft type,

$$G_i = \max_j (AG_{ij}) \tag{3.19}$$

By definition, the most demanding peak period for NLA and WB is 1, whereas for CJ it is 2, as illustrated in Figure 3.3. Therefore

$$G_N = \mu_{N1}(T_N + S_N) \tag{3.20}$$

$$G_W = \mu_{W1}(T_W + S_W) \tag{3.21}$$

$$G_C = \mu_{C2}(T_C + S_C) \tag{3.22}$$

The terminal airside frontage length for each peak period j will be the sum of frontage requirements for NLA, WB and CJ, i.e.:

$$L_j = \sum_i l_i AG_{ij} = \sum_i l_i \mu_{ij}(T_i + S_i), \quad j = \{1,2\} \tag{3.23}$$

where i represents aircraft types and j represents the peak period.

Note that L_1 and L_2 could have different values. In that case, the final length L of the terminal frontage will be the greater of the two length requirements:

$$L = \max(L_1, L_2) \tag{3.24}$$

Since, by definition, $\mu_{N1} > \mu_{N2}$, $\mu_{W1} > \mu_{W2}$, and $\mu_{C1} < \mu_{C2}$, it becomes clear that the above terminal airside frontage requirements will be less than with no space sharing. Therefore, the use of shared space could reduce the final length of the terminal and, consequently, reduce its construction cost without imposing any further delays.

During peak 1, $(AG_{C2} - AG_{C1})$ CJ gates will not be used. In the same way, $(AG_{N1} - AG_{N2} + AG_{W1} - AG_{W2})$ NLA/WB gates will not be in use during peak 2. Evidently, the space occupied by the CJ gates that are idle during peak 1 could be used by NLA/WB gates, and vice-versa during peak 2. Unfortunately, the terminal frontage lengths that can be shared are not necessarily equal. In Figure 3.4, the NLA/WB frontage length requirement that can be shared with CJ gates is given by the length AC; however, CJ gates will only require the sharing of the length BC. Therefore, the final frontage length sharing will be given by the minimum of the two lengths available for sharing, i.e.

$$\min[l_N(AG_{N1} - AG_{N2}) + l_W(AG_{W1} - AG_{W2}), l_C(AG_{C2} - AG_{C1})] \tag{3.25}$$

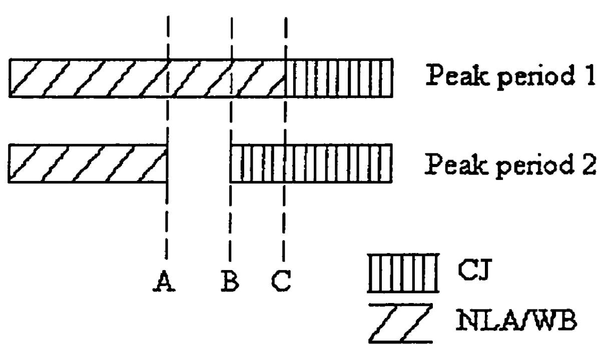


Figure 3.4: Terminal frontage length requirements for different peak periods

3.4 OPERATIONAL ISSUES

The use of a common area for CJ, WB and NLA in the terminal will create a number of problems to the operation of the terminal that must be taken into account when implementing the area-sharing model. This section will discuss the three main issues identified: the use of departure lounges by different gate types; the need to clear the gates in the common area of unwanted aircraft types before a peak period begins; and the separation of international and domestic passengers.

3.4.1 Sharing Passenger Departure Lounges

Should a part of the terminal area be used by CJ, WB and NLA – though not simultaneously – this area must be able to accommodate passengers of both types. The best way to do so would be through the use of common departure lounges as opposed to gate-dedicated lounges. Common lounges do not require any conversions from one aircraft type to another – passengers would simply arrive at the common lounge and settle near their assigned gate. Common lounges also have the advantage of saving a potentially considerable amount of space when compared to separate lounges [Wirasinghe & Shehata, 1988; Horonjeff & McKelvey, 1994]. To avoid confusion for passengers, gates sharing a lounge should have the same number denomination, with slight variations to distinguish the gates – e.g. gates 25A, 25B and 25C would all be served by the same lounge.

If separate lounges for each gate are required – e.g. when security screening is done separately for each gate – then it is still possible to use the same area for both CJ and NLA by using mobile walls. A special arrangement may be necessary, however, to ensure that all passenger and airline services – such as washrooms and airline processing counters – are still provided for each lounge.

It cannot be forgotten that the total area required for CJ, WB and NLA lounges may be different. In addition, while NLA could make use of two-level boarding and lounges [Barros & Wirasinghe, 1998a], CJ and WB will most likely require single-level lounges. Hence the lounge area will probably have to be determined by the greatest of the three requirements.

3.4.2 Clearing the Common Area before Peak Hour

During off-peak periods, the common CJ/WB/NLA area may be used for either type of aircraft as long as the proper wing-tip-to-wing-tip clearances are kept. In fact, depending on the terminal configuration and geometry, parking aircraft at the common area may even help reduce passenger walking, baggage transfer, and aircraft taxiing distances. However, when a CJ main peak period begins, it is mandatory that the common area be cleared of WB and NLA and vice-versa. To ensure this clearance, it is necessary to stop assigning aircraft of the opposite types long enough before the main peak period begins. If practical, it may even be useful to establish a time gap between the time of departure of the last aircraft and the beginning of the main peak period to allow some room for delays. For instance, if a WB/NLA peak starts at 10:00, then no CJ with an estimated departure time later than 9:30 should be assigned to a gate in the common area. Should an aircraft parked in the shared area be delayed such that it invades the main peak period of the other aircraft types, then it may be necessary to move this aircraft and redirect passengers to another gate. This situation can be avoided by reserving in the shared area peak hours only, if at all possible.

3.4.3 International/Domestic Passengers

In many airports, the flow of international passengers must be separated from domestic ones. Usually, this is done by creating international sections inside the terminal, to which only international passengers have access. Another solution that can be used when only international arrivals must be separated is forcing disembarking passengers to go through a sterile corridor as soon as they leave the plane [Berutti, 1990; Steinert & Moore, 1993]. International departures, in that case, are allowed to mix with domestic passengers.

If an international section is required for either WB or NLA operations, it is necessary to ensure there is no mixing of international and domestic flights in the CJ/WB/NLA common area. One way to do so is assigning only CJ that are international flights to the common area. This solution will not always be possible, as it would be necessary that the international CJ flights demand during the CJ main peak fits exactly the number of CJ gates in the common area. In this case, another solution would be the use of mobile walls. This would allow the common area to be converted from a domestic to an international section.

3.5 VARIATIONS OF THE GATE REQUIREMENT MODEL

The rationale presented in Section 3.3 assumes that CJ, WB and NLA gates could all be located in the same area without any restrictions – a CJ gate could even be separated from an NLA gate by only a couple of meters. It is also assumed that the gates will be used only by aircraft of the correspondent type. In practice, however, the location of gates too close to each other could create several other operational problems besides the ones mentioned in Section 3.4. In addition, WB/NLA gates can be used by CJ's. The addition of some constraints for the gate locations, and some consequent changes in the model, can be performed to overcome these problems.

Two variations of the space sharing model will be discussed:

- allowing the use of WB and NLA gates by CJ, with no space sharing;
- restricting the space sharing to one CJ gate between two WB or NLA gates and allowing CJ to use WB and NLA gates;

3.5.1 No Space Sharing

Where space sharing is undesirable or unfeasible due to operational constraints, it is still possible to use NLA/WB gates for CJ operations. By doing so, part of the requirement for CJ gates could be satisfied through the use of idle NLA/WB gates.

Under this scenario, the number of NLA and WB gates will remain the same as given in Equations 3.20 and 3.21. For CJ gates, however, the number of gates available during peak 2 can be found by subtracting the number of idle NLA/WB gates from the demand for CJ gates during that peak

$$AG_{C2} = \mu_{C2}(T_C + S_C) - (AG_{N1} - AG_{N2}) - (AG_{W1} - AG_{W2}) \tag{3.26}$$

The number of CJ gates available during peak 1 can be found by using Equation 3.18, yielding

$$AG_{C1} = \mu_{C1}(T_C + S_C) \tag{3.27}$$

Since all existing CJ gates will be available during both peak periods, it follows that

$$G_C = AG_{C1} = AG_{C2} \tag{3.28}$$

and therefore

$$\mu_{C1}(T_C + S_C) = \mu_{C2}(T_C + S_C) - (AG_{N1} - AG_{N2}) - (AG_{W1} - AG_{W2}) \tag{3.29}$$

Since there is no space sharing, the total terminal length will be the sum of the lengths of all gates provided

$$L = \sum_i l_i G_i \tag{3.30}$$

3.5.2 Constrained Space Sharing

If the frontage length requirement of the CJ gates that will be sharing space with WB gates is no larger than half the length requirement of a WB gate, then one CJ gate could be located between two WB, two NLA, or one WB and one NLA gates – provided, of course, that these NLA/WB gates are not in use. With this arrangement, WB and NLA gates would be used as such during NLA/WB peaks, and the CJ gates in this area would be blocked. During CJ peaks, all gates in this area – including NLA and WB ones – could be used by CJ whose wingspan allows them to be parked side by side in this area.

The suggested configuration can be adopted only if the idle NLA/WB gates are put together, side by side. For each group of g NLA/WB gates that are located side by side, g - 1 CJ gates can be inserted in-between the NLA/WB gates. Clearly, the number of CJ gates that can be inserted in this manner will depend on both the final gate arrangement and on the number of NLA/WB gates. However, the determination of the number of gates is almost always done prior to the definition of the gate arrangement. Hence, in many cases, the accurate determination of how many CJ gates can be inserted in-between NLA/WB gates must be done through an iterative process.

There is, however, a very special case where this can be done: when the terminal is supposed to be a single pier with the main entrance in the middle of the pier. In this case, it has been shown that the best place to locate NLA gates is as close as possible to the middle of the pier [Barros & Wirasinghe, 2000]. Assuming all NLA/WB gates will be agglomerated around the pier centre on both sides of the pier, then it is possible to insert (AG_{N1} + AG_{W1} - AG_{N2} - AG_{W2} - 2) CJ gates in that area – provided that number is non-negative. In this case, the number of CJ gates available during each peak is given by Equations 3.26 and 3.27. Since the CJ gates inserted in the NLA/WB gates area will not be available during peak 1, Equation 3.29 does not apply in this case, and the final terminal length will be the same as given in Equation 3.23, with the constraints that $L_1 = L_2$ and

$$AG_{C2} - AG_{C1} = \max(AG_{N1} + AG_{W1} - AG_{N2} - AG_{W2} - 2,\ 0) \tag{3.31}$$

3.6 COST OF GATE REQUIREMENT

Three types of cost are imposed both by the number of gates for each gate type and the amount of space shared by them: 1) cost of gate installation and operation, C_G; 2) cost of terminal airside (pier) construction, C_B; and 3) cost of delays imposed to aircraft, C_D.

The first type of cost, cost of gate installation and operation, will be mainly a function of the type of gate – NLA, WB or CJ. The specific installation requirements, the type of loading bridge used, and any special equipment for the operation of the gate – such as the addition of a second floor for the NLA departure lounge – will determine its cost. If we assume that the daily cost of operation per type i gate is a constant, k_i, then the total daily cost of type i gates is given by $k_i G_i$, where the number of type i gates G_i is given in Equation 3.19. The overall cost of gates C_G will equal the sum of the costs for each gate type.

The cost of terminal airside construction, C_B, can be assumed to be proportional to the total terminal airside frontage. The terminal airside is defined as the portion of the terminal beyond the security scrutiny, comprised of the gates, departure lounges, circulation areas and passenger amenities associated with the aircraft boarding/unboarding process. It does not include check-in, baggage claim, customs nor any other areas usually located in the terminal block.

The cost of terminal airside construction will include all capital costs associated with the civil construction of the terminal, excluding those associated with the gates, as mentioned above. Although NLA gates may require a double-level lounge, the cost of adding this second level can be included in the cost of gates. If a_f is the discounted daily cost per linear meter of terminal airside frontage, then the total daily cost of airside frontage will be $a_f L$.

Finally, the delay cost C_D will depend on both the type of aircraft and on the amount of delays generated by the gate availability. Therefore, if d_i is the cost per unit of time of delay imposed to aircraft of type i, and W_i is the total deterministic delay imposed to type i aircraft due to lack of available gates, then the total daily cost of delay for type i aircraft is $d_i W_i$. Note that d_i is actually the sum of aircraft operating costs and passengers' value of time. The actual value of the latter will vary according to the standard of living and the importance assigned by passengers to their time [Pant et al., 1995], but a mean value can be used for economic evaluation purposes. The FAA [1995b] estimates the mean passenger's value of time at US$ 44 per passenger per hour.

We are now ready to define the total daily cost imposed by the gate availability, C, which will be the sum of all three types of costs presented above:

$$C = \sum_i k_i G_i + a_f \, L + \sum_i d_i W_i \tag{3.32}$$

Gate installation and operation and terminal construction costs depend on the number of gates and on the terminal length, respectively. Both can be evaluated as previously discussed. The third type of cost, delays imposed to aircraft, will require the evaluation of these delays.

3.6.1 Evaluation of Deterministic Delays

It is known from queuing theory that the deterministic delay caused to aircraft is a function of both the arrival rates and service rates. If a peak j, where $j = \{1,2\}$, of an aircraft type i can be assumed to have an either parabolic or triangular shape, then the total aircraft deterministic delay for that peak will be a function of the maximum arrival rate A_{Mij}; the mean arrival rate $\bar{A}_i$; the time T_{0ij} during which the mean arrival rate is exceeded; and of the service rate [Bandara & Wirasinghe, 1990]. If the service rate exceeds the maximum arrival rate, there will be no delays imposed to aircraft. Otherwise, a queue will form when the arrival rate exceeds the service rate, and delays will occur. With two distinct peak periods on a day as illustrated in Figure 3.3, the total deterministic delays for both CJ and NLA can be written as:

$$W_i = \sum_j w(\mu_{ij}, A_{Mij}, \bar{A}_i, T_{0ij}), \quad i = \{\text{CJ, WB, NLA}\} \tag{3.33}$$

To evaluate the total cost of gate availability, it is necessary to determine the amount of deterministic delay as a function of both the peak shape and the service rate during the peak time. Newell [1982] and Bandara [1989] have developed analytical expressions to determine delays as a function of service rate and both average and maximum arrival rates when the peak has a parabolic or triangular shape, respectively. Figure 3.5 illustrates both cases. For a parabolic peak,

$$w(\eta, A_M, \bar{A}, T_0) = \frac{9T_0^{\,2}(A_M - \eta)^2}{16(A_M - \bar{A})} \tag{3.34}$$

and for the triangular peak case,

$$w(\eta, A_M, \bar{A}, T_0) = \frac{T_0^{\,2}(A_M - \eta)^3}{2\sqrt{2}(A_M - \bar{A})^2} \tag{3.35}$$

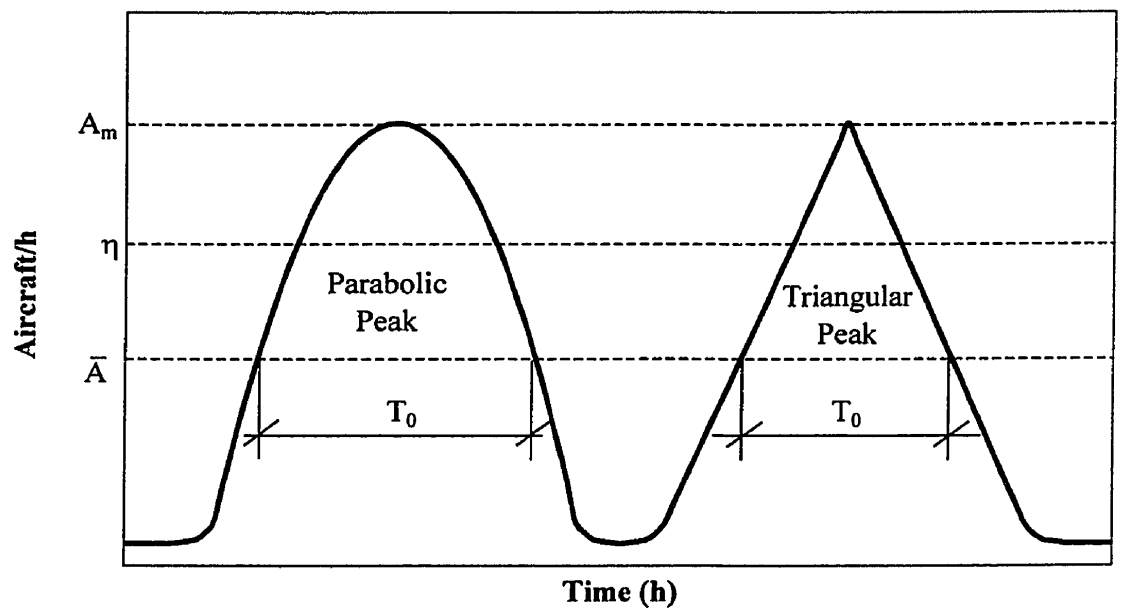


Figure 3.5: Parabolic and triangular peaks

where η = gate service rate for the duration of the peak.

It is assumed that a queue begins to form as soon as the arrival rate $A(t)$ exceeds the service rate η, and that the service rate is sufficiently higher than the mean arrival rate to guarantee that the queue vanishes before another one starts due to another peak. The latter assumption is satisfied if

$$\eta \geq \frac{3}{4} A_M + \frac{1}{4} \bar{A} \tag{3.36}$$

and

$$\eta \geq \frac{2}{2+\sqrt{2}} A_M + \frac{\sqrt{2}}{2+\sqrt{2}} \bar{A} \tag{3.37}$$

for a parabolic peak and a triangular peak respectively. If the inequality corresponding to the shape of the peak is satisfied, then the queue will vanish within the peak duration T_0. The deterministic delays for each peak as illustrated in Figure 3.3 can be determined by substituting its own parameters into either Equation 3.34 or 3.35, according to the peak shape.

When operational data show a peak with an undefined shape, it may be helpful to approximate it to a known form. Bandara [1989] suggests an approximation to either parabolic or triangular shapes with a 10% error for peaks with undefined shapes. If a measure of the area bounded by the arrival rate curve and the mean arrival rate line can be obtained, then if we let

$$E = \frac{A_M - \bar{A}}{\text{Area measured}} \tag{3.38}$$

then the peak can be approximated by a triangle and a parabola if $1.75 < E < 2.25$ and $1.30 < E < 1.75$ respectively. In cases where the delay cannot be analytically determined, the use of either graphical or numerical techniques will be necessary.

3.6.2 Cost Minimisation

If the shapes and parameters of the arrival rate functions are known, and so are all the unit costs, unit frontage requirements, and average gate occupancy and separation time, then the total cost C becomes a function of the service rates only, as it can be seen when we substitute from Equation 3.33 in Equation 3.32:

$$C = \sum_{i} k_i G_i + a_f\, L + \sum_{i,j} d_i w(\mu_{ij}, A_{Mij}, \bar{A}_i, T_{0ij}) \tag{3.39}$$

Since G_i is a function of the service rates μ_{ij}, and ultimately so is L, the problem then becomes to find the values for μ_{ij} that minimise the overall cost C. In the case of no space sharing allowed, we must add the constraint of constant number of available CJ gates represented by Equation 3.29.

In any of the three space sharing cases, the problem is also subject to the constraints of non-overlapping queues. Substituting for the peak parameters in Equations 3.36 and 3.37,

$$\mu_{ij} \geq \frac{3}{4} A_{Mij} + \frac{1}{4} \bar{A}_i \text{, for each } (i,j) \text{ peak with a parabolic shape} \tag{3.40}$$

and

$$\mu_{ij} \geq \frac{2}{2+\sqrt{2}} A_{Mij} + \frac{\sqrt{2}}{2+\sqrt{2}} \bar{A}_i \text{, for each } (i,j) \text{ peak with a triangular shape} \tag{3.41}$$

The problem above is a Non-Linear Programming (NLP) problem that can be solved with the use of any NLP optimisation technique available and will yield optimal non-integer numbers of gates. To have an integer solution, it will be necessary to add the constraints that the variables G_{ij} must be integer. The problem then becomes a Mixed Integer/Non-Linear Programming (MINLP) problem and its results will be the number of gates for every pair peak-gate type that yields the minimum total cost. Figure 3.6, Figure 3.7 and Figure 3.8 summarise the mathematical programming models for all space sharing cases.

UNCONSTRAINED SPACE SHARING

Minimize:

$$C = \sum_i k_i G_i + a_f\, L + \sum_{i,j} d_i w(\mu_{ij}, A_{Mij}, \bar{A}_i, T_{0ij})$$

Subject to:

$$G_i = \text{integer}$$
$$G_N = \mu_{N1}(T_N + S_N)$$
$$G_W = \mu_{W1}(T_W + S_W)$$
$$G_C = \mu_{C2}(T_C + S_C)$$
$$L = \max\left[\sum_i l_i \mu_{i1}(T_i + S_i), \sum_i l_i \mu_{i2}(T_i + S_i)\right]$$
$$\mu_{ij} \geq \frac{3}{4} A_{Mij} + \frac{1}{4}\bar{A}_i \text{, for each } (i,j) \text{ peak with a parabolic shape}$$
$$\mu_{ij} \geq \frac{2}{2+\sqrt{2}} A_{Mij} + \frac{\sqrt{2}}{2+\sqrt{2}}\bar{A}_i \text{, for each } (i,j) \text{ peak with a triangular shape}$$

Figure 3.6: MINLP model for the Unconstrained Space Sharing case

3.7 COMPOUND INTEREST AND DEMAND GROWTH OVER THE TERMINAL'S LIFE SPAN

The investment in construction can be assumed to occur at once at the beginning of the life span of the terminal. However, both maintenance and delay costs are incurred throughout the terminal's life span, and must therefore be discounted at the proper interest rate so that the present worth of the overall cost can be evaluated. Furthermore, the aircraft demand is bound to increase over the years, consequently increasing delays and their correspondent costs. Both factors – interest and demand growth – must therefore be accounted for when evaluating the terminal gate requirements.

CONSTRAINED SPACE SHARING

Minimize:

$$C = \sum_i k_i G_i + a_f\ L + \sum_{i,j} d_i w(\mu_{ij}, A_{Mij}, \bar{A}_i, T_{0ij})$$

Subject to:

$$G_i = \text{integer}$$
$$G_N = \mu_{N1}(T_N + S_N)$$
$$G_W = \mu_{W1}(T_W + S_W)$$
$$G_C = \mu_{C2}(T_C + S_C)$$
$$AG_{ij} = \mu_{ij}(T_i + S_i) \text{ for all pairs } (i,j) \text{ except } (R, 2)$$
$$AG_{C2} = \mu_{C2}(T_C + S_C) - (AG_{N1} - AG_{N2}) - (AG_{W1} - AG_{W2})$$
$$AG_{C2} - AG_{C1} = \max(AG_{N1} + AG_{W1} - AG_{N2} - AG_{W2} - 2,\ 0)$$
$$L = \max\left[\sum_i l_i \mu_{i1}(T_i + S_i), \sum_i l_i \mu_{i2}(T_i + S_i)\right]$$
$$\mu_{ij} \geq \frac{3}{4} A_{Mij} + \frac{1}{4} \bar{A}_i, \text{ for each } (i,j) \text{ peak with a parabolic shape}$$
$$\mu_{ij} \geq \frac{2}{2+\sqrt{2}} A_{Mij} + \frac{\sqrt{2}}{2+\sqrt{2}} \bar{A}_i, \text{ for each } (i,j) \text{ peak with a triangular shape}$$

Figure 3.7: MINLP model for the Constrained Space Sharing case

For the purpose of this work, both interest and demand growth rates will be assumed to be constant and continuously compounded during the life span of the terminal. Continuous compounding implies that, if A_0 is the aircraft demand at day 0, then the demand at day t will be $A_0\ e^{at}$, where a is the continuous growth rate – see Figure 3.9. Analogously, the present worth of a payment of x at time t will be given by $e^{-rt}\ x$, where r is the nominal interest rate for continuous compounding. It will also be assumed that the demand growth is equally distributed through the day, i.e. the shape of arrival rate curve for one day will remain the same over the terminal's life span.

NO SPACE SHARING

Minimize:

$$C = \sum_i k_i G_i + a_f L + \sum_{i,j} d_i w(\mu_{ij}, A_{Mij}, \bar{A}_i, T_{0ij})$$

Subject to:

$$G_i = \text{integer}$$
$$G_i = \mu_{i1}(T_i + S_i)$$
$$AG_{ij} = \mu_{ij}(T_i + S_i) \text{ for all pairs } (i,j) \text{ except } (R, 2)$$
$$AG_{C2} = \mu_{C2}(T_C + S_C) - (AG_{N1} - AG_{N2}) - (AG_{W1} - AG_{W2})$$
$$AG_{C1} = AG_{C2}$$
$$L = \sum_i l_i \mu_{i1}(T_i + S_i)$$
$$\mu_{ij} \geq \frac{3}{4} A_{Mij} + \frac{1}{4} \bar{A}_i \text{, for each } (i,j) \text{ peak with a parabolic shape}$$
$$\mu_{ij} \geq \frac{2}{2+\sqrt{2}} A_{Mij} + \frac{\sqrt{2}}{2+\sqrt{2}} \bar{A}_i \text{, for each } (i,j) \text{ peak with a triangular shape}$$

Figure 3.8: MINLP model for the No Space Sharing case

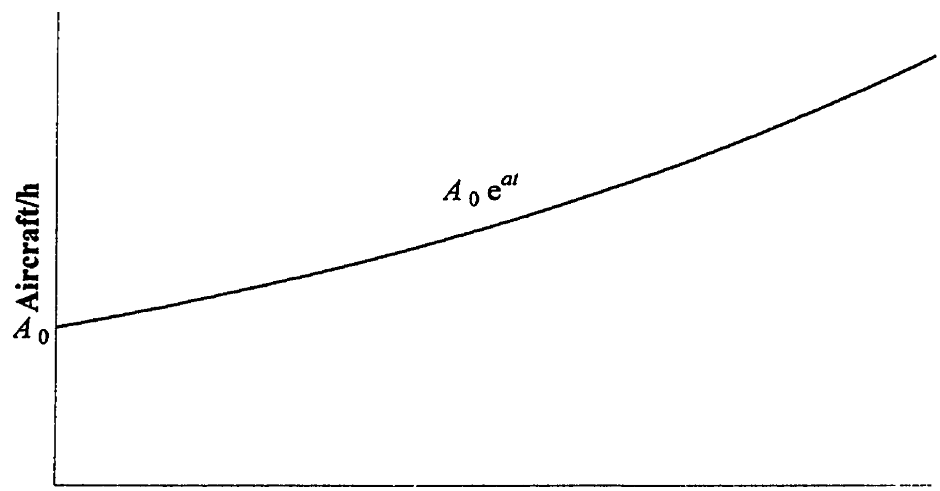


Figure 3.9: Aircraft demand growing at a constant rate *a*

3.7.1 Delay Costs

3.7.1.1 Parabolic Peak

If the aircraft demand is growing at a constant rate a, then the maximum arrival rate at day t will be $e^{at} A_M$, where A_M is the initial maximum arrival rate (at day 0). Delays will only begin to occur at day t_D when the maximum arrival rate becomes greater than the service rate η, i.e.

$$e^{at_D} A_M = \eta \tag{3.42}$$

It follows from the expression above that, if the maximum arrival rate A_M exceeds the service rate η sometime during the terminal's life span, then

$$t_D = \frac{1}{a}\ln(\frac{\eta}{A_M}) \tag{3.43}$$

It should be noted that, if the initial maximum arrival rate is already greater than η, then $t_D = 0$. On the other hand, if A_M never exceeds η during the terminal's life span, then t_D equals the terminal's life span. In summary,

$$t_D = \min[Z, \max[0, \frac{1}{a}\ln(\frac{\eta}{A_M})]] \tag{3.44}$$

where Z is the terminal's life span.

The total deterministic delay caused by one daily parabolic peak at day $t > t_D$ will be

$$w_t = \frac{9T_0^{\,2}(e^{at} A_M - \eta)^2}{16e^{at}(A_M - \bar{A})} \tag{3.45}$$

If we approximate w_t to the rate of total delay per day, and let d_D be the cost per unit of delay time at the beginning of the terminal's life span, then the value of the cost of delays resulting from a peak at time t during the infinitesimal period dt will be $d_D\, w_t\, dt$, as illustrated in Figure 3.10. To find the *present worth* of this cost, it must be multiplied by the continuous compound discount factor e^{-rt}. If $a \neq r$, then the present worth of the total delay costs over the terminal's life span Z will be

$$d_D \int_{t_D}^{Z} e^{-rt} w_t dt = d_D \frac{9T_0^{\,2}}{16(A_M - \bar{A})} \int_{t_D}^{Z} e^{-(a+r)t} (e^{at} A_M - \eta)^2 dt \tag{3.46}$$

Defining p_D, the *present worth of delay*, as

$$p_D(\eta, A_M, \bar{A}, T_0, t_D, Z) = \int_{t_D}^{Z} e^{-rt} w_t dt \tag{3.47}$$

then the present worth P of the total delay cost over the terminal's life span Z for a given peak of any shape can be written as

$$P = d_D p_D(\eta, A_M, \bar{A}, T_0, t_D, Z) \tag{3.48}$$

i.e., the product of the unitary cost of delay at the beginning of the terminal's life span and present worth of delay. Solving the integral in Equations 3.46 and 3.47 for $a \neq r$, we obtain

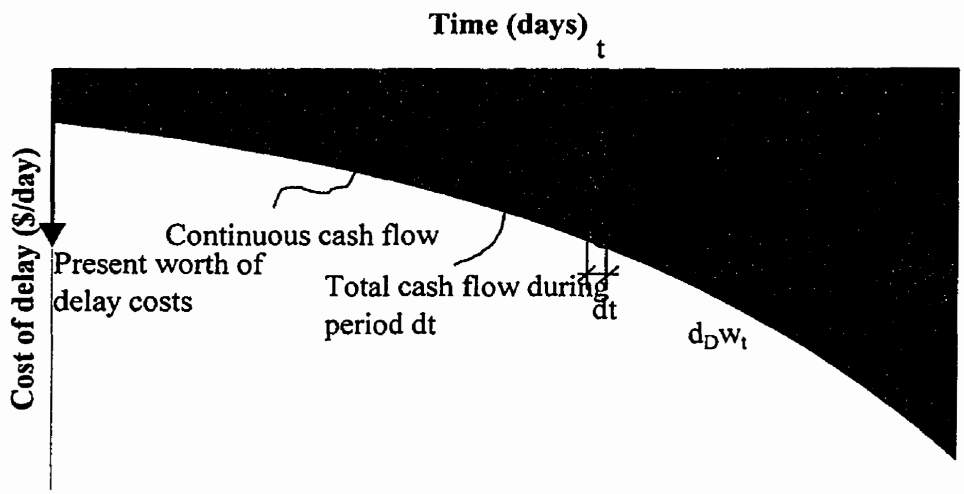


Figure 3.10: Continuous cash flows associated with delay costs

$$p_D(\eta, A_M, \bar{A}, T_0, t_D, Z) = \frac{9T_0^{\,2}}{16(A_M - \bar{A})}\{\frac{A_M^{\,2}}{a-r}\left[e^{(a-r)Z} - e^{(a-r)t_D}\right] + \frac{2\eta A_M}{r}\left[e^{-rZ} - e^{-rt_D}\right] - \frac{\eta^2}{a+r}\left[e^{-(a+r)Z} - e^{-(a+r)t_D}\right]\} \quad (3.49)$$

Analogously, when the demand growth factor a equals the interest rate r, the present worth of the total deterministic delay will be found by solving Equations 3.46 and 3.47 for $a = r$:

$$p_D(\eta, A_M, \bar{A}, T_0, t_D, Z) = \frac{9T_0^{\,2}}{16(A_M - \bar{A})}\{A_M^{\,2}(Z - t_D) + \frac{2\eta A_M}{r}\left[e^{-rZ} - e^{-rt_D}\right] - \frac{\eta^2}{2r}\left[e^{-2rZ} - e^{-2rt_D}\right]\} \quad (3.50)$$

The non-overlapping queues constraint must be satisfied all along the life span of the terminal. As demand is assumed to be growing at a rate a, so is the lower limit for the service rate (represented by the right side of Equation 3.36). It follows that

$$\eta \geq e^{aZ}\left(\frac{3}{4}A_M + \frac{1}{4}\bar{A}\right) \quad (3.51)$$

3.7.1.2 Triangular Peak

The calculations for the triangular peak are analogous to those derived for the parabolic peak. The total deterministic delay caused by one daily triangular peak at day $t > t_D$ will be

$$w_t = \frac{T_0^{\,2}(e^{at}A_M - \eta)^3}{2\sqrt{2}e^{2at}(A_M - \bar{A})^2} \quad (3.52)$$

Substituting for w_t from Equation 3.52 in Equation 3.46, the resulting present worth of delay for a triangular peak and $a \neq r$ will be

$$p_D(\eta, A_M, \bar{A}, T_0, t_D, Z) = \frac{T_0^{\ 2}}{2\sqrt{2}(A_M - \bar{A})^2}\{\frac{A_M^{\ 3}}{a-r}[e^{(a-r)Z} - e^{(a-r)t_D}] + \frac{3\eta A_M^2}{r}\left[e^{-rZ} - e^{-rt_D}\right] - \frac{3\eta^2 A_M}{a+r}[e^{-(a+r)Z} - e^{-(a+r)t_D}] + \frac{\eta^3}{2a+r}\left[e^{-(2a+r)Z} - e^{-(2a+r)t_D}\right]\} \quad (3.53)$$

and for $a = r$

$$p_D(\eta, A_M, \bar{A}, T_0, t_D, Z) = \frac{T_0^{\ 2}}{2\sqrt{2}(A_M - \bar{A})^2}\{A_M^{\ 3}(Z - t_D) + \frac{3\eta A_M^2}{r}\left[e^{-rT} - e^{-rt_D}\right] - \frac{3\eta^2 A_M}{2r}[e^{-2rZ} - e^{-2rt_D}] + \frac{\eta^3}{3r}\left[e^{-3rZ} - e^{-3rt_D}\right]\} \quad (3.54)$$

The non-overlapping queues constraint for the triangular peak is

$$\eta \geq e^{aZ}\left(\frac{2}{2+\sqrt{2}}A_M + \frac{\sqrt{2}}{2+\sqrt{2}}\bar{A}\right) \quad (3.55)$$

3.7.1.3 Total Cost of Delays

The present worth of the overall cost of delays for all peaks over the terminal's life span can be found by evaluating the present worth of the cost for each daily peak and then adding them up. Defining t_{Dij} as the time at which the maximum arrival rate of peak j and aircraft type i exceeds the service rate and calculated as t_D in Equation 3.44, the total cost of delays will be given by

$$C_D = \sum_{i,j} d_i p_D(\mu_{ij}, A_{Mij}, \bar{A}_i, T_{0ij}, t_{Mij}, Z) \quad (3.56)$$

where each p_D is evaluated as in Equations 3.49 to 3.54, according to the case.

3.7.2 Cost of Gate Installation and Maintenance

In order to take compound interest into account in the model, it is necessary to break the cost of gate installation and maintenance into two separate components: cost of installation and cost of maintenance and operation, hereafter referred to only as cost of maintenance.

Let us define the cost of installation of one gate, k_{Ci}; and the cost of maintenance per type *i* gate per unit of time, k_{Mi}. In turn, the cost of gate maintenance will occur all along the gate's life. Thus the total cost of gate maintenance along period *Z* will have to be discounted at the interest rate *r*. Assuming the cash flow generated by maintenance cost is continuous and constant, the *present worth factor* for the cost of gate maintenance is $(1 - e^{-Z})/r$ [Heggie, 1972]. Therefore, the total cost of gate installation and maintenance, C_G, is the sum of both costs defined above:

$$C_G = \sum_i k_{Ci} G_i + \frac{1 - e^{-rZ}}{r} \sum_i k_{Mi} G_i \tag{3.57}$$

3.7.3 Overall Cost with Compound Interest and Demand Growth

The new overall cost of the terminal will be the sum of gate maintenance and installation given in Equation 3.57; terminal building construction costs; and delay costs (Equation 3.56). The resulting expression is

$$\begin{aligned} C = & \sum_i k_{Ci} G_i + \frac{1 - e^{-rZ}}{r} \sum_i k_{Mi} G_i + a_f L + \\ & + \sum_{i,j} d_i p_D(\mu_{ij}, A_{Mij}, \bar{A}_i, T_{0ij}, t_{Mij}, Z) \end{aligned} \tag{3.58}$$

Minimisation of the terminal's overall cost as given in Equation 3.58 is the new objective function for when both interest and demand growth are taken into account. This minimisation is still subject to the constraint of constant number of CJ gates given in Equation 3.29 in case no space sharing is allowed. The non-overlapping queues constraints represented by Equations 3.51 and 3.55 also apply, becoming

$$\mu_{ij} \geq e^{aZ} \left(\frac{3}{4} A_{Mij} + \frac{1}{4} \bar{A}_i \right) \tag{3.59}$$

for parabolic peaks and

$$\mu_{ij} \geq e^{aZ} \left(\frac{2}{2 + \sqrt{2}} A_{Mij} + \frac{\sqrt{2}}{2 + \sqrt{2}} \bar{A}_i \right) \tag{3.60}$$

for triangular peaks.

3.8 STAGE CONSTRUCTION

Airport passenger terminals are usually built with a project horizon of 10-20 years. Should the demand grow at an average annual rate of 2.8% – as forecast by Boeing [2000] for short-haul flights in North America, with even higher rates for long-haul flights – the terminal at the end of its planned life span might have to cope with approximately double the current demand. Building the terminal with its final configuration at once would mean highly under-utilised resources during the first years and high delay costs in the last years. Interest paid on the amount invested on construction will also have a significant contribution to the final cost.

Both the cost of delays and interest could be reduced if the terminal were constructed in stages. The first stage would be built to service the demand in the next few years. As demand grows, so would the terminal, which would be expanded to cope with the demand expected for the next period.

The problem then is to determine how much to build and when. In terms of the mathematical model presented here, "how much to build" means what service rates must be provided for each stage. "When" means at which point in the project's horizon each stage should be built. With small modifications in the model and a few simplifying assumptions, both questions can be answered.

Let us assume that the terminal will be built in m stages. Let also h be the index that identifies the construction stage, i.e. $h = \{1,2,\ldots, m\}$. To determine "how much to build", we have to find the service rates μ_{ijh} – and the consequent numbers of available gates AG_{ijh}, such that

$$AG_{ijh} = \mu_{ijh}(T_i + S_i) \tag{3.61}$$

The actual number of gates for each aircraft type i to be provided at each stage h will be

$$G_{ih} = \max_j(AG_{ijh}) \tag{3.62}$$

The question "when to build" can be answered by determining the instants Z_h at which the h^{th} stage should be built.

The choice of the number of stages must be done prior to the use of the model. Although theoretically this number could be any non-negative integer, it should not exceed 3, for the marginal benefit will be very small, and it will penalise the optimisation process with the addition of 6 integer variables for each additional construction stage.

It is now necessary to re-evaluate the costs and the terminal length constraint for when construction is done in m stages.

3.8.1 Delay Costs

For m-stage construction the cost of delays for each peak and each aircraft type must be further split into construction stages 1 to m. The discount period for stage h is t_{Dijh} to Z_{h+1}, where t_{Dijh} will be either the time Z_h when the current stage is built or the time at which the maximum arrival rate exceeds the service rate for period h, whatever is greater, without exceeding the time Z_{h+1} at which the next stage is built. In summary,

$$t_{Dijh} = \min[Z_{h+1}, \max[Z_h, \frac{1}{a}\ln(\frac{\mu_{ijh}}{A_{Mij}})]] \qquad (3.63)$$

Note that $Z_1 = 0$ and $Z_{m+1} = Z$. An example for 3 stages is presented in Figure 3.11.

The total cost of delay with stage construction will be the sum of the costs for aircraft types, peaks and construction stages:

$$C_W = \sum_{i,j,h} d_i p_D(\mu_{ijh}, A_{Mij}, \bar{A}_i, T_{0ij}, t_{Dijh}, Z_{h+1}) \qquad (3.64)$$

3.8.2 Gate Installation and Maintenance Cost

The cash flows representing the cost of gate installation can be assumed to occur at the time of construction of each stage, i.e. at each time Z_h, $h = \{1,..,m\}$. At time Z_h, the maximum service rate for NLA, which by convention occurs at peak 1 (as seen in Figure 3.3), will be increased by (μ_{N1h} - μ_{N1h-1}), which means (AG_{N1h} - AG_{N1h-1}) NLA gates will be built. Similarly, (AG_{W1h} - AG_{W1h-1}) WB and (AG_{C2h} - AG_{C2h-1}) CJ gates will also be built at time Z_h, since the maximum service rate for CJ occurs at peak 2. The cash flow for gate installation at time Z_h must be discounted at interest rate r to have its present worth value at time 0 evaluated.

From engineering economics, it is known that the calculation of the cost of gate maintenance for any stage h is done in two steps. First, the present worth of the cost at time Z_h is evaluated using the present worth factor $(1 - e^{-Z})/r$, as discussed in Section 3.7.2. Then it is necessary to discount interest during the time interval 0 to Z_h to evaluate the present worth of the cost of gate maintenance at time 0. Figure 3.12 illustrates the application of this process to stage 2. Applying this process to all peaks, the total cost of gate construction and maintenance will become

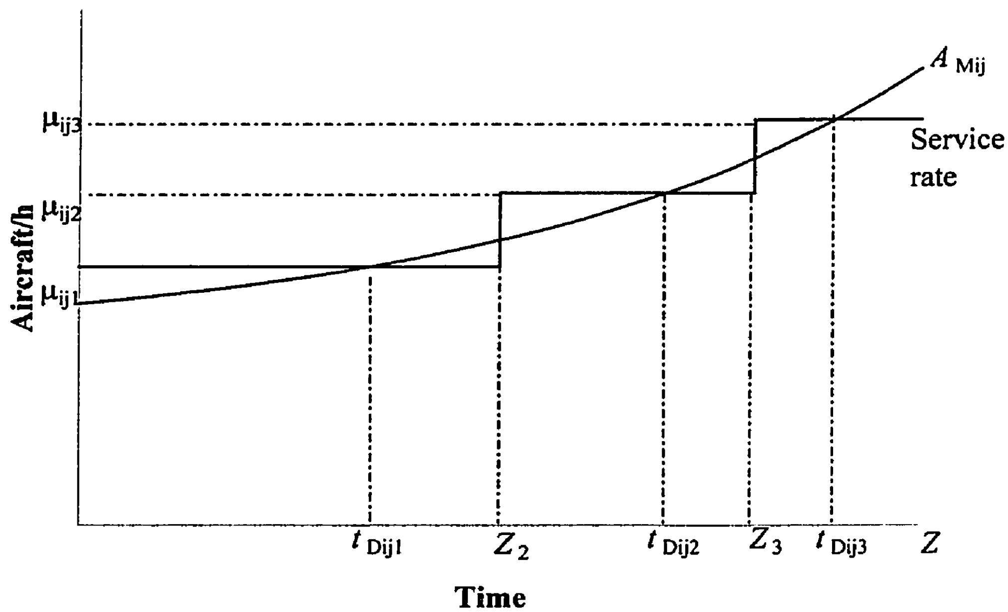


Figure 3.11: Integration limits for evaluation of delay costs with stage construction

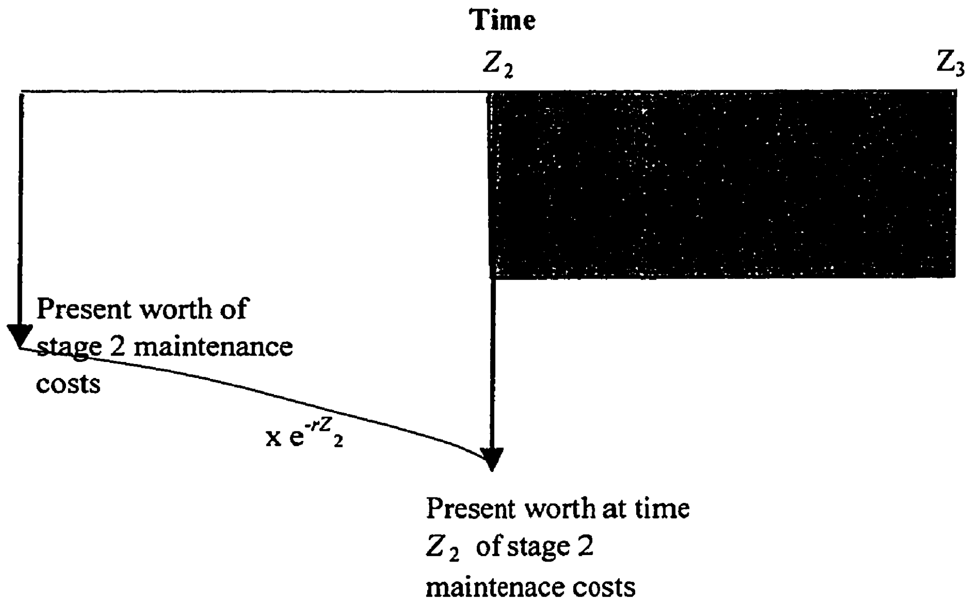


Figure 3.12: Present worth of cash flows for stage 2 of terminal construction

$$\begin{aligned} C_G &= \sum_i k_{Ci} G_{i1} + \sum_{h=2}^{m} \left[e^{-rZ_h} \sum_i k_{Ci} (G_{ih} - G_{ih-1}) \right] \\ &\quad + \sum_{h=1}^{m} \left[e^{-rZ_h} \frac{1 - e^{-r(Z_{h+1} - Z_h)}}{r} \sum_i k_{Mi} G_{ih} \right] \end{aligned} \tag{3.65}$$

where $Z_1 = 0$ and $Z_{m+1} = Z$.

3.8.3 Terminal Airside Construction Cost

Just like the cost of gate installations, the cost of terminal airside construction in stages 2 to m will have to be discounted at the interest rate r, whereas the present worth of the construction cost of stage 1 can be assumed to occur at once at time 0. The total cost of terminal airside construction C_B will then be given by

$$C_B = a_f \left[\max_j \left(\sum_i l_i AG_{ij1} \right) + \sum_{h=2}^{m} e^{-rZ_h} \left(\max_j (\sum_i l_i AG_{ijh}) - \max_j (\sum_i l_i AG_{ijh-1}) \right) \right] \tag{3.66}$$

3.8.4 Cost Minimisation

The choice of the service rates for both peak periods and for both construction phases, as well as the choice of the time of implementation of construction phase 2, will be done such that the overall cost of the terminal C is minimised. The overall cost C will be

$$C = C_W + C_G + C_B \tag{3.67}$$

where C_W, C_G and C_B are calculated using Equations 3.64, 3.65 and 3.66 respectively.

If space sharing cannot be used, then the problem will also be subject to the set of constraints of constant number of CJ gates during each stage:

$$\mu_{C1h}(T_R + S_R) = \mu_{C2h}(T_C + S_C) - (AG_{N1h} - AG_{N2h}) - (AG_{W1h} - AG_{W2h}), \quad \forall\, h = \{1,2\} \tag{3.68}$$

The service rates are also constrained by the non-overlapping queues requirement all along the terminal's life span. To meet this requirement, it suffices to warrant that the queues will not overlap at the end of each stage, i.e.

$$\mu_{ijh} \geq e^{aZ_{h+1}}\left(\frac{3}{4}A_{Mij} + \frac{1}{4}\bar{A}_i\right), \text{ for each } (i,j) \text{ peak with a parabolic shape} \tag{3.69}$$

and

$$\mu_{ijh} \geq e^{aZ_{h+1}}\left(\frac{2}{2+\sqrt{2}}A_{Mij} + \frac{\sqrt{2}}{2+\sqrt{2}}\bar{A}_i\right), \text{ for each triangular } (i,j) \text{ peak} \tag{3.70}$$

Figure 3.13, Figure 3.14 and Figure 3.15 summarise the MINLP models that will be used.

3.9 NUMERICAL EXAMPLE

Let us consider the example of an airport terminal under planning for servicing NLA, WB and CJ demands for the next 20 years. The terminal is to be constructed in stages, i.e. it will be partially built now and expanded at some time ahead. The characteristics of the peaks, as well as the aircraft operational parameters, are given in Table 3.1. This table also gives the values of the costs used in this example. As the determination of these costs is beyond the scope of this work, fictitious values were used to produce this example except where indicated otherwise.

STAGE CONSTRUCTION
UNCONSTRAINED SPACE SHARING

Minimize:

$$C = C_W + C_G + C_B$$

Subject to:

$$C_W = \sum_{i,j,h} d_i p_D(\mu_{ijh}, A_{Mij}, \bar{A}_i, T_{0ij}, t_{Dijh}, Z_{h+1})$$

$$C_G = \sum_i k_{Ci} G_{i1} + \sum_{h=2}^{m} \left[e^{-rZ_h} \sum_i k_{Ci} (G_{ih} - G_{ih-1}) \right] + \sum_{h=1}^{m} \left[e^{-rZ_h} \frac{1 - e^{-r(Z_{h+1} - Z_h)}}{r} \sum_i k_{Mi} G_{ih} \right]$$

$$C_B = a_f \left[\max_j \left(\sum_i l_i A G_{ij1} \right) + \sum_{h=2}^{m} e^{-rZ_h} \left(\max_j (\sum_i l_i A G_{ijh}) - \max_j (\sum_i l_i A G_{ijh-1}) \right) \right]$$

$$G_{ih} = \text{integer}$$

$$G_{Nh} = \mu_{N1h}(T_{Nh} + S_{Nh})$$

$$G_{Wh} = \mu_{W1h}(T_{Wh} + S_{Wh})$$

$$G_{Ch} = \mu_{C2h}(T_{Ch} + S_{Ch})$$

$$\mu_{ijh} \geq e^{aZ_{h+1}} \left(\frac{3}{4} A_{Mij} + \frac{1}{4} \bar{A}_i \right), \text{ for each } (i,j) \text{ peak with a parabolic shape}$$

$$\mu_{ijh} \geq e^{aZ_{h+1}} \left(\frac{2}{2+\sqrt{2}} A_{Mij} + \frac{\sqrt{2}}{2+\sqrt{2}} \bar{A}_i \right), \text{ for each } (i,j) \text{ peak with a triangular shape}$$

Figure 3.13: MINLP model for the Stage Construction + Unconstrained Space Sharing case

The optimisation was performed using the Microsoft Excel® Solver add-in. To avoid getting stuck in a local optimum, several runs were performed, each with a different randomly generated initial solution. After each run, the solution found was compared to the best solution so far and was discarded if its cost was higher, or became the new best solution if it yielded a lower cost. The resulting optimal numbers of gates are in Table 3.2 and Table 3.3, respectively.

For 2 stages, there will be the need for 6 CJ gates to share the same space with NLA and WB gates during the first stage. In stage two, the number of CJ gates sharing space with NLA and WB gates increases to 8. The second stage should be built 9.6 years after the first one. The total cost of this solution is \$ 183.5 million, including approximately \$ 4 million in delay costs.

STAGE CONSTRUCTION
CONSTRAINED SPACE SHARING

Minimize:

$$C = C_W + C_G + C_B$$

Subject to:

$$C_W = \sum_{i,j,h} d_i p_D(\mu_{ijh}, A_{Mij}, \bar{A}_i, T_{0ij}, t_{Dijh}, Z_{h+1})$$

$$C_G = \sum_i k_{Ci} G_{i1} + \sum_{h=2}^{m} \left[e^{-rZ_h} \sum_i k_{Ci}(G_{ih} - G_{ih-1}) \right] + \sum_{h=1}^{m} \left[e^{-rZ_h} \frac{1 - e^{-r(Z_{h+1} - Z_h)}}{r} \sum_i k_{Mi} G_{ih} \right]$$

$$C_B = a_f \left[\max_j \left(\sum_i l_i AG_{ij1} \right) + \sum_{h=2}^{m} e^{-rZ_h} \left(\max_j (\sum_i l_i AG_{ijh}) - \max_j (\sum_i l_i AG_{ijh-1}) \right) \right]$$

$$G_{ih} = \text{integer}$$

$$G_{Nh} = \mu_{N1h}(T_{Nh} + S_{Nh})$$

$$G_{Wh} = \mu_{W1h}(T_{Wh} + S_{Wh})$$

$$G_{Ch} = \mu_{C2h}(T_{Ch} + S_{Ch})$$

$$AG_{ijh} = \mu_{ijh}(T_i + S_i) \text{ for all pairs } (i,j) \text{ except (R, 2)}$$

$$AG_{C2h} = \mu_{C2h}(T_C + S_C) - (AG_{N1h} - AG_{N2h}) - (AG_{W1h} - AG_{W2h})$$

$$AG_{C2h} - AG_{C1h} = \max(AG_{N1h} + AG_{W1h} - AG_{N2h} - AG_{W2h} - 2,\ 0)$$

$$\mu_{ijh} \geq e^{aZ_{h+1}} \left(\frac{3}{4} A_{Mij} + \frac{1}{4} \bar{A}_i \right), \text{ for each } (i,j) \text{ peak with a parabolic shape}$$

$$\mu_{ijh} \geq e^{aZ_{h+1}} \left(\frac{2}{2+\sqrt{2}} A_{Mij} + \frac{\sqrt{2}}{2+\sqrt{2}} \bar{A}_i \right), \text{ for each } (i,j) \text{ peak with a triangular shape}$$

Figure 3.14: MINLP model for the Stage Construction + Constrained Space Sharing case

STAGE CONSTRUCTION
NO SPACE SHARING

Minimize:

$$C = C_W + C_G + C_B$$

Subject to:

$$C_W = \sum_{i,j,h} d_i p_D(\mu_{ijh}, A_{Mij}, \bar{A}_i, T_{0ij}, t_{Dijh}, Z_{h+1})$$

$$C_G = \sum_i k_{Ci} G_{i1} + \sum_{h=2}^{m} \left[e^{-rZ_h} \sum_i k_{Ci} (G_{ih} - G_{ih-1}) \right] + \sum_{h=1}^{m} \left[e^{-rZ_h} \frac{1 - e^{-r(Z_{h+1} - Z_h)}}{r} \sum_i k_{Mi} G_{ih} \right]$$

$$C_B = a_f \left[\sum_i l_i G_{i1} + \sum_{h=2}^{m} e^{-rZ_h} \sum_i l_i (G_{ih} - G_{ih-1}) \right]$$

$$G_{ih} = \text{integer}$$

$$G_{Nh} = \mu_{N1h}(T_{Nh} + S_{Nh})$$

$$G_{Wh} = \mu_{W1h}(T_{Wh} + S_{Wh})$$

$$G_{Ch} = \mu_{C2h}(T_{Ch} + S_{Ch})$$

$$AG_{ijh} = \mu_{ijh}(T_i + S_i) \text{ for all pairs } (i,j) \text{ except } (R, 2)$$

$$AG_{C2h} = \mu_{C2h}(T_C + S_C) - (AG_{N1h} - AG_{N2h}) - (AG_{W1h} - AG_{W2h})$$

$$AG_{C1h} = AG_{C2h}$$

$$\mu_{ijh} \geq e^{aZ_{h+1}} \left(\frac{3}{4} A_{Mij} + \frac{1}{4} \bar{A}_i \right), \text{ for each } (i,j) \text{ peak with a parabolic shape}$$

$$\mu_{ijh} \geq e^{aZ_{h+1}} \left(\frac{2}{2+\sqrt{2}} A_{Mij} + \frac{\sqrt{2}}{2+\sqrt{2}} \bar{A}_i \right), \text{ for each } (i,j) \text{ peak with a triangular shape}$$

Figure 3.15: MINLP model for the Stage Construction + No Space Sharing case

Should 3 stages be used, then the second and third stages should be built respectively 6 and 12.5 years after the first one. During the first stage, 6 CJ gates will share the same space with NLA and WB gates. The second stage will feature 7 CJ gates occupying the same space as NLA and WB gates, whereas in the third stage this space sharing increases to 9 CJ gates. The total cost for 3 stages is \$177.4 million, representing a \$6.1 million saving when compared to the 2-stage solution. The cost of delays, however, is raised to \$4.5 million.

Table 3.1 - Input parameters for the numerical example

		AIRCRAFT TYPE		
	GENERAL	NLA	WB	CJ
Nominal annual demand growth rate (%)	3			
Nominal annual interest rate (%)	8			
Project life span (years)	20			
COSTS				
Cost of terminal construction ($1000 per meter of terminal frontage)	65			
Cost of gate installation ($1000 per gate)		640	520	400
Cost of gate maintenance ($1000 per gate per year)		60	60	50
Cost of delay imposed to aircraft ($1000 per hour of delay)		29.4	15.4	7.5
AIRCRAFT CHARACTERISTICS				
Terminal frontage requirement (meters per gate)		87.5	59.5	40.5
Gate turnaround time (hours)		1.483	1	0.667
PEAKS PARAMETERS				
Peak 1				
Maximum arrival rate (aircraft per hour)		5	8	13
Average arrival rate (aircraft per hour)		1	3	8
T_0 (hours)		2	2	2
Peak 2				
Maximum arrival rate (aircraft per hour)		3	4	20
Average arrival rate (aircraft per hour)		1	3	8
T_0 (hours)		1	1	3

- The cost of terminal frontage was determined based on the value of $2,400/m^2 for Orlando Airside Terminal 2 [Westhart, 2000], with parking on both sides of the 36.5 m wide concourse.
- Cost of WB gate installation based on $520,000 per gate found in Westhart [2000]. Costs of CJ and NLA gates are fictitious.
- Cost of aircraft delay based on $66 per passenger found in FAA [1995b], average occupation of 91 passengers per CJ, 200 per WB and 400 passengers per NLA (fictitious). Aircraft operating costs used were $1,500, $2,250 and $3,000 per hour of delay for CJ, WB and NLA respectively. These operating costs are fictitious but consistent with the U.S. industry global average of $2,242.5 found in FAA [1995b].
- Monetary values are in Canadian dollars. Conversion rate used: US$1.00 = CAN$1.50.

Table 3.2: Optimal number of gates for 2 stages

	NLA		WB		CJ		
	Peak		Peak		Peak		
Stage	1	2	1	2	1	2	Z (years)
1	9	6	10	6	11	17	0
2	12	9	13	8	15	23	9.6

Total Cost ($ million) 183.5

Table 3.3: Optimal number of gates for 3 stages

	NLA		WB		CJ		
	Peak		Peak		Peak		
Stage	1	2	1	2	1	2	Z (years)
1	8	6	9	5	10	16	0
2	10	7	11	6	12	19	6
3	12	9	13	8	15	24	12.5
Total Cost ($ million)		177.4					

3.10 SUMMARY

Three common problems in airport terminal planning have been addressed in this chapter: the determination of the number of gates to be provided; the sharing of space by gates of different types for better utilisation of resources; and the construction of the terminal in stages. These three problems gain a new dimension under the light of the introduction of NLA.

It has been shown that the use of common areas by NLA, WB and CJ gates can reduce the cost of construction and consequently the overall cost of the terminal. This space sharing can only be done, however, if the main peaks for both types are sufficiently separated in time, so that there is no overlapping of the respective queues. The implementation of proper operational policies will facilitate the sharing of terminal space. The use of stage construction has also proved to reduce costs when interest is accounted for in the model.

The reader should note that although the motivation for this work is the advent of NLA, the concepts and the model described here apply to any kind of aircraft. Should one be planning an airport terminal with two different types of gates, e.g. wide-bodies and conventional jets, then the proposed model can be used with practically no need for changes.

CHAPTER 4
TERMINAL CONFIGURATIONS FOR THE NLA

4.1 INTRODUCTION

Terminal configuration refers, in general, to the way aircraft gate positions are arranged at the terminal. The choice of the terminal configuration is usually the next step after evaluating the number of gates. The configuration is comprised of a combination of the terminal *concept* and *geometry*.

Terminal *concept* refers to the general physical and functional shape of the terminal buildings. The literature on airport planning [de Neufville, 1976; Hart, 1985; FAA, 1988; Ashford & Wright, 1992; Horonjeff & McKelvey, 1994; IATA, 1995] divides the existing terminal concepts into four groups: (1) linear; (2) pier or finger; (3) satellite; (4) transporter. Figure 4.1 shows examples of these four types of terminals. These terminal concepts could be combined – a good example would be the pier-satellite concept shown in Figure 4.2. Practically all existing airports fit in one or more of these categories.

In the linear configuration, aircraft park side by side along a concourse. This concept is generally used in small terminals and has the ability to provide short walking distances for passengers who are either starting or ending their air travel at this terminal. For large terminals with a high proportion of transfers, this arrangement is not desirable because of the very high walking distances for transfers and the inefficiency in the use of terminal resources. Frankfurt Terminal 2 and London Heathrow Terminal 4 are examples of linear terminals.

Piers are similar to linear terminals. However, aircraft are parked on both faces of the pier, and the passenger processing is concentrated in the terminal block, allowing a more efficient use of the terminal resources. Pier terminals provide lower walking distances for hub transfers and are very easy to expand, but feature long walking distances for non-transfer passengers. Calgary, Vancouver and Baltimore/Washington Airports are examples of pier terminals.

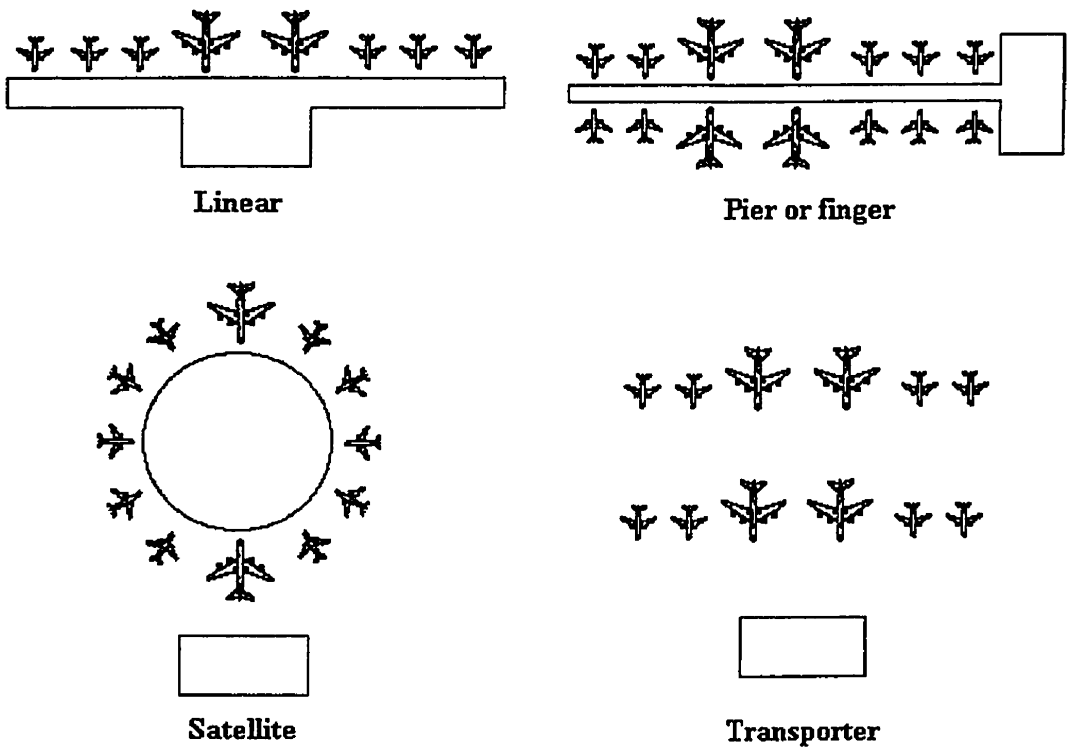


Figure 4.1: Terminal concepts

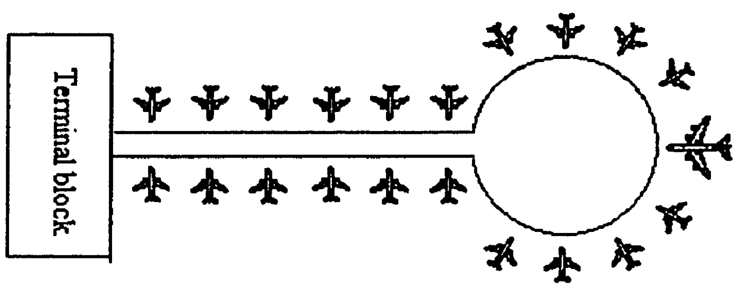


Figure 4.2: Combination of pier and satellite concepts

In the satellite terminal configuration, passenger processing is also concentrated in the terminal main building. Aircraft, however, are parked remotely from the terminal, in one or more midfield buildings. Satellite terminals provide more flexibility for aircraft operations and for future expansions, but require an expensive underground system – usually with the use of Automated People Movers – to connect the remote buildings to the central terminal and to each other. Examples of this type of terminal are Tampa and Orlando airports.

Transporter terminals are by far the most flexible in terms of aircraft parking positions. In this concept, aircraft are parked away from the terminal, on positions drawn on the apron. It allows great flexibility in parking aircraft of very different sizes, but requires that passengers be transported with buses or mobile lounges to the aircraft positions, creating an undesirable traffic of ground vehicles on the apron. This concept also relies heavily on the efficiency of the transporters system. The most prominent examples of transporter terminals are Washington/Dulles and the now deactivated Montreal/Mirabel.

Besides the traditional concepts described above, Robinson & Duncan [1997] and Rourke [1998] suggest a new concept called "gate pods". Instead of being parked side by side at long concourses, aircraft would be parked around small buildings – the pods – connected to the terminal block by Personal Rapid Transit (PRT) vehicles. Passengers would stay in the terminal block until boarding starts, and then move to the gate using the PRT system. This would eliminate the need for individual lounges for each gate and would allow taxi-in-taxi-out parking of aircraft, eliminating the need for tugs to push the aircraft out of the parking position. However, PRT technology has not achieved the ability to work efficiently with a very large number of stations and vehicles as would be the case in a large airport, so it is very unlikely that this terminal concept will be implemented any time soon [Sulkin, 1999].

Once the terminal concept is chosen, then it is time to set its *geometry*, which is defined as the set of parameters that give the final shape of the terminal. As an example, if the terminal is to be built as a set of parallel piers, its geometry can be defined as the number of piers, the length of each pier, and the spacing between them.

The determination of the terminal configuration is of critical importance to the good functioning of the terminal. In fact, on the terminal configuration will depend:

- the passenger walking distances;
- the baggage handling distances;
- the aircraft taxiing distances;

- the configuration and sizing of the ramp services;
- ultimately, the overall costs associated with the construction and operation of the terminal.

The introduction of the NLA will influence the terminal configuration in two ways. Existing airports may adapt to NLA operations by either converting existing gates to NLA ones, or building a new terminal or satellite. The former would be preferred should the number of NLA operations be small and if it does not imply significant restrictions to airside operations. There are at least three cases, however, in which the construction of a new terminal may be required:

- where the number of NLA positions necessary to meet the demand is relatively high, making the conversion of existing positions excessively costly;
- where the existing apron configuration imposes too many restrictions to NLA operations, implying an excessive loss of airside capacity, or even preventing them from operating there;
- where an airline requires an exclusive[1] terminal for its NLA operations.

In the case of adding NLA gates to existing facilities, the problem is reduced to determining the optimum location of those gates at the pre-configured terminal.

This section will analyse the gate arrangement for a terminal designed to accommodate one or more NLA. It is assumed that the number and size of gates of each type – and consequently the terminal dimensions – have been previously determined. The objective of this work is to determine, for each configuration studied, where in the terminal the NLA gates should be located. After a brief review of the existing literature on the subject, three of the most popular configurations will be analysed: a single pier, a pier-satellite and a parallel-pier terminal with Automated People Mover. The first case attempts to solve the problem of an airline-owned pier, where it is predetermined which pier of a multiple-pier terminal the NLA must be parked at. Pier-satellites are very interesting due to the possibility of using a great part of the satellite section as a single departure lounge for the NLA. The third

[1] Exclusive, in this case, means the airline will be the only one to operate in the terminal. The airline might mix NLA and CJ operations.

case is an analysis of a configuration that has become very popular in the last decade for large airports and where the NLA could be located at any pier.

In Section 4.6, a spreadsheet analysis is performed to evaluate the effect of intelligent gate assignments on the choice of the terminal configuration. Intelligent gate assignment is the placement of connecting flights close to each other, such that the walking distance for these passengers is reduced. The objective of this spreadsheet analysis is to determine the impact that intelligent gate assignment will have in the choice of the optimal configuration.

The criterion used in this work to choose the best terminal configuration is the mean walking distance for NLA passengers. Walking could actually be measured in terms of either distance or time spent. Walking time is chosen when it must be compared with other passenger inconveniences such as standing and riding moving belts or Automated People Movers (APM). Modal choice models such as the one described by Kumarage & Wirasinghe [1990] for Atlanta Hartsfield Airport favour walking time over distance. In this work, walking distance will be used when only walking is taken into account, while the *disutility* – which can be measured as time – of walking will be preferred when a comparison with riding APM is necessary.

4.2 LITERATURE REVIEW

The works found in the literature regarding the choice of the terminal configuration can be grouped in two major categories: system simulation and analytical models.

System simulation models consist of building a mathematical model to represent the terminal entities and the relationships between them. Operational parameters can be either deterministic – i.e. represented by mean values – or stochastic – modelled as probability distribution functions. If stochastic variables are involved, these variables are assigned randomly generated values using the distributions given, thus requiring several runs for each scenario. Simulation models are very useful to analyse specific scenarios in great detail. However, they only allow the modeller to compare the scenarios modelled; the optimal solution is not given. The major drawback of simulation models, though, is the fact that they require complete knowledge of the operational rules and parameter behaviours that is not available in the early stages of terminal planning. Recent examples of terminal simulation models are found in Brunetta et al [1999], Jim & Chang [1998] and Setti & Hutchinson [1994]. Mumayiz [1991] provides a broad overview of terminal simulation models developed in the seventies and eighties.

Analytical models attempt to model the airport terminal as a set of mathematical relations. Most studies done on the subject of optimising the terminal configuration with analytical models have used walking distance as the main factor in the objective function. Each of those studies attempts to find the optimal geometry for one or more pre-defined configurations. The definition of the terminal geometry depends on the configuration studied. All of the models found in the literature assume the total number of gates as being defined *a priori*, and that all gates are of the same type and equally spaced along the terminal frontage.

Wirasinghe et al [1987] were among the first to propose an analytical method to determine the optimal geometry of a terminal. The configuration chosen for their analysis was parallel equal-length pier-fingers. Their goal was to determine the number of piers that would minimise passenger walking distance, for a given number of aircraft gates of the same type.

Wirasinghe & Vandebona [1988] analysed the distribution of walking distances in pier-finger terminals with just two piers. They formulated the walking distance much in the same way as was done in Wirasinghe et al [1987], except that here, instead of determining the optimal geometry of the terminal based on the mean walking distance, they plotted the distribution of the walking distance for the purpose of level-of-service analysis. To do so, they made the assumption that, in the long run, passenger arrivals and departures are uniformly distributed through all gates. The evaluation of the walking distribution allows one to select the best configuration based on the proportion of passengers who are forced to walk excessive walking distances.

Bandara [1990] and Bandara & Wirasinghe [1992a] evaluated the mean walking distance for several terminal configurations and determined the optimal terminal geometry for each of them. Gates were assumed to be equally spaced and used by an equal number of passengers in the long run. Passengers were divided into three main categories: arriving/departing, hub transfers, and non-hub transfers. The mean walking distance was formulated for each passenger category, and the mean overall walking distance was calculated as:

$$\overline{W} = (1-P)W_A + P[Q\,W_H + (1-Q)W_{NH}] \tag{4.1}$$

where

$\overline{W}$ = mean overall walking distance;

W_A = arriving/departing passengers walking distance;

W_H = hub transfers walking distance;

W_{NH} = non-hub transfers walking distance;

P = proportion of transfers;

Q = proportion of hub transfers, with respect to overall transfers.

The mean walking distances for each passenger category – arriving/departing, hub transfers and non-hub transfers – were evaluated for several configurations and the optimum geometry determined for each of them. A simulation model was also used to determine the walking distributions. A comparison between the configurations was performed for different values of P and Q. The same approach was used in Bandara & Wirasinghe [1992b] to analyse pier terminals.

Wirasinghe & Bandara [1992] took a slightly different approach for the case of remote parallel pier terminals with Automated People Movers (APM), as illustrated in Figure 4.3. They modelled the disutility of passenger movements as the sum of the disutilities of walking and riding the APM. Given the number of gates, the spacing between gates, and the spacing between piers, the model seeks the number of piers and the lengths of each pier that minimise the total disutility of passenger movement. The optimum terminal geometry was proven to depend on the ratio of walking to APM riding disutilities.

Robusté [1991] analysed several centralised hub terminal layouts, determining the walking distance for each of them and using it to choose the best terminal geometry. This work was expanded by Robusté & Daganzo [1991] to include baggage handling. They used simulated annealing to determine the optimum geometry of a parallel pier-finger terminal like the one studied by Wirasinghe et al [1987], except that they allowed different pier lengths. They also showed that the optimum geometry for a parallel pier-finger terminal has longer piers near the terminal block.

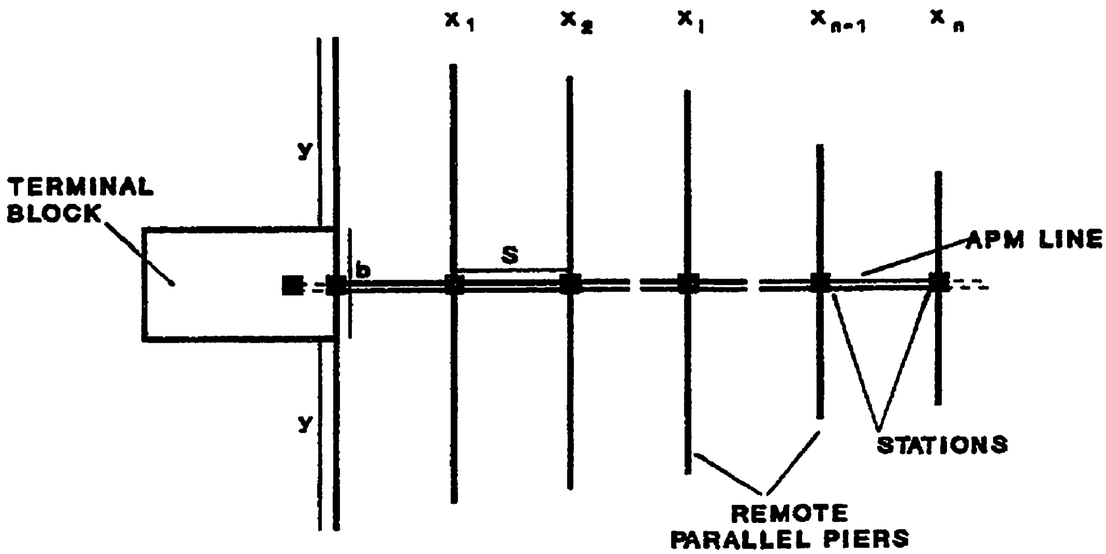


Figure 4.3: Parallel pier configuration

All the aforementioned works have a common drawback: they assume passengers are equally distributed along the terminal length, which is very often not true. In the case of an NLA terminal, the specific location of the NLA gates in the terminal will have a significant influence in the overall walking distance. Thus the importance of studying specific terminal configurations for the NLA.

4.3 SINGLE PIER TERMINALS

In this work, the criterion used to define the optimal location of the NLA gate is the overall average walking distance of NLA passengers. For one or two NLA gates only at a large terminal, the effect of the location of these gates on the walking distance of non-NLA-related passengers can be assumed to be negligible, especially if these gates can be used by Conventional Jets (CJ) when not in use by NLA.

In the case of 1 NLA position only, two types of passengers with common characteristics can be identified: hub transfers to conventional jets and originating/terminating/non-hub transfers (OTNH). Hub transfers are passengers who transfer directly from one aircraft to another, where both aircraft are parked at the pier under consideration. The second group, OTNH passengers, embraces arriving passengers who have to leave the pier either for the terminal block or for another concourse, and departing passengers who have either checked in at the terminal block or arrived on a flight that docked at another concourse. In those cases, passengers have to walk between the pier's main entrance and the aircraft. The walking distances for these passengers will therefore be determined by the location of the NLA gate with respect to the main entrance. Note that non-hub transfers whose both arriving and departing flights are docked at the pier under consideration must walk both from the aircraft to the entrance and vice-versa, but only the NLA-related part of their walking will be of importance to the problem.

Because NLA will be almost exclusively used in international routes, it is most likely that all NLA arrivals will be forced to go through customs and immigration, which are usually located at either the terminal building or the pier entrance. In this case, NLA arriving passengers – which account for roughly half the NLA passengers – should be included in the OTNH group. However, new techniques and procedures are under study that would allow customs/immigration clearance to be done at either the airport of origin or on board the aircraft, thus allowing connecting passengers to walk directly between the NLA and their re-departure gate. These passengers should therefore be considered hub transfers. The determination of the correct proportions of transfers will depend on these procedures and should be performed with caution.

4.3.1 Pier Configurations for 1 NLA Gate

As the market for NLA is predicted to be fairly small for some time ahead, it is very likely that many airports will not need more than one NLA gate. In this case, the problem is to find the best location for this sole NLA gate in the pier.

In most known cases, the pier entrance is either located at one end or at the pier centre. The former is the case of pier-finger terminals, whereas the latter is more common in remote piers with underground access to the terminal block. Figure 4.4 shows a schematic of a pier terminal, with the two possible locations for the pier entrance.

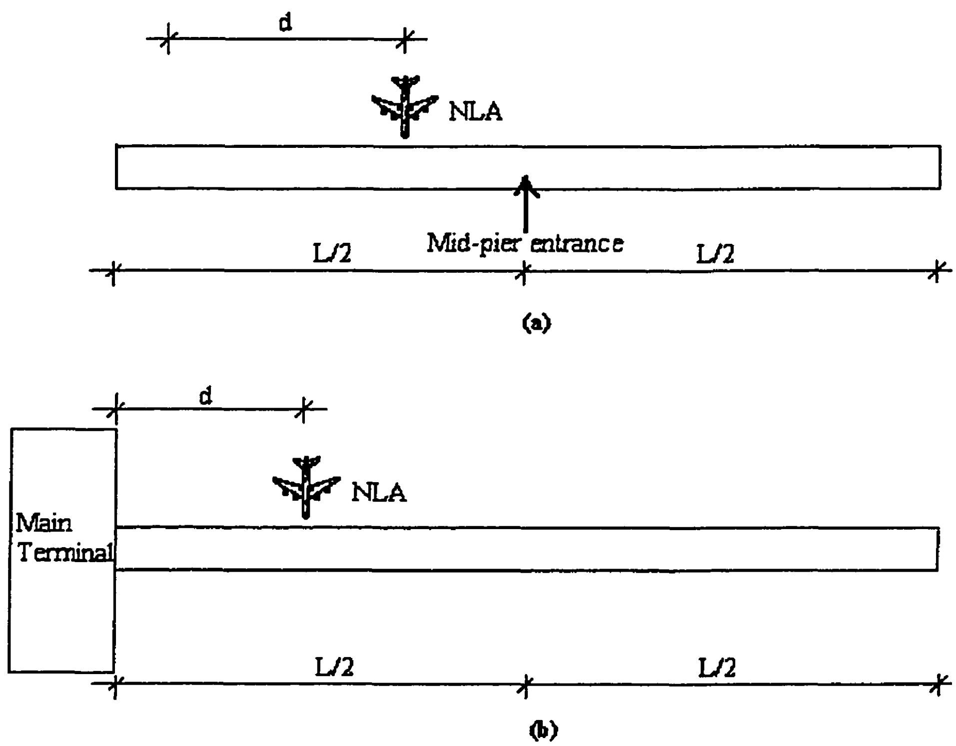


Figure 4.4: Pier configuration for 1 NLA
(a) Mid-pier entrance
(b) Pier-end entrance

4.3.1.1 Pier with Entrance in the Middle

Airports such as Atlanta and Denver have a number of remote parallel piers with access to the terminal block provided through the use of Automated People Movers (APM), where the APM stations are located at the pier centre. The new Northwest Airlines terminal in Detroit is an example of a terminal block attached to the pier centre. In both cases, OTNH passengers have to pass through the pier centre, whereas hub transfers can move directly between the NLA and the CJ.

Let us consider two extreme cases of transfers from the NLA: no transfers at all, and all transfers. In the first case, all passengers would be moving from the NLA to the pier entrance; therefore the location that minimises walking distance for these passengers would be as close as possible to the entrance. In the second case, the whole NLA load would be transferring to CJ's, thus the location of the NLA in the middle of the pier would yield the minimum walking distance. Clearly, the best place to put the NLA gate would be as close as possible to the pier middle, independent of the proportion of transfers. Still, this will be proven mathematically, as this will provide the basis for the evaluation of the cases in which there will be more than one NLA.

Let L be the length of the pier; d be the distance from one of the pier ends to the NLA position; and p_T be the proportion of NLA passengers who are hub transfers – i.e. the proportion of NLA passenger who will transfer directly to a conventional jet docked at the pier. The problem then is to find the value of d as a function of L and p_T that minimises the overall average walking distance.

Assuming the hub transfers to CJ's are equally distributed along the pier length, and approaching both the location of the NLA position and of the destination aircraft to continuous variables, then the average walking distance for hub transfers W_T is

$$W_T = \frac{d^2 + (L-d)^2}{2L} \tag{4.2}$$

Originating/terminating/non-hub transfer passengers have to walk between the NLA gate and the centre of the pier, where the pier entrance is located. Therefore, the average walking distance for these passengers, W_O, is

$$W_O = \frac{L}{2} - d \tag{4.3}$$

where, due to the symmetry of the pier,

$$0 \le d \le L/2 \tag{4.4}$$

Outside of the pier under consideration, OTNH passengers have more walking to do: to and from curbsides, parking lots, check-in counters, security checks, customs, and baggage claims. The walking distance related to these activities depends on the location of the pier with respect to the other terminal components, the type of connection between them, and the configuration of the terminal block. However, the walking distances outside of the pier under consideration do not depend on the pier configuration. Therefore, they will not impact the choice of the best gate arrangement within the pier.

Whatever the number of NLA gates, the overall average walking distance can be written as

$$W = p_T W_T + p_N W_N + (1 - p_T - p_N) W_O \tag{4.5}$$

where p_N and W_N are respectively the proportion of transfers between NLA and the corresponding walking distance for those transfers. Both equal zero for 1 NLA gate only.

With no constraints, the overall average walking distance W reaches its minimum when the value of d is set such that the partial derivative of W with respect to d equals zero. This derivative can be evaluated by substituting for W_T and W_O from Equations 4.2 and 4.3 in Equation 4.5, and is given by

$$\frac{\partial W}{\partial d} = p_T \left[\frac{2d}{L} - 1 \right] - (1 - p_T - p_N) \tag{4.6}$$

It can be shown that, for $0 \leq d \leq L/2$ and p_T and p_N ranging from 0 to 1

$$\frac{\partial W}{\partial d} \leq 0 \tag{4.7}$$

which means that W decreases with d. Therefore, W is minimum at $d = L/2$, with a consequent walking distance

$$W_{OPT} = \frac{p_T L}{4} \tag{4.8}$$

In other words, for 1 NLA gate only and the pier entrance located in the middle of the pier, the best location of this NLA gate is as close as possible to the middle of the pier. Figure 4.5 illustrates this solution. Note that this conclusion does not depend on the proportion of hub transfers p_T. This result is consistent with the intuitive statement made in the beginning of this analysis that the NLA gate should be located in the middle of the pier.

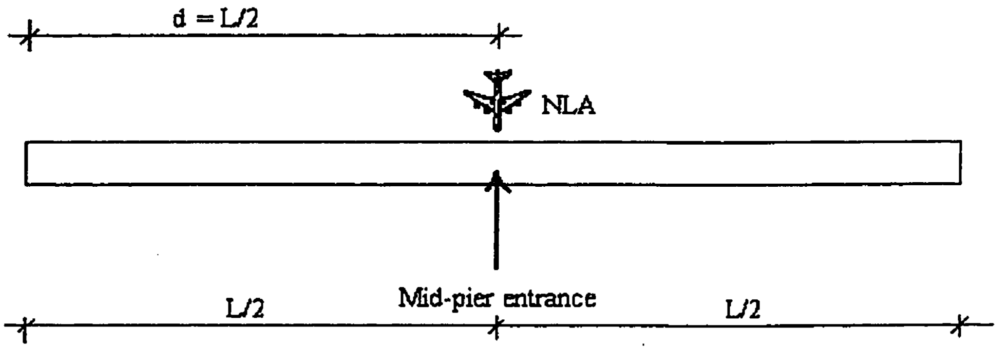


Figure 4.5: Optimal NLA gate location for the mid-pier entrance case

4.3.1.2 Pier with Entrance at One End

Pier-finger terminals like Calgary International Airport and remote piers like Orlando are connected to the terminal block through an entrance located at one end of the pier. Hub transfers are still able to walk directly between the NLA and the conventional jet. OTNH passengers, however, must move between the NLA and the end of the pier.

For a pier with entrance at one end, the walking distance for hub transfers, W_T, will remain the same as for a pier with entrance in the middle, as given in Equation 4.2. As to the OTNH passengers' walking distance, it will now be the distance between the NLA gate and the end of the pier where the entrance is located:

$$W_O = d \tag{4.9}$$

As the pier now loses its symmetry characteristic due to the entrance not being located at the centre of the pier, the variable d may now assume any value between 0 and the length of the pier:

$$0 \leq d \leq L \tag{4.10}$$

Substituting for W_T and W_O in Equation 4.5 from Equations 4.2 and 4.9, the derivative of W with respect to d is

$$\frac{\partial W}{\partial d} = p_T\left[\frac{2d}{L} - 1\right] + (1 - p_T - p_N) \quad (4.11)$$

For $p_T \leq (1 - p_N)/2$ it can be shown that $\partial W/\partial d$ is always non-negative, which means W is a crescent function of d. Hence W is minimum when d is minimum, i.e. when $d = 0$. For $p_T > (1 - p_N)/2$, $\partial W/\partial d$ could be either positive or negative, thus W is minimum when the value of d is such that $\partial W/\partial d$ equals zero. Setting $\partial W/\partial d$ as in Equation 4.11 to zero, we find

$$d = \frac{L}{2}\left[2 - \frac{(1 - p_N)}{p_T}\right]\text{s} \quad (4.12)$$

In summary, since $p_N = 0$, if the proportion of NLA hub transfers is less than half, then the best location for the NLA gate will be as close as possible to the entrance. In this case, OTNH passengers will have to walk only the negligible distance between the NLA gate and the entrance. Substituting for $d = 0$ in Equation 4.2 and multiplying by p_T, we find

$$W_{OPT} = \frac{p_T L}{2} \quad (4.13)$$

On the other hand, if the whole load of the NLA is comprised of hub transfers, then the NLA should be located at the pier centre and the average walking distance will be the average walking distance of NLA hub transfers as calculated in Equation 4.2, i.e.

$$W_{OPT} = \frac{L}{4} \quad (4.14)$$

Finally, for a proportion of NLA hub transfers between 0.5 and 1, the NLA gate should be located at a distance d from the entrance. The distance d is given in Equation 4.12 and the average walking distance is found by substituting for d in Equations 4.2 and 4.9, and for W_T and W_O in Equation 4.5, resulting in

$$W_{OPT} = \left(\frac{2p_N(1 - 2p_T) + 4p_T - p_N^2 - 2p_T^2 - 1}{4p_T}\right)L \quad (4.15)$$

Figure 4.6 summarises the optimal location of the NLA gate as a proportion of the terminal length, L, and as a function of the proportion of transfers, p_T.

The optimal location of the NLA gate and the correspondent average walking distance in the case of pier-end entrance are obviously very sensitive to the proportion of transfers to CJ's, p_T. For example, if the terminal is planned for 50% transfers, and the actual proportion of transfers turns out to be 60%, then the average walking distance will be 20% higher than what it could have been, had the NLA gate location been determined for the correct transfers rate. This is a serious problem for airport planners, as the actual transfer rate is hardly known in advance. However, it is clear from the results above that, whatever the proportion of transfers, the NLA gate must be located in the pier half where the entrance is located. This conclusion rules out the location of the NLA gate at the end of a pier-finger terminal, for instance – provided the goal is to minimise walking distance and no other constraints exist.

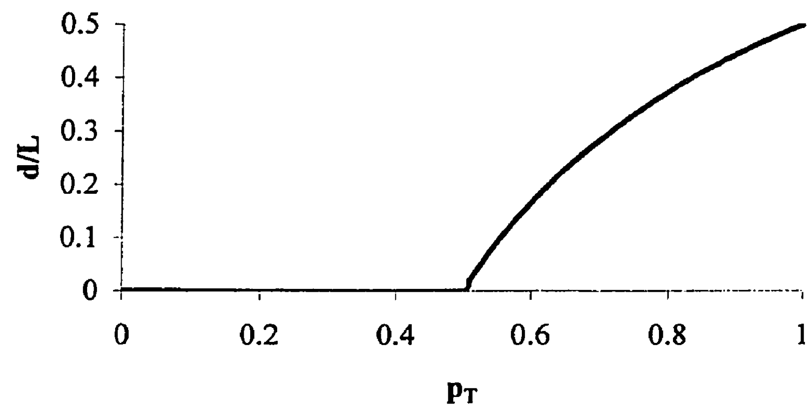


Figure 4.6: Optimal NLA gate location for the pier-end entrance case

4.3.2 Pier Configurations for 2 NLA Gates

Piers that are expected to have two NLA docked simultaneously at any time will, of course, need two NLA positions. These two NLA gates can be placed on opposite sides of the pier, facing each other as illustrated in Figure 4.7-a, or could be offset such that there is a distance S along the pier axis between the two positions, as shown in Figure 4.7-b. The distance S is assumed to be not smaller than a minimum S_{min}, which must be no less than the sum of the NLA wingspan and the minimum wing-tip-to-wing-tip distance.

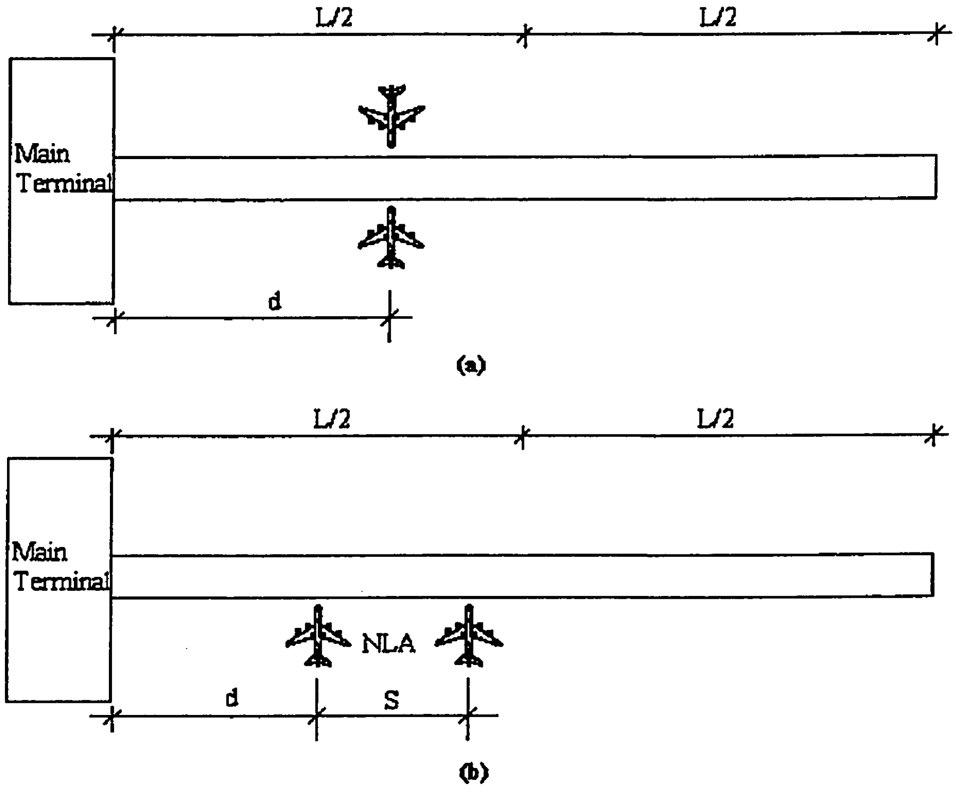


Figure 4.7: Pier Configuration for 2 NLA gates:
(a) on opposite sides of the pier;
(b) on the same side of the pier, offset by a distance *S*.

The choice between the configurations shown in Figure 4.7 will depend on several factors. Putting the two NLA on opposite sides of the pier as in Figure 4.7-a has the advantage of allowing a very short walking distance between the two aircraft. This advantage may be especially significant when a high proportion of the NLA passengers transfer to another NLA. However, existing apron configuration constraints may allow only one pier side to be used for NLA operations. Besides, mobile ramp service equipment that is to be shared by the two gates can be much more easily moved between the gates if they are located side by side.

The main difference in the formulation of the walking distances of 2 NLA gates when compared to 1 NLA is that, for 2 NLA, there will be passengers transferring from one NLA to another. The proportion of these passengers – which can be quite significant at major international hubs – and their respective walking distance may have an important role in the determination of the optimal location for the NLA gates. It should be noted, however, that in many countries international transfers are still required to clear customs and immigration; such passengers should be counted as OTNH as they are required to report to the main building. Even where this requirement does not exist, NLA-to-NLA hub transfers on long-haul flights may actually prefer to walk during the connection time, to compensate for the long time spent on the plane. Still, the compulsory walking distance – i.e. the distance passengers are *forced* to walk – should be minimised, leaving passengers with the choice of how much they *want* to walk.

It is assumed that the number of passengers and the proportions of transfers will be the same for both NLA positions. Other than that, the same assumptions made for the case of 1 NLA gate will be made for 2. The problem then is to find the values of d and S that minimise the overall passenger walking distance.

4.3.2.1 Two NLA Gates on Opposite Sides of the Pier

If the two NLA gates are located at the same point in the terminal but on opposite sides of the pier, facing each other as shown in Figure 4.7-a, then the problem is similar to the one with only one NLA gate and the same equations apply. The walking distance between the two NLA gates is negligible and will be assumed to equal zero in this analysis.

For a pier with entrance in the middle, it has been shown that the optimal location for the NLA gates depends neither on the proportion of CJ transfers, p_T, nor on the proportion of transfers between NLA, p_N. Therefore, the optimal location for the NLA gates is the same as for 1 NLA gate, i.e. as close as possible to the pier centre, with the average walking distance given in Equation 4.8.

In the case of the entrance being at one of the pier ends, it has also been shown that, for $p_T \leq (1 - p_N)/2$, the best place to put the NLA gate is as close as possible to the entrance. However, if $p_T > (1 - p_N)/2$, then the NLA gate should be located at a distance d from the entrance, with d given in Equation 4.12 and average walking distance given in Equation 4.15.

4.3.2.2 NLA Gates on One Side and Pier-End Entrance

With the assumption of hub transfers to CJ's being equally distributed along the terminal length, the average walking distance for those hub transfers is

$$W_T = \frac{d^2 + (L-d)^2 + (d+S)^2 + (L-d-S)^2}{4L} \tag{4.16}$$

For OTNH passengers, the average walking distance is

$$W_O = d + \frac{S}{2} \tag{4.17}$$

Passengers transferring from one NLA to another must walk the distance S that separates the two aircraft, i.e.

$$W_N = S \tag{4.18}$$

The domain of variables d and S is shown in Figure 4.8. The formula for the overall walking distance can be found by substituting for W_T, W_O and W_N from Equations 4.16, 4.17 and 4.18 in Equation 4.5. The gradient of W in Equation 4.5, denoted by ∇W and given by

$$\nabla W = \left(\frac{\partial W}{\partial d}, \frac{\partial W}{\partial S} \right) \tag{4.19}$$

can then be found:

$$\nabla W = \left(\frac{p_T}{L}(2d + S - L) + (1 - p_T - p_N),\ \frac{p_T}{L}(d + S - \frac{L}{2}) + p_N + \frac{(1 - p_T - p_N)}{2} \right) \tag{4.20}$$

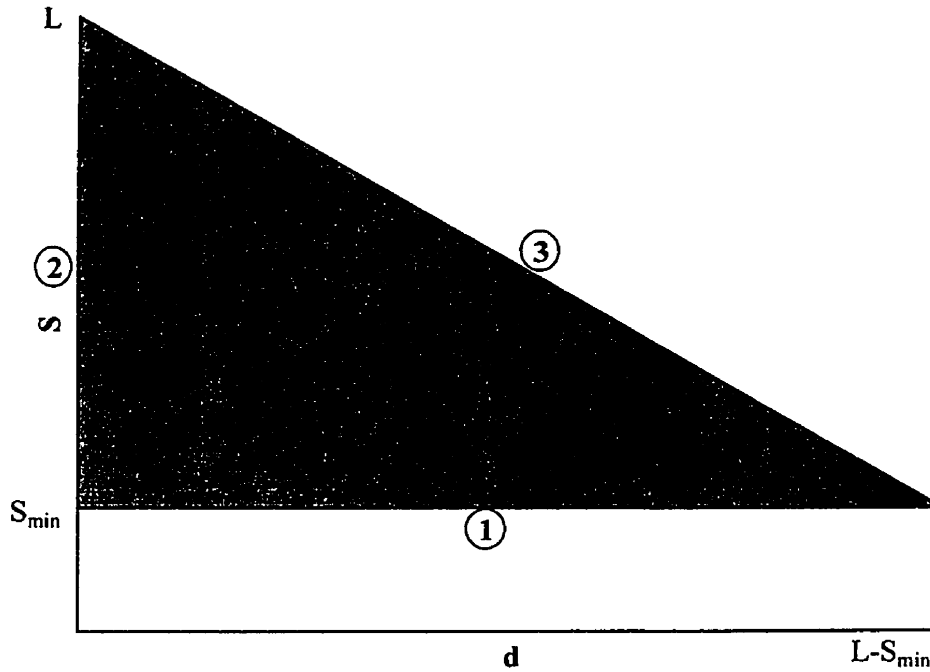


Figure 4.8: Ranges of d and S for the pier-end entrance case

Let S' and d' be the values assumed respectively by S and d that yield the minimum walking distance. Setting ∇W to (0,0), the pair (d, S) that yields the minimum value of W is (d', S') such that

$$(d', S') = \left(\left[\frac{2p_T + 3p_N - 1}{2p_T}\right]L,\ -\frac{2p_N}{p_T}L\right) \tag{4.21}$$

Since the value of S' is negative and not contained in the variable's range, the conclusion is that the W function does not have a critical point within its defined domain. The point of minimal value of W is thus located on one of the borders of the domain. By finding the local optimums on the domain borders and comparing them, it is found that the optimum is on Segment 1 shown in Figure 4.8. The optimal solution is shown in Table 4.1. It can be seen from that table that the optimal solution requires the location of the two NLA gates to be separated by the minimum distance S_{min}. The NLA gate closer to the entrance should either be at the pier end or at the distance d' given in Table 4.1, according to the relationship given.

Table 4.1: Optimal solution for 2 NLA gates and pier-end entrance

Condition	d'	S'	W_{OPT}
$p_T > \frac{(1-p_N)}{2[1-S_{min}/L]}$	$\left[1-\frac{1-p_N}{2p_T}\right]L - S_{min}$	S_{min}	$\left[1-\frac{p_T}{2}-p_N-\frac{(1-p_N)^2}{4p_T}\right]L + \left[\frac{p_T}{4}\frac{S_{min}}{L}+p_N\right]S_{min}$
$p_T \le \frac{(1-p_N)}{2[1-S_{min}/L]}$	0	S_{min}	$\frac{p_T}{4L}\left[L^2+S_{min}^2+(L-S_{min})^2\right] + \frac{(1-p_T+p_N)}{2}S_{min}$

The solution given in Table 4.1 can be translated to graphs that give the optimal value of d as a proportion of the terminal length L. For a given ratio S_{min}/L, the coefficient α such that $d' = \alpha L$ is presented as function of the proportions p_N and p_T. As an example, Figure 4.9 shows a graph for $S_{min}/L = 0.05$. If the point (p_N, p_T) falls within the shaded area, then $\alpha = 0$ and consequently $d' = 0$. The curves represent pairs (p_N, p_T) that yield a given value of α. The optimal location of the NLA gates can then be determined by inputting the values of p_N and p_T into the graph and using interpolation to determine the exact value of the coefficient α. For instance, if $S_{min}/L = 0.05$, $p_N = 0.2$, and $p_T = 0.6$, then inputting these values into the graph we find $\alpha \cong 0.28$. Similar figures can be developed for other ratios of S_{min}/L.

4.3.2.3 NLA Gates on One Side and Mid-Pier Entrance

The walking distances for passengers transferring to CJ's and to other NLA remain the same as for the case when the pier entrance is located at one of the pier ends. For OTNH passengers, however, the average walking distance will depend on whether the two NLA gates are on the same half of the pier or on opposite halves:

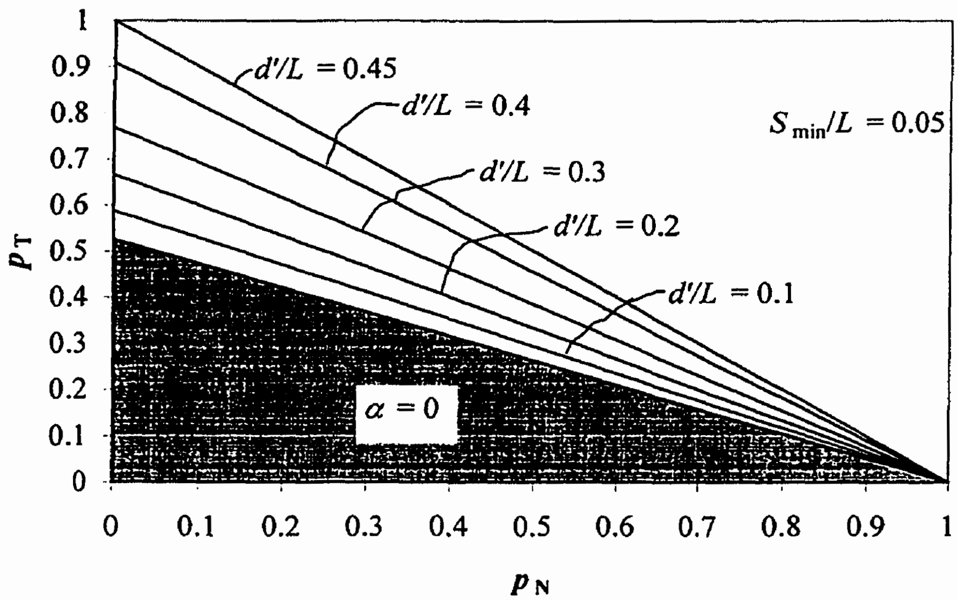


Figure 4.9: Isometric curves for the location of the NLA gates

$$W_O = \begin{cases} \dfrac{S}{2} & \text{, for one NLA on each half of the pier} \\ \dfrac{L-S}{2} - d & \text{, for both NLA on one half of the pier} \end{cases} \tag{4.22}$$

The expression for the overall walking distance can be found by substituting for W_T, W_O and W_N from Equations 4.16, 4.17 and 4.22 in Equation 4.5.

If both NLA gates are on the same half on the pier, then the optimal solution regardless of the variables constraints – which can be found by setting the gradient of the walking distance to (0, 0) – is

$$(d', S') = \left(\left[\frac{1 + p_N}{2p_T} \right] L,\ -\frac{(1 - p_T + p_N)}{p_T} L \right) \tag{4.23}$$

and for the two gates on opposite halves,

$$(d', S') = \left(\left[\frac{1 + p_N}{2 p_T} \right] L, \; - \frac{2 p_N}{p_T} L \right) \tag{4.24}$$

In both cases, the value of S' is out of the bounds defined for the variable and shown in Figure 4.10 and Figure 4.11. As in the case of pier-end entrance, the minimums for each domain's border segment – also illustrated in Figure 4.10 and Figure 4.11 – must be evaluated and compared to find the global optimum. This process was performed and yielded the results summarised in Table 4.2. The optimal solution is to have both gates symmetrically located near the pier centre, separated by the minimum distance $S_{\min}$.

Table 4.2: Optimal solution for 2 NLA gates and mid-pier entrance

Condition	d'	S'	W_{OPT}
$\forall\, p_T, p_N, S_{\min}, L$	$\frac{L - S_{\min}}{2}$	$S_{\min}$	$\left[1 - \frac{p_T}{2} - p_N - \frac{(1-p_N)^2}{4 p_T}\right] L + \left[\frac{p_T}{4}\frac{S_{\min}}{L} + p_N\right] S_{\min}$

4.3.3 Pier Configurations for 3 or More NLA

Should a pier terminal be designed to accommodate more than 2 NLA, the error introduced by the approach to continuously distribute passengers along the pier may become undesirably high. In this case, it is better to use a discrete approach that takes into account the space occupied by each gate position and the exact location of these gates in the pier, as well as the exact walking distance for CJ passengers. Although for the purpose of this work the objective function is to minimise walking distance, other performance criteria – such as baggage handling – can also be added.

For the purpose of this work, we will assume that CJ and NLA gates are provided in pairs, positioned at the same point in the pier, but located on opposite pier faces. This assumption will greatly simplify the formulation of the walking distances and will have little effect on the configuration of large terminals (20 gates or more). Figure 4.12 shows the general configuration of a pier terminal. The terminal configuration can be described by the sets $n^f = \{ n_1^f, n_2^f, ..., n_{N^f/2}^f \}$ of pairs of gate positions that will be reserved to aircraft type f, where N^f is the total number of gates type f.

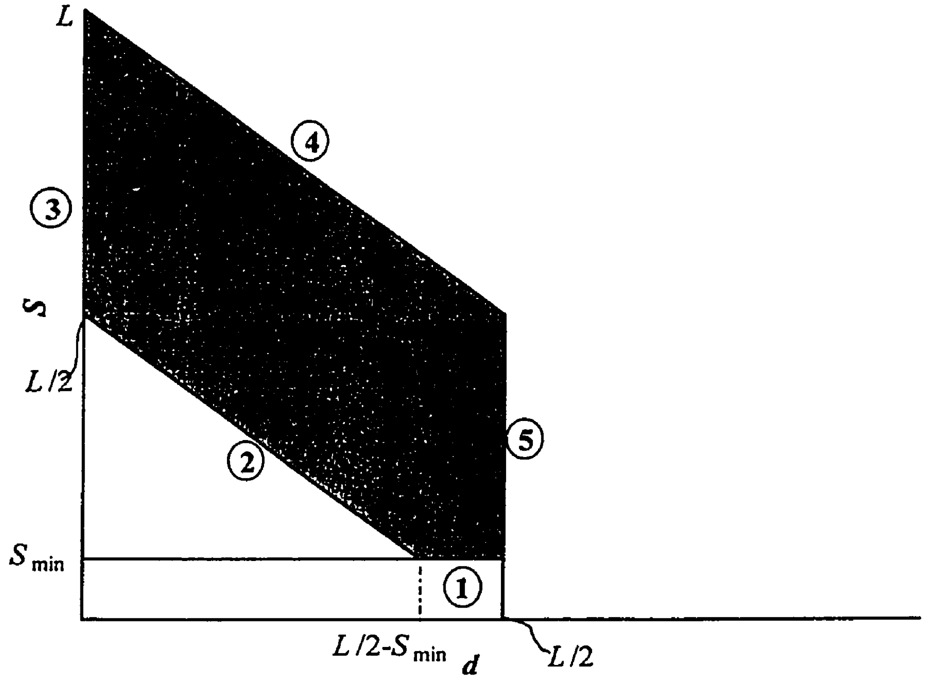


Figure 4.10: Ranges of *d* and *S* for mid-pier entrance and both NLA on the same pier half

The equations for the walking distances vary according to the terminal concept. These equations are found by determining the walking distance between every pair of gate positions (i, j) and averaging for the appropriate movement type (NLA to CJ, CJ to entrance, and so on). The inputs for the model are: the number of type f gates, N^f, for each aircraft type f; the location of the pier entrance, represented by the distance from the entrance to gate position 1; the fraction of passengers who arrive by each aircraft type f, r_f; and the proportions of each movement type. The representation of the pier entrance location using the distance from the end allows the analysis of special scenarios – e.g. when a pier with a mid-pier entrance has to be expanded in just one direction due to existing physical constraints. The output of the model is the order in which the gates are to be arranged along the pier, represented by the sets n^f as explained above.

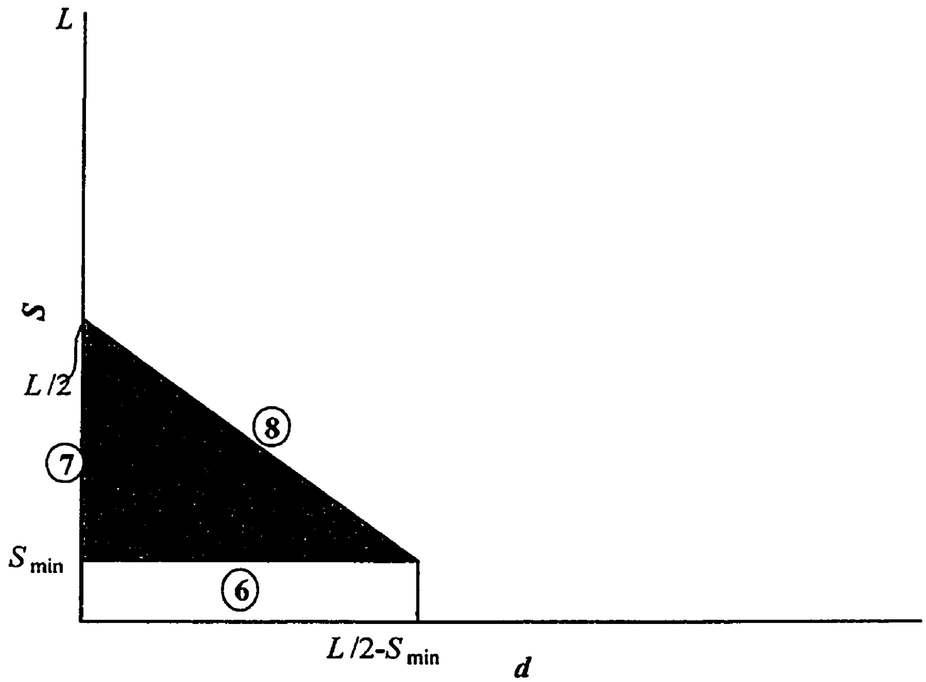


Figure 4.11: Ranges of *d* and *S* for mid-pier entrance and both NLA on opposite pier halves

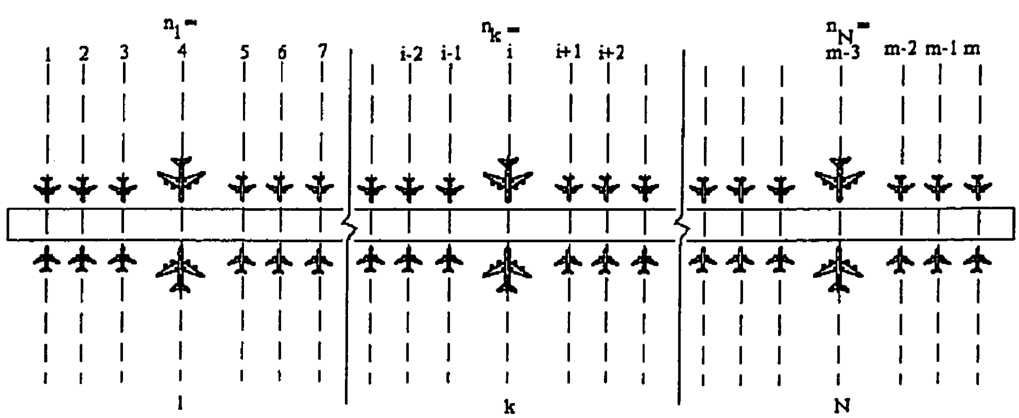


Figure 4.12: Description of a pier terminal configuration

Appendix A contains the equations used in this model.

4.3.3.1 Optimisation

The search for the optimal configuration – where the objective, for the purpose of this work, is the walking distance implied by a given configuration – is a combinatorial optimisation problem of the NP-complete type. The exact optimal solution for this type of problems can only be found by analysing a very large number of possible configurations. Such exhaustive analysis, however, can have a prohibitive time or computing costs for a large number of gates. Nonetheless, heuristic methods are available that can provide a very good local optimum without consuming too many computational resources.

One heuristic that has been used in some air transportation applications [Robusté & Daganzo, 1991; Lucic & Teodorovic, 1999] is *simulated annealing* [Kirkpatrick et al., 1983]. This is an iterative method in which, for each iteration, a perturbation is performed on the current solution, generating a new one. The new solution is accepted with probability 1 if it is better than the old solution and with probability p if it is worse. The process is performed according to a *temperature schedule* – an analogy to the physical process of annealing. The search for the optimum is done in phases, where the probability p – which is a function of the *temperature* – is larger for the early phases and is reduced as the process progresses from one phase to another. The use of this probability p allows the process to escape from local optimums and search for optimums in other regions, always keeping the best solution found. If the perturbation is such that it does not prevent any possible solution from being tested, then the process leads to a state of system equilibrium that yields a near-optimal solution.

For the problem of locating NLA positions in a pier terminal, simulated annealing seems to be an adequate technique for its easiness of modelling and implementation. The technique also leads to a very good solution very quickly, using little computing resources. The perturbation in the current solution is done by randomly selecting two elements from the sets n^f and switching their values. An example of a perturbation would be picking a WB pair of gates at position 3 and switching positions with a pair of NLA gates at position 7. The temperature schedule should be set to allow the system to "cool down" and "crystallise" smoothly and at the minimum processing time. A good solution, that offers a balance between an acceptable deviation from the optimum and a low computing time, can then be found using this method.

A program in C++ was written to evaluate the optimal gate arrangement for a pier terminal under the aforementioned conditions, using simulated annealing. An example is presented for a pier-finger with a total of 24 gates, of which 4 are NLA, 6 are WB and the remaining gates are CJ ones, and input parameters given in Table 4.3. Figure 4.13 shows the optimal gate arrangement with these parameters. Notice how the CJ gates are put together, with the WB and NLA gates at the extremities of the building. Due to the high proportion of passengers transferring to and from CJ gates, this is the arrangement that provides the minimum overall walking distance. Locating the NLA gates near the middle of the building would reduce the mean walking distance of NLA passengers transferring to CJ gates. On the other hand, since gate sharing is not taken into account in this model, it would also have the adverse effect of increasing walking distance for CJ transfers and OTNH passengers using the gates located at the far terminal half.

Table 4.3: Input parameters for the numerical example

NLA maximum wingspan (m)	80
WB maximum wingspan (m)	55
CJ maximum wingspan (m)	38
Wing-tip-to-wing-tip clearance (m)	7.5
r_N	0.17
r_W	0.25
r_C	0.58
P_{Cm}	0.3
P_{Wm}	0.3
P_{WC}	0.5
P_{Nm}	0.3
P_{NC}	0.5
P_{NW}	0.19

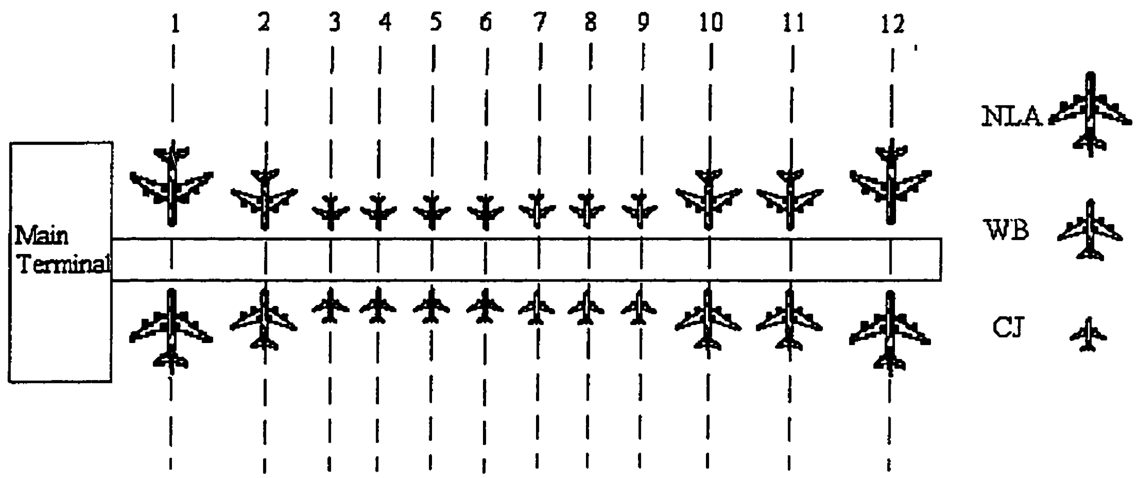


Figure 4.13: Optimal gate arrangement for the numerical example

4.4 PIER SATELLITE TERMINALS

Pier satellite terminals feature a pier that serves both as a boarding area, with aircraft parking at its faces, and as a connector between the terminal block at one end of the pier and a satellite terminal located at the other end. Figure 4.14, Figure 4.15 and Figure 4.16 show examples of the three different types of pier-satellite terminals: circular, T-shaped and Y-shaped pier satellites.

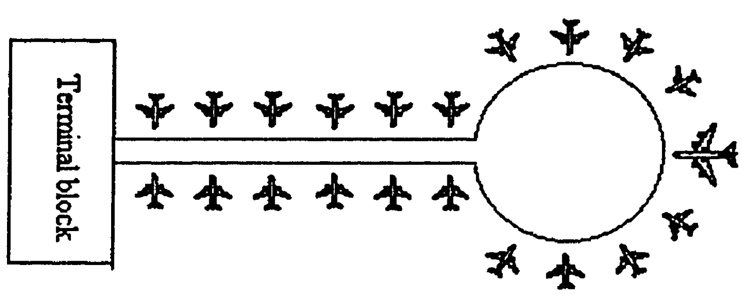


Figure 4.14: Circular pier-satellite

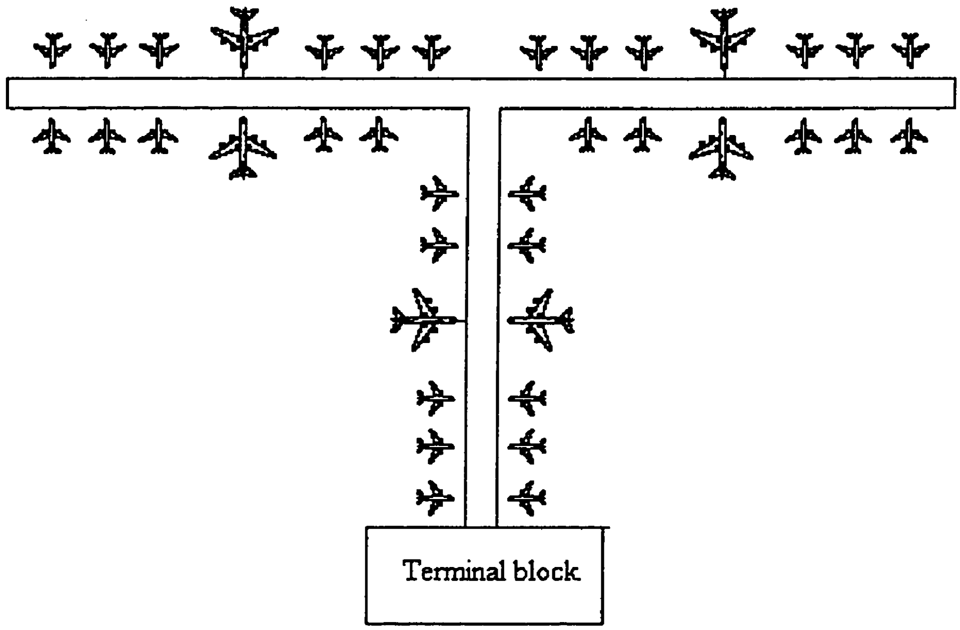


Figure 4.15: T-shaped pier-satellite

The analyses done in this section will be based on the same definitions and assumptions made for the pier terminal case. However, as pier satellites are usually attached to the terminal block, only the case of entrance through the pier end will be considered.

4.4.1 Description of the pier satellite types

4.4.1.1 Circular Pier Satellite

The greatest advantage of a circular pier satellite for NLA operations is the existence of a very large departure lounge at the satellite section, which is usually of common use for all gates at the satellite section. If the size of the departure lounge is a constraint at the pier section, then the NLA could be parked at the satellite section and take advantage of the departure lounge commonality as will be described in Chapter 5.

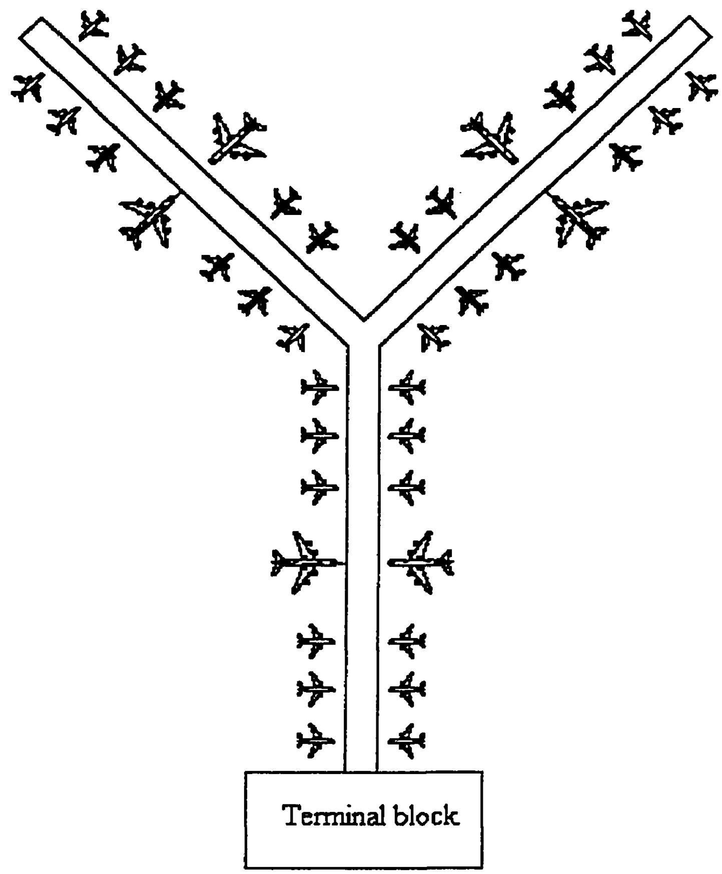


Figure 4.16: Y-shaped pier-satellite

Figure 4.17 shows the configuration of a circular pier-satellite terminal for 1 NLA position. The pier section has a useful length L_1, whereas 2 L_2 is the useful perimeter of the circular satellite. At the junction of the pier and the satellite portions, an extra clearance must be kept where no aircraft can be parked due to manoeuvring constraints. Thus a section of the pier of length y_1 cannot be used for aircraft docking, neither can a section 2 y_2 of the satellite perimeter. Under these circumstances, the useful perimeter of the satellite section is

$$L_2 = \pi R - y_2 \tag{4.25}$$

where

R = radius of the circular satellite section.

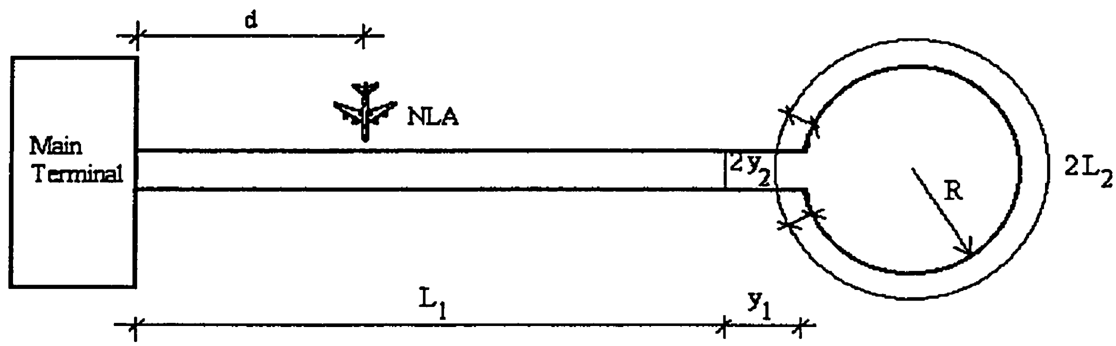


Figure 4.17: Circular pier satellite configuration for 1 NLA gate

4.4.1.2 T-shaped Pier Satellite

The configuration of a T-shaped pier satellite is shown in Figure 4.18. In a T-shaped configuration, the terminal consists of two piers: one is the main concourse, with one end attached to the terminal building and the other to the centre of the satellite section. This main concourse has a useful length L_1 and must keep a clearance y_T of the satellite section. Each arm of the satellite section has a useful length L_2. Both arms must keep a clearance y_T of the main concourse on the inner face; however, aircraft can be parked all along the outer face of the satellite.

4.4.1.3 Y-shaped Pier Satellite

The Y-shaped pier satellite can be considered a special case of the T-shaped one where the angles between the arms and the main concourse are not 90°, and aircraft cannot be parked near the junctions. Figure 4.19 illustrates this configuration. In our study, the angles are assumed to be 120°, and the satellite arms to be of the equal length.

4.4.2 Evaluation of Walking Distances

The three types of pier satellite terminals in this study have in common a main concourse to which a satellite is attached. Defining 2 L_3 as the total terminal frontage length available for aircraft parking at the satellite section, it follows that

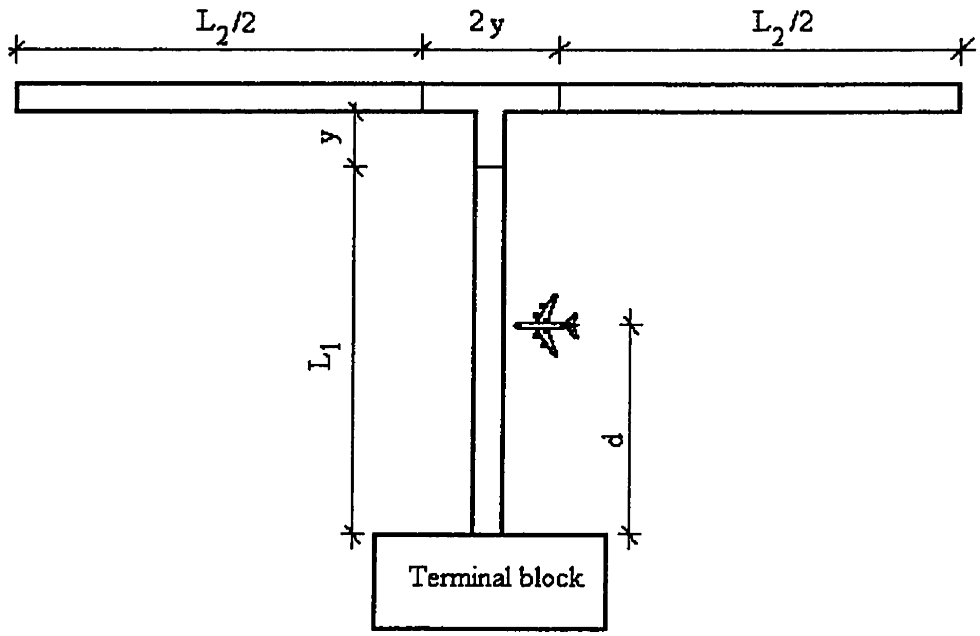


Figure 4.18: T-shaped pier satellite configuration for 1 NLA gate

$$L_3 = \begin{cases} L_2, & \text{Circular and Y - shaped satellites;} \\ L_2 + y, & \text{T - shaped pier satellite} \end{cases} \tag{4.26}$$

For the calculation of the walking distances, in addition to the assumptions made for the pier terminal case, we will further assume that passengers going to or from a gate within the circular satellite must pass through the satellite centre. Therefore, if the NLA gate is located at the pier section, then the mean walking distance for all NLA passengers will be

$$W = p_T \left[\frac{d^2 + (L_1 - d)^2 + (L_1 - d + y_1 + 2R)2L_3}{2(L_1 + L_3)} \right] + (1 - p_T)d \tag{4.27}$$

$$W = p_T \left[\frac{d^2 + (L_1 - d)^2 + 2(L_1 - d + \frac{L_3 + 7y}{4})(L_3 - y) + 2(L_1 - d + \frac{3y}{2})y}{2(L_1 + L_3)} \right] \tag{4.28}$$
$$+ (1 - p_T)d$$

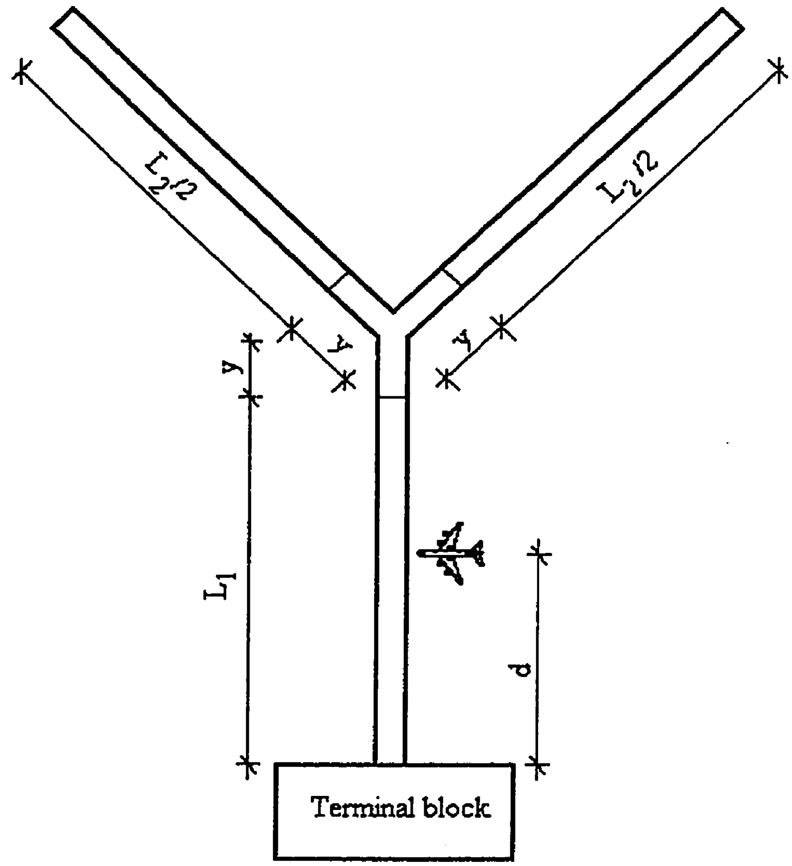


Figure 4.19: Y-shaped pier satellite configuration for 1 NLA gate

$$W = p_T \left[\frac{d^2 + (L_1 - d)^2 + 2(L_1 - d + 2y + L_3 / 4)L_3}{2(L_1 + L_3)} \right] + (1 - p_T)d \qquad (4.29)$$

for a circular, T-shaped and Y-shaped pier satellite, respectively.

Differentiating W with respect to d and comparing it to zero, we find that the optimal location for the NLA gate within the concourse section is

$$d' = \begin{cases} L_1, & p_T \geq 0.5(1 + L_1 / L_3) \text{ and } L_3 \geq L_1; \\ 0, & p_T < 0.5; \\ (L_1 + L_3)\left(1 - \dfrac{1}{2p_T}\right), & \text{otherwise.} \end{cases} \quad (4.30)$$

for all pier satellite types. This location yields the mean walking distances given in Table 4.4. The optimal location for the NLA gate is illustrated in Figure 4.20. It can be seen that the optimal location within the concourse changes more rapidly towards the satellite section with p_T as the ratio L_3/L_1 increases.

So far, we have studied the location of the NLA gate restrained to within the pier section. In order to determine whether the NLA gate should be at the main concourse or at the satellite section, we must compare the walking distances yielded by each location. In the case of a circular satellite, any position within the satellite section will yield the same mean walking distance. As to T- and Y-shaped pier satellites, the minimum walking distance will occur when the NLA gate is located as close as possible to the junction with the main concourse. Table 4.5 shows the mean walking distances for this case. By comparing W^{CONC} and W^{SAT}, one can determine the conditions under which $W^{CONC} > W^{SAT}$, i.e. the mean walking distance will be greater if the NLA gate is positioned within the main concourse instead of at the satellite section. In this case, the best location for the NLA gate would be at the satellite section – anywhere within the circular satellite or as close as possible to the junction at a T- or Y-shaped pier satellite. Table 4.6 shows these conditions for each pier satellite type.

4.4.3 More than One NLA Gate

At many airports, two or more NLA gates must be provided to meet the demand. In that case, it is possible to draw some conclusions from the analyses done for one NLA gate and for single piers.

Two NLA gates could be placed on opposite sides of the main concourse or of one of the satellite arms, at the same distance from the terminal block. In that case, the results of the one-gate analysis still apply. Exception is made to passengers who transfer directly between the two NLA gates, who must be subtracted from the total passengers for the computation of p_T. This is due to the fact that transfers between NLA have a negligible walking distance (the width of the pier).

Table 4.4: Mean walking distances for optimal NLA gate location within the concourse

Pier satellite type	W^{CONC}
Circular	$L_1(1-p_T)+\frac{p_T[(L_1)^2+2L_3(y_1+2R)]}{2(L_1+L_3)}$, $p_T \ge (1+L_1/L_3)/2$ and $L_3 \ge L_1$; $\frac{p_T[L_1^2+2L_3(L_1+y_1+2R)]}{2(L_1+L_3)}$, $p_T < 0.5$; $\frac{1}{4p_T(L_1+L_3)}\left\{\begin{matrix}-L_1(1-4p_T+2p_T^2)(L_1+2L_3)\\+L_3[4p_T^2(y_1+2R)-L_3(1-p_T^2)]\end{matrix}\right\}$, otherwise.
T-shaped	$L_1(1-p_T)+\frac{p_T[L_1^2+(2L_3-y)\frac{L_3+7y}{4}+3y^2]}{2(L_1+L_3)}$, $p_T \ge (1+L_1/L_3)/2$ and $L_3 \ge L_1$; $\frac{p_T[L_1^2+2(L_3-y)(L_1+\frac{L_3+7y}{4})+2y(L_1+3y/2)]}{2(L_1+L_3)}$, $p_T < 0.5$; $\frac{1}{4p_T(L_1+L_3)}\left\{\begin{matrix}(-1+4p_T-2p_T^2)[L_1^2+y^2+2L_1(L_3)]\\+(L_3-y)[2y(4p_T-1)\\+(-1+4p_T-3p_T^2)(L_3-y)]\end{matrix}\right\}$, otherwise
Y-shaped	$L_1(1-p_T)+\frac{p_T[L_1^2+2L_3(2y+L_3/4)]}{2(L_1+L_3)}$, $p_T \ge (1+L_1/L_3)/2$ and $L_3 \ge L_1$; $\frac{p_T[L_1^2+2L_3(L_1+2y+L_3/4)]}{2(L_1+L_3)}$, $p_T < 0.5$; $\frac{1}{4p_T(L_1+L_3)}\left\{\begin{matrix}-L_1(1-4p_T+2p_T^2)(L_1+2L_3)\\+L_3[8yp_T^2+(-1+4p_T-3p_T^2)L_3]\end{matrix}\right\}$, otherwise

Table 4.5: Mean walking distances for NLA gate located at the satellite section

Pier satellite type	W^{SAT}
Circular	$p_T\left[\frac{2L_3R + L_1(L_1/2 + y_1 + 2R)}{L_1 + L_3}\right] + (1 - p_T)(L_1 + y_1 + 2R)$
T-shaped	$p_T\left[\frac{(L_1 + y)^2 + (L_3 - y)(3y + L_3)/2}{2(L_1 + L_3)}\right] + (1 - p_T)(L_1 + y)$
Y-shaped	$p_T\left[\frac{2L_1(L_1/2 + 2y) + L_3(2y + L_3/4) + L_3^2/4}{2(L_1 + L_3)}\right] + (1 - p_T)(L_1 + 2y)$

Table 4.6: Conditions for the location of the NLA gate at the satellite section

Pier satellite type	Conditions for $W^{CONC} > W^{SAT}$ (optimal location at the satellite section)
Circular	$L_3 > L_1$ $p_T > (1 + L_1/L_3)/2$ $y_1 > \frac{4p_T[L_1 + L_3(1 - p_T)](L_3 - 2\frac{L_3 - y_2}{\pi}) - (L_1 + L_3)^2}{4p_T[L_1 + L_3(1 - 2p_T)]}$
T-shaped	$L_3 \geq L_1$ $p_T > (1 + L_1/L_3)/2$
Y-shaped	$L_3 > 2L_1$ $p_T > 2(1 + L_1/L_3)/3$

The location of three or more NLA gates will have a greater impact on the walking distance of non-NLA passengers. Therefore, it cannot be determined analytically for a general case. However, from the analyses performed so far, it is possible to infer that the gates should be clustered at the main concourse near the terminal block, if the proportion of OTNH passengers is high, or near the concourse-satellite junction, if that proportion is low. In the case of a circular satellite, it may be preferable to park all NLA's at the satellite, to take advantage of the common lounge provided by this configuration.

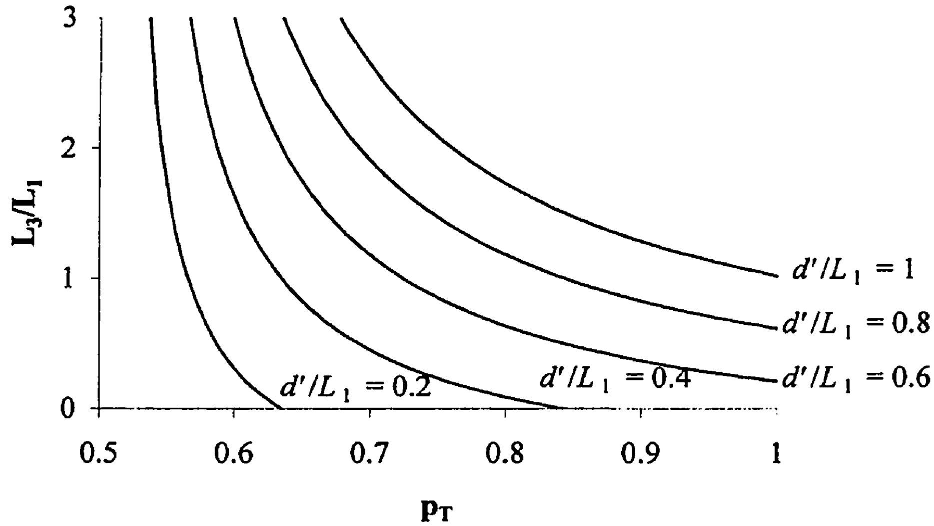


Figure 4.20: Optimal location of the NLA gate within the concourse section

4.5 PARALLEL PIER TERMINAL CONFIGURATION

Parallel-pier terminals have become very popular in the 80's and 90's. Not only does this configuration provide shorter walking distances for hub operations; it also allows for easy expansion of each individual pier and for the construction of other piers as demand makes it necessary. However, this configuration usually requires the use of underground Automated People Movers (APM) to connect the piers and the terminal block. These APM systems are very costly and also impose a certain level of disutility to the passenger, although this disutility is supposedly much lower than that of walking. Blow [1997] suggests that early investment in an underground APM system is not necessary and presents a multiple pier configuration that would not require such systems. Besides increasing walking distance, the configuration proposed by Blow may cause longer aircraft taxiing distances. Denver International (DIA) and Atlanta Hartsfield are the most prominent examples of this type of terminal configuration with the use of APMs.

With the exclusive-use policy adopted in most North American airports, airlines usually own one or more piers and have exclusive rights over those facilities – e.g. Denver's concourse B, which is exclusively operated by United Airlines. In this case, the location of NLA gates may be restricted to those piers managed and controlled by the airport authority. If an airline wishes to operate its own NLA at its own terminal, the location of the NLA gates can be done using the methodology described in Section 4.3. The same is valid for the cases where an international pier is provided – e.g. concourse A at Denver and concourse E at Atlanta – and one wishes to provide one or more NLA gate positions for international flights. These exclusive pier use policies are, however, very inefficient as every pier must be designed for its own peak hour. Peak hours for different operations may not be concurrent, however, which means that while one pier is fully occupied at a given time, the others may have a large amount of idle resources. Steinert & Moore [1993] suggest that terminals be designed for joint use by several airlines, for both international and domestic passengers. The new terminal at London Stansted is an example of parallel-pier configuration with common-gate usage policy. In this case, the NLA gates can be located at any piers and the impact on the terminal performance parameters such as walking distance and baggage handling requires a unique model to determine the best location of those gates, as well as the best overall geometry of the terminal.

4.5.1 Optimal Location – Basics and Assumptions

4.5.1.1 Terminal Configuration

Figure 4.21 shows the generic configuration of a parallel-pier terminal. The pier extended from the terminal block is numbered 0 and is assumed to have aircraft parking on the external face only. The remote piers are numbered 1 to *n* from the closest to the terminal block to the farthest and can accommodate aircraft on both faces. It is also assumed that the centres of the piers are aligned.

4.5.1.2 APM System

All APM stations are assumed to be similar and located at the pier centres. The distances between the pier stations are assumed to be the same whereas the distance between pier 1 and the terminal block can be different. The passenger capacity of the vehicles and the frequency of service are known and remain constant for the duration of the terminal's life span.

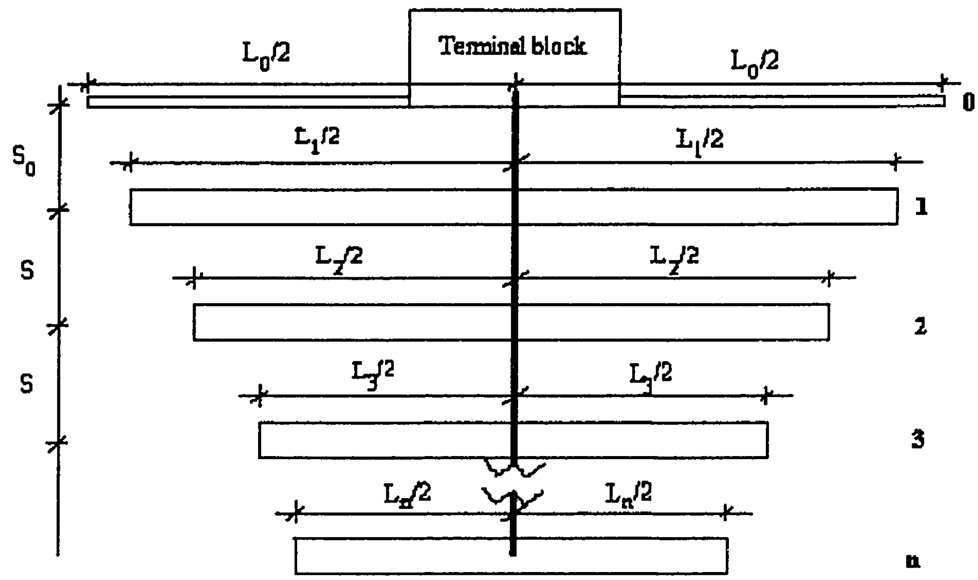


Figure 4.21: Parallel pier terminal

4.5.1.3 Types of Passengers

Passengers are divided into two categories: originating/terminating and transfers. Originating/terminating passengers initiate or terminate their flight at the airport; therefore they move in one direction only between the NLA gate and the terminal block. For terminating passengers, their movement consists of:

- walk from the NLA gate to the APM station;
- ride the APM to the terminal block;
- walk through the terminal block.

Originating passengers will take the same steps in the opposite direction.

Transfers arrive at and depart from the airport by aeroplane. They must therefore move from one gate to another. The proportion of transfers with respect to total passengers, p_T, is assumed to be known. Transfers are further subdivided into two subcategories: hub and non-hub transfers. Hub transfers move directly between the NLA gate and their arrival/departure gate, whereas non-hub transfers must pass through the terminal block for further processing. The proportion of hub transfers with respect to the total number of transfers, q, is also assumed to be known.

The movement of non-hub transfers consists of the following (the NLA gate could be either the arrival or the departure one):

- walk from the arrival gate to the APM station;
- ride the APM to the terminal block;
- walk through the terminal block;
- ride the APM to their departure pier;
- walk from the APM station to their departure gate.

Finally, hub transfers, if transferring to another gate at the same pier, just have to walk directly from their arrival gate to their departure gate. Those transferring to a flight parked at another pier take the following steps:

- walk from the arrival gate to the APM station;
- ride the APM to their departure pier;
- walk from the APM station to their departure gate.

4.5.1.4 Disutility of Passenger Movement

The disutility of passenger movement is comprised of three elements: walking, riding the APM, and access to the APM. The disutility of walking can be assumed to be proportional to the distance walked. In the same way, the disutility of riding the APM is proportional to the distance ridden. The disutility of access to the APM comprises all extra walking, changes of levels, and waiting associated with the process of boarding and unboarding the APM at the station. This disutility can be considered constant for those passengers who use the APM system [Wirasinghe & Bandara, 1992]. All the mean disutilities in the objective function are a function of the pier i where the NLA gate is located. The pier i is the decision variable in the problem. We will determine i such that the total mean disutility of passenger movement is minimised.

The objective function is to minimise the mean disutility of passenger movement, including walking and riding the APM. This objective function is similar to the one presented in Bandara [1989] and can be written as

$$\min W = (1 - p_T)W_O + p_T[q\,W_H + (1-q)W_{NH}] \tag{4.31}$$

where

W = mean disutility of passenger movement for all passenger types;

W_O = mean disutility of passenger movement for originating/terminating passengers;

W_H = mean disutility of passenger movement for hub transfers;

W_{NH} = mean disutility of passenger movement for non-hub transfers.

The expressions for each disutility type depend on the number of NLA gates under consideration and on whether they will be located at the pier centre or at the pier end.

4.5.2 One NLA Gate

The location of a single NLA gate in a parallel pier terminal consists of determining both the pier and the point within the pier where the NLA gate should be located. With respect to the pier where the NLA gate will be located, it has been shown in Section 4.3 that, if no airside constraints prevent this, the best location is in the middle of the pier, as close as possible to the pier entrance. If airside constraints exist – such as insufficient inter-pier lane width – then the NLA should be parked at the end of the pier. Given the airside constraints, the problem is then reduced to choosing which of the piers should accommodate the NLA gate.

4.5.2.1 No Airside Constraints – NLA Gate at the Pier Centre

In the case of one NLA gate located at the middle of the pier, the walking of passengers from the NLA gate to the APM station is negligible. Clearly the mean walking distance from the APM station to the other aircraft gates – and to the terminal block – is independent of the pier where the NLA gate is located. Therefore, the location of this NLA gate will be based on the disutility of using the APM system.

Originating/terminating passengers must ride the APM between the pier where the NLA gate is and the terminal block. For these passengers, the NLA gate should be positioned as close as possible to the terminal block. Non-hub transfers must move to and from the terminal block. The part of the movement between the CJ gate and the terminal block does not depend on the NLA gate location; the part comprising the movement between the terminal block and the NLA gate is similar to the case of originating/terminating passengers. Therefore, the disutility of these passengers will be minimised when the NLA is near the terminal block. Only hub transfers, who move directly from their origin pier to their destination one, will benefit from locating the NLA at an intermediate pier. The best location for the NLA gate is hence dependent of the total proportion of hub transfers, $p_T \cdot q$.

Should there be no hub transfers, it is clear that the NLA gate location that minimises the disutility of using the APM system is at or near the terminal block. Figure 4.22 shows this solution for a terminal where the NLA is allowed to park at the terminal block. Conversely, if all NLA passengers are hub transfers, the middle pier is preferred. The conclusion is that only when the total proportion of hub transfers $p_T \cdot q$ is very high should the NLA gate be located somewhere else than at or close to the terminal block pier.

4.5.2.2 Airside Constraints – NLA Gate at the Pier End

Airside constraints, such as the spacing available between piers, may restrict NLA operations to the pier end. This solution may even be the best when other factors are counted in, like the possibility of parking at 45 degrees to allow for two NLA to park at the pier end and the widening of the pier at the end to provide a larger departure lounge.

If, due to any of the factors mentioned above, the NLA gate must be located at the pier end, then all NLA passengers must walk between the end of the pier and the APM station, i.e. half the length of that pier. Exception is made for the hub transfers within the pier -– who can walk directly between the NLA and the CJ gates. Therefore, the optimal location of the NLA gate will be a balance between walking and APM riding disutilities.

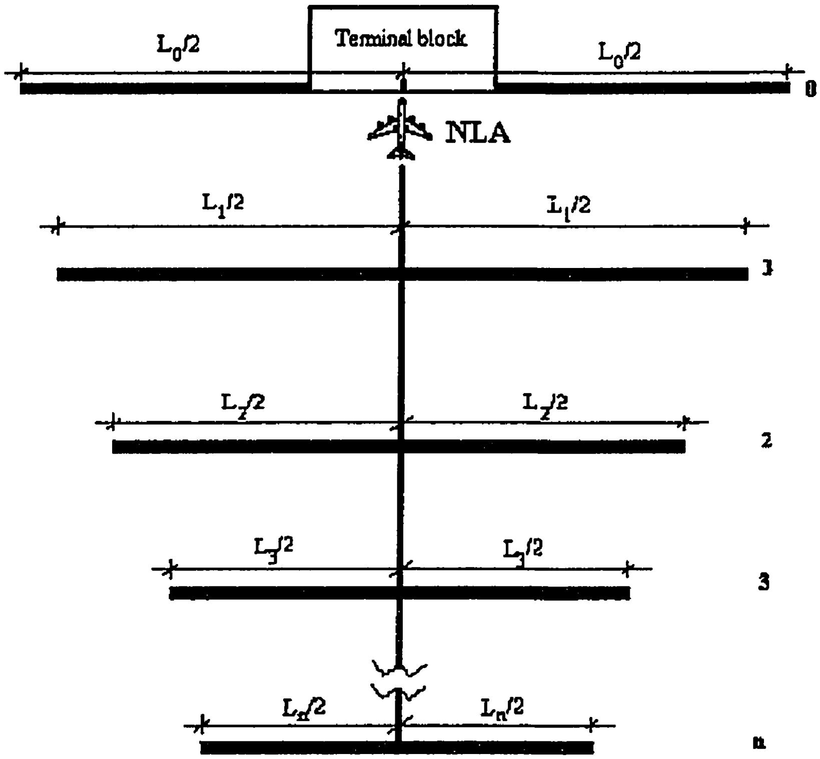


Figure 4.22: NLA gate at the middle of the pier attached to the terminal block

Wirasinghe & Bandara [1992] showed that the best geometry for a parallel pier terminal with APM is with the length of the piers increasing towards the terminal block. In a terminal with such configuration, the best location for the NLA will depend on the walking/APM riding disutility ratio. If this ratio is high, the NLA should be parked at the end of the shortest pier – as illustrated in Figure 4.23, for this will provide the lowest disutility of walking for all passengers. For a low walking/APM disutility ratio, OTNH passengers will be best served when the NLA gate is close to terminal block, whereas hub transfers would have the lowest mean disutility when the NLA gate is at an intermediate pier. The best overall location in this case will therefore be near the terminal for a low proportion of hub transfers, and moving towards the middle pier for higher proportions of hub movements.

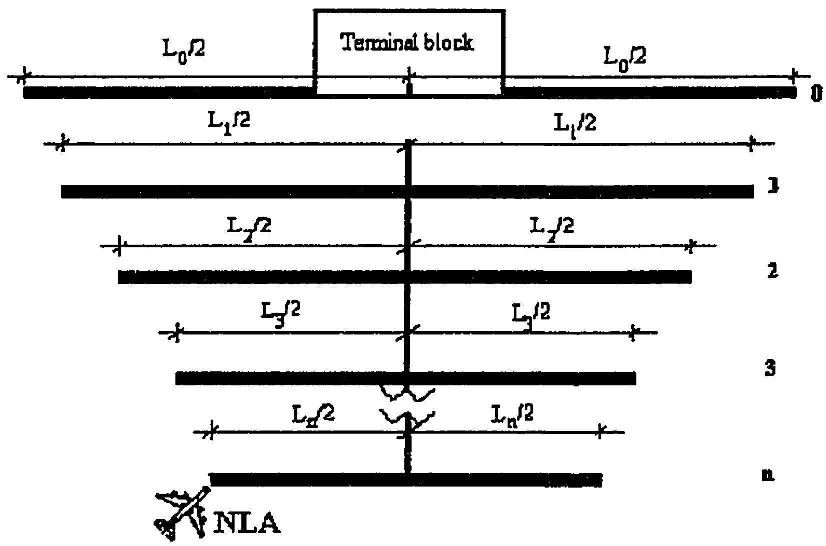


Figure 4.23: NLA at the end of the shortest pier

4.5.3 Two or More NLA Gates

4.5.3.1 NLA allowed at the Pier Centre

It has been show that, if NLA are allowed at the pier centre, then one single NLA gate should be positioned at the centre of one of the piers closer to the terminal block. For more than one NLA, it seems clear that they should always be clustered around the centre of one or more piers. Besides providing minimum disutility for passengers, this solution will also minimise passenger walking/baggage transfer between NLA. The size of each NLA cluster will depend mainly on the walking/APM riding disutility ratio.

For two NLA only, the solution found for one NLA could be easily adapted for two. At the terminal block pier, two NLA could be put side by side at the pier centre. At a remote pier, these two aircraft could be parked on opposite faces of the pier. Up to four NLA can be parked this way at the centre of a remote pier.

For one pier, as the number of NLA increases, so does the walking/baggage handling distance between the NLA farther away from the centre and the APM station, to a point where the increment in the walking disutility – with respect to the disutility yielded by parking the NLA at the pier middle – exceeds the increment in the disutility of APM riding that would be yielded by parking this NLA at the next remote pier, moving away from the terminal block. In this case, those NLA should be parked at or near the centre of the next remote pier, initiating a new cluster at that pier. As the number of NLA increases, the clusters tend to form a triangle as shown in Figure 4.24, with the size of the clusters increasing towards the terminal block. The actual form of that cluster triangle will depend on the ratio of walking to APM riding disutilities. The lower that ratio, the larger the clusters located closer to the terminal block. Figure 4.24 shows different arrangements for 10 NLA gates at a terminal with a terminal block pier and 3 remote piers. In Figure 4.24 (a), the high walking/APM riding disutility ratio causes the NLA to be more scarcely distributed among the piers. In Figure 4.24 (b), the low ratio allows the NLA to be more concentrated near the terminal block.

4.6 OPTIMAL CONFIGURATION WITH INTELLIGENT GATE ASSIGNMENT

The formulation used in the previous sections is based on the assumption that hub transfers are evenly distributed through the gates. However, airlines attempt to reduce walking distance by parking aircraft with connecting passengers as close to each other as possible, and by assigning larger aircraft to gates closer to the entrance of the airside building. This intelligent gate assignment can reduce the mean walking distance in a terminal considerably, to the extent that the shape of the building may cease to be the main determinant of walking distances for transfers.

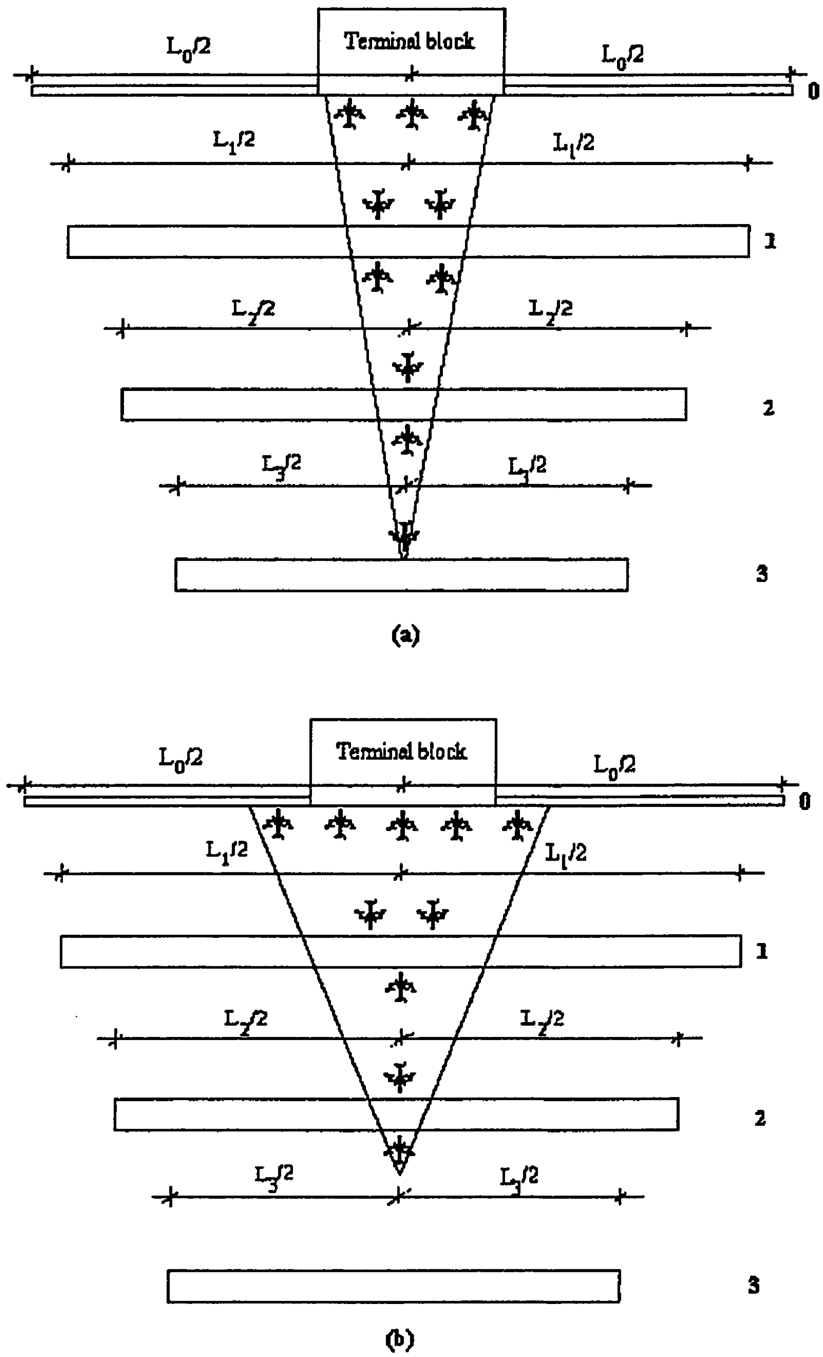


Figure 4.24: NLA gate locations for different ratios of walking to APM riding disutilities.
(a) high ratio (b) low ratio

To evaluate the impact of intelligent gate assignment on passenger walking distance, de Neufville et al [2001] have developed a spreadsheet model that allows the airport planner to model any airport configuration and objectively evaluate different scenarios. The spreadsheet model consists of an impedance matrix and a flow matrix. The impedance matrix gives a measure of the disutility of moving between gates and between the gates and the entrance of the building. This disutility could be represented by walking distance, walking time, or whatever other measures associated with the difficulty of moving within the terminal. In turn, the flow matrix shows the number of passengers moving between the gates and from/to the entrance. Multiplying those two matrices, one obtains a "passenger-impedance" matrix that can be used to plot a walking distance distribution chart such as the one shown in Figure 4.25 and to obtain the mean walking distance.

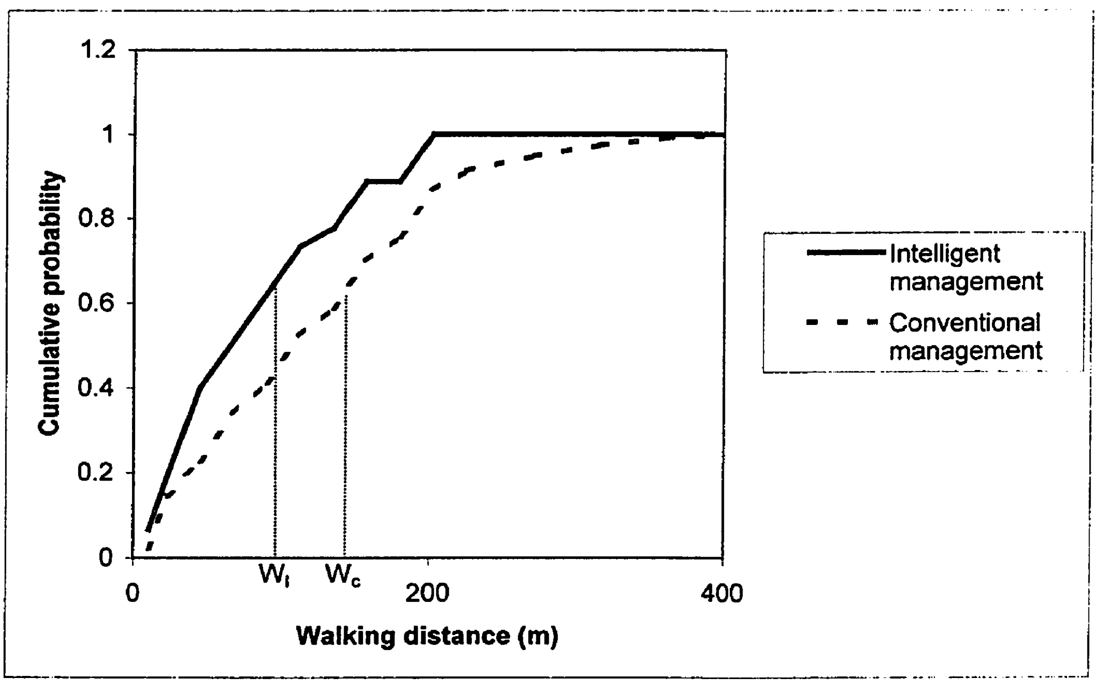


Figure 4.25: Effect of intelligent gate assignment on walking distances in a pier terminal with entrance in the middle

Figure 4.25 was drawn from an analysis considering 20 gates in a pier terminal with the entrance in the middle. In this analysis, one gate, located near the middle of the terminal building, was assumed to be an NLA gate that handles 10% of all passenger traffic. The proportion of transfers is 60%, and the axial distance between gates is 45.5 m. It can be seen in Figure 4.25 how intelligent gate assignment considerably improves the performance of the terminal.

Similar analyses were performed for a pier-finger (with entrance at one end), a T-shaped and a Y-shaped pier satellite terminals. The pier satellites were assumed to have 8 gates in the concourse section and 6 gates in each of the satellite "arms". In the T-shaped case, the NLA gate was parked at the T junction, whereas in the other two cases it was parked at the far end of the pier or of one of the Y arms.

In Figure 4.26, it can be seen how the location of the entrance to the building affects walking distance. Both designs have similar performances for transfers. However, because in pier-fingers passengers must walk all the way to one end of the terminal, and because the NLA is parked at the opposite end, walking distances are much greater, especially for local passengers.

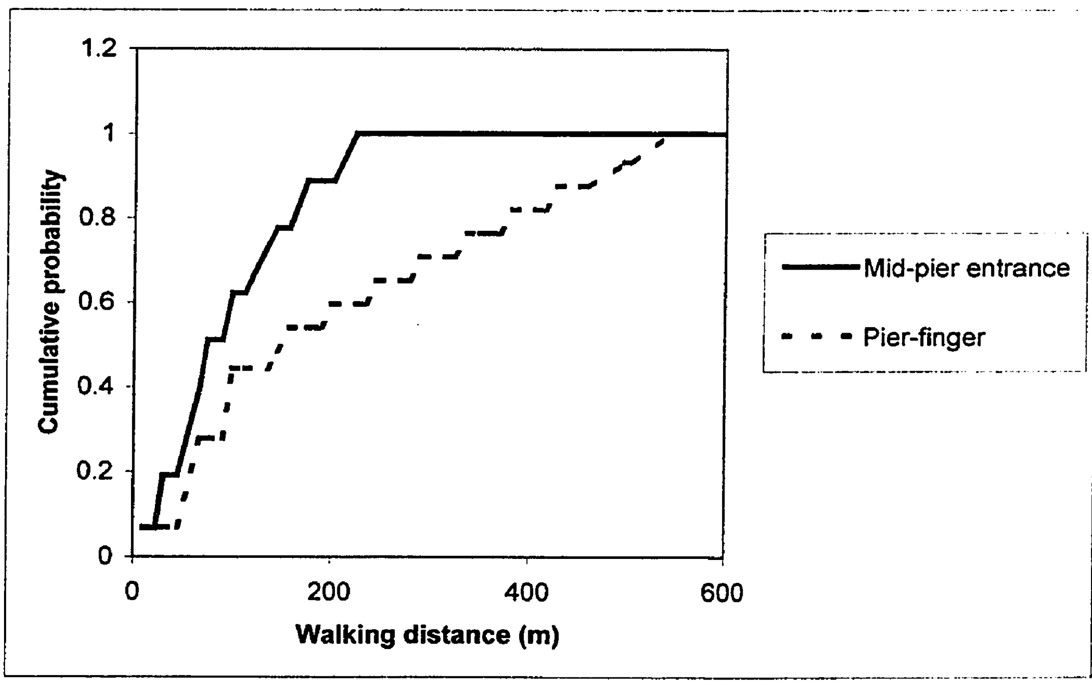


Figure 4.26: Comparison of a pier with entrance in the middle and a pier-finger, proportion of transfers = 0.6

Pier satellites are an attempt to reduce maximum walking distances by splitting the terminal into shorter arms. However, this advantage is somewhat lost because aircraft cannot be docked near the junction. A comparison between these three designs shown in Figure 4.27 illustrates this point. It can be seen that pier-satellites have a lower maximum but roughly the same mean walking distances, which are shown in Table 4.7

Table 4.7: Mean walking distances within the terminal, proportion of transfers = 0.6

Terminal types	Mean walking distance (m)
Pier, entrance in the middle	90
Pier finger	202
T-shaped pier satellite	199
Y-shaped pier satellite	204

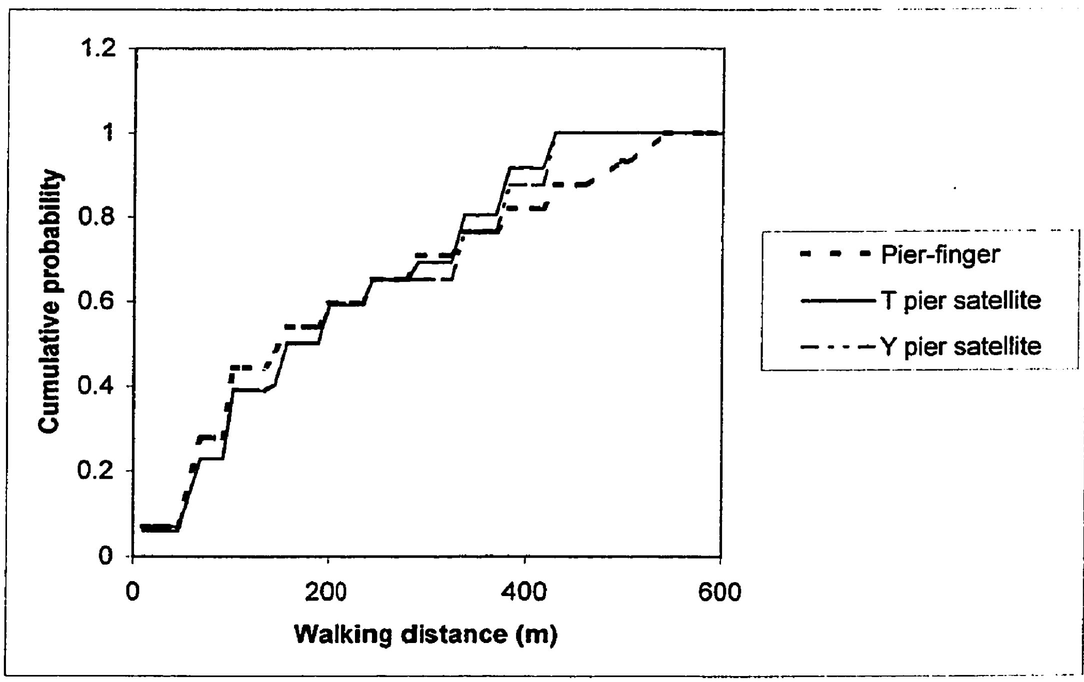


Figure 4.27: Comparison of pier-finger, T-shaped and Y-shaped pier satellites performances, proportion of transfers = 0.6

4.7 SUMMARY

4.7.1 Single Pier

For piers with only one or two NLA positions, the approximation of the problem to a continuous distribution of passengers along the pier provides an accurate, easy to understand insight to the problem of locating those gates in the pier. Four basic scenarios were studied using this approach, combining the location of the pier entrance – at one of the pier ends or at the pier centre – and the number of NLA positions – one or two.

In the case of either a sole NLA gate or two gates facing each other and entrance at the pier centre, the best location is as close as possible to the pier centre. If the pier entrance is located at one end of the pier, the best location will vary according to the proportion of passengers who are hub transfers. However, regardless of the proportion of transfers, the NLA gate position should be located in the same pier half as the entrance.

For two NLA gates positioned on the same side of the pier, it has been shown that they should be located side by side at the pier centre, if that is where the entrance is. On the other hand, if the pier entrance is located at one of the pier ends, then the best location for the NLA gates will depend on the proportions of hub transfers and on the minimum separation between those gates, as they should also be put side by side.

A method to exactly locate more than two NLA gates in pier terminals using simulated annealing has been proposed. This method can be expanded for application to other terminal concepts by determining the correct functions for walking distance for each different terminal concept. It can also be adapted to include other criteria in the objective function, such as baggage operations.

4.7.2 Pier Satellite

For pier satellites it has been shown that, just as in the case of a single pier, the NLA gate should be located as close as possible to the terminal block if the proportion of passengers who must walk to or from the terminal block is above 50%. If more than 50% of the NLA passengers are allowed to walk directly between the NLA gate and another gate within the terminal, then the best location for the NLA gate will depend on the actual proportion of transfers and on the relative lengths of the main concourse and of the satellite. If the main concourse airside frontage is longer than that found at the satellite section, then the minimum walking distance will occur when the NLA gate is located at the main concourse. Only if the satellite airside frontage is longer than that of the main concourse and with a very high rate of transfers should the NLA be parked at the satellite section.

In the case of more than two NLA gates, it can be inferred from the analysis done for one gate that those gates should be clustered near the terminal block for a low rate of hub transfers, and at or near the satellite section for a high rate. A circular satellite provides a very large common departure lounge and thus it may be preferable to park the NLA at the satellite in the case.

4.7.3 Parallel Pier Terminal

Parallel remote piers may pose a severe constraint to NLA operations due to possible lack of sufficient clearance in-between the piers. If that is the case, then the NLA gates should be positioned at the end of the shortest piers, as allowed by the airside constraints.

If the distance between piers allows NLA to be parked near the centre of the pier, then the NLA positions should be clustered at the centres of piers, with the size of the clusters resembling a triangle. The shape of the triangle will depend on the disutility ratio between walking and APM riding – the greater that ratio, the smaller the base of the triangle.

CHAPTER 5

SIZING THE DEPARTURE LOUNGE FOR THE NLA

5.1 INTRODUCTION

Departure lounges – also known as holding rooms – are "buffer" areas designed to accumulate passengers until the time of boarding. The lounge is located next to the boarding gate and is the very last airport terminal facility used by enplaning passengers before boarding the aircraft.

Moving passengers into the aircraft is a critical activity for both aircraft and gate productivity. For both turnaround and thru flights, boarding of passengers cannot start until cabin cleaning is done. Braaksma and Shortreed [1971] have shown that cabin cleaning is in the critical path of the gate activity schedule for all turnaround flights and most thru flights using conventional jets. For starting flights, there is no literature covering critical path for gate activities, and it will be assumed in this work that passenger boarding is in the critical path. Hence, boarding usually starts as close to the scheduled door-closure time as possible, and must be performed as quickly as possible to allow for the minimum gate occupancy time.

The departure lounge not only provides space for passengers. Many passengers arrive long in advance of the boarding time and have considerably high dwelling times. Such passengers require servicing facilities such as washrooms and cafeterias. Airlines also require space for counters and circulation.

The main problem in designing the departure lounge is to determine the amount of space that should be made available to passengers. Since passengers spend a considerable time in this facility, their perception of comfort standards can be higher than in other facilities. Passengers who arrive early would prefer to be seated while they wait. As seated passengers occupy a larger area than standing passengers, the number of seats is also of critical importance for the determination of the total lounge area [Wirasinghe & Shehata, 1988].

Some specific issues are brought up by the introduction of the NLA. Since the boarding process is in the critical path of gate activities, it is crucial that boarding be done as fast as possible. Manufacturers are struggling to allow for a turnaround time not much higher than the Boeing 747's, with two hours as the maximum acceptable [Airport World, 1996]. To achieve this goal, the NLA will most likely require special boarding arrangements, such as the addition of a second floor to the departure lounge and the simultaneous use of two loading bridges, as seen in Figure 5.1.

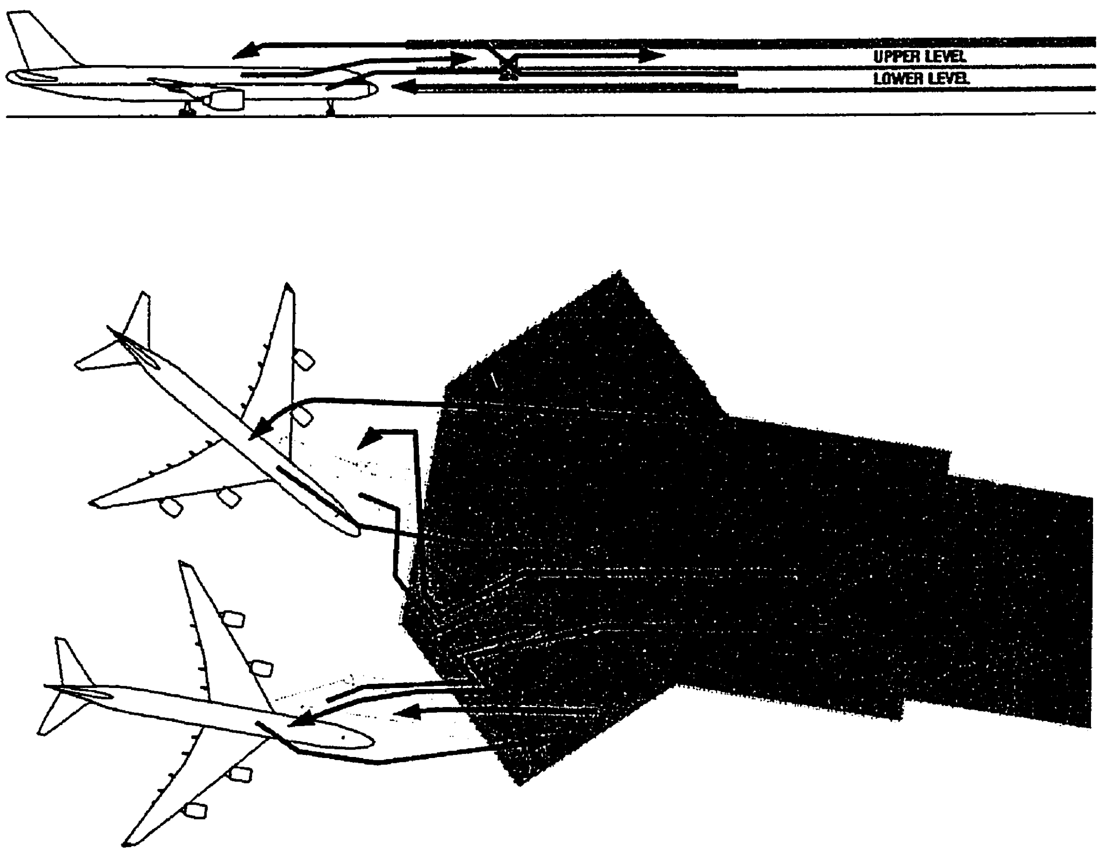


Figure 5.1: Use of two-level lounge and boarding bridge at Vancouver International Airport [Bianconi, 1999]

The boarding method currently in use by almost all large airports consists of making passengers walk through a boarding bridge connecting the departure lounge to the aircraft's main front door. This arrangement imposes a severe limitation on boarding rates, due to the small width of the door. The use of a second bridge, connecting the lounge to another aircraft door, helps overcome this limitation and improve the boarding rate. Schiphol Amsterdam, Frankfurt am Main and Zürich Kloten airports have already been using double bridges in high-capacity aircraft operations such as the Boeing 747 [Ashford et al., 1997; Blow, 1997]. Airbus [2000b] claims the use of two bridges will allow the A380 to have a turnaround time similar to the 747's. Figure 5.2 shows the passenger movements suggested by Airbus for the A380 with the use of two single-level bridges. Although only unloading movements are shown, loading would use the same movements with the directions inverted.

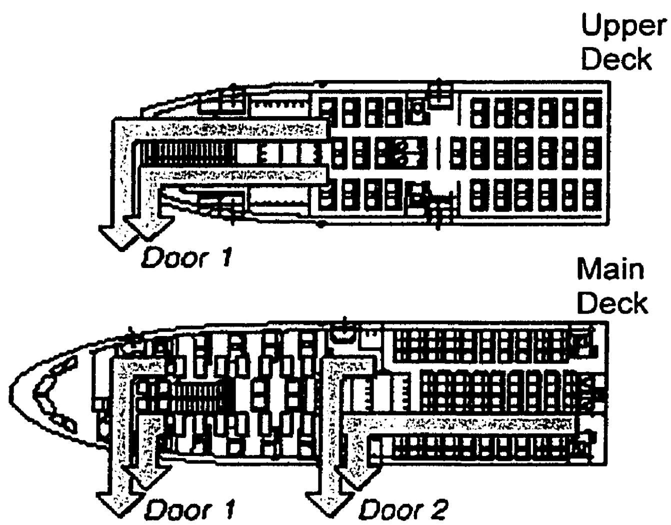


Figure 5.2: A380 de-boarding flows [Airbus, 2000b]

As the NLA will feature a second deck, separation of upper-deck and lower-deck passengers would allow for separate flows and a consequent lower boarding time. In addition, a lounge with two floors would require less ground area and would even facilitate the adaptation of existing terminals for NLA operations where the existing structure and operations allow for the addition of a second floor.

In fact, some airports already feature a second floor in the gate area, mostly for other purposes. Some airports such as Calgary International make use of a second floor to conduct international arriving passengers from the gate area to customs, separating them from departing and domestic arriving passengers. The new midfield terminal at Detroit

Metropolitan will have an Automated People Mover (APM) running right above the lounges. In such cases, a two-level arrangement for the departure lounge may be difficult or even impossible to implement. The following analysis, however, will not consider these cases. Rather, only airports where an additional level is either possible or already existent but adaptable – such as at the new international terminals at San Francisco and Vancouver – will be considered.

In this chapter, we discuss the implications of the NLA for the passenger departure lounge. A methodology based on deterministic queuing theory [Newell, 1982; Wirasinghe & Shehata, 1988] is presented to determine both the optimal area size and the optimal number of seats, such that the overall cost of using the lounge is minimised. The methodology also takes into account the effects of adding a second level and a second loading bridge to the existing structure.

For the purpose of this work, we will break the problem of sizing the departure lounge into two parts: designing a new facility and converting existing ones for the NLA.

5.2 LITERATURE REVIEW

The main concern of researchers regarding the sizing of the departure lounge has been to determine the number of passengers for which the lounge should be sized – the lounge *design capacity*. Different suggestions for the determination of this parameter are found in the literature. Transport Canada [1977] recommends that the lounge should be able to accommodate 80% of the passenger load for the largest aircraft to use the lounge, in case of a regular scheduled flight. For charter flights, the percentage recommended is 90%. A similar suggestion is given by Hart [1985], who proposed that 85% of the passenger load for a given design aircraft be used.

The numbers suggested above have the disadvantage of overlooking local passenger behaviour – i.e. how long in advance to the departure time the passengers arrive at the departure lounge, and how they value seat availability – which could make the ideal design capacity either higher or lower. Realising that, Hamzawi [1984] recommended that the lounge be sized to accommodate the peak 15-minute average occupancy throughout a given planning day. Paullin and Horonjeff [1969] proposed the use of deterministic queuing theory to size the departure lounge, as illustrated in Figure 5.3. If *A(t)* is the curve representing the cumulative passenger arrivals to the departure lounge, and *B(t)* represents the cumulative passenger departures from the lounge at the available boarding rate, and assuming the arrival rate is never higher than the boarding rate, then the maximum accumulation of passengers Q occurs at the time of commencement of boarding, t_B.

Using deterministic queuing theory [Newell, 1982], Wirasinghe & Shehata [1988] developed a method to determine both the lounge area and the number of seats, so that the overall cost of using the lounge is minimised. Figure 5.4 shows what happens when S seats are provided in the lounge. If *A(t)* is the cumulative number of arrivals at the lounge for a given flight, then the curve *G(t)* is the number of passengers who are forced to stand, i.e. the number of passengers who do not find seats available. The curve *G'(t)* represents passengers who are voluntarily standing – a phenomenon observed when boarding starts and some passengers get off their seats and line up for boarding. The area between *G'(t)*, *G(t)* and *B(t)* represents the total voluntary standing time. Area R_I represents the total compulsory standing time. It is easy to see that Area R_I decreases as the number of seats is increased.

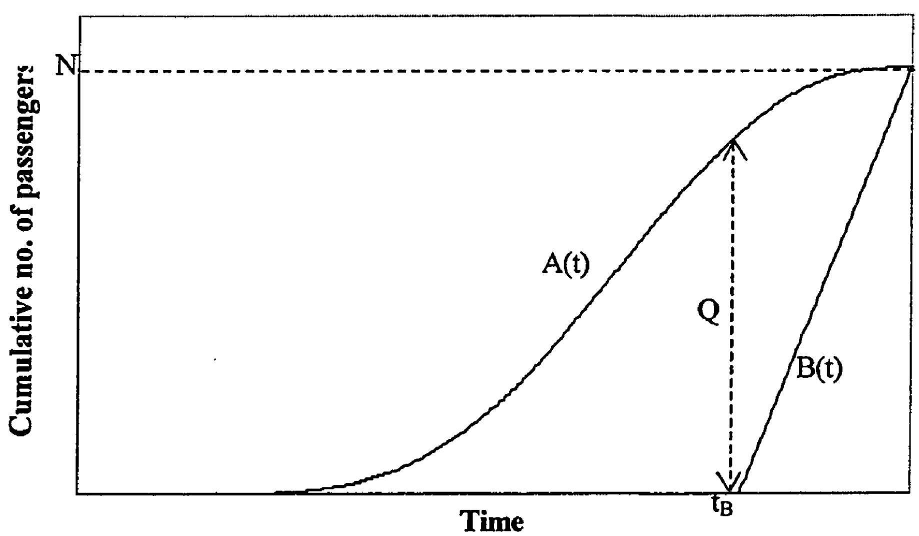


Figure 5.3: Typical boarding sequence

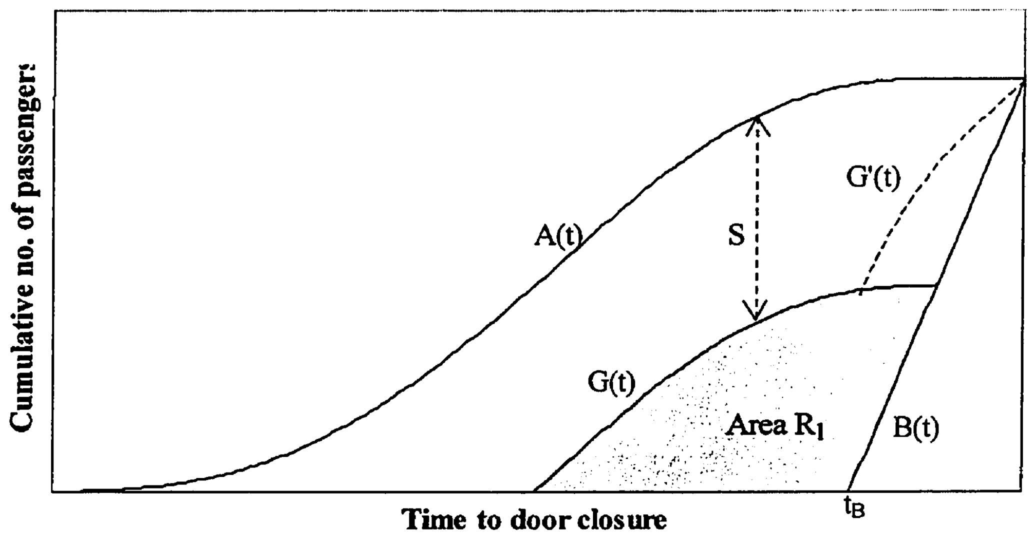


Figure 5.4: Determination of the number of seats

The overall cost of the lounge is given by the sum of the cost of construction, the cost of seats and a penalty for passenger standing time. Since seated passengers require more space than standing passengers [Transport Canada, 1977], both the cost of construction and the cost of seats increase with the number of seats provided. On the other hand, passenger standing time decreases as the number of seats increases. Hence there must be a value of the number of seats that minimises the overall cost of the lounge.

The method proposed by Wirasinghe & Shehata [1988] is the basis of the analysis done in this chapter. Thus, it will be explained in more detail and expanded when necessary in the following sections.

5.3 PLANNING FOR A NEW TERMINAL

A macro-model that is developed to analyse a large system such as a large airport or the national airport system must take into consideration the elasticity of the demand to the cost of the trip. When analysing a part of the system such as one departure lounge, however, it is very difficult to estimate the demand-price curve. In addition, the cost of the lounge accounts for just a small part of the total cost of the air trip for the passenger. In that case, the demand can be assumed to be inelastic to the cost of the lounge, allowing the planner to minimise the cost of the lounge for a fixed demand. The model explained in this section does so by taking into account the cost of lounge construction and the disutility of passenger standing, which substitutes for the passenger discomfort. The objective of the model is to determine the optimal lounge configuration in terms of number and seats and number of levels that minimise the overall cost of the lounge as described above.

5.3.1 The Basic Model

5.3.1.1 Determination of the Number of Passengers

Passengers arrive at the departure lounge following a cumulative arrival distribution $A(t)$, where t is the time remaining to door closure. Given the boarding rate b, it is assumed that boarding begins as late as possible, such that by the time of door closure, all passengers are on board. Thus the instant at which boarding begins, t_b, is given by

$$t_b = \frac{N}{b} \tag{5.1}$$

where N is the number of passengers who will be on the flight. The value of N is set to the passenger load of the largest aircraft that will make use of the lounge.

If the boarding rate b is high enough to ensure it is higher than the passenger arrival rate for the duration of the boarding process, then the maximum number of passengers simultaneously at the departure lounge, Q, is the cumulative number of passengers who will have arrived at the time of beginning of boarding, i.e.:

$$Q = A(t_b) = A(N/b) \tag{5.2}$$

It may happen – though unlikely – that the passenger arrival rate is higher than b at some instant during boarding. This is particularly true when the lounge is sized for the NLA, due to the high number of passengers being serviced at the same time. In this case, the maximum number of passengers at the departure lounge will be the highest value of the difference between the cumulative number of passengers arrived and the cumulative number of passengers boarded, i.e.:

$$Q = Max[A(t) - B(t)] \tag{5.3}$$

where *B(t)* is the boarding function, defined as:

$$B(t) = \begin{cases} N - bt, & t \le t_b \\ 0, & \text{otherwise} \end{cases} \tag{5.4}$$

Note that Equation 5.2 is a special case of Equation 5.3, in which b is always higher than the instant arrival rate.

The maximum accumulation of passengers could only happen at two points in time: the time of commencement of boarding, t_b, as shown in Figure 5.3; or the time after t_b at which the arrival rate falls below the boarding rate b, i.e. the time $t_M < t_b$ such that

$$\frac{dA(t_M)}{dt} = b \tag{5.5}$$

and

$$\frac{d^2 A(t_M)}{dt^2} < 0 \tag{5.6}$$

as shown in Figure 5.5.

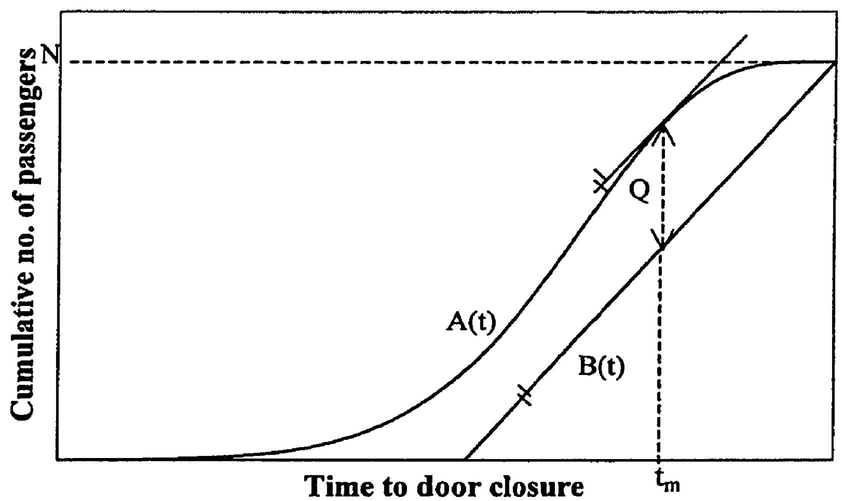


Figure 5.5: Example of Q occurring during boarding

If t_M exists, then the definition of Q is

$$Q = Max\left[A(t_b); A(t_M) - B(t_M)\right] \tag{5.7}$$

The above calculations are valid for one flight type only – flight type being defined as the combination of aircraft load and arrivals pattern. If more than one flight type will be sharing the lounge, then it must be sized for the most stringent one, i.e. the value of Q will be the highest passenger accumulation for all flight types.

5.3.1.2 Evaluation of the Lounge Area

The minimum total area of the departure lounge, A, is equal to the sum of the areas occupied by both sitting and standing passengers:

$$A = \alpha\left[m_1 S + m_2 (Q - S)\right] \tag{5.8}$$

where

S = number of seats in the lounge;

α = multiplier which accounts for passenger circulation, service and airline activities;

m_1 = area per sitting passenger;

m_2 = area per standing passenger.

Other areas may be added for service facilities and for architectural reasons.

The parameters m_1 and m_2 are of critical importance to the determination of the lounge area. Transport Canada [1977] suggests the values of 1.5 and 1.0 m^2/passenger, respectively. At Geneva Airport, the design criteria used to size the lounge were 1.4 and 0.9 m^2/passenger, respectively [Horonjeff & McKelvey, 1994].

5.3.1.3 Passenger Standing Time

The lower curve *G(t)* in Figure 5.4 represents the number of passengers that are forced to stand – because all available seats are occupied by other passengers – when S seats are available. The shaded area, called area R_1, is the area delineated by the seating curve, the boarding curve and the time axis. It represents the total passenger-standing time per aircraft departure for the design aircraft.

If the lounge is intended for shared use by different types of aircraft and flights, it is necessary to average the time of passenger standing for all flight types weighted by the probability of that flight type occurring. This weighted average passenger standing time per aircraft departure is

$$T_S = \sum_i p_i \,(\text{area } R_1)_i \tag{5.9}$$

where

(area R_1)$_i$ = value of area R_1 for flight type i;

p_i = probability of flight type i.

5.3.1.4 Choice of the Number of Seats

The choice of the value of S is made so that the overall cost of the lounge per aircraft departure

$$C_L = \gamma_C S + \alpha\gamma_L m_2 Q + \gamma_P T_S \tag{5.10}$$

is minimised, with the additional cost due to installing a seat, including the extra space, per aircraft departure:

$$\gamma_C = \alpha\gamma_L(m_1 - m_2) + \gamma_S \tag{5.11}$$

where

γ_L = cost of lounge per unit area per aircraft departure;

γ_S = cost of a seat per aircraft departure;

γ_P = disutility of compulsory standing, per passenger per unit of time.

In Equation 5.10, the first term represents the additional cost of installing seats; the second term represents the total cost of building and operating the departure lounge, excluding the additional cost due to seats; and the third term is the total cost of passenger compulsory standing. Since the second term does not depend on the value of S, the problem becomes minimising the sum of the first and third terms of Equation 5.10, i.e. finding the value of S that minimises the sum of the additional cost of seats and the cost of passenger standing:

$$C_S = \gamma_C S + \gamma_P T_S \tag{5.12}$$

The first term in Equation 5.12 increases with S, whereas the second term decreases as the value of S increases. Clearly, there must be a trade-off, i.e. a value of S for which the function C_S is minimised. The solution for this problem with the use of a spreadsheet is explained later in this chapter.

5.3.2 Expanded Model

5.3.2.1 Flight Delay

Everything does not always go right during the preparation for a flight, and it may happen that the start of boarding is delayed. Should that occur, passengers who are standing will have to keep doing so for an extra amount of time, with a correspondent addition in passenger discomfort. The added standing disutility is represented by the dark grey area in Figure 5.6. To account for that delay in the choice of the number of seats, we consider an average flight delay w_i and include its correspondent standing time for each flight type i in the calculation of the average passenger standing time:

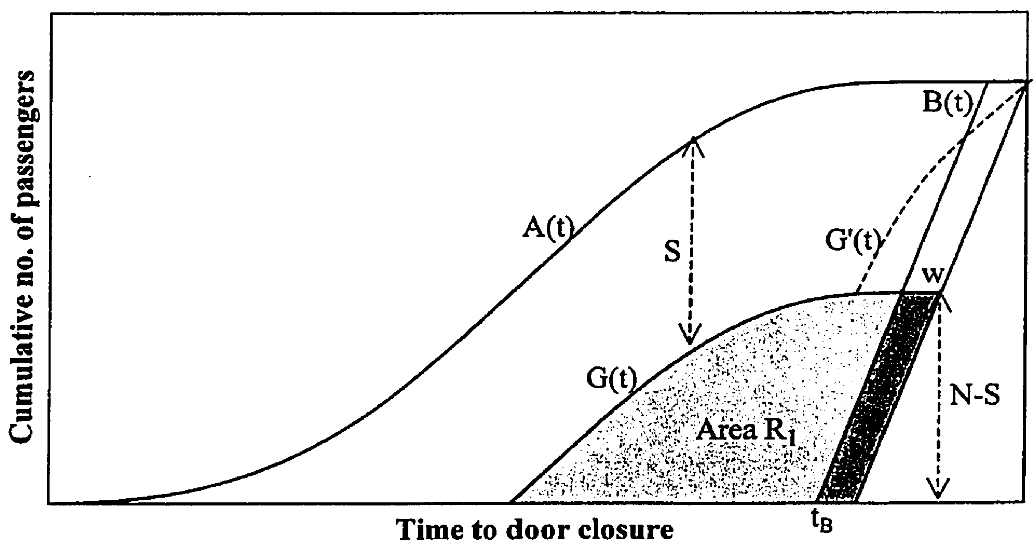


Figure 5.6: Passenger standing time with flight delay

$$T_S = \sum_i p_i[(\text{area } R_1)_i + w_i(N_i - S)] \tag{5.13}$$

where

N_i = design aircraft load for flight type i.

The parameters m_1 and m_2 represent the desired area per passenger so that a given level of service is provided to the passenger when Q passengers are in the lounge. However, should the flight be delayed, the lounge must then accommodate the full aircraft load N. It is then desirable to set a minimum area per standing passenger, m_3. As passengers will probably stand in circulation areas for short periods, it is also desirable to establish a new multiplier α_2 to replace α, such that $\alpha_2 < \alpha$. Hence, a constraint is added to the problem to account for this minimum level of service:

$$A \geq \alpha_2\left[m_1 S + m_3(N - S)\right] \tag{5.14}$$

Substituting for A from Equation 5.8 in Equation 5.14, it follows that:

$$S \leq \frac{(\alpha/\alpha_2)m_2 Q - m_3 N}{m_1 - m_3 - (\alpha/\alpha_2)(m_1 - m_2)} \tag{5.15}$$

i.e. an upper limit is imposed to the number of seats. Since the number of seats S must be non-negative, it follows from Equation 5.15 that

$$\frac{Q}{N} \geq \frac{m_3}{m_2}\frac{\alpha_2}{\alpha} \tag{5.16}$$

i.e. the proportion of the aircraft load for which the lounge is sized must be greater than or equal to the ratio between minimum and desired area per passenger – including circulation, passenger services, and airline activities – in order to satisfy the minimum level of service requirement. This imposes a lower limit to the design capacity Q, preventing one from choosing a low value even if that is the expected maximum demand in normal situations.

Since S will always be less than or equal to Q, the constraint represented by Equation 5.15 can only be active when the right side of the equation is less than Q; otherwise, that constraint will be redundant. The right side of Equation 5.15 will only be less than Q when

$$m_3 > (\alpha / \alpha_2 - 1) m_1 \frac{Q / N}{1 - Q / N} \tag{5.17}$$

If the inequality above is not satisfied, then the constraint in Equation 5.15 is redundant and the optimal solution will not depend on the value of m_3. Otherwise, the value of m_3 may determine the optimal solution if that constraint becomes active. It is then important to choose its value with care. It should be a value that allows passengers to spend short periods of time with a reasonable level of comfort. IATA [1995] suggests an area of 0.8 m^2 per passenger for a level of service D.

5.3.2.2 Calculation of the Area R_l

The cost minimisation problems discussed in the previous sections are non-linear programming problems, due to the presence of area R_l, a non-linear function of the number of seats, in the objective function.

Area R_l can be calculated using:

$$\int_0^{t_d} [G(t) - B(t)] dt \tag{5.18}$$

where

$$G(t) = \begin{cases} A(t) - S, & if \quad A(t) - S \geq B(t); \\ B(t), & otherwise \end{cases} \tag{5.19}$$

where t_d is the time at which passengers start to arrive at the lounge, and $G(t)$ is the cumulative number of passengers at instant t who did not find a seat when they arrived at the lounge.

In order to evaluate the value of the area R_l, the *trapezoidal rule* is used. Both the passenger arrival function $A(t)$ and the boarding function $B(t)$ can be made discrete for given time intervals. If we set this time interval to be 1 minute and assume that $A(t) = 0$ for $t > 120$ minutes, then it can be shown that

$$\text{area } R_1 = \frac{1}{2}\{[G(0) + 2G(1) + 2G(2) + 2G(3) + \ldots + 2G(118) + 2G(119) + G(120)] - [B(0) + 2B(1) + 2B(2) + 2B(3) + \ldots + 2B(118) + 2B(119) + B(120)]\} \quad (5.20)$$

is an accurate approximation for the value of area R_1.

An electronic spreadsheet can be easily set up to calculate Equation 5.20. The cost represented by Equation 5.12 can also be automatically evaluated by the spreadsheet. With no constraints, the optimum number of seats can be found by varying the number of seats and comparing the costs of each solution. In other cases, where constraints exist, the use of a solver algorithm will be necessary.

5.3.3 Numerical Example

In this example, a departure lounge must be designed to serve an A380-900 with 656 seats. It is assumed that two bridges will be used to board the passengers, with a boarding rate of 30 passengers per minute, as determined in tests conducted by Airbus [2000b]. The lounge is to be used by an equal number of A380's and 747-400s. As of today, it is not clear whether both bridges used for the NLA will be compatible with the 747-400. For the purpose of this exercise, we assume that only one bridge will be used with the 747, yielding a boarding rate of 15 passengers per minute. The load factor is 80% for both flight types, i.e. the aircraft loads will be 525 and 320 for the NLA and the 747, respectively. Table 5.1 summarises all the parameter values used in this example. The passenger arrival distribution is shown in Figure 5.4 and is assumed to have the same shape for both aircraft types.

The first step is to assess the value of Q, the maximum number of passengers simultaneously in the lounge. The spreadsheet described earlier in this section can be set up to perform this assessment using Equation 5.3. The value found is 489 passengers, or 93% of the A380-900 design load (525 passengers). This value satisfies the constraint represented by Equation 5.16, whose value is 47.7%. That means the constraint of minimum level of service can also be satisfied.

Table 5.1: Parameter values for the NLA lounge design example

Parameter	Value
N_{NLA} (passengers)	525
N_{747} (passengers)	320
$p_{NLA} = p_{747}$	0.5
$w_{NLA} = w_{747}$ (minutes)	2
b_{NLA} (passengers / minute)	30
b_{747} (passengers / minute)	15
m_1 (m^2/passenger)[a]	1.5
m_2 (m^2/passenger)[a]	1
m_3 (m^2/passenger)[b]	0.8
α[a]	1.1
α_2	1.05
γ_L ($/$m^2$/aircraft departure)[c]	0.15
γ_P ($/hour/passenger)	0.5
γ_S ($/seat/aircraft departure)[c]	0.01

Sources: [a] Transport Canada [1977]; [b] IATA [1995]; [c] Wirasinghe & Shehata [1988]

The next step is to evaluate the optimal number of seats. Making use of the same spreadsheet used to choose the lounge capacity, it is possible to vary the number of seats until the minimum cost is found. The use of a commercial solver – available with many electronic spreadsheets – could make this search automatic. Table 5.2 summarises the results for this analysis performed with the built-in solver of Microsoft Excel®, which gives the exact optimal solution.

Table 5.2: Lounge area and optimal number of seats for the NLA lounge

Area (m^2)	Lounge Capacity	No. of seats	Overall cost ($/departure)
741	489	369	121.54

The optimal number of seats and the correspondent lounge area are heavily dependent on the values of p_i and the relation γ_P/γ_C. To investigate this dependence, a sensitivity analysis can be performed. Figure 5.7 shows the sensitivity of the optimal number of seats for the arrivals pattern used in the numerical example to the values of γ_P/γ_C and p_{NLA}. It is noteworthy how the number of seats grows rapidly with γ_P/γ_C until that ratio reaches approximately the value of 2, and then begins to grow much more slowly. For $\gamma_P/\gamma_C > 4$, the number of seats practically stabilises. The actual value of γ_P is dependent on local factors and its evaluation is beyond the scope of this work. It is therefore recommended that its exact value be carefully investigated where γ_P/γ_C is expected to be less than 4.

In this example, the relation given in Equation 5.17 says that m_3 should be greater than 0.97 m^2 per passenger. Since we used a value of 0.8 m^2 per passenger that relation is not satisfied Therefore, the constraint of minimum area is redundant. A sensitivity analysis for m_3 should also be performed in cases where it can affect the optimal solution.

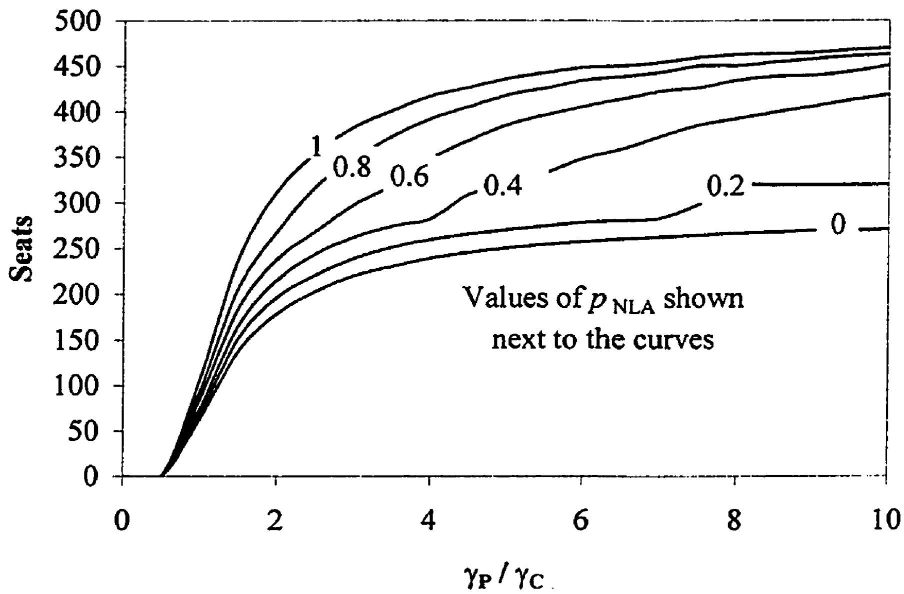


Figure 5.7: Sensitivity of the optimal number of seats to γ_P/γ_C and p_{NLA}

5.4 CONVERTING EXISTING FACILITIES FOR THE NLA

The conversion of existing gates to serve the NLA is a little more complicated than the design of new ones. Existing terminals are originally designed to serve a given aircraft mix. This original design might represent some difficulty and even a severe constraint when it has to be changed to accommodate a larger aircraft.

Assuming the existing space between gates is not enough to allow unrestricted operation of NLA, there are two ways to overcome this problem. The first solution is to en-

enlarge the space between gates, relocating them such that the separation between positions provides the minimum wing-tip-to-wing-tip separation. A second solution would be to block positions adjacent to that in use by an NLA. Although the first solution might appear to be harder to implement – due to the need for relocation of the loading bridges – the second one may result in a greater loss of gate positions, if NLA peaks occur concurrently with CJ peaks.

In cases where only a few NLA operations are expected and a pier-satellite terminal exists, it might be an option to use the satellite section of the terminal as a single NLA gate. This option will also be discussed.

5.4.1 Re-spacing / Blocking Gates

Figure 5.8 shows the variation of aircraft capacity with the wingspan. It can be seen that aircraft capacity is linearly related to the wingspan. Thus, in a linear terminal configuration, a departure lounge with a fixed width will have an area proportional to aircraft capacity. However, should the lounge be modified to serve another aircraft type with a higher capacity, it may not be enough to just increase the lounge area in the same proportion, due to variations both in the time of boarding and in the passenger arrival patterns. Additionally, Figure 5.8 also shows that the second-stage NLA passenger capacity outlies the trend line, featuring a larger capacity for its wingspan. Therefore, the lounge area needed for the NLA must be evaluated and compared to the existing available area in order to decide whether a second level is necessary.

Let G_e be the existing space between gates and G_N the new space provided for NLA positions. Let also A_e be the area available for the existing departure lounge of one gate and A_N be the final area available for an NLA gate (see Figure 5.9). If a large number of NLA gates is to be provided and pier end effects can be neglected, then the new area available to the NLA in a linear terminal configuration is given by

$$A_N = A_e\left(1+\frac{G_N - G_e}{G_e}\right) \tag{5.21}$$

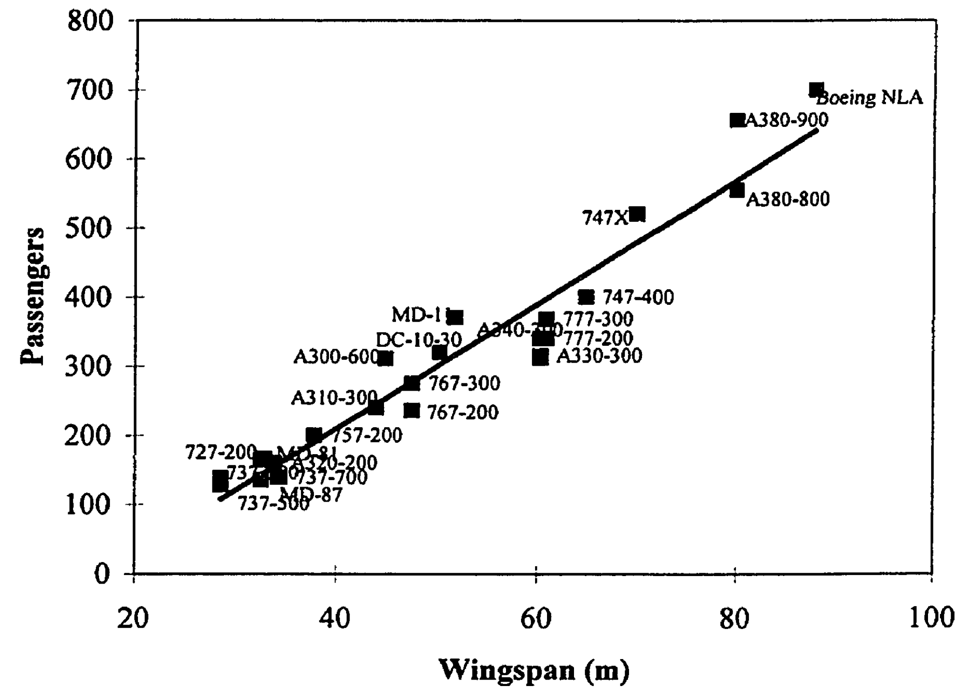


Figure 5.8: Aircraft passenger capacity x wingspan

If a second level is to be built, the available area given by Equation 5.21 will be doubled.

5.4.1.1 Second Level and Optimal Number of Seats

The decision of whether to build a second level is tied to both the area necessary to accommodate all passengers and the choice of the number of seats.

Let L be a zero-one decision variable. If L assumes the value of 0, then the decision is not to build the second level; otherwise, the second level must be built. The problem, then, is to find the values of S and L that minimise the overall cost of the lounge per aircraft departure, C_L, which will be composed by the sum of the cost of providing seats in both levels, the cost of building a second level, excluding the cost of seats; and the total cost of compulsory standing by passengers. The total lounge cost then is

$$C_L = \gamma_S S + L\gamma_L^* A_N + \gamma_P (areaR_1) \tag{5.22}$$

where γ_L^* is the cost of adding a second level per unit area per aircraft departure.

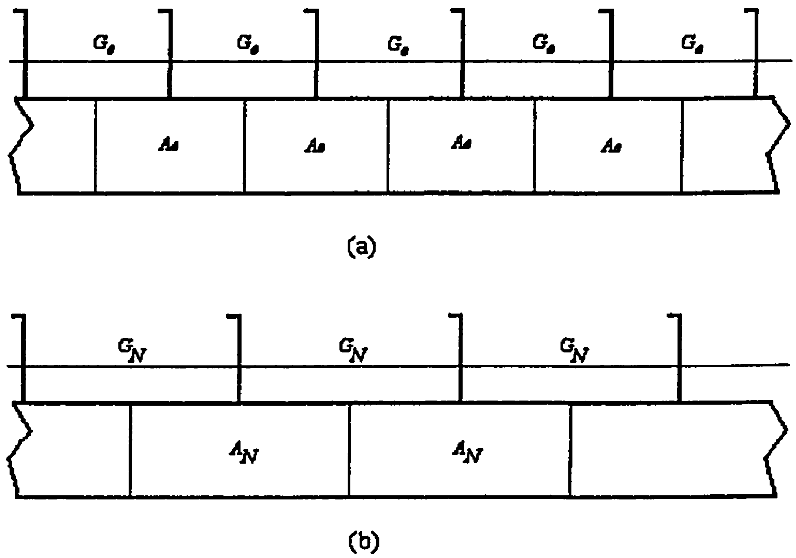


Figure 5.9: Re-spacing gates to accommodate the NLA
(a) Existing gate spacing
(b) New gate spacing for the NLA

In Equation 5.22, it is assumed that a second level will have exactly the same area as the existing level.

The minimisation above is constrained by the available area A_N. The required area A – calculated as in Equation 5.8 – must be less than the available area, whether one or two levels are provided. Therefore, the cost as given in Equation 5.22 must be minimised subject to

$$A \leq (L+1)A_N \tag{5.23}$$

Substituting for A from Equation 5.8 in Equation 5.23, the constraint becomes:

$$\alpha\left[m_1 S + m_2(Q-S)\right] \leq (L+1)A_N \tag{5.24}$$

To provide a minimum level of service, it must be ensured that the total final area is enough to accommodate the full aircraft load of passengers N and still provides a minimum area per passenger standing, m_3. Thus, the following constraint is also added:

$$(L+1)A_N \geq \alpha\left[m_1 S + m_3(N-S)\right] \tag{5.25}$$

Because the third term in Equation 5.22 is an integration, the problem is a non-linear mixed integer programming problem. The solution can be found with the use of a spreadsheet, as described in Section 5.3.2.

From Equation 5.22 we can conclude that the optimal solution will ultimately depend on the relative values of γ_S, γ_L^* and γ_P. Since γ_S is relatively much smaller than its counterparts, it appears clear that the optimal solution depends on the relation γ_P/γ_L^*. If the cost of building a second floor (second term in Equation 5.22) is higher than the consequent reduction in the penalty cost for passenger standing (third term), then the second floor is worth building. Otherwise, it is preferable to keep all passengers at one level.

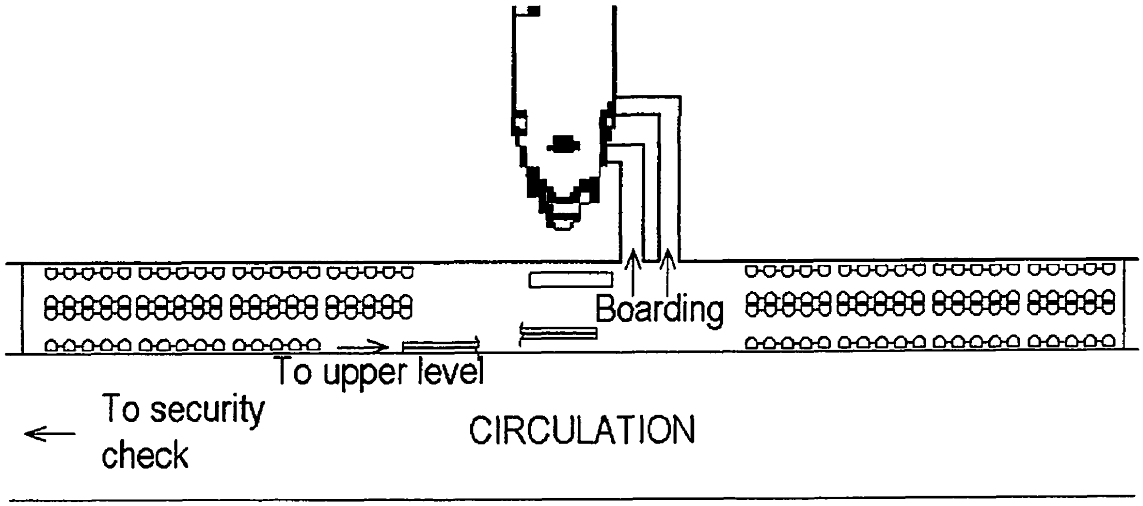
5.4.1.2 Second Level Configuration

Should a second level be added to the existing one, some issues will have to be addressed, such as:

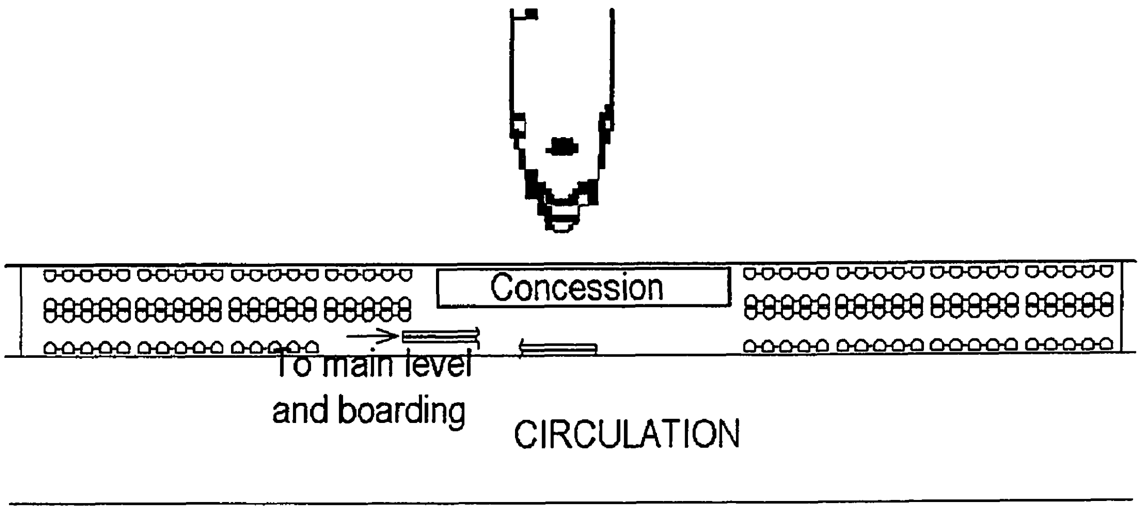
1. passenger split between levels;
2. connection between levels (stairways, escalators, elevators);
3. extra areas (circulation, airline activities, concessions).

The passenger split between lounge levels will largely depend on the boarding method and the split between aircraft decks. If boarding is to be done from one lounge level only – as suggested by Airbus [2000b], with two bridges loading the main aircraft deck as shown in Figure 5.2 – then passengers could be equally split between both lounge levels, coming down to the boarding bridge only at the time of boarding. This configuration – shown in Figure 5.10 – would allow passengers to choose which floor they want to wait on and to circulate freely between both levels. Concessions could also be installed on only one level, maximising the use of resources.

It might be desirable, however, to build a dedicated bridge connecting the upper lounge level to the upper aircraft deck. In this case, passengers would be routed to the lounge floor corresponding to their assigned aircraft deck. This would greatly diminish the



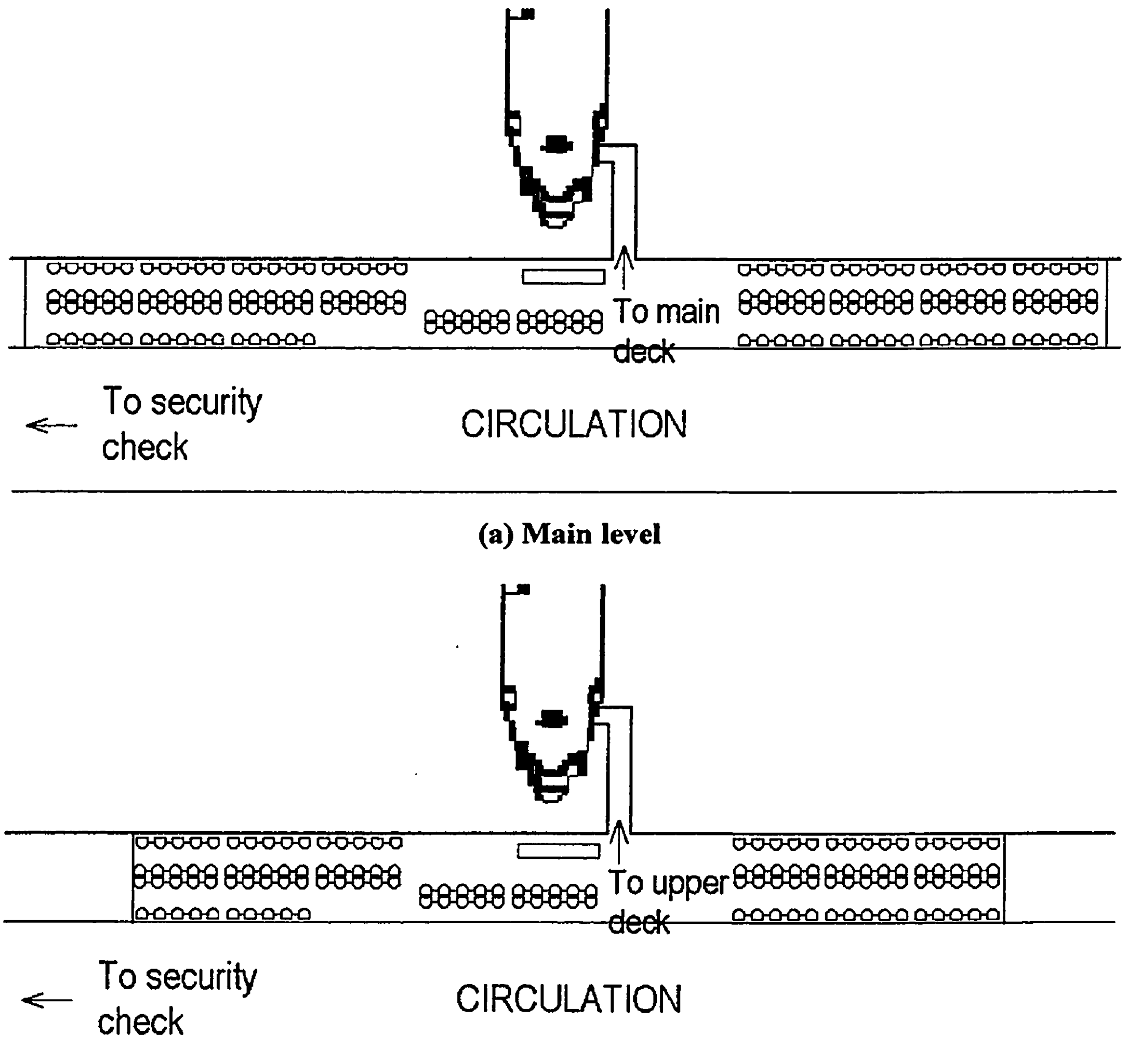
(a) Main level



(b) Upper level

Figure 5.10: Two-level lounge with one-level boarding

need for connection between floors, perhaps eliminating the need for lounge-dedicated escalators if concessions are provided on both levels. Passengers could have direct access to the levels through where they are supposed to board; lost passengers who go to the wrong level by mistake could change levels through escalators or elevators located at specific points in the terminal. On the other hand, the lounge level split would have to match the aircraft deck split, which is expected to be something around 65% for the main deck and 35% for the upper deck [Airbus, 2000b]. This would have the disadvantage of increasing the area requirement on the main floor, with a less-than-optimum resource utilisation. An example of this type of configuration can be seen in Figure 5.11.

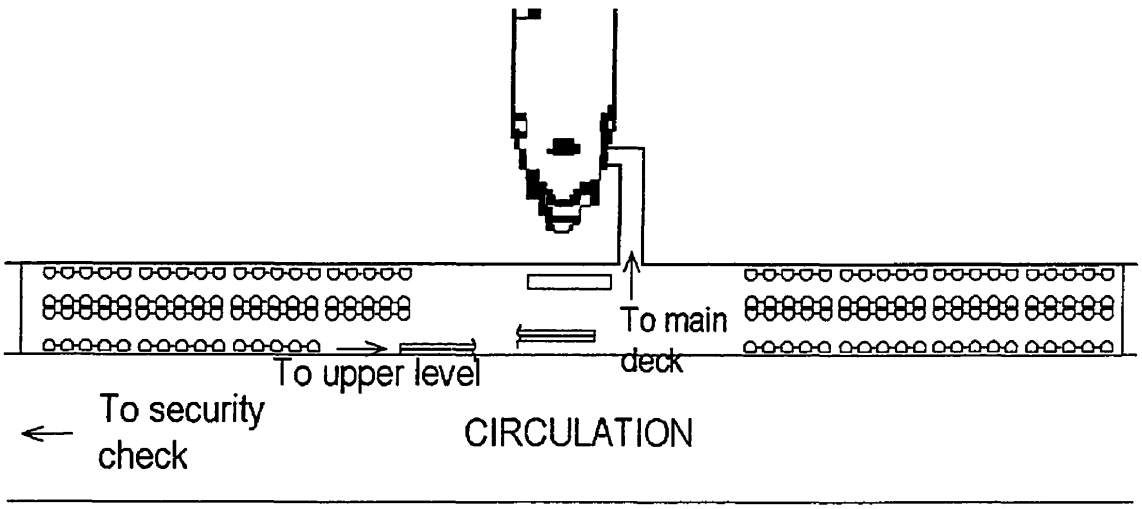


(a) Main level

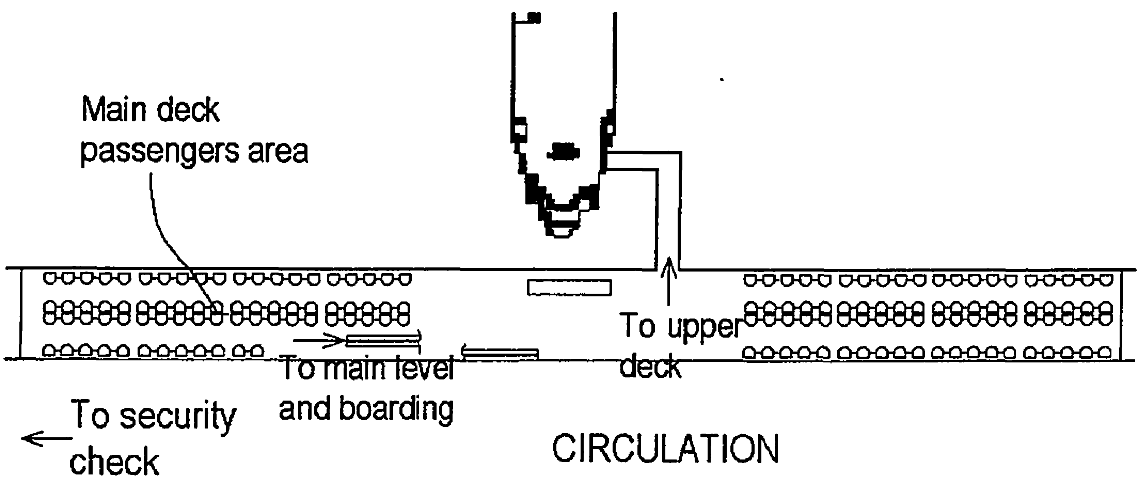
(b) Upper level

Figure 5.11: Separate two-level boarding

A third option would be a mix of the first two, with a few main deck passengers being routed to the upper lounge floor such that a 50/50 split is achieved. This configuration would again require a good connection between the two lounge floors, possibly with lounge-dedicated escalators. Main-deck passengers routed to the upper lounge floor would be directed to the main floor only at the time of boarding, as shown in Figure 5.12.



(a) Main level



(b) Upper level

Figure 5.12: Integrated two-level boarding

5.4.1.3 Numerical Example

Consider the problem of enlarging the space between gates designed for the B767. The existing separation between gates is 55 m, and the existing lounges have an area of 410 m^2 each. The space between gates for the NLA is estimated to be 87.5 m. These and other parameters necessary to solve this problem are summarised in Table 5.3. The passenger arrival distribution function used is shown in Figure 5.4.

Table 5.3: Parameter values for the NLA lounge configuration

Parameter	Value
G_e (m)	55
G_N (m)	87.5
A_e (m^2)	410
b (passengers / minute)[a]	30
m_1 (m^2/passenger)[a]	1.5
m_2 (m^2/passenger)[a]	1
m_3 (m^2/passenger)	0.8
α[a]	1.1
α_2	1.05
γ_L^* (\$/m^2/aircraft departure)[b]	0.15
γ_P (\$/hour/passenger)	0.5
γ_S (\$/seat/aircraft departure)[b]	0.01

Sources: [a] Transport Canada [1977]; [b] Wirasinghe & Shehata [1988]

The first step is to evaluate the lounge area available to the NLA. Substituting for the values of the parameters in Equation 5.21, it comes out that the available area is approximately 652 m^2.

The next step is to assess the value of Q, the maximum number of passengers simultaneously at the lounge. The spreadsheet described earlier in this section can be set up to perform this assessment automatically with the use of a cell formula based on Equation 5.3. The value found is 489 passengers, which also satisfies the minimum lounge capacity constraint represented by Equation 5.16.

Finally, the search for the optimal number of seats and for the decision whether to build a second level must be performed. There are two ways to do this search in our spreadsheet: setting up a zero-one variable as described above and making use of a solver; or making the assessment for two values of the area constraint – one with one level and the other with two levels. Table 5.4 shows the results using the former. It can be seen that the overall cost of the lounge will be higher if a second level is added. Therefore, the decision is not to build a second floor.

Table 5.4: Lounge capacity and optimal number of seats for the NLA lounges

No. of floors	Area (m^2)	Lounge Capacity (passengers)	No. of seats	Overall cost ($/departure)
1	652	489	207	35.80
2	1304	941	489	102.99

In this example, the value of γ_P is assumed to be constant. Its determination, however, may not be so simple. In addition, the proportion of NLA flights can also vary significantly over the life span of the lounge. Hence, a sensitivity analysis must be done for various values of γ_P and p_{NLA}. The results of such analysis are shown in Figure 5.13. That figure shows the breakpoint at which the costs of building or not building a second level are equivalent – if the pair $(\gamma_P/\gamma_L^*, p_{NLA})$ falls below the curve, build the second floor, otherwise stay with one floor only. In our example, with $p_{NLA} = 0.5$, the second level should only be built if γ_P is over 10 times greater than γ_L^*.

Note that the value of γ_L^* is given in dollars per aircraft departure. This value is found by dividing the present worth of the cost of construction cost of the second level by the expected number of aircraft departures over the lounge's life span. Consequently, the higher the frequency of flights using that lounge, the lower the value of γ_L^* and, for a given value of γ_P, the higher the ratio γ_P/γ_L^*. For given values of γ_P and p_{NLA}, Figure 5.13 can then be used to analyse the sensitivity of the optimal solution to the frequency of flights. Clearly, high lounge usage rates will lead to the construction of the second level.

5.4.2 Use of the Satellite Section of a Pier-Satellite Finger as a Single NLA Gate

The satellite section of a pier-satellite finger terminal usually features a departure lounge that is common to all gates in the satellite. Should one of the bridges be modified for loading an NLA, it might be possible to reserve this gate for NLA operations only.

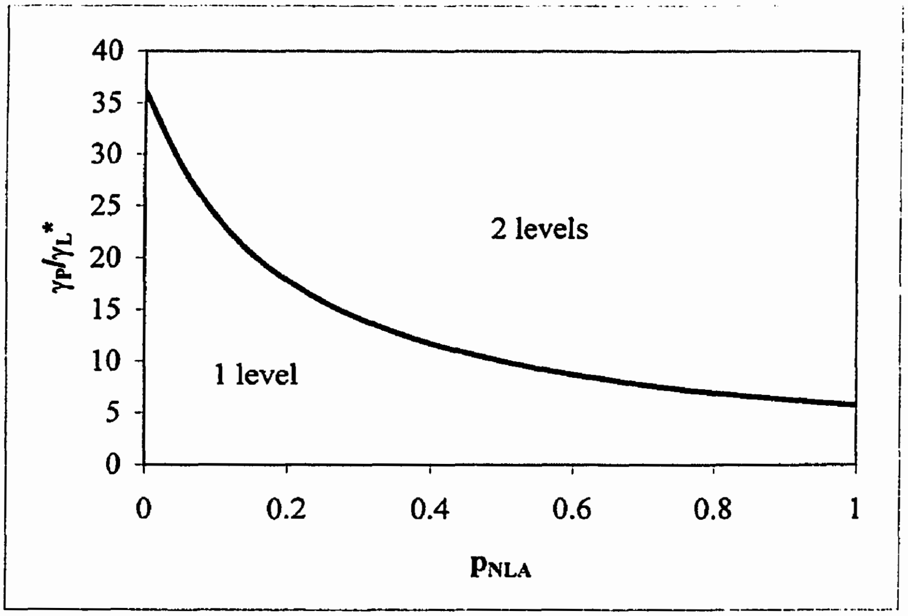


Figure 5.13: Sensitivity analysis for γ_P and p_{NLA}

Equation 5.8 can be used to determine the existing lounge capacity. Let A_e be the existing area; S_e the existing number of seats; and Q_e the current lounge capacity. Then it follows from Equation 5.8 that

$$Q_e = \frac{\frac{A_e}{\alpha} - (m_1 - m_2)S_e}{m_2} \tag{5.26}$$

Using deterministic queuing theory as described earlier, it is possible to determine the capacity of the lounge needed for the NLA, Q. If $Q_e < Q$, then the lounge cannot accommodate all the passengers of the NLA with its current configuration. However, the lounge capacity could be increased to a certain limit by reducing the number of seats, although at the expense of reducing passenger comfort. From Equation 5.8, the new number of seats will be given by:

$$S_N = \frac{\frac{A_e}{\alpha} - m_2 Q}{(m_1 - m_2)} \tag{5.27}$$

Since the number of seats S_N must be non-negative, it follows from Equations 5.16 and 5.27 that:

$$\frac{m_3}{m_2}N \leq Q \leq \frac{A_e}{\alpha m_2} \tag{5.28}$$

i.e. only if Q is within the range specified in Equation 5.28 can the lounge capacity be expanded to serve the NLA through the reduction in the number of seats. It must be noted that this capacity expansion would have the undesirable effect of increasing passenger standing time, with a consequent decrease in passenger satisfaction.

On the other hand, if $Q_e > Q$, then there is room for expansion of the seating capacity. If S' is the number of seats to be added, then the final number of seats is equal to the sum of the existing number of seats and the additional seats, i.e.:

$$S = S_e + S' \tag{5.29}$$

and the problem becomes to minimise:

$$C_L = \gamma_S S' + \gamma_P (areaR_1) \tag{5.30}$$

subject to:

$$\alpha\left[m_1 S + m_2 (Q - S)\right] \leq A_e \tag{5.31}$$

$$A_e \geq \alpha\left[m_1 S + m_3 (N - S)\right] \tag{5.32}$$

$$S = S_e + S' \tag{5.33}$$

Note that the area R_1 is still a function of S, which in turn is a function of S'.

5.4.2.1 Use of the Satellite by other Aircraft

In order to help reduce the loss of gate capacity, it may be possible to allow one or more aircraft to make use of the satellite concurrently with an NLA [Wirasinghe & Shehata, 1988; de Neufville & Belin, 2001]. To do so, it is necessary that wing-tip-to-wing-tip minimum separation requirements are met, and that the lounge capacity be enough to accommodate all passengers present at the lounge at any given time.

Figure 5.14 shows an example of the passenger arrival and boarding curves for both an NLA and two 747's sharing a departure lounge. These curves are added in Figure 5.15. The maximum accumulation of passengers at the lounge, Q, is the maximum passenger accumulation in time (Figure 5.15). Note that the departure times of both the 747 and the NLA can be staggered and that the value of Q will vary according to the difference in departure times. Varying this difference, it is possible to establish the exact time separation between NLA and other flight departures so that the lounge is able to accommodate all passengers, i.e. $Q_e \geq Q$. In addition, a minimum separation between the flight departures at the non-NLA gates can also be determined. However, if such separation is higher than the normal gate occupancy time, it will incur a loss of gate capacity, with a consequent cost if that capacity reduction occurs during peak hours. If the current schedule is such that the aircraft arrival rate exceeds the gate capacity at times, causing a queue to be formed, then blocking one gate for a short time t at those times will impose an additional delay. In Appendix B, it is shown that this extra delay can be approximated by

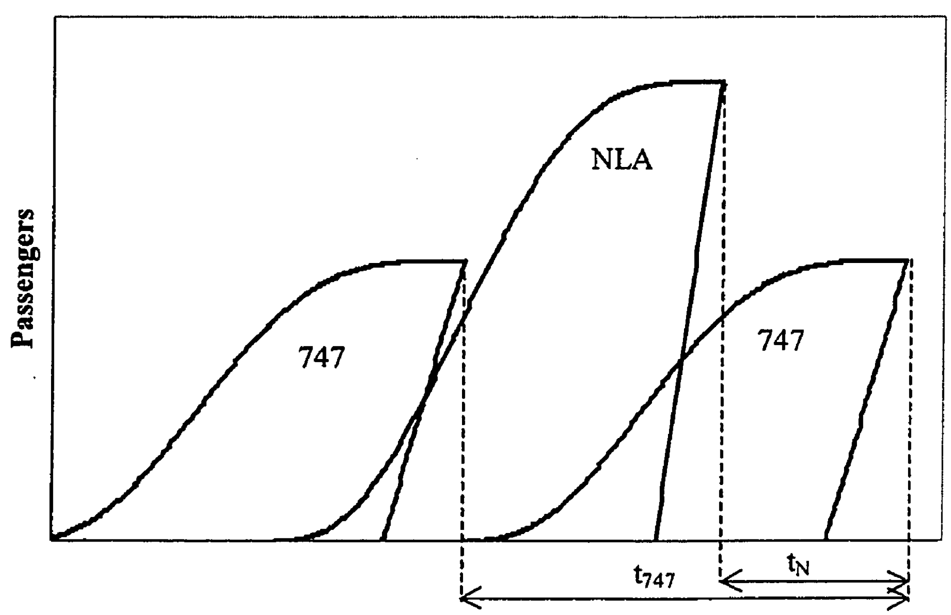


Figure 5.14: Arrival and boarding curves for the NLA and a 747 sharing the lounge

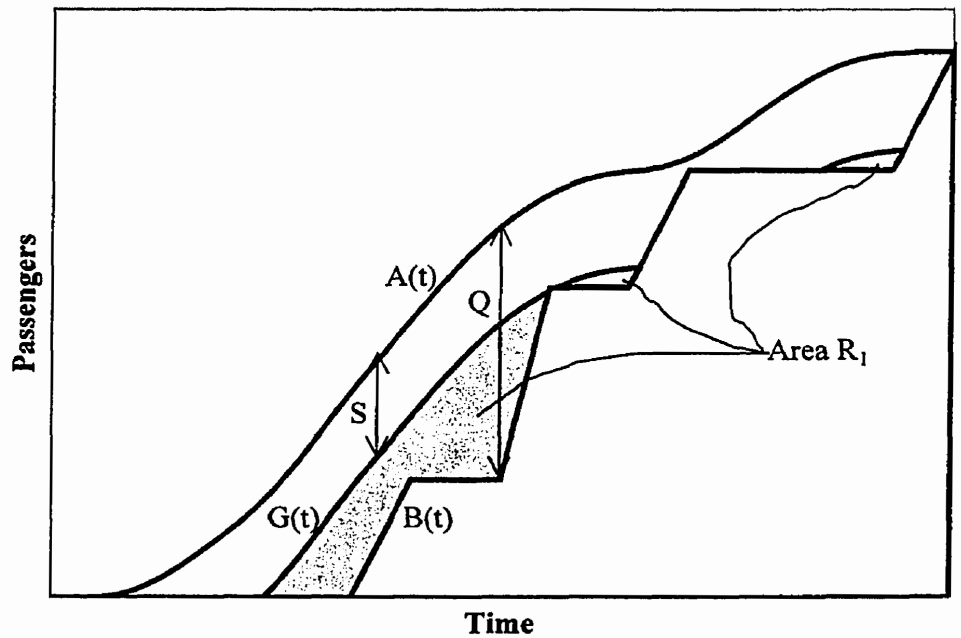


Figure 5.15: Cumulative arrival and boarding curves for the NLA and 747's

$$\frac{t(t+t_Q)}{2(T_G+T_S)} \tag{5.34}$$

where

T_G = average aircraft gate occupancy time;

T_S = manoeuvring time, or minimum time between the undocking of a flight and the docking of the next flight;

t_Q = duration of the queue for gate positions, calculated in Appendix B.

If the gate is blocked during non-peak hours, no extra delay will occur.

5.4.2.2 Lounge sharing: one NLA and one 747 gate

Consider, for instance, the problem of an existing lounge with area A_e. The lounge is shared by two gates, one NLA and one 747. The NLA gate can be used by the 747 as well, and will serve a very low number of NLA's. Let t_N be the time separation between the NLA departure and the next 747 departure. Let t_{747} be the time separation between two consecutive

747 departures with one NLA departure between them, as shown in Figure 5.14. The values of both t_N and t_{747} will influence the maximum passenger accumulation, Q. It is then necessary to adjust the time separations such that all Q passengers can be accommodated in the lounge.

Since the lounge area has a fixed value A_e, the adjustment of the time separations between flights will also affect the number of seats S that can be provided. This will in turn affect the cost of passenger standing discomfort. If γ_D is the unitary cost of delay imposed to aircraft, then the total cost of any solution is the sum of the costs of loss of gate capacity and passenger discomfort:

$$C = \gamma_D \frac{t(t + t_Q)}{2(T_G + T_S)} + \gamma_P (\text{Area R}_1) + \gamma_S S \tag{5.35}$$

The problem then is to minimise C subject to the constraint that the area requirement A, defined in Equation 5.8, is less than the existing area A_e:

$$A \leq A_e \tag{5.36}$$

A numerical example was performed with the input parameter values shown in Table 5.5, with the help of a spreadsheet similar to the one described in Section 5.4.1. The results are presented in Table 5.6. The optimal solution requires a separation time between 747 departures of 110 minutes, i.e. the 747 gate must be kept idle for 20 minutes after the last 747 departure prior to the NLA departure. In addition, the last 747 departure must occur 45 minutes before the NLA scheduled time at the latest. This scheduling will allow the optimal utilisation of the lounge by NLA's and 747's.

5.5 CONCLUSIONS

The advent of the NLA will bring out the need for changes in airports. Along with several other airport passenger terminal components, the passenger departure lounge is expected to be highly affected by the increase in aircraft passenger capacity.

In this chapter, analytical methods to evaluate the impact of the NLA on the passenger departure lounge using deterministic queuing theory have been presented. It has been shown that it is possible to size the departure lounge and to choose the best option to accommodate the NLA such that the overall cost of the lounge is minimised. For large airports that expect to serve several aircraft of that type, these methods can help saving a significant amount of money through the life of the passenger terminal.

Table 5.5: Parameter values for the NLA/747 lounge sharing numerical example

Parameter	Value
N_{NLA} (passengers)	525
N_{747} (passengers)	320
t_Q (minutes)	90
A_e (m^2)	900
b_{NLA} (passengers / minute)	30
b_{747} (passengers / minute)	15
m_1 (m^2/passenger)	1.5
m_2 (m^2/passenger)	1
m_3 (m^2/passenger)	0.8
α	1.1
α_2	1.05
T_G	90
T_S	5
γ_D ($/minute)	400
γ_P ($/hour/passenger)	0.5
γ_S ($/seat/aircraft departure)^b	0.01

Table 5.6: Results of the NLA/747 lounge sharing numerical example

Parameter	Value
Q (passengers)	612
S (seats)	412
t_N (minutes)	65
t_{747} (minutes)	110

The planning of new aircraft lounges can be done to minimise a cost function that includes the lounge construction cost and a penalty for passenger discomfort due to standing. The optimal size and number of seats will depend on the boarding method used – one or two bridges – and on the value of the unitary cost of passenger standing.

Existing facilities can also be adapted for use with the NLA. Where the lounge area is not enough to accommodate all NLA passengers, the available space can be increased by either reducing the number of seats or adding a second lounge floor. Again, the most economical solution will depend on both the passenger disutility and on the cost of construction of the second floor. Satellite lounges, which can usually accommodate a large number of passengers, can be reserved for NLA operations. This may require the temporary blocking of other gates that share the same lounge. A numerical analysis illustrated how the staggering of NLA and other aircraft departures can help reduce the loss of gate capacity by maximising lounge utilisation.

The disutility of passenger standing, γ_P, is critical for the evaluation of the optimal solution. It is therefore recommended that its determination be done with care.

CHAPTER 6
AUTOMATED PASSENGER/BAGGAGE PROCESSING

6.1 INTRODUCTION

Processing, along with *access interface* and *flight interface*, is one of the major components of the passenger terminal [Horonjeff & McKelvey, 1994]. In the processing component, passengers and baggage – that arrive sparsely in ground transportation vehicles or on other aircraft – are consolidated into batches that will be loaded onto aircraft. The opposite occurs when arriving loads of passengers and baggage are broken up, so each individual or group of passengers with their baggage can leave the airport through ground transportation or take another flight.

Traditionally, passenger processing activities are physically grouped at the terminal building – hence *processing* is considered a component of the terminal function. With the exception of ticket purchases – which can be done through travel agents or airline offices located off-airport – and a few off-airport baggage check-in systems, every pre- or post-flight activity related to the air trip is performed at the terminal. Early experiences with off-airport baggage check-in have not been successful in most cases due to the high costs involved. Today, only a few examples of this system can be found, e.g. Switzerland [Jud, 1994] and Hong Kong. Figure 6.1 depicts the normal passenger flows at a terminal. Departing passengers must report to the check-in counter, where their presence is acknowledged by an airline officer and input into the system, boarding passes are issued, and the baggage is separated from the passengers. Then they go through a security scrutiny, and in some countries have their passports checked if boarding an international flight. Finally, at the boarding gate, they present their boarding passes to another airline officer and board the plane.

Arriving domestic passengers do not need processing. They do need to reclaim their baggage, which in turn must be routed to their assigned baggage claim device. International passengers must also clear customs and immigration.

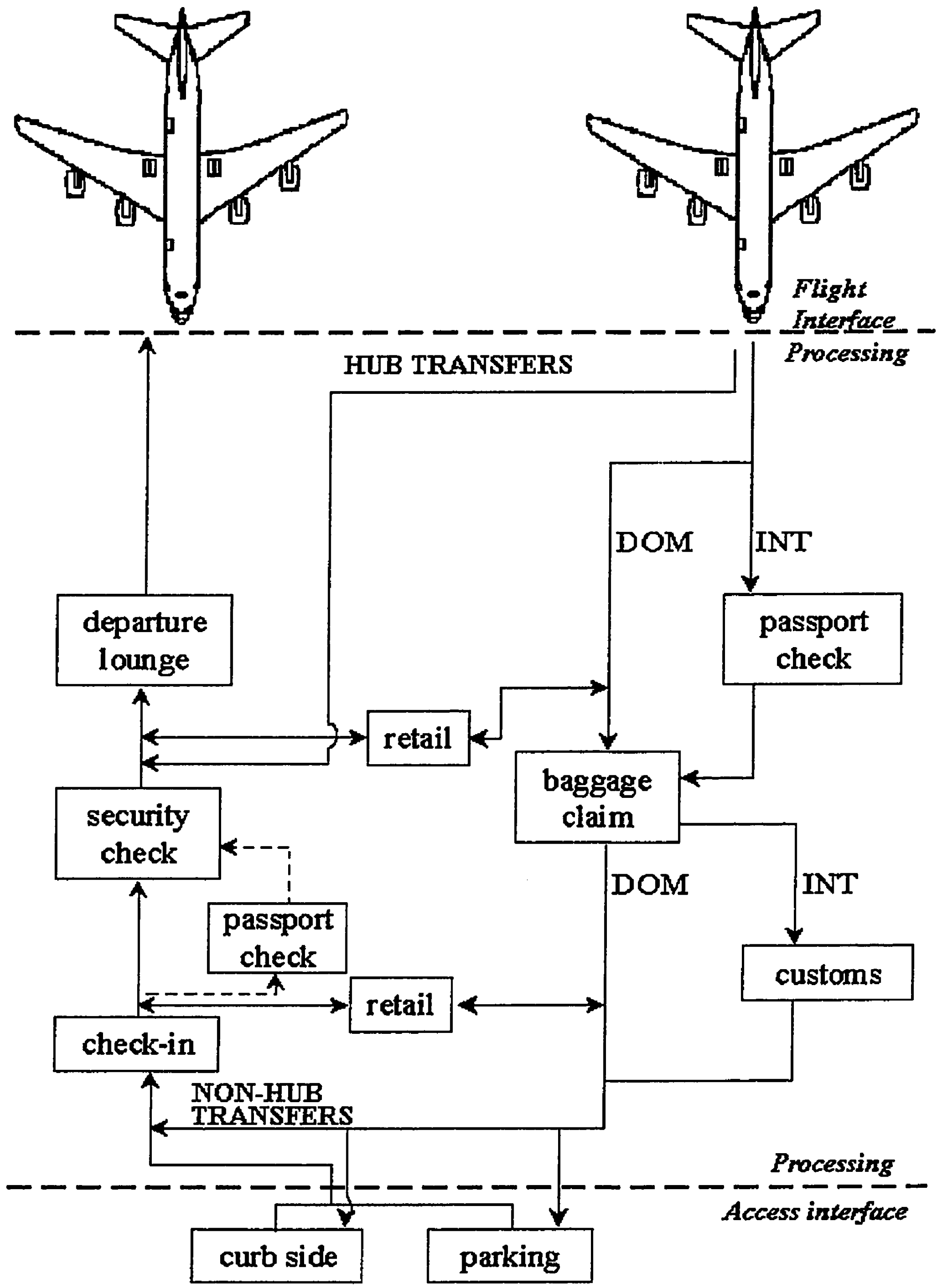


Figure 6.1: Normal passenger flows within a terminal

Sizing the processing units – in terms of numbers of servers and physical area – is done to meet the demand at peak periods. The capacity of the system is usually set such that a certain level of service will not be achieved during a few hours of the year [Ashford & Wright, 1992]. Several techniques could be used to determine the flows in individual facilities, such as queuing theory, network flow models and simulation [Horonjeff & McKelvey, 1994; Setti & Hutchinson, 1994]. Indices of area per passenger for certain levels of services can then be applied to size those facilities [FAA, 1988; IATA, 1995]. All facilities must provide areas to accommodate queues that will form during peak hours.

The introduction of larger aircraft is likely to have a significant impact on passenger processing, as the servers will now have to cope with much larger passenger batches that need to be served during a similar period of time and at least at the current level of service. In order to be able to accommodate this increase in the passenger demand without decreasing the level of service, it is necessary to increase the capacity of the system. Increasing capacity can be done in two ways: providing more servers – which may require more space – or improving the efficiency of the existing ones. With all the physical space constraints faced by most existing airports, concentrating on the latter seems warranted.

Enhancing system capacity without using more physical space can be done through the use of operations research and technology, which could allow for the simplification of procedures and lower service times. On the operations research side, Tosic [1992] presents a review of airport passenger models, and Odoni and de Neufville [1992] discuss issues related to passenger terminal design. More recently, Brunetta et al [1999] present a model to estimate the capacity of passenger terminal facilities. Every single process taking place in the terminal building can be improved with the use of technologies that are available. This chapter will review those technologies and make suggestions on how they can be used to improve the terminal system capacity, such that the surge in demand caused by the NLA can be absorbed while keeping the same or a better level of service.

6.1.1 Intelligent Transportation Systems

The recent years have seen a boom in applications of information technology to enhance the capacity and the efficiency of transportation systems. The set of applications of this type has become widely known as Intelligent Transportation Systems (ITS). This name is somewhat misleading, as not all applications involve the use of artificial intelligence; some may prefer the terms Telematics or Information Technology applied to Transportation.

Transport Canada [2000] divides the technology tools available for ITS into four categories: sensors, communications, computational and databases. Sensors – which include readers – are used to gather real-time information to trigger an action. A passenger putting a suitcase on an automated baggage check-in belt is an example of a sensor application: the sensor will detect the presence of the suitcase on the belt, and a reader will read the baggage tag. Communication tools are used to transmit the information gathered by the sensor to the appropriate control centre, which will then use computational tools to process the information and take the proper action. In order to do so, it will probably need to access a database tool, which will contain information specifically related to the unit that triggered the process. In our suitcase example, the reader would read the baggage tag to find out its flight number. This information would then be sent via the communication tools to a control centre, which will access a database that will check the gate number for that flight. The control centre then determines that the suitcase be moved to that gate.

ITS has become a major focus of transportation research in recent years. Many countries have established non-profit organisations in partnership between the public and private sectors to develop standards for ITS systems. The United States, Japan and several European countries are at the leading edge of ITS research. Surprisingly, however, the efforts developed by those countries have concentrated predominantly on ground transportation, most of it on urban and rural road systems. Air transportation applications seem to have been left almost entirely to individual initiatives, mostly by research institutes in the case of aircraft operations, and by companies in the case of passenger service. Nonetheless, Transport Canada has identified air transportation as a promising area for Canadian innovation [Transport Canada, 2000].

6.1.2 Use of Electronic Storage Devices (ESD) and Privacy

In the sections ahead, it will become clear that a key technology for automated passenger/baggage processing is the use of electronic storage devices (ESD). Such devices carry important information on the entity (passenger or bag) moving through the various components of the airport terminal system. This information is retrieved any time it is needed. Some examples of ESD's include smart cards, magnetic cards and radio frequency identification (RFID) tags.

The devices mentioned above will be further described in the following sections as their use is introduced. It should be noted now, however, that privacy concerns have been raised about the widespread use of those devices. These concerns are based on the fear that personal information stored on those devices could be catalogued and used for non-authorised purposes. Although such fear is legitimate, we can make the case that we are not better off without ESD's.

First, ESD's can store and provide only as much information about one person as that person wants. Smart cards, for example, have been advertised as small wonders that are able to store several megabits of information, but that does not mean one will *have to* fill it up with social insurance number, bank account and credit card numbers and passwords. And even if all that information is stored on a card, systems can be designed to retrieve only the information that is strictly necessary for a given transaction, with the rest of the information contained in the ESD being protected by cryptography. In addition, legislation can be made tough on the non-authorised retrieval and misuse of information from the ESD. Ultimately, this is exactly what is done with current systems such as credit cards and bank accounts.

Besides the fact that we can actually control the information we want to give and to whom, there is also what Woodward [1998] calls the "balkanisation" of systems and databases. The availability of many different technologies for the storage and treatment of information, combined with the diversity of user needs, will probably mean that many systems will not be able to exchange information between themselves without the use of a "translator" that can include security devices. Therefore it will be hard for a system to actually understand an information retrieved from an ESD that was not meant for that system. Privacy is thus protected by the use of different "languages".

In summary, ESD's were designed to facilitate the storage, retrieval and transfer of the very same information we store, retrieve and transfer today using paper and visual and oral communications. If proper measures are taken – such as passing legislation on the subject – ESD's can help improve services without harming privacy.

6.2 ELECTRONIC TICKETING AND AUTOMATED SALES

6.2.1 Electronic Ticketing

Before the development of integrated computer networks, the *air ticket* was an essential tool for passenger processing. The air ticket worked both as the receipt for the passenger and, more importantly, as the document that gave its holder the right to obtain a boarding pass for a specified flight to a certain destination. A passenger without a ticket would most likely be denied boarding, for the check-in officer would not have the means to verify that the passenger had effectively bought one. In some cases, passengers would have to buy another ticket and be refunded later if the lost one were never used.

Regulations require that an air ticket be issued to a specific person. The ticket is not transferable, i.e. it must be used by the person to whom it was issued. For that reason, identification may be required at the time of check-in. In that case, passengers have to present both the air ticket, as a proof that the person named on the ticket is entitled to board that flight, and a piece of identification, to prove that he/she is the person named on the ticket.

Nowadays, with airline systems integrated in such a manner that an airline check-in computer in Kuala Lumpur can easily access a reservations database located in Texas, the need for a physical air ticket is being reviewed – and with it, the whole process of purchasing a ticket and taking an air trip. Why make the passenger carry and present a ticket, if she will have to identify herself anyway? The passenger's ID information could be input into the computer and checked against the reservations database to ensure he/she has bought a seat in that flight [United Airlines, 2000a]. That is the concept of electronic ticket – or e-ticket, as it is also known. All major North American airlines have adopted e-ticketing for at least a portion of their flights. United Airlines [2000b] reports that, in May 2000, more than 60% of the tickets used by its customers were electronic.

Many limitations still exist with e-tickets, however. ICAO [1999b] reports that several airlines in the US have cancelled issuance of advanced boarding passes due to security reasons – passengers selling their tickets and boarding passes to someone else, for example. That means passengers are still required to present themselves at a check-in counter to get a boarding pass. In addition, e-tickets are generally limited to the airlines that issue them: if an air trip involves flying on more than one airline, then conventional paper tickets must be used [Naval Media Center, 1998]. That restriction is expected to be eliminated in the near future as airline ticket sales systems become more integrated. In fact, United Airlines [2000b] and Air Canada have recently announced the availability of e-tickets for passengers flying on both airlines during a trip. E-tickets are also a burden to people who are refunded for the trip – e.g. business people and education employees who must buy their tickets with their own resources and later apply for a refund. These people require a receipt as a proof of purchase. As of today, receipts are issued on demand and sent to the passenger by mail or fax. In the near future, an electronic receipt could be sent directly to the accounting department of the trip's sponsor.

Although the initial idea of e-ticketing is to eliminate the need for the passenger to carry a ticket, some airlines are considering replacing the paper ticket with a smart card [Eggert, 1995; ICAO, 1999b]. The advantage of the smart card is that it makes it possible to eliminate the check-in process almost completely. The ticketing information could be stored in the card along with other personal information related to the passenger's trip, such as immigration-related information – passport number, electronic visa, etc. The passenger could then do the check-in process all by himself, using an automated machine that would issue the boarding pass and store it electronically on the card. The same card would then be presented at the aircraft gate for boarding. These issues are discussed in more detail later in this chapter.

6.2.2 Automated Sales Systems

Since a paper ticket is no longer required, there is no point in forcing the passenger to go to an airline office or travel agent to buy the ticket. Automated telephone systems and, more recently, the Internet have made it possible to shop for flights, buy the tickets and make the reservations, all from a home phone or computer, respectively. Many air ticket sales systems are also offering integrated travel planning, including car rentals and hotel reservations with the ticket sale [Feldman, 1999]. All the passenger needs is a credit card to perform the purchase.

Internet ticket sales are actually independent of e-ticketing. There are several travel agencies and airlines that have been selling tickets online for a few years now, allowing passengers to do their reservations and buy their tickets in a "do-it-yourself" environment. Paper tickets are sent via mail or courier to the passenger's address. Combined with e-ticketing, however, internet sales can save passengers, airlines and airports a significant amount of money. Passengers can buy the ticket from the comfort of their homes or offices. Airlines save the costs of sales staff and of mailing the ticket. Airports see the need for ticket counters reduced, saving in physical space. Thus it comes as no surprise that online ticket sales are soaring. Flint [1998] reports that, in 1998, Northwest Airlines had increased their online sales to 800 tickets a day from 36 only 18 months earlier. In the same year, Delta reported having sold 2% of their tickets online, and expects that number to increase significantly [Air Transport World, 1998].

The Internet is not the only tool used for automated services. New technologies are also being tested to facilitate ticket sales via telephone. Several U.S. airlines are testing speech-recognition systems that will be able to serve passengers via telephone, allowing passengers to conduct ticket purchasing and reservation transactions without talking to a human agent. Northwest Airlines plans to issue electronic tickets to all sales done through this system [Flint, 1998]. However, it should be noted that many passengers do not approve of such systems – they would rather talk to a real person on the other side of the line. Provision should be made to satisfy this demand, such that the passenger may choose between automated and person-to-person systems.

6.3 AUTOMATED CHECK-IN

The design of the check-in area is one of the most critical issues in passenger terminal planning. The check-in area is where passengers are initially accepted by an airline to board its aircraft. It is, in essence, where the air portion of the passenger's trip begins; the point from where the airline takes responsibility for the passenger's baggage and a seat is definitively assigned to the passenger (with the exception of stand-by passengers).

What makes the check-in area so critical in the terminal design and operation is the "batching" nature of a flight, described in the introduction to this chapter. Passengers prefer to arrive at the terminal for a given flight as close to the departure time as they can. This results in large waves of passengers coming to the check-in counters during short periods of time. Put several flights departing at around the same time; add in the introduction of large-capacity aircraft (NLA) and the long times traditionally associated with the check-in process and the result is the need for very large areas to accommodate both the check-in counters area and the space allowed for queues to form. These imply very high costs in the form of construction, labour, equipment, delays and passenger discomfort.

Queuing theory tells us that, for a given passenger arrival rate, the higher the processing time, the more resources are consumed. Those resources could be both in the form of server-related resources – counters, airline officers, equipment – and queue-related ones – physical area to accommodate queues, delay times, passenger discomfort. Reducing or even eliminating the check-in processing time is therefore essential to increase the efficiency and the cost-effectiveness of the terminal.

6.3.1 The Traditional Check-in Process

To investigate how check-in time can be reduced, let us review the activities involved in the process. The first reason why a check-in is necessary is to acknowledge the presence of the passenger at the airport for boarding. Since there is very little chance that a passenger will change her mind after checking in, her presence at the airport can be assumed as a firm intention to board that flight. This information is important for pre-flight planning purposes – such as the determination of the amount of fuel necessary for the trip and of how much cargo can be loaded on the aircraft. It is also important to allow for acceptance of last minute reservations.

Acceptance of the passenger is done by verifying the passenger's ticket – or e-ticket – and identification, and assigning the passenger a seat on the aircraft. For international trips, it is also common that the airline officer verify that the passenger has the proper documents to enter the countries that will be visited during the trip. Seat assignment can also take some time if the passenger has any special requirements – e.g. a group of passengers who wish to be seated together. Last minute travel arrangements can also be performed at the check-in counter.

Passengers travelling with baggage must also hand it in here. The baggage is weighed – and measured, if necessary – to make sure it complies with the limitations imposed by the airline. It also receives an identification tag containing all the information needed for intra-terminal baggage handling – such as destination and flight number – and for passenger reclaiming at the destination airport. The information about the baggage is also input into the passenger file and a baggage receipt is issued to the passenger.

Finally, when all checks and arrangements are done, a boarding pass is issued to the passenger. The boarding pass contains all final information about the passenger and her flight – such as departure time and gate number. It also grants the passenger access to the aircraft as well as to areas that may be restricted to passengers only – as is the case, for instance, with departure lounges in Canadian airports.

Given the amount of activities performed during check-in, it is easy to see that the processing time can range widely. A business passenger on a domestic, point-to-point trip (i.e. with no connecting flights) will most likely be easier and faster to process than an international tourist with lots of baggage to check in who needs to rearrange her whole trip because her connection time at the next airport has become too tight due to a delay in her first flight.

Traditionally, airports try to improve the check-in process by adopting alternative ways of doing it. Curbside and remote check-ins attempt to perform the check-in tasks outside of the terminal, diminishing queues and reducing the need for physical space at the terminal building. Express counters may be provided to service passengers with electronic tickets and/or without baggage. However, reducing the processing time still has a greater potential to increase both the check-in efficiency and the level of service. Significant gains can be obtained by allowing the passenger to do some of the tasks herself from a remote location, and by automating the tasks that must be performed at the terminal. However, even such automated systems may require the presence of airline staff to help passengers who are unfamiliar with those systems.

6.3.2 The Check-in of the Future

In Section 6.2, we discussed how electronic tickets and automated sales systems can facilitate the purchase and use of air tickets in a "do-it-yourself" environment. The next logical step would be to extend that to the activities associated with checking in.

With the development of information technology, practically all check-in tasks can be done automatically, and most of them do not even require the physical presence of the passenger at the airport. Such automated and remote systems could greatly expedite passenger processing and significantly reduce the need for physical space in the terminal building. Moreover, it will allow those tasks to be performed farther in advance than it is possible today, greatly enhancing the flight planning by the airline and reducing the passenger dwelling time at the terminal.

Recent tests done by Air Canada, Alaska, Continental and Northwest Airlines have allowed passengers to do automated check-in in two ways: via Internet or at kiosks similar to banking machines [Schwartz & Nelms, 2000; Individual.com, 2000]. Kiosks can be located anywhere inside the terminal and even at remote locations [IATA, 1995]. However, while the Internet allows for the check-in to be done well in advance, with all the advantages mentioned above, the use of kiosks may actually have an effect to the contrary: assuming they do not need to allow a long time for check-in, passengers may decide to come later to the airport, imposing more uncertainty to the flight planning. Although this still contributes to a lower dwelling time, airlines might prefer Internet check-in. Awards and incentives to passengers may be used by airlines to encourage Internet check-in.

Confirmation of the intention of the passenger to board the flight is one activity that not only does not require the passenger to be at the airport; it also eases flight planning. By knowing farther in advance how many passengers will be on the plane, uncertainty about the aircraft takeoff weight, the amount of cargo that can be transported on the plane, and the need to accommodate overbooked passengers is reduced, allowing for better flight planning and better service to passengers. The Alaska Airlines system that is being tested includes both kiosks and Internet check-in. E-ticketed passengers can perform most tasks at one check-in kiosk or from their computer at home, including getting a seat assignment and upgrading to a higher class.

Baggage check-in seems to be more of a problem for automation. Passengers would have to get the baggage tags themselves, stick them to their luggage, and hand it in at automated baggage collection machines. Unlike check-in kiosks, baggage collection machines do not have the flexibility of being located anywhere, for they are physically collecting volumes that must be transferred to the aircraft. Three other issues can be identified that make this automation not so simple: security, issuance of the baggage tag and enforcement of size and weight limitations.

In many countries including the USA, current regulations require that, before accepting responsibility for the baggage, airlines ask the passengers a series of screening questions that aim at identifying potential hazards to flight security. Unfortunately, these questions have no value if asked well in advance of handing the baggage to the airline, which precludes passengers from performing this task on the Internet. Conceivably, with the development of advanced, high-speed baggage-screening machines the need for these questions could be suppressed. Up to this date, however, thorough screening machines are prohibitively slow and expensive, preventing their use for 100% of the baggage.

Some ways to overcome this problem are possible: passengers may be required to answer those screening questions at the baggage check-in, although at the expense of requiring some processing time and even forming queues at a critical point where passengers still have their baggage and are occupying a large area per passenger. Another alternative is an advanced home baggage pick-up service like the one being tested in Brussels by Sabena

Airlines. Sabena's system allows for a 24-hour advance baggage pick-up [ICAO, 1999b]. Such system, however, requires careful thought and modelling of the storage algorithm and of the pick-up logistics, as well as a cost/benefit analysis.

The issuance of the baggage tag should not really be a problem for passengers checking in at kiosks. These machines can deliver the baggage tag using proper ink and sticking paper; the passenger would just have to stick it to the pieces of luggage. Even if Radio Frequency Identification (RFID) tags are used, passengers should be able to get them at the kiosks. The real problem is with Internet check-in. RFID, which is described in more detail in Section 6.4, would require special equipment for the issuance of tags, which most passengers may not be willing to acquire – although such equipment could be made available at most large organisations. Bar-coded tags could be printed on regular paper and then either stuck to the luggage using glue or tape, or stored in a transparent container attached to the luggage. However, poor printing can hinder the reading of the bar code, and poorly stuck tags could be lost during baggage handling. Moreover, tags printed on media that does not follow the International Air Transport Association (IATA) specifications may be more easily damaged [IATA, 1999]. Frequent flyers may be able to purchase pre-printed tags and input the identification in the computer system manually. Again, a baggage pick-up service like the one under testing by Sabena could overcome this problem.

The third obstacle to baggage check-in automation is the size and weight of the baggage. Oversized and/or overweight baggage may require special handling – for instance, skis will not fit in belt curves or destination-coded vehicles (DCVs), as described in the next section, and may require special accommodation in the aircraft's baggage compartment. Provision must be made to ensure that the baggage being checked in complies with the limitations established by the airline.

The technology to verify the compliance of baggage with size and weight limitations already exists. A scale connected to the airline computer can easily measure the baggage's weight. Size may be a little harder to verify, but is certainly feasible. A simple, efficient way to enforce size limitations would be to force the piece of baggage to fit in a frame built with the limiting dimensions before it is accepted by the system. In a more sophisticated fashion, Yfantis [1997] proposes a system for baggage-tracking that uses a matrix of lasers and sensor lights to get the exact dimensions of the luggage. In either case of oversized or overweight baggage, the passenger would be instructed to bring it to a conventional check-in counter.

The final task of an automated check-in system is the issuance of the boarding passes. Passengers checking in via Internet could print their boarding passes on their home or office printers. Kiosks would not have any problem printing a standardised boarding pass. ESD users would initially be limited to the use of kiosks, as the equipment necessary to transfer information between their home or office computer and the ESD may not be easily available in the near future. Conceivably, however, if and when ESD's become very popular and standardised, ESD interfaces may even become standard on PC's.

6.3.3 Impact on the Airport Terminal Facilities

Terminal check-in areas are usually planned with the goal of offering a certain *level of service* to the passenger. This level of service is traditionally measured in terms of the waiting time and availability of space. The longer the waiting time, and the smaller the space available per passenger – and therefore the more crowded the area – the lower the level of service.

A maximum waiting time W_M is established either by the airline or the airport manager for a design peak. Then, using deterministic queuing theory [Newell, 1982] the service rate μ_0 necessary to limit the waiting time to W_M, as well as the maximum queue Q_M, can be evaluated. Figure 6.2 shows an example of this process. For a given arrivals pattern as a proportion of the aircraft load N, W_M remains constant as long as the arrivals pattern is kept the same. Under this condition μ_0 and Q_M are directly proportional to the aircraft load N. If the mean service time t_S is known, then the number of check-in counters necessary to maintain the specified level of service is

$$n_C = \mu_0 t_S \tag{6.1}$$

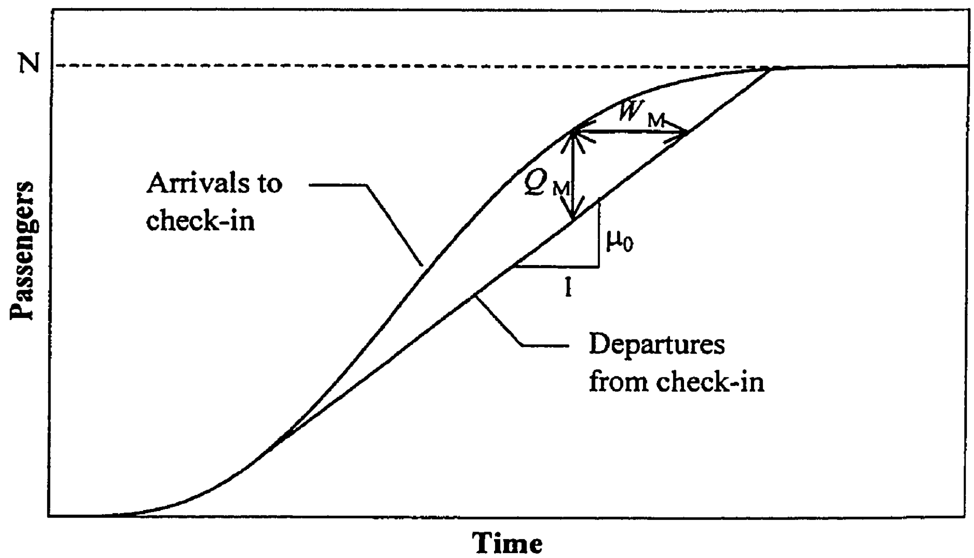


Figure 6.2: Maximum queue and waiting time at the check-in area

Wirasinghe et al [2001] evaluated the check-in area requirement for two different queue configurations: individual-line and multiple servers. The area A_Q necessary to accommodate the passenger queue in an individual-line configuration (see Figure 6.3) is

$$A_Q = w_c d_p Q_M \quad (6.2)$$

where

w_c = counter width;

d_p = linear headway between passengers.

Let

d_c = depth of a check-in position;

w_{circ} = width of the circulation corridor in the check-in area;

The area required for the check-in counters, passengers in service and circulation is

$$A - A_Q = n_c w_c (d_p + d_c + w_{circ}) \quad (6.3)$$

Substituting for n_c and A_Q in Equation 6.3 from Equations 6.1 and 6.2 respectively and solving for A, the total check-in area becomes

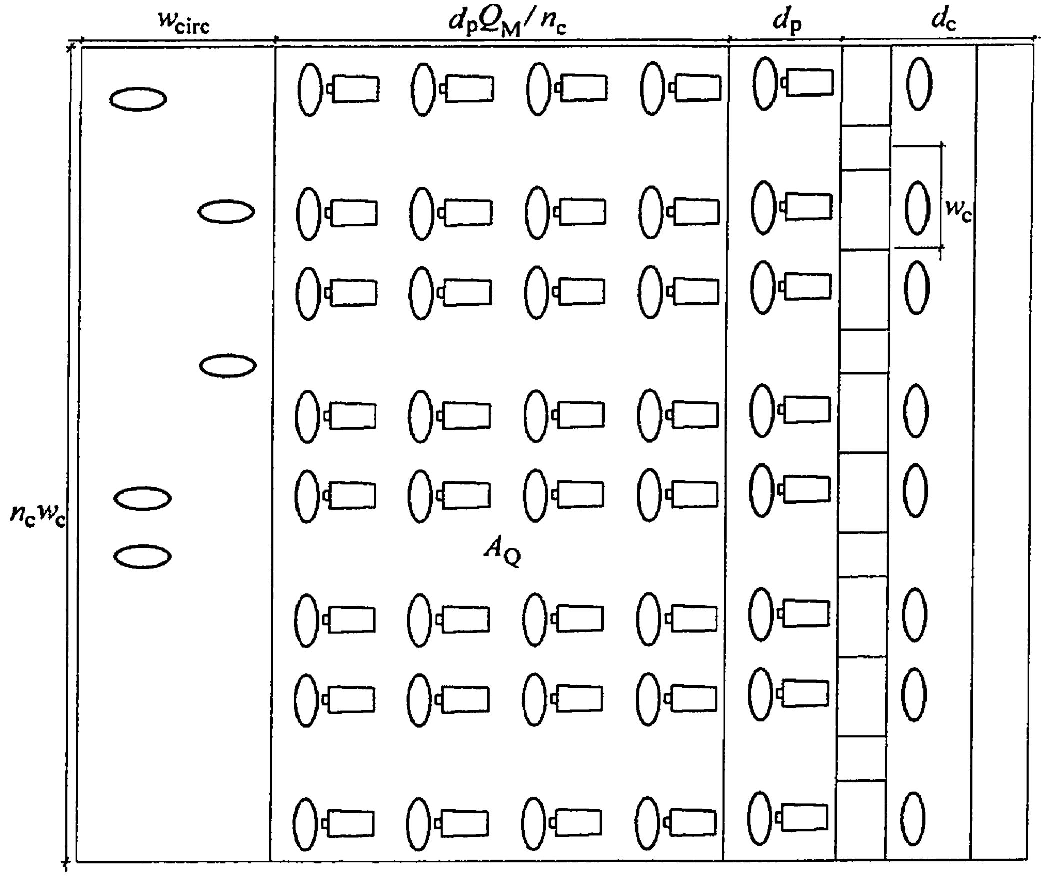


Figure 6.3: Check-in area

$$A = w_c \left[\left(d_p + d_c + w_{circ} \right) \mu_0 t_S + d_p Q_M \right] \tag{6.4}$$

As Q_M and μ_0 vary in the same proportion with N, it becomes clear from Equation 6.4 that, for a given arrivals pattern and a pre-established W_M, the required overall check-in area A is directly proportional to the aircraft load, assuming all passengers report to the check-in counter. Therefore, if we make the conservative assumption that all other parameters are to remain the same, then the reduction in the number of passengers reporting to check-in actually decreases the physical area requirement in the same proportion. Further improvements can be achieved if the check-in width can also be diminished.

Another effect expected from the automation of check-in operation besides the reduction in the amount of passengers using airport check-in is the reduction in the time of service, t_S. Because the area to accommodate the queue (the second term in Equation 6.4) is not dependent on t_S, the reduction in the overall area will be less than proportional to the decrease in the time of service.

6.3.4 Effect on NLA Operations

With the automation of check-in services, NLA operations may be accommodated within existing facilities at current or better levels of service. The expected enhancements in current standards of service time and total demand might exceed the need created by the increase in the number of passengers due to the NLA.

The main effect of NLA operations on the check-in process is the increase in arrival rates, which can be assumed proportional to the increase in the aircraft capacity (40-100%). Figure 6.4 illustrates the effect of the aircraft load being multiplied by a factor $k > 1$ on the check-in area without reducing the level of service, i.e. keeping the maximum waiting time at the same level. Should a conventional system be used, the overall check-in area must be expanded by the same factor k, as we conclude from Equation 6.4. However, if that increase in the arrival rate can be counterbalanced by a reduction in the number of passengers using the conventional check-in system, and by a decrease in the processing time, then existing check-in areas can deal with the NLA traffic without any major problems.

Let us consider the case of a check-in area, sized for an aircraft load N with the dimensions shown in section 6.3.3, that is to be converted to serve the NLA – i.e. the aircraft load is increased to $k\,N$ – with a mix of conventional check-in counters and automated kiosks. It is assumed that the arrivals pattern – i.e. the proportion of passenger arrivals with respect to the aircraft load – remains the same, and that the existing check-in configuration is enough to service and accommodate N passengers with a maximum waiting time W_M. Let

b_C = the proportion of passengers using the conventional check-in counters;

b_I = the proportion of passengers checking in remotely, via Internet or at off-terminal automated kiosks;

b_A = the proportion of passengers using automated check-in kiosks located in the check-in area;

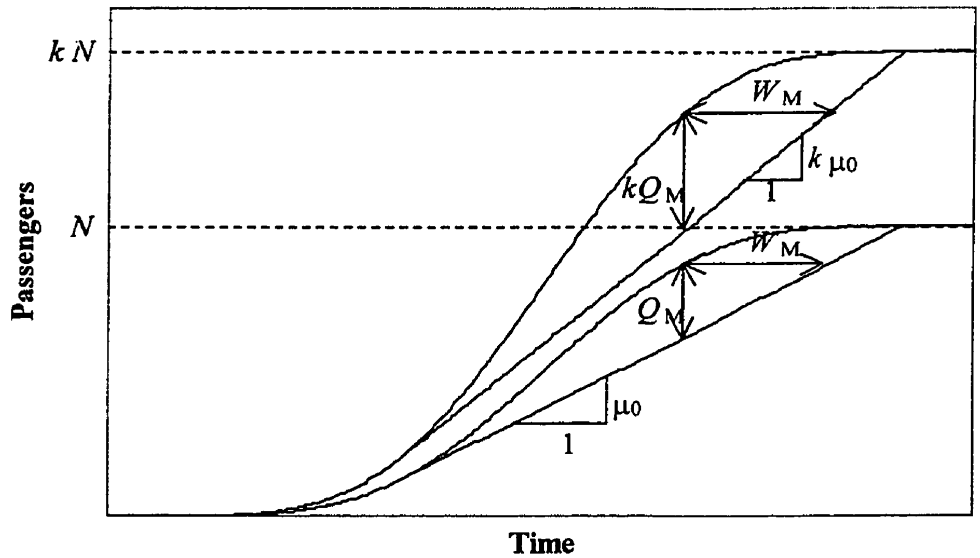


Figure 6.4: Effect of the increase in the aircraft passenger load on the check-in area

c = the proportion of reduction in processing time of kiosks with respect to traditional check-in.

The problem then reduces to finding the values of b_C, b_I, b_A and c that will allow the existing area to accommodate the increase k in the aircraft load.

The area requirements can be calculated separately for conventional and automated check-in. For conventional check-in, the total passenger demand is now $b_C\, k\, N$ passengers. Since the total area requirement is proportional to the aircraft load, the new area requirement for conventional check-in is

$$b_C kA \qquad (6.5)$$

In the automated check-in case, the calculation differs from the conventional check-in case due to the different service time, which is now $(1 - c)\, t_S$. It is assumed that passengers using the automated service need not check-in their baggage elsewhere. This can be achieved by either providing automated baggage check-in as suggested earlier in this section or by reserving the automated service for passengers without baggage. Since the service rate μ_0 is proportional to the aircraft load, the number of automated kiosks necessary to keep the maximum waiting time W_M is

$$b_A k(1-c)n_C \tag{6.6}$$

Check-in kiosks may require less area than conventional counters, especially because no circulation space has to be provided behind the kiosks. However, if baggage check-in is to be done at the kiosks, then it is necessary to provide a baggage conveyor that may end up compensating for the circulation area. Hence it will be assumed that the dimensions of the kiosks will equal those of the conventional counters. With this conservative assumption, the total area requirement for the automated check-in area is

$$b_A k\lfloor(1-c)(A-A_Q)+A_Q\rfloor \tag{6.7}$$

The overall area requirement for the check-in A_N equals the sum of conventional and automated check-in areas given respectively by Expressions 6.5 and 6.7, which when simplified reduces to

$$A_N = k\lfloor b_C A - cb_A(A-A_Q)\rfloor \tag{6.8}$$

In order to be able to accommodate all passengers at the same level of service, it is necessary that the new area requirement be less than the existing area, i.e.

$$A_N \leq A \tag{6.9}$$

Substituting for A_N from Equation 6.8 in Equation 6.9 and solving for b_A, we find the relation

$$b_C \leq 1/k - b_A[1-c(1-A_Q/A)] \tag{6.10}$$

which must be satisfied for the existing check-in area to be enough to service and accommodate all $k\,N$ passengers at the current level of service. Note that, if no in-site automated service is provided – i.e. $b_A = 0$ – then it follows from Equation 6.10 and from the fact the sum of the proportions of passengers using all different kinds of check-ins must equal one that

$$b_l \geq 1 - 1/k \tag{6.11}$$

i.e. at least a proportion 1 - 1/k of the passengers must be diverted to Internet and remote check-in in order for the level of service at the in-terminal check-in to be kept.

It should be noted that the mean conventional check-in service time is assumed to remain unchanged when automated alternatives are provided. That is a reasonable assumption if all or most of the check-in tasks can be performed via kiosks or Internet. If the most cumbersome tasks are not provided there – such as flight reschedule and oversized baggage handling – then the provision of automated services will actually increase the mean conventional check-in service time, affecting the total queue and the waiting time. If that is the case, then a separate analysis must be performed.

Two interesting features of Equation 6.10 are noteworthy. The first one is that the value of b_C becomes more constrained as A_Q/A increases. That happens because, for a fixed Q_M, the reduction in service time will only affect the kiosk area and not the queue area. And since for a fixed arrival pattern the ratio A_Q/A increases with W_M, the final effect is that the reduction in service time will be more effective for low values of the target waiting time W_M than for higher values.

The second interesting feature is that b_C becomes less constrained for lower values of k. This shows the importance of sharing facilities. If a check-in area used solely for a 747 flight is now to be used for an NLA, the value of k could be as high as 1.64 for an Airbus A380-900. That would require that at least 39% of the passengers use automated and remote check-in. If, however, the check-in uses shared facilities with Common Use Terminal Equipment (CUTE), then it is the total demand that must be taken into consideration now. The move from a 747 to an NLA would then be contributing to a slight increase in the total demand with $1 \leq k \leq 1.64$. Fewer passengers would then be required to use automated and remote services.

Note that the above calculations are valid for any multiple-server system. In the case of the security check, for example, the relation in Equation 6.10 applies if a new high technology procedure is to be implemented.

6.4 SECURITY CHECK AND BOARDING

6.4.1 Security Check

The current procedure for pre-flight security check uses a combination of an archway for metal detection and an X-ray machine for examining baggage. Due to the high sensitivity of the archway, passengers often find themselves having to go through the archways more than once, emptying their pockets of keys and coins between passages and delaying all other passengers in the queue. Meanwhile, their baggage is scrutinised by a security officer with the help of an X-ray machine that plots an image of the contents of the bag, which allows the officer to look for patterns that indicate items that may be a threat to flight security – such as hand guns.

New technologies are under testing to allow for faster, more accurate inspection of passengers and baggage [Marsh, 1997]. New metal detectors that deploy detector zones at different heights reduce the probability of small amounts of metal raising the alarm. New screening machines combined with artificial intelligence for image processing and pattern recognition speed up the baggage screening process [He et al, 1997]. As of today, however, screening remains a human-based process.

The security check is a significant factor on the boarding process, for it may become a bottleneck that will determine the arrivals rate at the departure lounge [Wirasinghe & Shehata, 1988]. Reduction in the processing time and its consequent increase in throughput is important especially during NLA peak hours, otherwise many passengers may find themselves stranded in the security check line when their flights are already boarding. In fact, an optimum balance between throughput and the number of positions must be sought.

6.4.2 Boarding

Boarding can also be made very easy by the use of information technology. If an ESD is used to store the boarding pass, all the passenger has to do at the time of boarding is insert the ESD in the proper slot and board. The airline system would then acknowledge that the passenger is on board and transmit that information to baggage handling for the purpose of positive passenger baggage matching (see Section 6.6). If pre-boarding customs and immigration clearance is done at this time, then it is also necessary to take the passenger's biometric print for identity authentication (see Section 6.5).

A disadvantage of the use of an electronic boarding pass is that the passenger does not have a printout containing the information about her flight – such as gate number, boarding time and seat number. For that reason, a printout for reference only given at the time of check-in may be necessary. Also, small kiosks spread throughout the boarding area may be used to read the electronic boarding pass and print the flight information on the screen, so that the passenger can get online updated information on the flight.

6.5 CUSTOMS AND IMMIGRATION

International passengers are a complicating factor for airport planning and operation. Arriving international passengers must not be mixed with domestic passengers before clearing customs and immigration. Departing international passengers must produce a valid passport and, in many cases, a valid entry visa to the destination country. In many countries, federal authorities check passports before allowing access to the departure lounges.

The processing of international passengers is expected to be one of the most critical issues brought up by the NLA, since long-haul international flights are the main market for those aircraft. Improving the service at these locations is thus essential to provide a smooth service for NLA passengers.

Due to the need to separate arriving international passengers from domestic ones, it is common practice to reserve a separate area at the terminal – or even a whole terminal – just for international flights. Evidently, this arrangement does not provide the best utilisation of resources, as international peaks may not coincide with domestic peaks. Joint use terminals, mixing not only international and domestic flights but also different airlines, may bring significant benefits in terms of resource utilisation. The flow of international arrivals could be separated from the others with the use of a sterile corridor that leads directly to the immigration area [Steinert and Moore, 1993; Blow, 1997]. Passengers can be directly diverted at the gate to this sterile corridor with the use of split-level boarding bridges as in

Hong Kong [Nelms, 1998] or swinging glass-panel doors as in Miami [Berutti, 1990]. Still this separation requires that such corridors – which can be several hundred meters long at some terminals – be built, consuming space that could be utilised for something else.

Regardless of the arrangement of the international terminal, international arrivals still have to go through a very time-, labour-, space-consuming process. First, they must provide to an immigration officer a valid proof of identification – usually a passport. In many cases, foreigners may have to present further documentation, such as an entry visa and air tickets. Next, they move to the baggage claim area to retrieve their baggage – whether they are terminating their trip at the airport or connecting to another flight. Finally, they go through customs, where they may be required to have their baggage checked. In some countries, the whole process – from the aircraft door to the customs exit – can take more than an hour.

The whole process described above can be expedited with the use of recently developed technologies and simplified procedures. Information technology, combined with biometrics – the use of physiological characteristics of a person for verifying her identity – have the potential to greatly reduce immigration time processing. Customs declaration could also be done electronically and, if airline systems were integrated with customs, clearance could be done at the airport of origin or on board the aircraft, allowing transfer baggage to be moved directly to their connecting flights.

6.5.1 Biometrics

Biometric technologies have greatly evolved in the last few years. Several types of biometric recognition are available, of which the most common are fingerprints, hand geometry, retinal scan, and face and voice recognition. Whatever the technology chosen, the system requires the voluntary enrolment of users, during which a sample of the biometric trait is taken and digitally stored in a database. Conceivably, this information can be later accessed for identification or authentication purposes. Identification – where the system tries to match the sample taken at the kiosk to one of the many samples stored in a database – has not been proved feasible yet. Wayman [1998] reports that in tests with face and voice prints and hand geometry recognition these technologies have not been able to positively identify a person from a group of more than a thousand. On the other hand, authentication – where the person provides both her identity and a biometric sample and the system then checks them against a unique file in the database – has been shown to have a failure rate of less than 1% [Dunn, 1998].

Due to the reasons above, biometric projects for immigration purposes have used a combination of a card for identification and a biometric reading for authentication. In the United States, pilot tests with INSPASS use hand geometry for authentication. The program is open to frequent travellers from the USA or from any country participating in the Visa Waiver Pilot Program [INS, 1998]. In Canada, the CANPASS system installed at Vancouver Airport uses an image of a fingerprint, which is compared to the image stored either on a database or on an encrypted card. The system also enables passengers to make their customs declarations electronically, with any duties and taxes debited to their credit cards [Canada Customs, 1999].

Both INSPASS and CANPASS require the issuance of a special card to the passenger. This characteristic of those programs requires the goodwill of the passenger to enrol and pay the cost of the card, which infrequent flyers may not be willing to do. To overcome this problem IBM has developed Fastgate, a system that can be triggered by swiping an existing card such as a credit card. In that case, no special card must be purchased – it suffices to provide the biometric sample and the number of the card [Norton, 1997].

6.5.2 Ideas for a Fully Automated Customs/Immigration System

Although INSPASS, CANPASS and Fastgate are a significant step in the direction of automation of immigration services, there is room for more accomplishments. These programs are available only to citizens who are not required an entry visa. As far as information technology is concerned, there is no reason why the same database that contains the passenger's biometric information could not accommodate information on travel authorisation. In fact, the Australian government has already implemented its Electronic Travel Authorisation System (ETAS), which allows passengers to have a visa issued electronically. At the check-in counter or at the immigration booth the officer may access a central database that contains the information on the visa. If both verifications of identity and entry authorisation were to be combined, the whole immigration process at the airport could be automated, greatly increasing the throughput of the system.

The opportunities do not end here. Customs declarations could be prepared and filed via Internet or through a kiosk at the originating airport. Immigration and customs clearance could be done at the time of boarding – the passenger would insert her card in a machine located at the gate, the same one used for electronic boarding passes. The machine would then verify not only the passenger's electronic boarding pass, but also her passport and visa information contained on the card. The machine would also read the passenger's biometric print and check it against the one stored in the immigration services' database. Clearance would therefore be given prior to boarding the aircraft. If the passenger is selected for customs inspection, the machine notifies her, perhaps printing out a "customs clearance pass" to serve as a reminder on arrival. This information would also be passed on to the destination airport's automated baggage system. On arrival at the destination airport, connecting passengers and baggage cleared from customs inspection could proceed immediately to their connecting flights. Terminating passengers could retrieve their baggage and leave. Passengers and baggage chosen for customs inspection would be diverted directly to the inspection room. This procedure, illustrated in Figure 6.5, would greatly reduce connecting times and improve the level of service to passengers. It would also reduce the need for immigration clearance area and for segregation of international and domestic passengers. Furthermore, because now connecting passengers do not need to claim their baggage, it would reduce the demand in the baggage claim area.

There are many variations to explore for these automated procedures. For instance, the communication between the gate boarding machine and a central database in a foreign country may fail or be very slow, increasing the boarding time. Until an acceptable level of reliability is achieved in those communications, it may be necessary to allow airlines to perform customs and immigration clearance on behalf of the passenger. The airline, using the information provided by the passenger when making the reservation, could access the immigration service's database and get the clearance for the passenger. It could also download a copy of the passenger's biometric print so that identification at the time of boarding would only need to access a file stored locally.

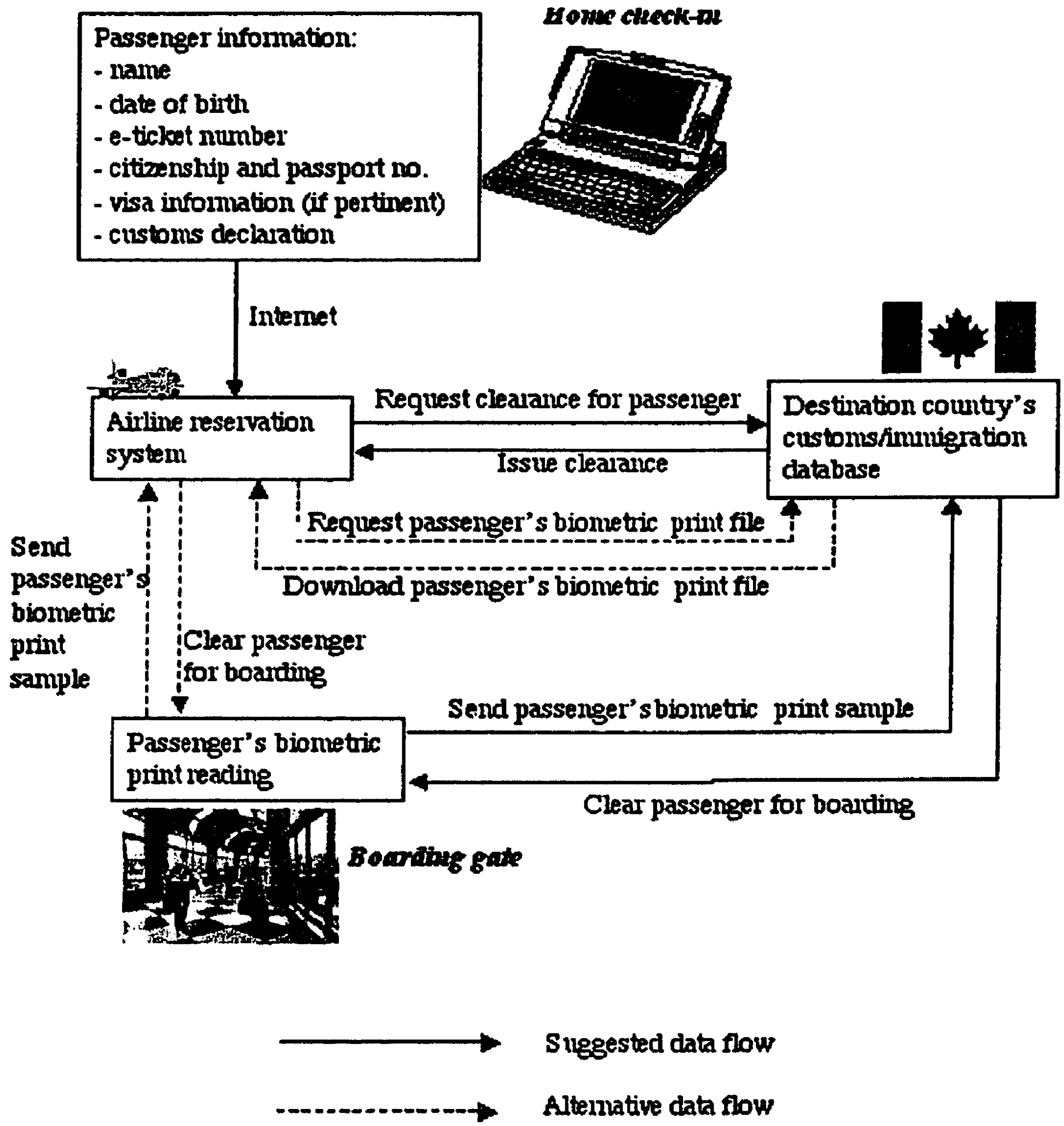


Figure 6.5: Pre-boarding customs/immigration clearance

Evidently, due to security concerns, the world wide adoption of such procedures is probably still far away. For instance, the USA's Immigration Services do not anticipate expanding the INSPASS service to non-immigrant classes in the foreseeable future [INS, 2000]. Nevertheless, the Airports Council International (ACI) is encouraging the development of such systems for all countries [Airport World, 1998a].

6.6 BAGGAGE HANDLING

"If you're looking for the heart of the aviation industry, it's in the bag." [Jackson, 1999]

The number of passengers is not the only parameter that has increased in the last years. Passengers usually travel with baggage, which for safety and comfort reasons must be separated from the passenger and accommodated in the aircraft's cargo compartment. Unfortunately, however, bags cannot find their ways to the aircraft by themselves, so it is the airport/airline responsibility to take them there. Easy task at small airports, but increasingly complex as the airport grows bigger.

6.6.1 Conventional Baggage Systems

In a conventional, manual baggage system, the outbound baggage is conveyed from the check-in counter to a *sorting and make-up room.* In this room, baggage handlers sort the baggage by flight – based on the information printed on the tag – and accumulate it in the corresponding baggage cart or container. When loading is completed, the carts are taken by a tug to their corresponding gates for loading onto the aircraft. Figure 6.6 shows an example of a manual sorting room.

The number and location of sorting rooms can vary. The most common configuration is the *centralised* room, where all of the terminal's outbound baggage is sorted and assembled into the carts or containers. At large airports, a central room needs to be very large and capable of handling the baggage of many flights simultaneously. It will also require a quite elaborate sorting system [Ashford et al., 1997]. In order to reduce the complexity of the sorting system, some airports adopt a *decentralised* system, with several baggage rooms each serving a small number of gates. At airports with remote concourses or satellites such as Atlanta Hartsfield, *remote* baggage rooms are used to serve the concourses. Figure 6.7 illustrates each type of baggage room system.

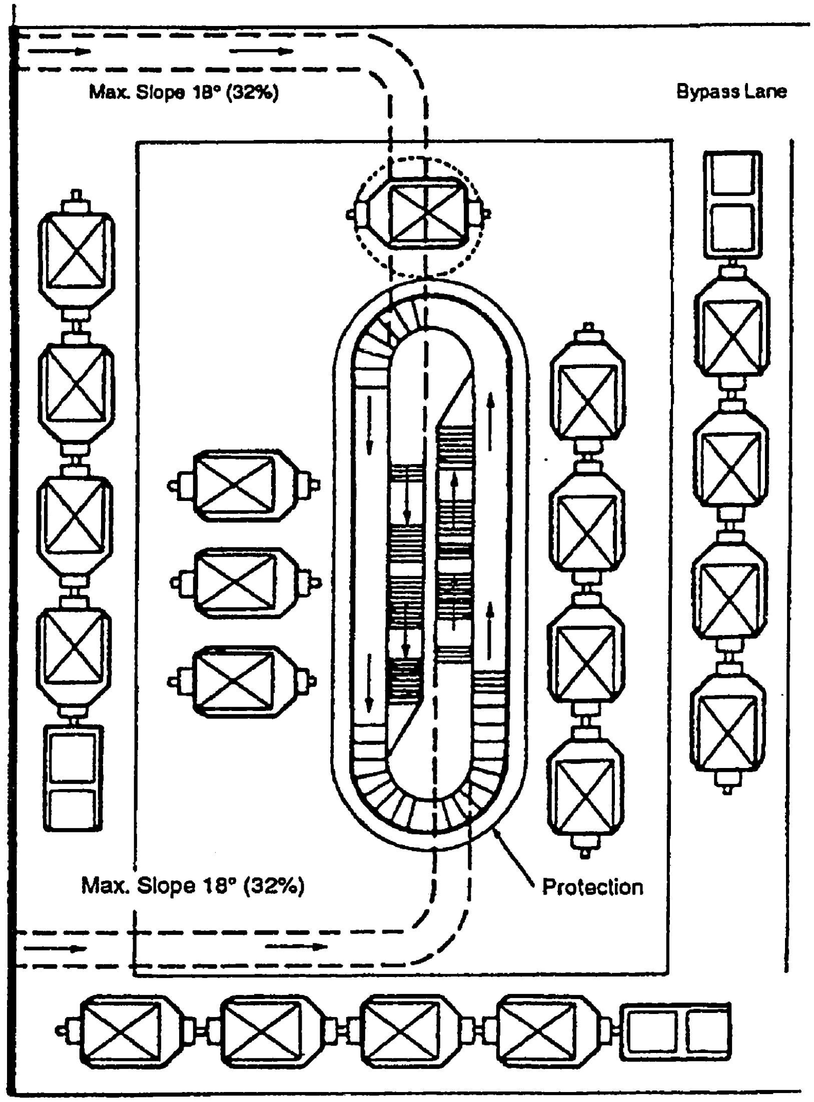


Figure 6.6: Manual sorting room [IATA, 1995]

Inbound baggage systems are simpler than their outbound counterparts. The baggage is unloaded from the aircraft onto the baggage carts/dollies and taken by a tug to the break-up area, where it is either unloaded onto the selected baggage claim conveyor or, in the case of transfer baggage, delivered to the sorting room for re-departure. At large terminals with a high number of transfers, airlines may arrange to carry transfer baggage directly from the aircraft to the sorting room or even to the connecting flight. Conventional systems have the main disadvantage of relying excessively on human-handled operations. This characteristic of conventional systems make them very inefficient and unreliable, with high baggage transfer times, high labour costs, and just too many bags misrouted. With larger aircraft, the tendency is for the problem to worsen, if all remains unchanged. For that reason, more and more airports are moving to automated systems.

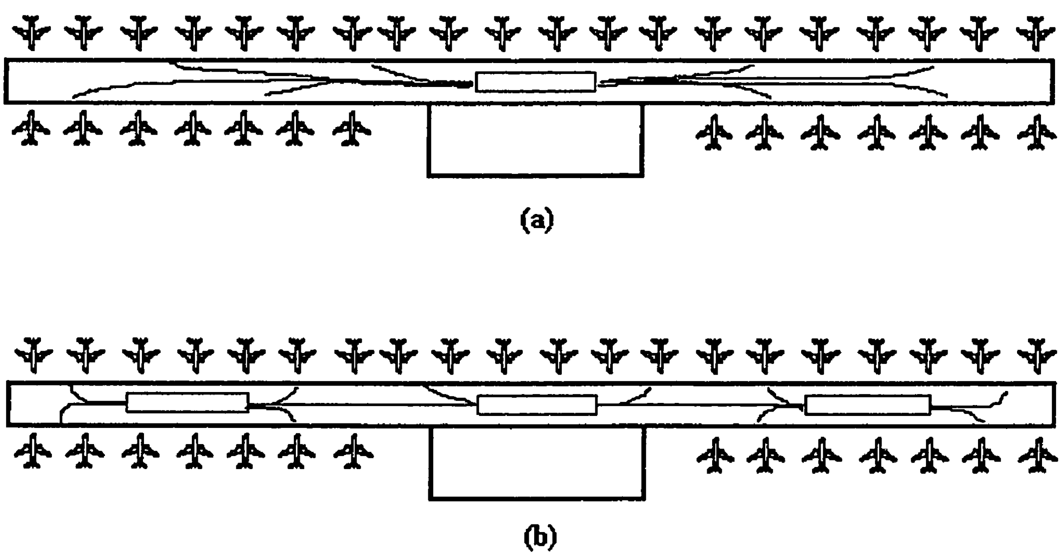


Figure 6.7: Baggage room systems: (a) central bag room; (b) decentralised bag rooms.

6.6.2 Automated Baggage Systems

Automated baggage handling systems are designed with the main goal of increasing the efficiency and reliability of the baggage handling process. These increases are sought through the use of high-speed baggage transporters and by reduction of dependence on human interference, which is known to be the main cause of problems and delays to the process [Jackson, 1999].

Automation can be achieved at several different levels. Ultimately, a fully automated baggage system must be able to move the baggage directly from the check-in point to the aircraft gate, and from the aircraft gate to its assigned baggage claim belt – or to the re-departing aircraft gate, in the case of transfer baggage – without human interference. In practice, however, the only place where that has been tried is at Denver International Airport (DIA). However, due to a variety of problems ranging from poor project management to technological issues, DIA's automated system has not been successful [Dempsey et al., 1997] and only recently began to be used for inbound baggage. Many airports have opted for a less complex system, where just part of the baggage system – usually the sorting of outbound baggage – is automated [Airport World, 1998b; Hussey, 1998; Airports International, 1998b, 1998c; Rowe, 1998]. Hong Kong Chek Lap Kok Airport chose a level of automation similar to Denver, but for the outbound baggage only [Airports International, 1998a].

There are three main technological issues associated with baggage handling systems: baggage identification, type of conveyance, and baggage screening. Each of these issues will be discussed below.

6.6.2.1 Baggage Identification and Tracking

In order to move a bag automatically from its origin to its correct destination within the terminal in a system that could be handling thousands of bags per hour, it is essential that the bag can be uniquely and unmistakably identified throughout the system. Furthermore, to provide an uninterrupted flow, the system must be able to recognise the bag's unique ID in motion. Two technologies are currently available for baggage identification: bar-coded and radio-frequency tags.

Bar-coded tags are the current standard of the aviation industry for baggage ID. Standards for the tags are established by IATA in its Resolution 740 on baggage tags. The tag is usually printed at the check-in computer on an adhesive-backed face paper, which is looped through the bag's handle with the two sides of the tag then adhered together. The bar code on the tag may be printed vertically, horizontally or orthogonally (both orientations). The latter is preferred because it allows tags to be read by all types of scanners [IATA, 1995].

The main advantages of bar-coded tagging are its easiness of issuance and relatively low price – 8 American cents a piece [Jackson, 1999]. It has, however, several disadvantages. The tag is relatively fragile and can be easily rendered unreadable. Inbound and transfer bags are especially subject to this problem, due mainly to the way they are piled when stored. In some cases, up to 60% of transfer bags cannot be identified automatically because the tag is either damaged or missing [Airport World, 1998a]. Even if the tag is okay, reading it automatically with the bag moving requires that the tag is in the line of sight of the scanner. With the increase in the variety of baggage's shapes and sizes [Ashford et al., 1997; Drury, 1999] and with automated conveyance, the number of misreads can be fairly high. It is estimated that 5 to 30% of bar code reading operations fail [Airports International, 1998d].

In an attempt to overcome the limitations imposed by optical reading, a new technology is being tested that uses radio transmissions instead. Known as Radio Frequency Identification (RFID) or Radio Data Tags (RDT), these tiny devices are able to combine ESD technology with radio communication. An RFID tag is usually composed of a chip, where all information about the bag is stored, and an antenna capable of transmitting to a reading station up to one metre away. Self-powered tags, with an internal battery, have a higher storage and longer communication range capabilities, but are also more expensive. Passive tags are less capable but are also cheaper. The energy for the transmission is provided by the reader itself through a magnetic field that "excites" the tag, causing it to transmit the information it has stored [Cerino, 1998]. A variant of the RFID tag uses no chip at all – the unique frequency transmitted by the tag is its ID. [Jackson, 1999; Airports International; 1998a].

The main advantage of the RFID over bar-coded tags is their ability to be read through visual obstacles. This ability greatly improves the efficiency and reliability of the system, for they can be read at higher speeds and seldom fail. They also have the potential to provide individual tracking capability for security reasons [Yfantis, 1997; Weil & Kirk, 1999]. However, two impediments still exist to the widespread adoption of RFID. First, RFID and bar-coded tags are totally incompatible. That means baggage originating from an airport that uses one technology cannot be automatically read at a destination airport using the other technology. Provision would have to be made to manually handle those bags, which can be a hurdle at airports with a high transfer rate. Second, the cost of the RFID system is still too high – 50 American cents a bag [Jackson, 1999]. Chipless tags could be significantly less expensive, and some trials have been performed to embed them in the paper tag, allowing for the use of either type of reading [Airports International, 1998d]. Further developments in chipless tag technology may make it viable in the near future.

6.6.2.2 Conveyance and Sorting System

Baggage can be conveyed by either belt conveyor, belt carry, tilt tray, or destination coded vehicle systems. The choice of the system will depend on the type of sortation system and on the speed and capacity requirements.

Belt conveyors are widely used in conventional baggage handling. A step up to automation is taken with the addition of automatic baggage diverters that take the bag out of the belt at the assigned point. These systems are frequently used in upgrades of centralised baggage rooms [IATA, 1995], and require tag reading just prior to entering the sorting system.

The principle behind the three other systems is the same: the ability to associate the bag with a vehicle, such that the bag has to be identified only when entering the system. Once loaded onto the vehicle, it is the vehicle that will be identified at checkpoints. Tilt tray systems such as the one used in Hong Kong CLK are comprised of a continuous chain of trays that tilt to unload the bags at the assigned position. System control technology is used to track each tray individually. A belt carry system (Figure 6.8) is a series of carts on a track, carrying a belt that moves at a 90° angle to the track. Bags are loaded and unloaded by synchronising the cart's belt with the loading/unloading belt, without physical impact on the bag. Both systems be combined with belt conveyors, with the tilt tray or belt carry system used only for sorting and the conveyor used for actual connection between the input and output points.

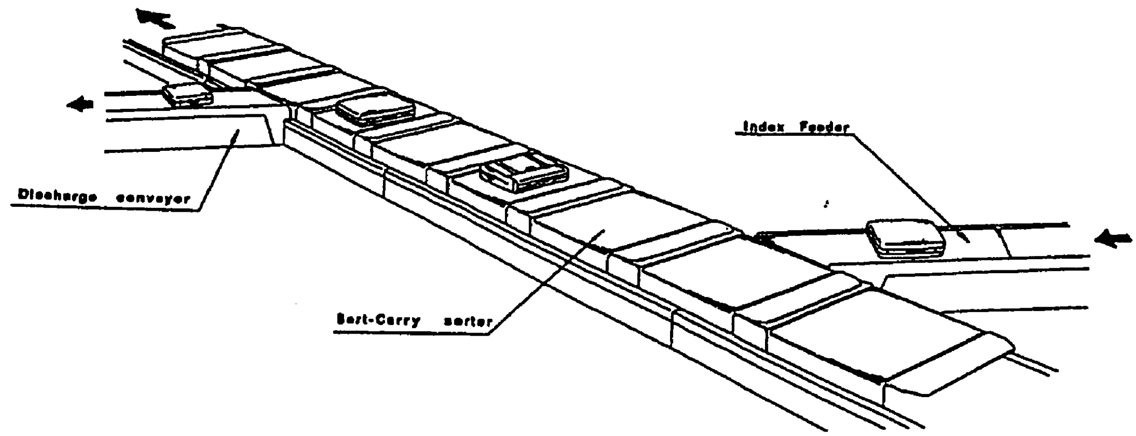


Figure 6.8: Belt-carry sorter [IATA, 1995]

DCV systems (Figure 6.9) differ from tilt tray and belt carry ones in that the carts move independently through a system of tracks that resemble a rail system. Each vehicle moves at high speeds – up to 600 m per minute, compared to a maximum of 120 m per minute in other systems – and has the ability of changing tracks, which enables the bag to go from any of a number of input points to any of a similar number of output points without changing vehicles. When the bag is loaded, the destination code is input into the central control system, and the cart is then routed through the system using RFID or bar code reading until it reaches its final destination. DCVs are very useful where very long distances must be covered in short times. Provision must be made, however, for empty cars to be promptly available wherever and whenever needed. In a very large system, such as in Denver, the co-ordination of all activities involved can become a huge task and must be planned and performed with care, allowing sufficient time for testing before entering operation. Other airports using DCV systems are San Francisco, Munich, Frankfurt, Oslo, Amsterdam Schiphol, Zurich and London Heathrow [Airport World, 1998c].

Due to its high speed and capacity and potential to be used in large systems with any number of feeding and unloading points, DCV systems seem to be the technology to be used to achieve 100% automation. However, due to the uniqueness of every airport design, such systems must be custom-tailored, hence very expensive and effort consuming.

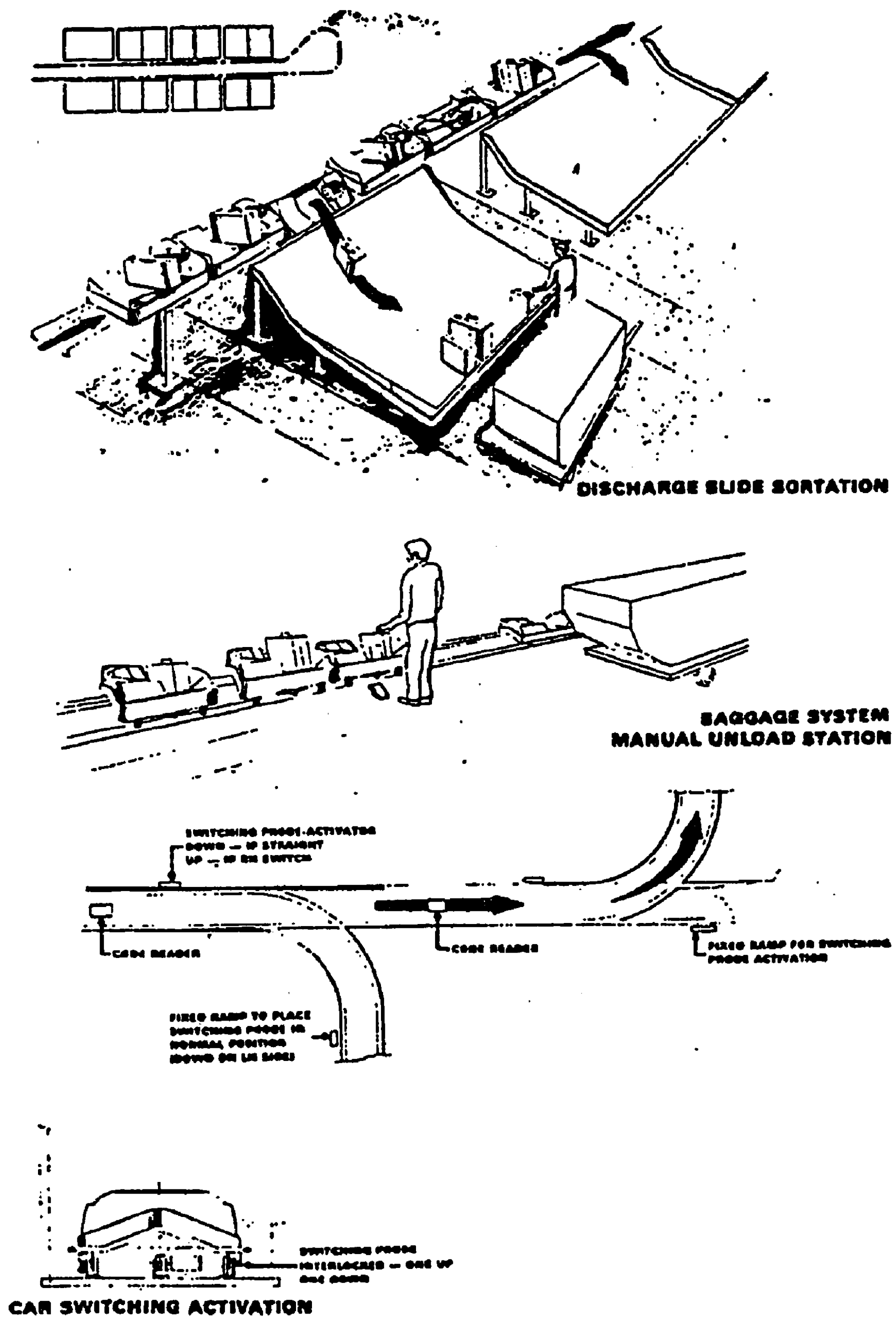


Figure 6.9: Destination coded vehicle [FAA, 1988]

6.6.2.3 Baggage Reconciliation and Screening

Although air transportation is widely regarded as the safest mode of transportation in operation, it is unfortunately one of the most vulnerable. Due to this vulnerability, their very high prices, and the fact that they carry hundreds of people, aircraft have become the favourite target of terrorist actions. The most common way of terrorism against aircraft is to bring a bomb aboard hidden in the baggage. In principle, the author of this plan would not board the aircraft, so checking that the owner of the bag has boarded should suffice as a precautionary measure. However, terrorists have become bolder and bolder, and cases where the passenger – knowingly or not – accompanies the bomb are now common. For these reasons, measures have to be taken to ensure that no baggage contains any kinds of hazard for the sake of the flight. The two most common measures with that purpose are baggage reconciliation – also known as positive passenger-baggage match (PPBM) – and baggage screening.

PPBM is currently a policy in effect for all flights in Europe and for international flights in North America [Jackson, 1999]. Basically, PPBM consists of not allowing baggage to fly unaccompanied by the passenger who checked it in. If the baggage is on the flight, so must be the passenger.

The current procedure to achieve PPBM is to completely ignore it until the time of closing the aircraft door, as can be seen in the reconciliation procedures suggested by IATA [1999]. At that time, if a passenger has checked in baggage but has not shown up for boarding, her baggage must be taken out of the plane. It is easy to see how painfully slow this process can be if one or more bags have to be retrieved from a wide-bodied aircraft with hundreds of bags randomly arranged in the containers.

Again, technology comes to the rescue. Drury [1999] suggests that RFID bag tracking be linked to smart boarding cards. In that case, bags could be loaded into the container as their respective owners are acknowledged by the system to have shown up for boarding. This procedure decreases, but does not eliminate, the risk of having to unload the bag after door close-out time. RFID can also be used to locate individual bags in the container. Yfantis [1997] has proposed a system that uses laser arrays to input the dimensions of the bag into the computer. The computer uses this information to assign the bag a specific location in the container. If the bag needs to be retrieved, it is possible to know exactly where it is. This system also uses a chipless tag that can be used to locate a bag with a directional frequency transmitter. A similar system is in use in the new International Terminal at New York JFK [Airport World, 1998a]. The main problem with this procedure is that it greatly complicates the assembling of the container, requiring additional baggage storage at the make-up area and highly specialised labour.

PPBM does not fully guarantee the safety of the flight. A suicidal terrorist, or a person who inadvertently carries a bomb put in her baggage by someone else, will be on the aircraft with the bomb. For that reason, baggage screening devices were developed and many airports are committed to 100% baggage screening. Integrating them with the baggage flow has become the biggest issue. The British Airport Authority (BAA) recently conducted a pilot project at Glasgow Airport, where advanced X-ray machines are integrated into the baggage handling equipment. The system is capable of processing up to 1,200 bags per hour per line [Aldo, 1993].

Conventional X-ray machines are very slow, but can be installed at the baggage system's entry points. However, they do not provide enough explosives detection capability. More sophisticated explosive detection devices, such as the ones that use cranium axial tomography (CAT) technology [Marsh, 1997], may be very expensive and not very fast, creating a serious bottleneck in the baggage flow. The development of high-speed devices capable of a thorough scan is therefore necessary to ensure 100% baggage screening without disruption of the baggage flow.

Until such high-speed devices come, many airports are adopting a two- or three-level screening. In this scheme, all baggage goes through X-ray machines and only suspect ones are diverted for more thorough inspection. This way, it is possible to use just a small number of sophisticated screening machines, with little disruption caused to the baggage flow. In other cases, airlines use a computer-assisted passenger screening (CAPS) system that determines, based on the data found on the reservation file, which bags are to be searched.

6.6.3 NLA Operations

NLA's are expected to have a very large proportion of their passenger load transferring to other flights. If these transfers are from an international flight to domestic ones, then baggage must clear customs before being re-routed to the connecting flights. In this case, if pre-boarding customs clearance is not possible, then there is not much that can be done to improve the process except for the use of the technologies described above.

Where pre-boarding clearance is possible, or in the case of NLA passengers connecting mainly to other international flights – like in the case of international hubs such as Hong Kong and London Heathrow – the transfer of baggage can be made more efficient by using different containers for different destination flights. For example, if an NLA arriving in Toronto has a high percentage of passengers transferring to a flight to Chicago, then all their baggage could be stored in one or more containers reserved exclusively for that flight. Upon arrival in Toronto, those containers could be transported directly to their connecting flight, without the need to break them up. Even if break-up is necessary due to a possible incompatibility of NLA containers and conventional jets, break-up could be done at the baggage make-up station, with a simple transfer of baggage from the NLA containers to the conventional jet ones. Such procedures would greatly improve the efficiency of the connection procedure, without the need for baggage tag reading.

6.7 SUMMARY

At the airport terminal, the main consequence of the increase in aircraft capacity through the introduction of the NLA is a boost in passenger flow rates if the level of service is to be kept at current or better standards. With the current practices, the operation of several NLA combined with other large aircraft in a short period of time may put too much pressure on passenger processing. Ultimately, this increase in passenger flows would require more resources in the form of terminal space, equipment and labour; if more resources are not provided, the level of service could decrease and several delays could occur.

With the use of new technologies, either existing or ones under development, it is possible to increase the throughput of the system significantly. In fact, even with larger aircraft, it is possible to provide a better service than what is done today. A combination of new technologies and procedures for ticketing, check-in, baggage handling, customs and immigration can make a passenger terminal much more efficient, with a very high perception of quality of service by the passenger and better operational performance for the airport and the airlines.

This is what the future looks like: the passenger buys a ticket and, if necessary, acquires a visa, both via Internet. Hours before the flight, he checks in via Internet and arranges for his baggage to be picked up at home. He also files an electronic customs declaration for the country he is going to. At the airport, he skips the check-in counter and goes directly to the departure lounge. At the gate, he presents his ESD (smart or magnetic card), which contains all information necessary for the trip, including: his identification; number of bags checked with their respective ID's; frequent flyer number; and passport and visa information. A biometric reading is used to confirm his identity. The machine accesses the destination country's database and gives him immediate immigration and customs clearance. His baggage is brought to a feeding point at the terminal and transported directly to his flight's gate via the automated baggage system. On the way, it is automatically screened by scanners integrated to the baggage flow system. As soon as the passenger boards the aircraft, the baggage system receives a message clearing his baggage for boarding. If he misses the flight, his baggage is not loaded or is immediately removed from the aircraft with the help of a baggage tracking system.

Upon arrival, if the passenger received the okay from customs, he simply moves to the gate of his next flight or to the baggage claim if that is his final destination. If he is transferring, his baggage is automatically taken from his arrival gate to his departure gate by the automated baggage system. If terminating his trip, the same system takes his baggage to the assigned baggage carousel. In case he has been selected for customs inspection, his baggage is automatically sent to the customs room, to where he will go as soon as he gets off the aircraft.

It may still be several years until such smooth, seamless air trip is possible. Most technologies involved already exist, but combining them and putting them to work with a reasonably low failure rate remains a challenge. The most probable scenario is the one in which these technologies evolve separately, being debugged and combined little by little. The example of the automated baggage system in Denver shows that the actual implementation of untried technologies is not easy at all, and much effort must be reserved for testing and debugging the system until it can perform to satisfaction [Dempsey et al., 1997]. Nevertheless, it is undoubtedly the way to go.

CHAPTER 7
SIZING THE BAGGAGE CLAIM AREA FOR THE NLA

7.1 INTRODUCTION

The separation of passengers and bags during the flight requires a way to return the baggage to passengers in an efficient manner after the flight is over. Since the process of unloading baggage is much more complicated than unloading passengers, the match cannot be done right at the aircraft door. The baggage is thus brought to a mechanised display at the terminal, where passengers can then retrieve it.

Evidently, the need for physical space in this area has become greater as the size of the aircraft has increased [Ashford et al, 1997]. The introduction of the NLA is now adding to the problem, with more passengers and respectively more bags needing accommodation while waiting for a match. In fact, the baggage claim area is already seen as the biggest problem encountered during a typical air trip [FAA, 1998b].

To avoid confusion to passengers – which would lead to an increased dwelling time in the claim area, with a corresponding increase in the area requirement and/or a decrease in the level of service – it is imperative that the passenger be directed to the exact device where his bag will be displayed. For this reason, current practice is to use only one claim device for a given flight [Hart, 1985; Horonjeff & McKelvey, 1994]. However, existing claim devices at the great majority of existing airport terminals will not be enough for the number of passengers and bags carried by the NLA. At those terminals, it may be imperative to use two devices for an NLA flight. Fortunately, the NLA will feature two different passenger decks, allowing the baggage to be separated between upper and lower decks.

For new airports, however, the question remains whether the use of two short devices would be more efficient than one long device. Investigating this is the first objective of this chapter. In addition, it is important to investigate how other factors associated with the NLA will impact the planning of the baggage claim area. Existing methodologies either do not take into account clusters of passengers claiming multiple bags, or consider the arrival times of bags belonging to one cluster to be independent. Both assumptions have significant drawbacks and affect the size requirement for the baggage claim.

In this chapter, a model will be developed that overcomes the drawbacks of existing methodologies and allows one to investigate the effects of the NLA on the baggage claim area more deeply. The model attempts to determine the maximum accumulation of passengers and baggage in the claim area using deterministic queuing theory. The model is then used to analyse the possible scenarios brought up by the NLA and to investigate the solutions that have been suggested, such as the use of two claim devices. The application of the model is done with the help of a spreadsheet, which allows for the fast evaluation of the model's sensitivity to the various parameters involved.

7.2 LITERATURE REVIEW

IATA [1995] and FAA [1988] have developed standards for the design and sizing of the baggage claim area. These standards are basic directives for the executive design of the claim area, defining minimum and typical values for the various measures involved in the area, such as the separation between adjacent devices, the width of the access corridors, and the levels of service in terms of area per passenger. These are important for when the demand is known and the design of the claim area is in the detailing phase. No directions are given on how to determine that demand.

The first significant attempt to model the passenger and baggage flows at the baggage claim was made by Barbo [1967] and Horonjeff [1969]. These works attempted to determine the maximum accumulation of bags on the claim device using deterministic queuing theory. The accumulation of bags at any time on the device is simply the difference between the number of bags arrived and the number departed,

$$A_B(t) - A_B(t-\delta)A_P(t-\delta) \qquad (7.1)$$

where

$A_B(t)$ = cumulative number of bag arrivals;

$A_P(t)$ = cumulative number of passenger arrivals;

δ= average time it takes for the passenger to remove the bag from the device.

No reference to the passenger accumulation is made in these works. A further step in this direction was given by Browne et al [1970], who developed several formulae for the maximum accumulations of baggage and passengers for the case of linear, uninterrupted arrivals of bags and passengers. The formulae take into account the delay between the beginning of passenger arrivals and baggage, but only for the case where passengers carry one bag each. In the case of more than one passenger per bag, that delay is assumed to be zero. Furthermore, baggage arrival times are assumed to be independent.

The sensitivity of the deterministic queuing models used in the works above to the delay δ is investigated and modelled by Ghobrial et al [1982]. The delay is modelled as a function of the congestion occurring around the claim device. This is based on the principle that, the more congested the claim area is, the more difficult it is for passengers to reach their baggage on the device and retrieve it. The measure of congestion used is the density ρ in passenger per square meter around the claim device. The delay is then modelled as a linear function of ρ. An interesting feature of this model is that bags belonging to a passenger cluster are assumed to arrive together, a scenario that is the exact opposite of the independence of bag arrival times assumed in Barbo [1967], Horonjeff [1969] and Browne et al [1970].

In spite of the importance of the works above, their limitation is in the fact that the correlation between the arrival times of bags belonging to a cluster is ignored. In addition, no consideration is given to passengers who travel in clusters and remain in the claim area until all bags are retrieved. These are the points that will deserve the most attention in the model explained below.

7.3 FORMULATION OF PASSENGER AND BAGGAGE ACCUMULATIONS

Domestic passenger arrivals at the baggage claim area usually follow an S-shaped distribution, as shown in Figure 7.1. NLA's, however, are expected to be used mostly for international flights, where passengers must clear immigration control – often together with passengers from other flights – before claiming baggage. In that case, the passenger arrival is proportional to the immigration service rate. This passenger arrival rate can thus be assumed to be constant over time with value α_P. Hence, for NLA international flights it is preferable to use a linear arrivals curve as shown in Figure 7.2.

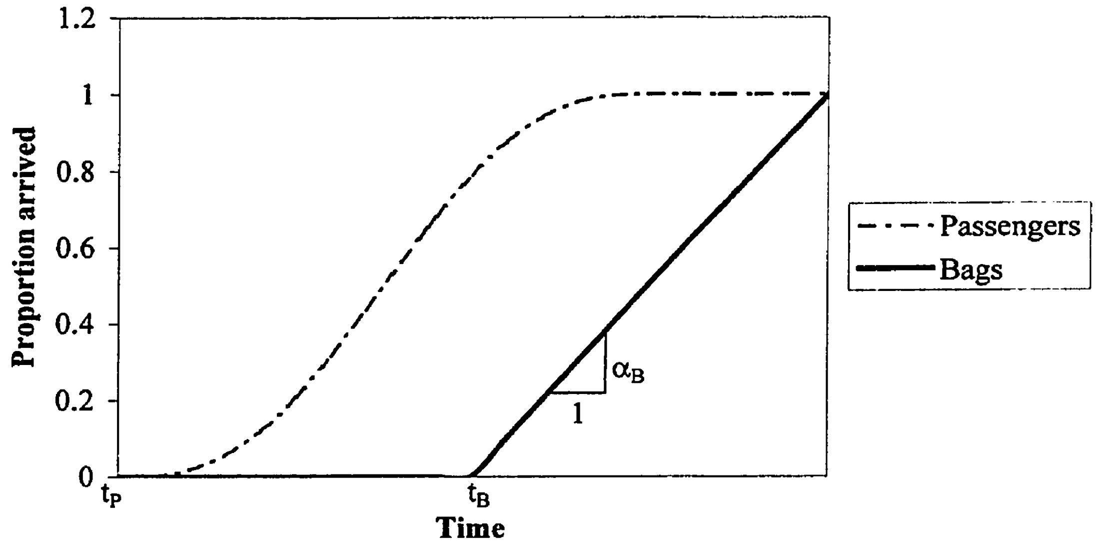


Figure 7.1: Cumulative arrivals at the baggage claim area: domestic flight

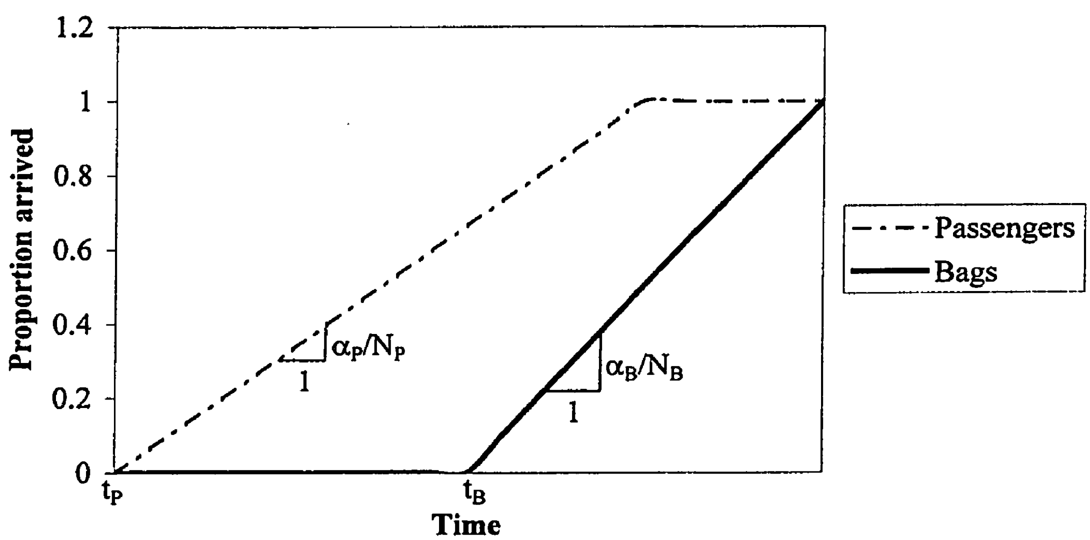


Figure 7.2: Cumulative arrivals at the baggage claim area: international flight

The time t_B at which the bags begin to be loaded onto the claiming device is a random variable dependent on the availability of baggage carts and tractors, the size of the baggage load, the unloading process, the distance from the gate to the unloading device, and the traffic conditions between the gate and the break-up area. Once the unloading of bags from the carts onto the claiming device starts, it can be assumed that the unloading occurs at a constant rate α_B for as long as there are bags to be unloaded. If one set of carts is finished being emptied and the next one has not arrived yet, an interruption will occur, increasing the passengers' dwelling time at the baggage claim area. This situation is highly undesirable and should be avoided by use of proper operational measures. Thus, for the purpose of this work, bags will be considered to be unloaded uninterruptedly.

7.3.1 Passenger Accumulation

Let n_B be the average number of bags per passenger. If $n_B = 1$, then the number of passengers in the baggage claiming area at time t equals the aircraft load N_P times the probability that a passenger has arrived and his bag has not arrived yet [Newell, 1982]:

$$Q_P(t) = N_P[F_P(t) - F_P(t)F_B(t)] \tag{7.2}$$

where

$F_P(t)$ = probability that the passenger has arrived at time t (cumulative distribution of passenger arrivals at the claiming area);

$F_B(t)$ = probability that the bag has arrived at time t (cumulative distribution of baggage arrivals at the claiming device).

For simplicity, the time t_P at which the first passenger arrives at the baggage claim is set to zero, such that t_B is now the delay between the start of passenger arrivals and baggage arrivals. As discussed above, $F_P(t)$ and $F_B(t)$ are assumed to be linear, i.e.

$$F_P(t) = \frac{\alpha_P}{N_P}t \tag{7.3}$$

and

$$F_B(t) = \frac{\alpha_B}{n_B N_P}(t - t_B) \tag{7.4}$$

Passengers may, however, carry more than one bag – particularly on long-haul, international flights. Furthermore, passengers may also travel in groups, forming clusters of passengers that enter and leave the baggage claim area together. In that case, the whole cluster remains in the baggage area until all their bags have been reclaimed. It is therefore necessary to consider the existence of clusters waiting for more than one bag in the formulation of the passenger accumulation.

Passengers can be divided into sets, where each passenger in a set belongs to a cluster that has i bags in total. For instance, a couple and a child travelling together and reclaiming four bags in total belong to set 4. Let r_i be the fraction of the aircraft passenger load who belong to a cluster with i bags to reclaim, i.e.

$$\sum_{i \geq 0} r_i = 1 \ , \quad 0 \leq r_i \leq 1 \tag{7.5}$$

Then the accumulation of passengers belonging to a cluster that is claiming i bags at time t is

$$Q_P^i(t) = r_i N_P [F_P(t) - F_P(t - \tau - \delta_B) F_B^i(t - \tau - \delta_B)] \tag{7.6}$$

where

$F_B{}^i(t)$ = probability that all i bags belonging to a cluster have arrived at time t;

τ = average time lag between retrieval of the last bag of a passenger cluster and the departure of the cluster from the claim area;

δ_B = average time it takes for a passenger to retrieve the bag from the claim device – takes into account the fact that, after both passenger and bag have arrived, the bag still has to move on the device to reach the passenger [Barbo, 1967].

The total passenger accumulation at time t is the sum of passenger accumulations for all sets,

$$Q_P(t) = \sum_i Q_P^i(t) \tag{7.7}$$

Not all of those passengers actually need to approach the claim device. In fact, under crowded conditions, only a fraction of the passengers belonging to a cluster approach the device, while the others wait outside of the active claim area (see Figure 7.3). Ultimately, just one passenger representing the cluster would be enough to retrieve all the cluster's baggage. In that case, the number of passengers in the active claim area could be evaluated by dividing the passenger accumulation calculated in Equation 7.7 by the average cluster size. In reality, however, some passenger clusters may have more than one representative within the active claim area. It is then postulated that, in average, a percentage p of the cluster requires some space for claiming. Hence the *accumulation of active claim passengers* at any given time t is

$$Q_{active}(t) = pQ_P \tag{7.8}$$

where

$$p \geq 1/s \tag{7.9}$$

s = the average number of passengers per cluster.

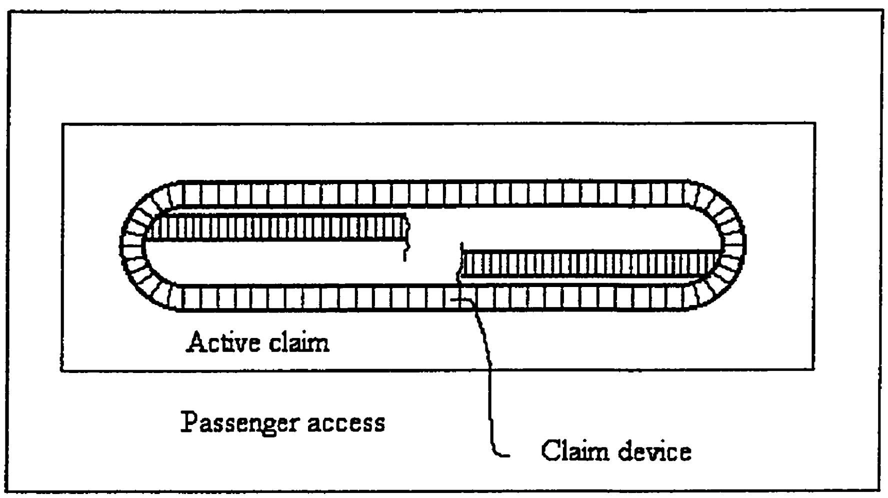


Figure 7.3: Active claim and passenger access areas

7.3.1.1 Area Requirement

The total area required for the claim area to accommodate all passengers is derived from the maximum accumulations of passengers over time. If l_P is the linear space per passenger to be provided along the claim device, then

$$L_P = l_P \, Q_{active}^{max} \tag{7.10}$$

is the length requirement for the claim device, where Q_{active}^{max} is the maximum accumulation of active claim passengers over time. The total area occupied by the device and its active claim area will depend on the type of device and its configuration. Additional space must also be provided for the passengers who wait for their cluster representatives to claim their baggage. For reasonable values of the average cluster size, these passengers can be accommodated in the access area provided in the vicinity of the device (see Figure 7.3). Therefore, the total area requirement for the device will be a function of the length requirement L_P.

7.3.1.2 Statistical Dependence of Bag Arrival Times

Let T_j be the arrival time on the belt of the j^{th} bag of a passenger cluster that has n bags. If we reorder the times T_j in increasing order of magnitude, we now have the order statistics $T_{(j)}$, such that

$$T_{(j+1)} \geq T_{(j)}, \quad j = 1,2,\ldots,n \tag{7.11}$$

The probability that all bags will have arrived at time t is

$$F_B^n = P(T_{(1)} < t, T_{(2)} < t, \ldots, T_{(n)} < t) = P(T_{(n)} < t) \tag{7.12}$$

$T_{(j)}$ is called a *partition* of the uniform interval $[t_B, t_B + n_B N_P / \alpha_B]$ during which all bags arrive. This concept is shown in Figure 7.4. A passenger cluster with n bags remains in the baggage claim room until the last bag has arrived. Hence we are interested in the distribution of $T_{(n)}$, the arrival time of the last bag belonging to the passenger cluster.

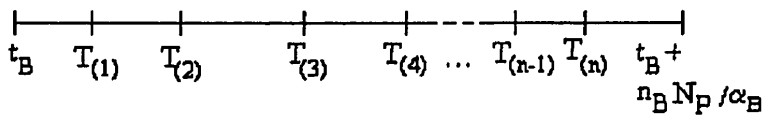


Figure 7.4: Ordered statistics as a partition of the bag arrival times interval

If the arrival times T_j are mutually independent, then it can be shown that for a uniform arrival process with constant rate the distribution and density functions of $T_{(n)}$ are [Feller, 1971]

$$F_B^n(t) = \mathrm{P}(T_{(n)} < t) = \left[\frac{\alpha_B}{n_B N_P}(t - t_B)\right]^{\beta+1} \tag{7.13}$$

and

$$f_B^n(t) = (\beta + 1)\frac{\alpha_B}{n_B N_B}\left[\frac{\alpha_B}{n_B N_P}(t - t_B)\right]^{\beta} \tag{7.14}$$

respectively, where $\beta = n - 1$.

The density function of $T_{(n)}$ when the times $T_{(j)}$ are independent, as shown in Equation 7.14, is a *beta* distribution with parameters $\alpha = 1$ and $\beta = n - 1$.

Unfortunately, the assumption of mutual independence of arrival times for bags belonging to one passenger cluster does not hold for baggage claim. In the case of perfect correlation, the bags belonging to a passenger cluster would be stored and unloaded together, thus arriving together at the claiming device. Neglecting the short time between arrivals, the distribution of $T_{(n)}$ in this case will be uniform over the interval $[t_B, t_B + n_B N_P/\alpha_B]$ – i.e. a beta distribution with $\alpha = 1$ and $\beta = 0$. However, due to perturbations in the baggage processing sequence, the bags are separated, but not to the point that their arrival times can be considered independent. Therefore, some correlation will exist between the arrival times of a passenger cluster's bags. The smaller this correlation, the more the distribution function of $T_{(n)}$ will tend towards a beta distribution as shown in Equation 7.14. As this correlation increases, the shape of the distribution of $T_{(n)}$ moves towards a uniform distribution, i.e.

the value of the parameter β tends to zero. Note that in either case of independence or perfect correlation the value of the parameter α remains unchanged, equal to 1.

Mathematically, the correlation between bag arrival times can be modelled with a correlation factor c that will adjust the value of the parameter β. By doing so, the density function of $T_{(n)}$ becomes the beta distribution with $\alpha = 1$ and

$$\beta = (1-c)(n-1) \tag{7.15}$$

where c ranges between 0 (independence of bag arrival times) and 1 (perfect correlation of bag arrival times). Figure 7.5 illustrates how the shape of the distribution of $T_{(n)}$ changes with c.

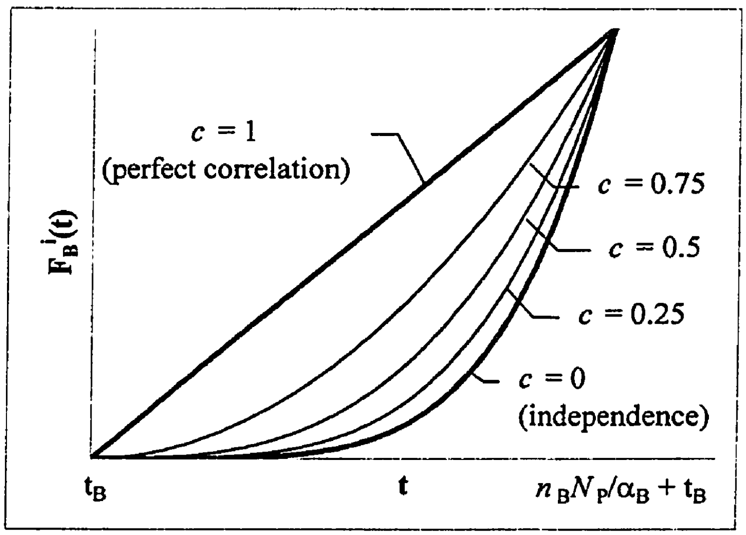


Figure 7.5: Relationship between the cumulative distribution of $T_{(n)}$ and the correlation of bag arrival times at the baggage claim device for $n = 5$.

7.3.1.3 Estimation of the Correlation Factor

The exact evaluation of the correlation factor c is beyond the scope of this work. Rather, we will discuss some of the factors affecting the value of c.

In principle, one would expect that bags that are checked in together be stored and reclaimed together. That could be the case of a small commuter flight originating at a small airport, with only one check-in counter and only originating passengers. As the size of the aircraft, the airport and the number of connections increase, a number of factors make the bags more and more shuffled:

- The baggage dispatch during check-in involves tagging the bags and in many cases weighing them. This process is performed individually for each bag; after one bag is finished, it is sent to the baggage make-up area (see Section 6.6) while the next one is processed. This creates a time heading between bag departures, during which bags belonging to other passengers can be sent from other check-in counters. The more check-in points are used, the more bags belonging to other passengers are likely to get in-between the bags being checked in by one cluster.
- Baggage screening performed in-line with more than one screening station may delay a subset of a passenger cluster's bags, separating them from the others. In many instances, baggage screening is done for selected baggage only, increasing the possibility that a cluster's bags will be separated before getting to the baggage make-up.
- Storage constraints may cause a cluster's bags to be stored in separate containers during baggage make-up. Furthermore, depending on the type of make-up process (see Section 6.6), bags may be randomly directed to different containers, especially when several containers are loaded simultaneously.
- Transfer bags must go through the above processes more than once, increasing the randomness of the separation between them.
- Simultaneous unloading of two or more baggage containers onto the claim device will increase baggage shuffling.

Clearly, the degree of baggage shuffling increases with the size of the airport where the baggage is loaded onto the plane and with the number of connections a passenger cluster has to make – the more connections, the more times baggage is subject to the shuffling factors described above. The diagram in Figure 7.6 illustrates this relationship. Therefore, passengers taking a one-leg flight originating at a small airport are more likely to have their bags arriving together, whereas those taking two- or three-leg flights going through one or more large airports can expect to have their bags to arrive more spread at the claim device.

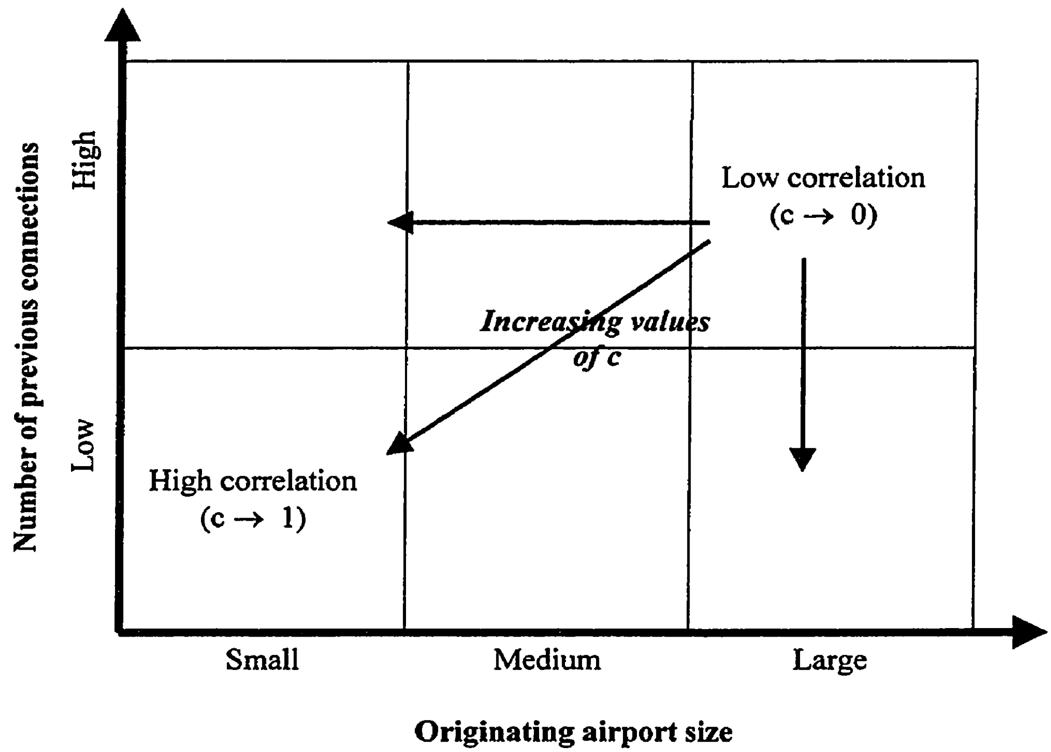


Figure 7.6: Value of the correlation factor *c* decreasing with the size of the originating airport and the number of previous flight connections

7.3.2 Baggage Accumulation

The baggage accumulation on the claim device has been evaluated by Barbo [1967] as

$$Q_B(t) = n_B N_P [F_B(t) - F_B(t-\delta_B) F_P(t-\delta_B)] \tag{7.16}$$

Substituting from Equations 7.3 and 7.4 in Equation 7.16, one can find the expression for the baggage accumulation on the claim device. Differentiating that expression and equalling to zero, we also find the maximum value of Q_B,

$$Q_B^{\max} = \begin{cases} \alpha_B\left(\dfrac{N_P}{4\alpha_P} - \dfrac{t_B}{2} + \dfrac{\alpha_P}{4N_P}t_B^{\ 2} + \delta_B\right), & \delta_B \le \dfrac{1}{2}\left(\dfrac{N_P}{\alpha_P} - t_B\right) \le \dfrac{n_B N_P}{\alpha_B} - \delta_B; \\ \alpha_B t_B, & \dfrac{1}{2}\left(\dfrac{N_P}{\alpha_P} - t_B\right) < \delta_B; \\ n_B N_P - \alpha_P\left(n_B - \dfrac{\alpha_B \delta_B}{N_P}\right)\left[t_B + \dfrac{n_B N_P}{\alpha_B} - \delta_B\right], & \text{otherwise.} \end{cases} \tag{7.17}$$

The length requirement for the bag device equals the maximum accumulation of bags times the average linear length per bag l_B

$$L_B = l_B\, Q_B^{\max} \tag{7.18}$$

7.3.3 Evaluation of the Baggage Claim Length Requirement

The length required for the baggage claim device is the maximum between the requirements for passengers and for bags,

$$L = \max(L_B, L_P) \tag{7.19}$$

However, these requirements were evaluated as a function of δ_B – the time lag between the appearance of the bag on the device and its claim by the passenger – whose value is evidently dependent on the length. A good estimate for δ_B is half the rotation period of the claim device [Balbo, 1969], i.e.

$$\delta_B = L / v / 2 \tag{7.20}$$

where v is the moving speed of the device's belt.

It is therefore necessary to resort to a simple iterative algorithm to make sure the right value of δ_B is used. The algorithm is as follows:

1. Start with an initial estimation for L;
2. Evaluate δ_B using Equation 7.20;
3. Evaluate L;
4. Check the value of δ_B. If Equation 7.20 is satisfied within a certain precision level then stop; else go back to step 2.

A Microsoft Excel® spreadsheet was developed to perform the calculations above. The values of $Q_B(t)$ and $Q_P(t)$ were evaluated for each one-minute period, from which the maximum value for both accumulations can be extracted with the use of the spreadsheet built-in function. The algorithm above is also performed by the spreadsheet with the help of the Excel Solver. The spreadsheet facilitates the development of sensitivity analyses for the various parameters involved in the model.

7.4 NLA ANALYSIS

Using the spreadsheet described above, an analysis was run to determine the baggage claim area requirements for the NLA. Most of the parameters of the model are site-specific, making it very difficult to goal for final results in this work. Thus we concentrate on illustrating the application of the model to the NLA problem through a numerical example, and on a sensitivity analysis for some of those parameters.

Table 7.1 shows the values of the parameters used in this analysis. The number of passengers was calculated based on the capacity of the Airbus A380-800, which is 555 passengers [Airbus, 2000b]. The assumptions included an aircraft load of 80%, with 80% of these passengers claiming baggage. Because passengers are slowed down by customs and the walking distance between the aircraft and the baggage claim, the arrival rate was assumed to be less than the aircraft unloading rate of 50 passengers per minute claimed by Airbus [Airbus Industrie, 1999].

As the NLA is expected to be used on long-haul routes between hub airports, the baggage arrival correlation factor is expected to be low – most passengers are likely to be on their second or third flight, and the airport of origin will certainly be a large one with several check-in counters available. Hence a low value of 0.2 is used in this analysis.

The baggage arrival rate can be adjusted up to the lower of the capacities of the feeder and the claim device. The capacity of the claim device can be obtained dividing the average space used by a bag, l_B, by the belt speed, v. The capacity of the feeder will depend on the type of device. For manual feeding, a handler can unload about 12.5 bags per minute onto the claim device [Hart, 1985]. Remote feeders can usually handle a number of bags similar to the capacity of the claim belt. Since the bag arrival rate can be adjusted in accordance with the need, the claim device length requirement can be evaluated for a range of values, and the minimum requirement found should be used for planning purposes.

Figure 7.7 shows two important results from the analysis performed. First, it can be seen that the use of two devices instead of one reduces the total length requirement, thus reducing the need for physical space. The use of two separate devices is only possible if some sort of criterion is used to separate the bags when they are loaded into the aircraft. Since the NLA features two passenger decks, this would be an obvious criterion with a low probability of confusing passengers. Passengers would then be directed to the correct device according to the flight number and the deck on which they travelled. The use of two devices also has the advantage of allowing their use for separate smaller aircraft when not in use by an NLA – an advantage even greater at existing airports.

Table 7.1: Parameters used in the NLA analysis

Parameter	Value
N_P (passengers)	355
α_P (passengers/minute)	20
t_B (minutes)	5
n_B (bags/passenger)	1.4
s (passengers/cluster)	1.4
c	0.2
l_B (m/bag)	0.6
l_P (m/passenger)	0.6
v (m/minute)	27
τ (minutes)	0.5
r_1	0.35
r_2	0.2
r_3	0.15
r_4	0.15
r_5	0.05
r_6	0.05
r_7	0.03
r_8	0.02

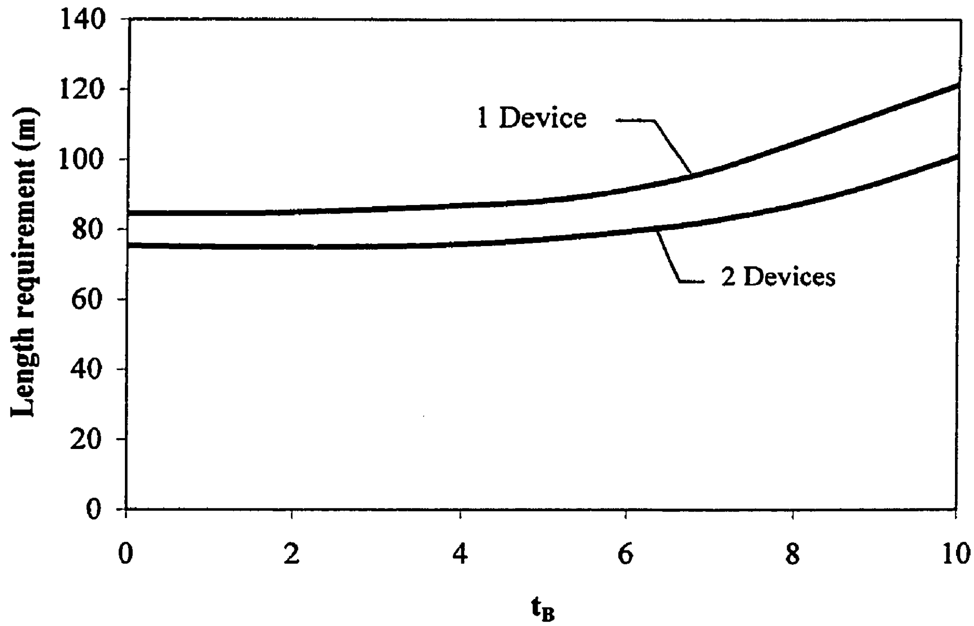


Figure 7.7: Effect of the variation of t_B on the claim device's total length requirement

The second important result shown in Figure 7.7 is the influence of the delay t_B on the length requirement. For delays over 5 minutes, the length requirement increases significantly with the delay. Provisions must be made to keep the delay of the baggage arrival below that critical value.

Figure 7.8 shows the variation of the length requirement for two devices with the passenger arrival rate, α_P. It can be seen that, for various values of the baggage arrival rate, α_B, there is always a critical value of α_P. This result is important because it shows that the length requirement can actually be reduced by either delaying or rushing passengers at customs, where passengers occupy less space without their baggage carts. The total waiting time would not be affected, as the delay in the baggage claim would simply be transferred to customs. At existing airport terminals where expansion is not possible or is too expensive, co-ordination between the airport authority and customs may help reduce the total need for physical space.

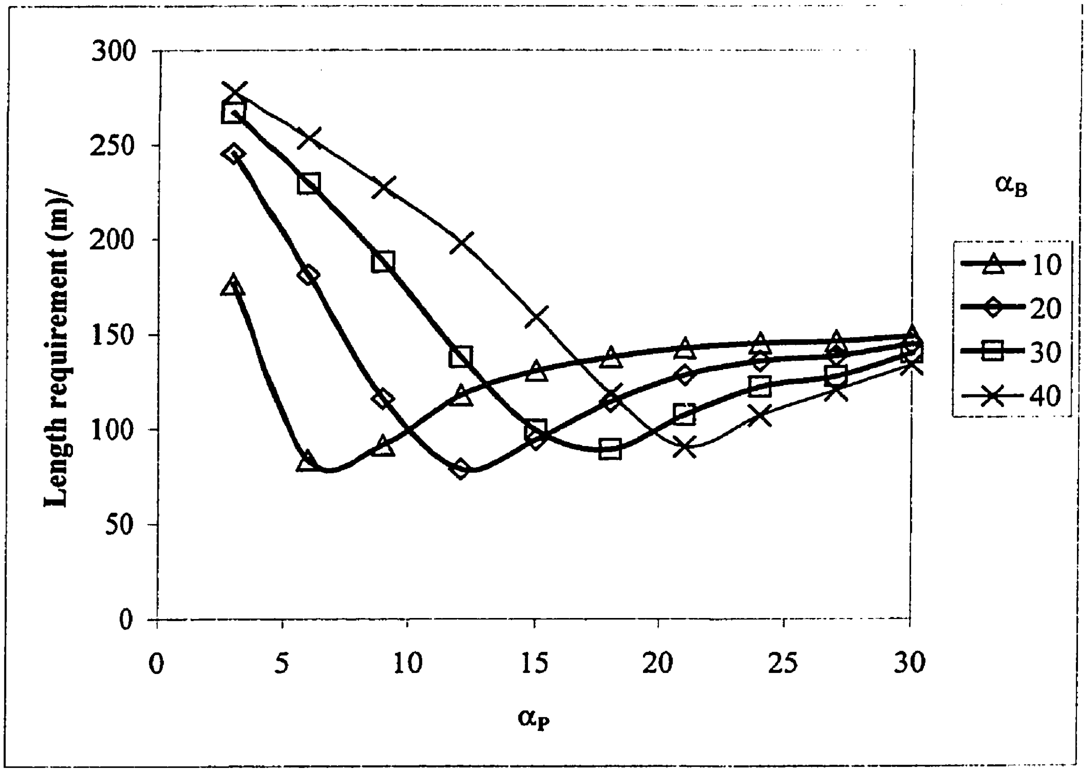


Figure 7.8: Effect of the variation of α_P on the total length requirement for 2 claim devices

The importance of the correlation factor between bag arrivals, *c*, is shown in Figure 7.9. The higher the correlation – i.e., the closer bags belonging to a given cluster arrive to each other – the lower the need for physical space. This shows the importance of the use of technologies that allow for the bags of a cluster to be kept together during handling.

7.5 CONCLUSIONS

The presence of passengers travelling together forming clusters, and the correlation between the arrival times of bags belonging to a passenger cluster, have a significant impact on the planning of the design area. These issues were addressed and incorporated in the model developed in this chapter.

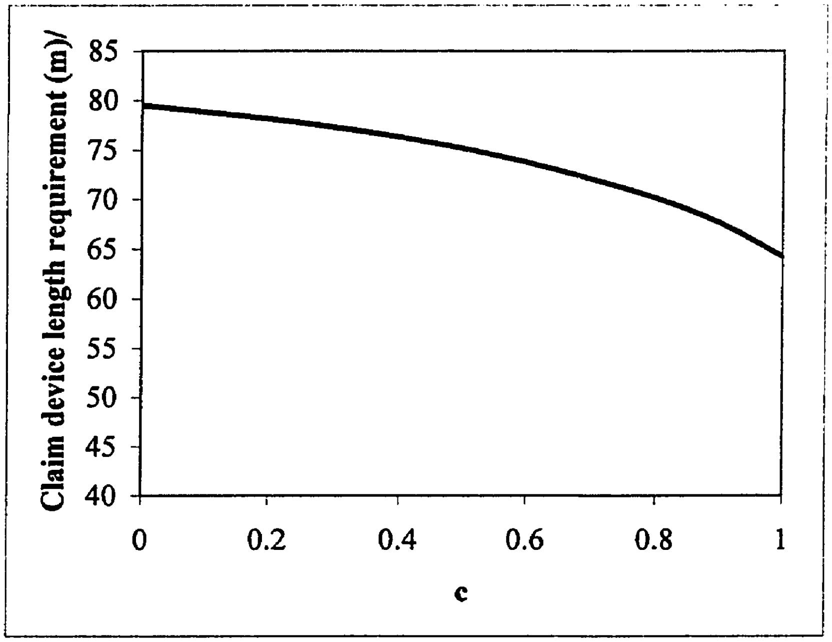


Figure 7.9: Effect of the variation of *c* on the total length requirement for 2 claim devices

Besides the claim device area planning model developed – which can be applied to any type and size of aircraft – an analysis of different solutions for the upcoming problem of accommodating NLA passengers and baggage was developed. The use of two separate claim devices for the two aircraft passenger decks is shown to be more space-efficient, in addition to allow for more flexibility. However, for this arrangement to work properly, it is necessary to fully separate the baggage according to the passenger decks upon make-up at the originating airport. Co-ordination between the airlines operating the NLA and the airport authorities is fundamental to allow such separation.

The adjustment of customs service rate also showed to be an efficient way to reduce the need for physical space and the consequent need for expansion in existing terminals. This procedure is very difficult to be agreed upon by all parts involved – airlines, customs authority and airport management. However, if all costs and benefits are properly distributed among the parts involved, the final result can be much better for the airport system as a whole.

CHAPTER 8
CONCLUSIONS

8.1 SUMMARY

The New Large Aircraft (NLA) will impact the planning and operation of new and existing airports. The first NLA, the Airbus A380, is scheduled to enter service in early 2006, with the Boeing 747X Stretch possibly following right after. The larger dimensions of those aircraft, as well as their increased passenger load, will require many creative solutions and changes in the way the airside and terminal facilities are planned.

A review of the existing literature on the NLA showed that both airside and passenger terminal issues have been identified regarding the compatibility of those aircraft and airports, but only the airside issues have been extensively analysed. The various issues associated with the compatibility of the NLA and the passenger terminal have been mentioned in studies performed by aviation institutions [ACI-NA, 1994; Airport World, 1996; FAA, 1998a, 1998b] but have not been addressed in detail until now. This is certainly the main contribution of this research: it provides a comprehensive insight on how the NLA will affect passenger terminal planning and operations, and how new and existing airports should prepare for it. The literature on the airside effects has shown that with certain modifications in the airside configuration, plus some possible changes in existing standards to account for the use of the latest technology, NLA's can be accommodated in existing airports. Now, this thesis has provided the basis to help in the planning of the terminal facilities, showing that NLA's can be accommodated with careful thinking and by optimising the use of resources.

The following subsections present the conclusions and recommendations for the individual issues discussed in this thesis.

8.1.1 Airside

The review of airside issues identified by several references shows that existing standards established by ICAO and the FAA for aircraft with the dimensions of the currently proposed NLA are sufficient for the task of planning new facilities from scratch. However, the problem is that the cost of a new airport has skyrocketed to many billions of dollars, making it more desirable to make better use of the existing infrastructure through physical and operational improvements. However, most existing airports were planned for aircraft much smaller than the NLA and have used up all the available space for their infrastructure. In summary, the existing infrastructure is in general unsuitable for the NLA and very expensive to upgrade to currently established standards.

Many different solutions are being studied for the NLA/airside compatibility problem, mostly in a case-by-case basis. Some airports plan to upgrade only a part of their facilities to FAA code VI or ICAO code F standards, limiting NLA operations to those facilities. In many others, operational restrictions are being considered for when the NLA is on site. For example, in parallel taxiways where wingtip clearance standards cannot be met, one taxiway is closed for as long as an NLA is on the other taxiway. Such solutions, however, have the potential to considerably reduce airside capacity and are highly undesirable during peak hours.

In more extreme cases, NLA operations could take place even if the FAA and ICAO standards cannot be met. Being newly developed aircraft, the NLA are expected to have several improvements in navigation equipment that could allow many safety margins incorporated in the FAA and ICAO standards to be reduced. By doing so, the cost of upgrading the facilities would also be reduced and even existing infrastructure could be allowed to be used.

8.1.2 Gate Requirement

Due to its larger wingspan and length, the NLA will require more space for its parking positions, meaning more space between gates and consequently more terminal space. If NLA exclusive-use gates were to be provided, a very high cost would be imposed, either through the provision of large terminal areas and equipment, or the delays caused by lack of enough positions for all aircraft types.

The wide range of aircraft sizes at a large terminal and the existence of different peak periods for groups of aircraft of similar size make it possible to share some terminal space for the operation of any aircraft sizes. That common area can be used by conventional (narrow-bodied) jets during their main peak, and by NLA and wide-bodied aircraft during the main peak of these aircraft. By doing so, it is possible to provide a higher aircraft service rate for the same physical space. In addition, space sharing provides flexibility in terminal operations, providing room for changes in the aircraft mix and the arrivals pattern over the years. It is important to determine the requirement for terminal space sharing during the early planning phases.

The contribution of this research in this matter is a methodology to balance the cost of delays against terminal construction and operational costs, based on the work of Bandara & Wirasinghe [1990] and taking shared use and stage construction into account. Delays are calculated based on the aircraft arrival patterns for NLA, wide-bodied and conventional jets, and on the service rates as a function of the number of gates provided. Terminal construction and operational costs are evaluated as a function of the number of gates and aircraft space and equipment required by each of the three aircraft types, as well as the amount of space sharing. It is shown that, depending on the peak characteristics, sharing facilities may allow airport terminals to accommodate a wide variety of aircraft sizes – including the NLA – with a reasonable level of service while reducing overall costs. Another important contribution of this research is that it provides a quantitative proof that sharing facilities is in the best interest of airlines and airports, for it can actually bring them significant savings.

In addition to space sharing, it is also important to plan stage construction. Airport terminals are planned for a very long term, usually several decades. During that time, the demand varies considerably, most times increasing. Understanding how the choice of the times for terminal expansion affects the present worth of the overall terminal cost is crucial for good planning. This issue has been addressed in this work with an analytical model that evaluates the present worth of the terminal cost based on the gate requirement for each stage, the time each stage is built, the rate of demand growth, and the cost of borrowing money – represented by the interest rate.

Some limitations of the model can be identified and should perhaps be improved in the future. First, queues for individual peak periods of the same aircraft type cannot overlap, i.e. the queue for one peak period must vanish before another one starts to form. Second, the number of stages is defined externally to the model. In practice, expansion of facilities is unlikely to be done more than three times during their life span and therefore this limitation does not invalidate the model. However, it might be interesting to investigate what effects the application of a continuous or quasi-continuous expansion model would have on the optimal solution.

8.1.3 Terminal Configuration

Three types of terminal configurations have been analysed: single pier, pier-satellite and multiple parallel piers. The analysis attempted to determine the best location for the NLA gates at the terminal, and to evaluate the cons and pros of each configuration for NLA operations. The mean passenger walking distance is used as the optimality criterion. The choice of the pier configurations for these analyses is based on their popularity, ease of expansion, flexibility and capacity to accommodate sharing space, making them suitable for large airports.

8.1.3.1 Single Pier

For a single pier, the best location for the NLA gates depends on the proportion of the aircraft load that are hub transfers – i.e. that walk directly from the arriving aircraft to the departing aircraft – and on the location of the pier entrance. For a pier-finger where the entrance is located at one of the pier ends, the NLA gates should be located close together somewhere between the pier base and its middle. In the case of a pier with mid-pier entrance, locating the NLA gates as close as possible to the entrance would minimise the walking distance for both connecting and originating/terminating passengers.

If several NLA gates are to be provided, then the assumption that the mean passenger walking distance for other aircraft is not affected by the location of the NLA gates may not be valid anymore. In that case, a discrete approach is necessary. This thesis reports a combinatorial analysis model for the search of the optimal location of NLA, wide-bodied and conventional jet gates that uses simulated annealing to search for the optimal solution.

In this case, the optimal location of all gates depends not only on the proportions of transfers, but also on the passenger split between aircraft types.

Pier-fingers have been shown to have a high average passenger walking distance, a drawback aggravated by the difficulty to accommodate NLA positions near the pier root – where walking distance would be minimised. If airside constraints force the NLA to be parked at the opposite end of the pier, NLA passengers would have the highest average walking distance. A pier with mid-pier access would be preferred due to its lower walking distance even if the NLA is forced to park at one of the pier ends.

8.1.3.2 Pier-Satellite

Pier-satellite terminals, like pier-fingers, feature a long walking distance for originating/terminating passengers coming from/to an aircraft parked at the satellite portion of the terminal. Hub transfer passengers, however, may have a reasonably low walking distance due to the parking of aircraft close together around the satellite. In addition, the pier section can be more easily designed to accommodate larger aircraft, allowing the NLA to park near the pier base if the proportion of hub transfers is low.

If the proportion of NLA hub transfers is high enough to warrant the location of the NLA gate at the satellite portion, then a T-shaped pier-satellite is preferred over a Y-shaped one. This is because a T-shaped pier-satellite allows for the NLA to be located at the T junction, where the walking distance for NLA passengers is minimised. A Y-shaped satellite, on the other hand, may require some clearance near the junction, thus increasing the walking distance.

Circular pier-satellites have the great advantage of a large shared departure lounge. For NLA operations, the availability of such a large departure lounge may actually constrain the location of the NLA gate. Further research is necessary to find the right balance between passenger walking distance and departure lounge cost.

8.1.3.3 Parallel Piers

Parallel piers may prevent the NLA from parking at the middle of a pier if the taxilanes between piers cannot provide the standard safety clearances established by ICAO and the FAA. In that case, the NLA should be parked at the ends of the shortest piers, to minimise walking distance. If, however, the NLA is allowed to park at the pier middle, that is the best location for it. In the case of several NLA gates, the best solution is to spread those positions throughout the piers, resembling a triangle as shown in Figure 4.24. The shape of the triangle will depend on the relative cost of walking compared to the disutility of riding an automated people mover.

8.1.4 Departure Lounge

The higher passenger capacity of the NLA will require larger departure lounges. If a new terminal is being planned, it suffices to size the lounges that will be used for NLA operations for its passenger load. However, for existing airports, changes will be necessary to the design of currently existing lounges.

An individual lounge can be re-sized for the NLA passenger load, provided that enough space is available. If not, two solutions are possible: reducing the number of seats or building an upper floor. Reduction of the number of seats implies an increase in passenger discomfort, whereas the construction of an upper level may have a very high financing cost. This research has shown that the choice depends on the money value associated with passenger discomfort. If we take the total passenger compulsory standing time as a measure of discomfort and associate a cost to it, then using queuing theory it is possible to evaluate the total cost of passenger discomfort. This cost can then be balanced against the cost of building a second floor.

Satellite terminals with a large shared departure lounge can be reserved for NLA operations. Again, if the lounge capacity is not enough, then it is still possible to use this lounge by reducing the number of seats. In any case, blocking one or more of the gates that use that lounge can reduce gate capacity. To avoid that, other flights could still be assigned to that lounge, provided that they are scheduled such that the lounge capacity is never exceeded. This may require that one or more gates be shut down for a period of time to avoid an excessive superposition of arrival curves as shown in Figure 5.14, or that the number of seats be reduced. Again, it is necessary to find the right balance between the cost of loss of gate capacity and the cost of passenger discomfort.

Due to the additional benefits awarded by the use of shared facilities, the use of the satellite common lounge is the most recommended solution for the NLA/departure lounge problem when evaluated as an isolated problem. Evidently, other issues such as airside constraints and passenger walking distance should be factored in. The choice of the best solution should therefore be done in conjunction with the analysis of the terminal configuration.

8.1.5 Passenger Processing

The use of information technology (IT) in passenger processing is revolutionising air travel. Just like banks and many other services, airlines and airports are automating the process of check-in and security, greatly enhancing the quality of service as perceived by the passenger, increasing system throughput, and reducing the need for resources. However, acceptance of these technologies by the passengers takes time and thus it is necessary to continue to provide conventional service for those who cannot deal with the automated service. It has been shown in this work, however, that existing physical space in a multiple-server system with a queue area A_Q and an overall area A will be able to assimilate an increase k in the passenger demand if the proportions b_I and b_A of the passengers switch from conventional service to off-site and on-site automated services, respectively, such that the relation in Equation 6.10 is satisfied. It should be noted that the calculations performed in this thesis assume that most check-in services will be available at kiosks, and that the mean service time at the conventional check-in counters will remain unchanged.

A great number of new applications of IT combined with other technologies have been developed in the last few years. They include automated and Internet check-in, use of biometrics for the validation of passenger ID at boarding and at customs/immigration, new methods for passenger and baggage security check, and automated baggage handling. The ongoing development of those technologies, including the appearance of new ones, is expected to compensate for the increase in passenger demand made possible by the NLA.

8.1.6 Baggage Claim

Due to the international nature of long-haul flights – which is the principal market for the NLA – it is expected that in many cases all NLA passengers will be required to reclaim their baggage, even those ones who are connecting to a subsequent flight. Hence the impact of the NLA on the baggage claim area can be quite significant.

Since international passengers are forced to go through immigration before being directed to baggage claim, their arrival pattern at the claim area can be assumed to be linear with a constant rate proportional to the immigration service rate. If bag arrivals can also be assumed to be linear, then the total length requirement of the claim device – which the claim area is ultimately dependent on – is a function of the passenger and baggage arrival rates, the delay between the arrivals of the first passenger and the first bag from the aeroplane, and the correlation between arrivals of bags belonging to one passenger cluster. All these factors must be accounted for when sizing the baggage claim area.

The correlation of one cluster's bag arrivals has been shown to have a significant influence on the claim device's length requirement. For flights originating at big airports and carrying a considerable number of passengers who are on their second or third flight leg – as is the case with most long-haul flights that are to be covered by the NLA – that correlation can be assumed to be low.

It has been shown that, for any given baggage arrival rate, there is one passenger arrival rate that minimises the claim device's length requirement. If airside or terminal layout constraints limit the baggage unloading rate, co-ordination between the airport authority and immigration to reduce the service rate at immigration could help reduce the need for space in the baggage claim area. The drawback of such procedure is a consequent increase in the queue length and waiting time at immigration. Since passengers are not yet driving a baggage cart at immigration, the space needed here would be significantly smaller.

8.2 ANALYTICAL VS SIMULATION MODELS

In Section 1.5, the reason why analytical models as opposed to simulation were used in this research was explained. It was argued that simulation models require an amount of information that is not readily available in the early stages of planning, in addition to being case-specific. The objectives of this research were to provide a better understanding of the problems caused by NLA to airports in general. Thus analytical models were favoured, for analytical thinking is an excellent exercise to better understand processes and can be developed for a general case and used in early planning when little information is available.

Simulation is a very powerful tool for planning, as it provides a natural, intuitive way to analyse and understand systems that would otherwise be very complicated to model analytically. For airports with very well defined physical and operational configurations, simulation is the most recommended technique for a detailed, site-specific analysis of alternatives and "what-if" scenarios. In fact, simulation could be used for an integrated analysis of all the effects of the NLA on the airport terminal facilities when sufficient data becomes available for such analysis.

As natural and intuitive as they are, many simulation models also include decision models within their logic. The development of such decision models can help improve the quality of the simulation results. In this respect, some of the analytical models developed in this research could be used as a module within simulation. As an example, the model used to size the departure lounge for joint use by NLA and other aircraft could be embedded in a larger model that simulates delays in scheduled flights and has to choose between assigning 747 flights to the joint-use lounge or to other lounges.

In summary, this research has made an important contribution to airport planning through the use of analytical models that help us better understand the problems addressed regarding the NLA and airports. Such models can be used in isolation or as part of a larger simulation model.

8.3 FUTURE RESEARCH

Models are by definition a simplifying representation of the real world. For that reason, the mathematical models used in this work are evidently based on assumptions and simplifications that aim at making the study viable without compromising the results. However, there is always room for improvement, and the need to constantly enhance the models proposed in this work is acknowledged.

Several individual models have been proposed in this work to deal with separate problems related to the compatibility of the NLA and terminal facilities. As those problems are actually interrelated, it would surely be preferable to deal with them all at once, with a systems approach. Other works have taken such systems approach to analyse the impact of the NLA on airports [Trani & Venturini, 1999] – but with very limited results. Integration of the models presented in this work would bring more effectiveness to their application. For example, the cost of the mean walking distance for a given terminal configuration could be balanced against the cost of the level of departure lounge sharing allowed by that same configuration.

The individual models can also be improved. The gate requirement model could be extended to include a probability distribution of the aircraft size and determine the optimal numbers and sizes of the gates. The number of stages could also be determined by the model, and further development could eliminate the existing constraint of non-overlapping queues. More work is also necessary to help evaluate the model's input parameters such as the costs of terminal construction and gate equipment.

The simulated annealing model used for the analysis of the terminal configuration could be expanded to include terminal concepts other than the pier terminal, such as pier-satellites and remote terminals. Since space sharing is key to the economical efficiency of future airport terminal operations, it could also be included in the model to account for its effects on passenger walking distance.

In the analysis of the departure lounge, further research could determine better values for the disutility of passenger standing and for the area per passenger requirements. These parameters could also be made variable with the actual time of standing, e.g. the penalty for passenger standing could be modelled such that it increases with the total standing time.

Passenger processing is perhaps where most of the need for further research is. The rapid development of new technologies is making it possible to completely re-think the way passenger processing and even air transportation itself is done. Many of the features of automated processing suggested in this thesis still need to be developed. Examples are:

- baggage check-in – a safe, efficient way to allow passengers to check-in their baggage on their own is still to be found;

- baggage screening – 100% in-line baggage screening is still an utopia but could greatly enhance flight safety without interfering with the baggage handling process;
- customs/immigration – automated pre-boarding clearance with the use of biometrics could greatly reduce the need for physical space at the terminal, as well as reduce passenger walking distance and connection times for passenger transfers.

Further research is also necessary to determine more exactly the impact these technologies will have on terminal operations. Improvements in the models presented here can also be made. It was mentioned in Section 8.1 that the model used in this thesis assumes the mean service time at the conventional check-in will not change with the introduction of automated services. This is a reasonable assumption if the same services are performed at the conventional and automated check-in. In case only the easiest tasks are moved to kiosks, the mean service time at the conventional counters may increase as now they handle only the more complicated cases that cannot be handled by kiosks. It would be interesting to study this case.

Finally, the baggage claim area could be further studied, perhaps to seek a better way to return the baggage to the passengers. In fact, Ashford et al [1997] recommend that the whole baggage handling process be rethought. In that respect, the development of new technologies may also allow for more efficient procedures that would reduce the current problems encountered – delays, baggage loss and damage, etc.

As to the model proposed in this research for the baggage claim, further research could help in the evaluation of the correlation between the arrivals of bags belonging to the same passenger cluster. As shown in this research, the actual value of that correlation significantly affects the area requirement for a given level of service, and its determination could bring great benefits in both financial costs and passenger level of service. It is thus recommended that surveys be performed to find how exactly that correlation varies.

8.3.1 Data availability

Probably the greatest problem encountered during the development of this research was the lack of real-world data for the validation of the models. Data such as details of the final configuration of the NLA and construction and operational costs of airport equipment and facilities were very difficult to obtain. The reasons for this vary. The first NLA has only recently had its configuration finalised – Airbus officially launched the A380 in December 2000, when this research was already being concluded. Both Airbus and Boeing have been very protective about the information regarding the development of their new products. Manufacturers of airport equipment have also declined to release information on their plans to produce equipment compatible with the NLA.

On the airport side, the problem is a little different – although of the same nature. In the last decades, airports have become commercial entities of a private nature that in many instances compete fiercely against each other. In such a competitive environment, all information regarding cost structures has acquired a great importance. Thus airports have also become very protective about this information – when it is available. In many instances, some of the information is just not promptly available and would require some effort to acquire, efforts that most airports are not willing to spend.

Although the models in this thesis have been built on strongly supported fundamentals and therefore their validity is not affected by the lack of data, it is acknowledged here that real-world data would allow the application of the models to real examples, improving the appeal of the research. It is suggested that, for future research in the field, researchers should work more closely together with the air transport world players: airports, airlines and manufacturers.

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APPENDIX A
WALKING DISTANCES FOR THE PIER CONFIGURATION COMBINATORIAL ANALYSIS MODEL

The average walking distance within the pier is given by:

$$W = \sum_{i \neq m} r_i \sum_j P_{ij} W_{ij} \tag{A.1}$$

where:

P_{ij} = probability of walking to destination j given the origin i;

W_{ij} = mean walking distance from i to j;

i = {NLA, CJ, WB},

j ={ NLA, CJ, WB, m};

m = main entrance;

r_i = the fraction of the total passengers who arrive by aircraft type i.

In the long run, it can be assumed that the total number of enplaning passengers equals the total number of deplaning passengers. Under this assumption, the total number of passengers transferring from i to j must equal the number of passengers that transfer the other way around. Therefore

$$r_C P_{CN} = r_N P_{NC} \tag{A.2}$$

$$r_C P_{CW} = r_W P_{WC} \tag{A.3}$$

$$r_W P_{WN} = r_N P_{NW} \tag{A.4}$$

If the proportions r_i, P_{im}, P_{NC}, P_{NW} and P_{WC} are given, then P_{CN}, P_{CW}, P_{WN} can be evaluated using Equations A.2, A.3 and A.4 above. The proportions of passengers transferring between aircraft of the same type i can be determined from the fact that the sum of proportions of passengers transferring from aircraft type i must equal one. Hence

$$P_{ii} = 1 - \sum_{j \neq i} P_{ij} \tag{A.5}$$

Therefore, P_{CN}, P_{CW}, P_{WN} and P_{ii} are internal parameters in the model, whereas the proportions r_i, P_{im}, P_{NC}, P_{NW} and P_{WC} will be external parameters to be input in the model by the planner.

Transfers within the terminal are assumed to be of the "hub" type, i.e. passengers move directly from the arrival gate to the departure gate. "Non-hub" transfers – when the passenger has to go to the main block – are assumed to have the same walking distance as arriving/departing passengers.

Let:

S_i = size of gates type i; the size of a gate is defined as the maximum wingspan allowed for an aircraft parking at the gate;

c = wing-tip-to-wing-tip clearance;

N^i = number of type i gate positions;

For the more general case of walking distance between two NLA positions i and j, we must add the extra length of NLA positions, i.e.:

$$\begin{aligned} w_{NNij} &= \left|n_i^{NLA} - n_j^{NLA}\right|\left(S_{CJ} + c\right) + \left|i - j\right|\left(S_{NLA} - S_{RJ}\right) \\ &\quad + \left|\delta\left(n_i^{NLA}, WB\right) - \delta\left(n_j^{NLA}, WB\right)\right|\left(S_{WB} - S_{RJ}\right) \end{aligned} \tag{A.6}$$

where:

$i = \{1, 2, \ldots, N^{NLA}/2\}$

$j = \{1, 2, \ldots, N^{NLA}/2\}$

$$\delta(a, f) = \begin{cases} N^f/2, & a > n^f_{N^f/2} \\ \varphi \mid n^f_\varphi < a < n^f_{\varphi+1}, & n^f_1 < a < n^f_{N^f/2} \\ 0, & a < n^f_1 \end{cases} \tag{A.7}$$

Assuming that NLA passengers are equally distributed through all NLA positions, then the mean walking distance for a passenger transferring from an NLA to another will be:

$$W_{NN} = \frac{4}{N^{NLA}(N^{NLA}-1)}\{\sum_{i=1}^{N^{NLA}/2}\sum_{j\neq i}[|n_i^{NLA} - n_j^{NLA}|(S_{CJ}+c) + |i-j|(S_{NLA}-S_{CJ}) + |\delta(n_i^{NLA},WB) - \delta(n_j^{NLA},WB)|(S_{WB}-S_{CJ})]\} \quad \text{(A.8)}$$

Deduction of the other mean walking distances is analog. For passengers transferring from an NLA to a regular jet, the mean walking distance will be given by:

$$W_{NC} = \frac{S_{NLA}-S_{CJ}}{2} + \frac{4}{N^{NLA}N^{CJ}}\sum_{i=1}^{N^{NLA}/2}\sum_{j=1}^{N^{CJ}/2}[|n_i^{NLA} - n_j^{CJ}|(S_{CJ}+c) + |\beta(n_j^{CJ},i,NLA) - i|(S_{NLA}-S_{CJ}) + |\delta(n_i^{NLA},WB) - \delta(n_j^{CJ},WB)|(S_{WB}-S_{CJ})] \quad \text{(A.9)}$$

where:

$$\beta(a,i,f) = \begin{cases} N^f/2, & a > n^f_{N^f/2} \\ l \mid n_l^f < a < n_{l+1}^f, & n_i^f < a < n^f_{N^f/2} \\ l \mid n_{l-1}^f < a < n_l^f, & n_1^f < a < n_i^f \\ 1, & j < n_1^f \end{cases} \quad \text{(A.10)}$$

$\beta(a, i, f)$ = sequential number of the next type f position to the left or to the right of position a, depending on whether position j is to the right or to the left of the i^{th} type f position, respectively;

$n = \{n_1, n_2, \ldots, n_{N/2}\}$.

The mean walking distance for passengers transferring between an NLA and a WB is

$$W_{NW} = \frac{S_{NLA}+S_{WB}-2S_{CJ}}{2} + \frac{4}{N^{NLA}N^{WB}}\sum_{i=1}^{N^{NLA}/2}\sum_{j=1}^{N^{WB}/2}[|n_i^{NLA} - n_j^{WB}|(S_{CJ}+c) + |\beta(n_j^{WB},i,NLA) - i|(S_{NLA}-S_{CJ}) + |\beta(n_i^{NLA},j,WB) - j|(S_{WB}-S_{CJ})] \quad \text{(A.11)}$$

$$W_{CW} = \frac{S_{WB} - S_{CJ}}{2} + \frac{4}{N^{CJ} N^{WB}} \sum_{i=1}^{N^{CJ}/2} \sum_{j=1}^{N^{WB}/2} [|n_i^{CJ} - n_j^{WB}|(S_{CJ} + c)$$
$$+ |\delta(n_j^{WB}, NLA) - \delta(n_i^{CJ}, NLA)|(S_{NLA} - S_{CJ})$$
$$+ |\beta(n_i^{CJ}, j, WB) - k|(S_{WB} - S_{CJ})] \tag{A.12}$$

For passengers transferring from one regular jet to another, the mean walking distance will be:

$$W_{CC} = \frac{4}{N^{CJ}(N^{CJ} - 1)} \{ \sum_{i=1}^{N^{CJ}/2} \sum_{j=1}^{N^{CJ}/2} [|n_i^{CJ} - n_j^{CJ}|(S_{CJ} + c)$$
$$+ |\delta(n_j^{CJ}, NLA) - \delta(n_i^{CJ}, NLA)|(S_{NLA} - S_{CJ})$$
$$+ |\delta(n_j^{CJ}, WB) - \delta(n_i^{CJ}, WB)|(S_{WB} - S_{CJ})]\} \tag{A.13}$$

$$W_{WW} = \frac{4}{N^{WB}(N^{WB} - 1)} \{ \sum_{i=1}^{N^{WB}/2} \sum_{j=1}^{N^{WB}/2} [|n_i^{WB} - n_j^{WB}|(S_{CJ} + c)$$
$$+ |\delta(n_j^{WB}, NLA) - \delta(n_i^{WB}, NLA)|(S_{NLA} - S_{CJ})$$
$$+ |i - j|(S_{WB} - S_{CJ})]\} \tag{A.14}$$

Terminating passengers and non-hub transfers will have to leave the terminal through the connection to the main terminal. The walking distances for these passengers will depend on both their origin (NLA or regular jet) and on whether the connection point is closer to an NLA or a regular jet position.

For terminating passengers and non-hub transfers disembarking from an NLA, the mean walking distances will be:

$$W_{Nm} = \begin{cases} d_0 + \dfrac{2}{N^{NLA}} \displaystyle\sum_{i=1}^{N^{NLA}/2} [\left|b - n_i^{NLA}\right|(S_{CJ} + c) \\ + \left|\varepsilon(b, NLA) - i\right|(S_{NLA} - S_{CJ}) \\ + \left|\delta(n_i^{NLA}, WB) - \delta(b, WB)\right|(S_{WB} - S_{CJ})], \\ \qquad\qquad\qquad\qquad\qquad\qquad b\text{Type} = \text{NLA} \\ \\ d_0 + \dfrac{S_{NLA} + S_{WB} - 2S_{CJ}}{2} \\ + \dfrac{2}{N^{NLA}} \displaystyle\sum_{i=1}^{N^{NLA}/2} [\left|b - n_i^{NLA}\right|(S_{CJ} + c) \\ + \left|\beta(b, i, NLA) - i\right|(S_{NLA} - S_{CJ}) \\ + \left|\beta(n_i^{NLA}, \varepsilon(b, WB), WB) - \varepsilon(b, WB)\right|(S_{WB} - S_{CJ})], \\ \qquad\qquad\qquad\qquad\qquad\qquad b\text{Type} = \text{WB} \\ \\ d_0 + \dfrac{S_{NLA} - S_{CJ}}{2} + \dfrac{2}{N^{NLA}} \displaystyle\sum_{i=1}^{N^{NLA}/2} [\left|b - n_i^{NLA}\right|(S_{CJ} + c) \\ + \left|\beta(b, i, NLA) - i\right|(S_{NLA} - S_{CJ}) \\ + \left|\delta(n_i^{NLA}, WB) - \delta(b, WB)\right|(S_{WB} - S_{CJ})], \\ \qquad\qquad\qquad\qquad\qquad\qquad b\text{Type} = \text{CJ} \end{cases} \tag{A.15}$$

where

b = gate position closest to the point connecting to the main terminal.

$$\varepsilon(a, f) = k \mid n_k^f = b \tag{A.16}$$

Analogously, for passengers going from a wide body to the connecting point, the mean walking distances will be:

$$
W_{Wm} = \begin{cases}
d_0 + \dfrac{S_{NLA} + S_{WB} - 2S_{CJ}}{2} \\
+ \dfrac{2}{N^{WB}} \sum_{i=1}^{N^{WB}/2} [\left|b - n_i^{WB}\right|(S_{CJ} + c) \\
+ \left|\beta(n_i^{WB}, \varepsilon(b, NLA), NLA) - \varepsilon(b, NLA)\right|(S_{NLA} - S_{CJ}) \\
+ \left|\beta(b, i, WB) - i\right|(S_{WB} - S_{CJ})], \\
\qquad\qquad\qquad\qquad b\text{Type} = \text{NLA} \\
d_0 + \dfrac{2}{N^{WB}} \sum_{i=1}^{N^{WB}/2} [\left|b - n_i^{WB}\right|(S_{CJ} + c) \\
+ \left|\delta(n_i^{WB}, NLA) - \delta(b, NLA)\right|(S_{NLA} - S_{CJ}) \\
+ \left|i - \varepsilon(b, WB)\right|(S_{WB} - S_{CJ})], \\
\qquad\qquad\qquad\qquad b\text{Type} = \text{WB} \\
d_0 + \dfrac{S_{WB} - S_{CJ}}{2} + \dfrac{2}{N^{WB}} \sum_{i=1}^{N^{WB}/2} [\left|b - n_i^{WB}\right|(S_{CJ} + c) \\
+ \left|\delta(n_i^{WB}, NLA) - \delta(b, NLA)\right|(S_{NLA} - S_{CJ}) \\
+ \left|\beta(b, i, WB) - i\right|(S_{WB} - S_{CJ})], \\
\qquad\qquad\qquad\qquad b\text{Type} = \text{CJ}
\end{cases} \tag{A.17}
$$

$$W_{Cm} = \begin{cases} d_0 + \frac{S_{NLA} - S_{CJ}}{2} + \frac{2}{N^{CJ}} \sum_{i=1}^{N^{CJ}/2} [|b - n_i^{CJ}|(S_{CJ} + c) \\ + |\beta(n_i^{CJ}, \varepsilon(b, NLA), NLA) - \varepsilon(b, NLA)|(S_{NLA} - S_{CJ}) \\ + |\delta(n_i^{CJ}, WB) - \delta(b, WB)|(S_{WB} - S_{CJ})], \\ \qquad\qquad\qquad\qquad\qquad\qquad b\text{Type} = \text{NLA} \\ \\ d_0 + \frac{S_{WB} - S_{CJ}}{2} + \frac{2}{N^{CJ}} \sum_{i=1}^{N^{CJ}/2} [|b - n_i^{CJ}|(S_{CJ} + c) \\ + |\delta(n_i^{CJ}, NLA) - \delta(b, NLA)|(S_{NLA} - S_{CJ}) \\ + |\beta(n_i^{CJ}, \varepsilon(b, WB), WB) - \varepsilon(b, WB)|(S_{WB} - S_{CJ})], \\ \qquad\qquad\qquad\qquad\qquad\qquad b\text{Type} = \text{WB} \\ \\ d_0 + \frac{2}{N^{CJ}} \sum_{i=1}^{N^{CJ}/2} [|b - n_i^{CJ}|(S_{CJ} + c) \\ + |\delta(n_i^{CJ}, NLA) - \delta(b, NLA)|(S_{NLA} - S_{CJ}) \\ + |\delta(n_i^{CJ}, WB) - \delta(b, WB)|(S_{WB} - S_{CJ})], \\ \qquad\qquad\qquad\qquad\qquad\qquad b\text{Type} = \text{CJ} \end{cases} \tag{A.18}$$

APPENDIX B

EXTRA DELAY CAUSED BY SHUTTING DOWN ONE GATE DURING A PEAK HOUR

If the aircraft arrival rate $A(t)$ exceeds the service rate (gate capacity) η, then a queue begins to form at time t_1 as shown in Figure B.1. The length of the queue is [Newell, 1982]

$$Q(t) = \int_{t_1}^{t} [A(t) - \eta]dt \qquad \text{(A.1)}$$

The queue reaches its maximum length at time t_2, when it begins to decrease until it completely vanishes at time t_3, such that the light grey and the dark grey areas in Figure B.1 are equivalent. Figure B.2 plots the behaviour of $Q(t)$. The area under the curve $Q(t)$ is the total delay imposed to aircraft during the peak hour.

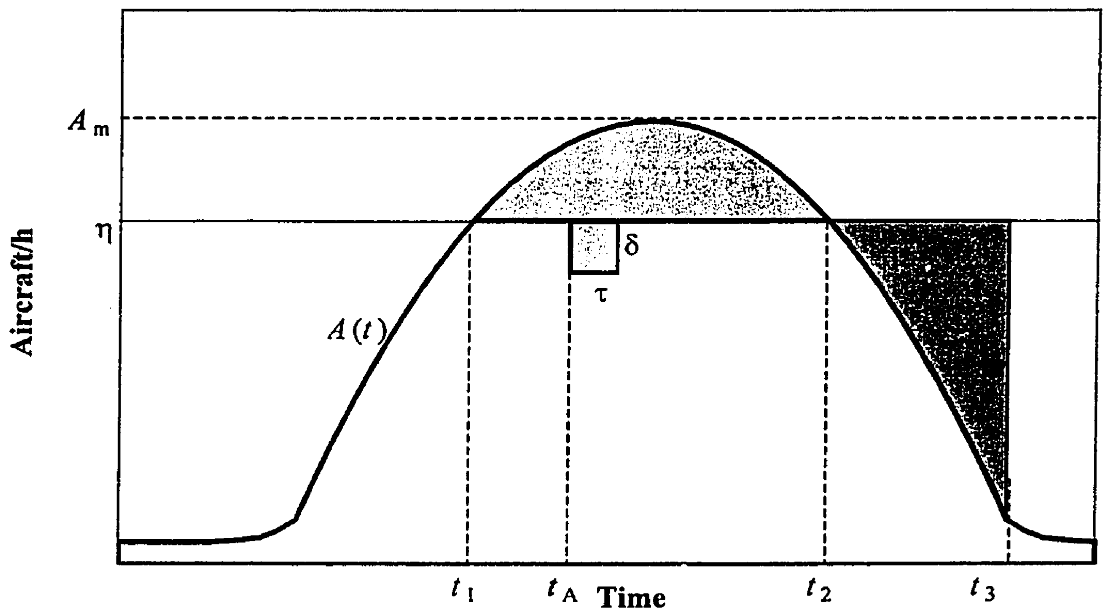

Figure B.1: Reduction of gate capacity during a peak hour

Should a reduction in the service rate δ of duration τ happen at a time t_A between $t_1$and t_3, an increase in the queue length and a consequent extra delay will occur. In this case, the dark grey area in Figure B.1 will have to be increased to match the sum of the dark grey areas. As a consequence, the queue will not vanish at t_3, but at t_4 instead as shown in Figure B.2. The extra delay caused by the capacity reduction is represented by the grey area in Figure B.2. The exact value of this extra delay is

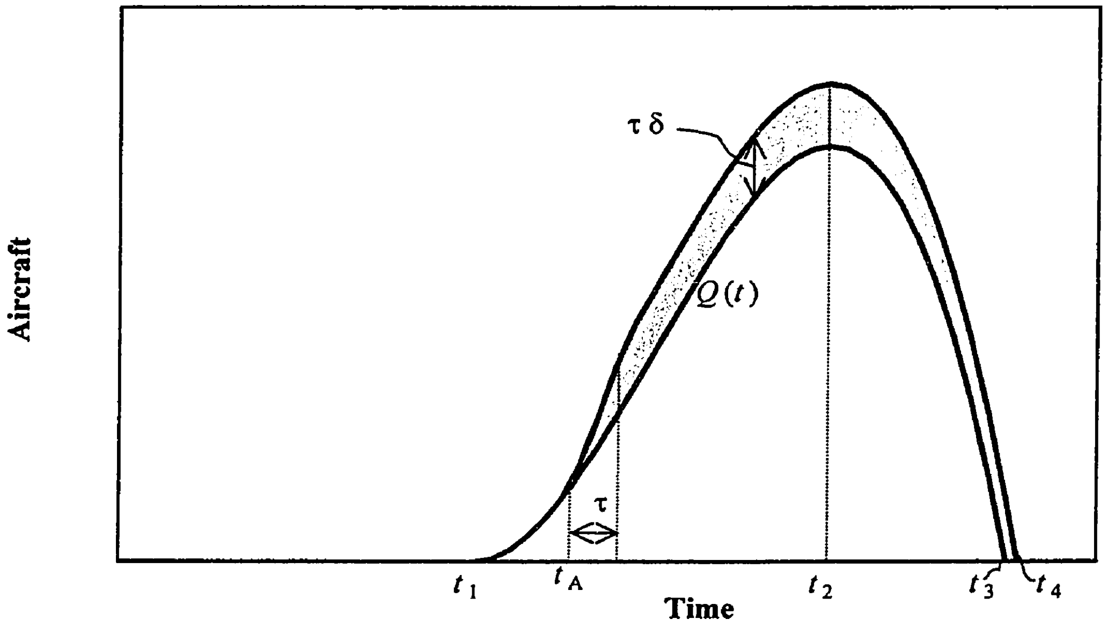

Figure B.2: Evolution of the queue length and extra delay

$$\frac{\delta}{2}\tau^2 + \delta\tau(t_4 - t_A + \tau) + \int_{t_3}^{t_4}[A(t) - \eta]dt \qquad \text{(A.2)}$$

which can be re-written as

$$\frac{\delta\tau}{2}[3\tau + 2(t_3 - t_A)] + \delta\tau(t_4 - t_3) + \int_{t_3}^{t_4}[A(t) - \eta]dt \qquad \text{(A.3)}$$

The last two terms in Equation A.3 represent the delay that is added between t_3 and t_4. For $\delta << A_m - \eta$, that delay is very small compared to the total extra delay and can therefore be neglected. In addition, the exact value of t_A may be difficult to determine due to variations in the schedule and flight lateness. If t_A is uniformly distributed over $[t_1, t_3]$, then $(t_3 + t_1)/2$ is a good estimate of t_A. The value of extra delay can then be approximated by

$$\frac{\delta\tau}{2}[3\tau + (t_3 - t_1)] \tag{A.4}$$