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An Optimum Resource Utilization Model For Airport Passenger Terminal Buildings

by

Mahmoud Saffarzadeh Parizi, B.Eng, M.Eng

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Doctor of Philosophy*

Department of Civil and Environmental Engineering
Carleton University
Ottawa, Ontario

* The Doctor of Philosophy Program in Civil and
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**"An Optimum Resource Utilization Model For
Airport Passenger Terminal Buildings"**

Submitted by

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in partial fulfilment of the requirements
for the degree of Doctor of Philosophy

Chair, Department of Civil and Environmental Engineering

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Abstract

The standard procedures for designing and operating airport Passenger Terminal Buildings, PTBs, often lead to either high operating and maintenance costs or passenger dissatisfaction. Increasingly restrained public funding will require more innovative scientific approaches to increase the efficiency and cost effectiveness of existing or proposed airport systems. This research has initiated a new philosophy of planning, design and operation which is based upon optimum resource utilization and passenger flow management and control. An optimization methodology was developed based on important issues such as; early association of physical and operational plans, stochastic nature of airport demand, long term costs of over- and under-supply of PTB facilities, performance measures, and utilization of scarce resources. The methodology was then converted to an optimum resource utilization model by using a mathematical and simulation approach. As parts of the optimum resource utilization model three submodels, i.e., simulation, optimization, and flow management and control models, were developed.

An object oriented simulation model, consisting of a set of simple submodels and nodes, was developed to perform as a real world airport terminal. The simulation model provide real-time interactive information about different segments of the PTB. The optimization model, based on a mathematical relationship between over- and under-supply costs, stochastic demand, levels of service, and PTB resources, will provide a list of optimum required resources for all predefined segments of the PTB. A real-time flow management and control model was developed, in which the PTB operator would be able to respond to preplanned or spontaneous events. Several applications of the resource utilization model in planning, design, and operation are also discussed.

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Abbreviations

ALSIM	Airport Landside Simulation Model
ATAA	Air Transport Association of America
ATC	Air Traffic Control
CFCF	Central Flow Control Facility
FAA	Federal Aviation Administration
FMC	Flow Management and Control
IATA	International Air Transport Association
IVHS	Intelligent Vehicle-Highway System
LOS	Level Of Service
MCA	Macdonald Cartier Airport
MIA	Mirabel International Airport
OAG	Official Airline Guide
OOP	Object Oriented Programming
PIL	Primary Inspection Lines
PMF	Probability Mass Function
PPHP	Planning Peak Hour Passenger
PTB	Passenger Terminal Building
PTBSIM	Passenger Terminal Building Simulation Model
PTV	Passenger Transfer Vehicle
SBR	Standard Busy Rate
SCOOT	Split, Cycle, Offset Optimization Technique
SES	Scientific Engineering Software
SPSS	Statistical Package for Social Science
TC	Transport Canada

TMS	Traffic Management System
TPHP	Typical Peak Hour Passenger
TRB	Transportation Research Board

Nomenclature

A_t	space available at time t
A_{space}	active passenger processing area
α_j	unit cost of over-supply
β_j	unit cost of under-supply
C_T	total over- and under-supply cost of the system
c'_j	derivative of the cost function
$C_j(x_j)$	expected over- and under-supply cost
δ	integer value of (x_j/θ_j)
Δ	difference between available and optimum resources
$F_j(y)$	cumulative demand distribution
$first$	time when the first passenger arrives at the PTB
$F\&t$	statistical parameters
$f(t)$	percentage of aircraft load at time t
$Gspace$	total gross area of the PTB
γ	unit cost of maintaining the PTB
i	number of meeters associated with each passenger
j	the PTB segment number
$last$	time when the last passenger arrives at the PTB
λ	unit cost of active PTB operation
m	number of meeters/greeters associated with each passenger
max	maximum number of meeters with each passenger
min	minimum number of meeters with each passenger
μ	mean of probability distribution function
$mode$	time when maximum number of passenger arrive at the PTB

MOD	module of the specified area, m^2/pax .
n	total number of PTB segments
N	total available resource
NPI_t	number of passengers entered the area at time t
NPO_t	number of passengers exit the area at time t
ν	average service time
ω	average number of greeters/meeters
OPS_{total}	total PTB operating and maintenance cost
$p_j(y)$	probability mass function of demand at each segment
$p(i)$	probability of having i number of meeters
r	coefficient of correlation
RES_{total}	total resource available
σ	coefficient of mode selection in triangular distribution
t	time before flight departure
t_i	time to release the passengers towards processing unit
t_a	arrival time of passengers from the aircraft to the gate area
t_w	walking time from hold room to the next processing unit
$TOMC$	total operations and maintenance cost
θ	resource allocated to each demand unit
w_i	queue dissipation time at the next processing unit
x_j	resource allocated to each segment
y	demand, number of occupants
Y	maximum expected demand
z	service time of each passenger

Chapter 1

Introduction

1.1 Overview

The airport is a complex system comprising many physical components all interconnected by traffic flows. It basically serves as a transfer point between the ground transportation system and the air transportation system. The airport Passenger Terminal Building (PTB) is the interface between the air mode and the ground transportation mode. Its main function is to facilitate the processing of passengers and their baggage prior to boarding and after leaving the aircraft. It also should provide a comfortable environment, in which passengers and those accompanying them may wait, and provide certain supporting services that users of the terminal may need, such as food and beverage services, car rental agencies, etc. A schematic representation of the airport system showing the main subsystems is illustrated in Figure 1.1. A more detailed description of the PTB and its components is given in Chapter 2.

Capital and operating costs of airport passenger terminals are very extensive. For

Figure 1.1: Schematic Representation of the Airport System

Source: Modified From Braaksma, 1973

example, the capital cost of new airport PTB for Sydney, Australia airport is estimated about US \$200 million, and for the new Milan/Malpensa, Italy airport was US \$500 million as of 1990 (Odoni, and Neufville, 1990). Taking into account that airport PTBs are one of the most expensive public transportation facilities, the goal of public policy should be to ensure that these resources are employed as effectively as possible. A quick review of the existing literature would give the impression of over-supply of airport terminals for most of the planning horizon. The over-supply either for aesthetic purposes or for avoiding future congestion can be very expensive. For example, making one corridor of the new two-level Sydney airport 12 metres wide, instead of a feasible six metres, caused an extra capital cost of about US \$1 million. Moreover, in Canada, 94 percent of all air passengers use only 26 of 726 airports (Transport Canada, 1994). The costs involved in operating and maintaining of these airports are now being heavily subsidized. Just in 1994, direct subsidies (including rail and marine) required \$ 1.6 billion and indirect subsidies raise that total to \$ 2.3 billion by federal government alone. Taxpayers and users have been burdened by expenditures made on these under-utilized airports.

However, there are a growing number of cases where some segments of airport terminals have been clogged due to either misestimation of traffic volumes or misallocation of resources. In other words, congestion problems will occur in components of the PTB which may have sufficient overall space. This phenomenon, under-supply of PTB resources, has also been costly. For instance, insufficient analysis and errors in the original design of the interior spaces for the Air France terminal at Paris/Roissy, France caused an extra cost of about US \$75 million in 1990 terms (de Neufville, and Grillo, 1982).

While in the past, due to over-supply of facilities, airports were seen as wasted resources, recently, the growing number of air passengers is causing concern about

insufficient capacity to serve the rapidly rising demand. The three major interest groups affected are users, airlines, and airport authorities. The negative impacts of under-sizing for users can be: congestion, delays, and reduced level of service, while for airport authorities, there may be operational problems, and loss of potential customers. Over-sizing can also be a problem and its negative impacts to users can be increased charges to pay for the oversized facilities, while for airport authorities it may be reduced revenue and increased overhead costs. Other interest groups such as carriers, airport owners, and airport concessionaires are also affected. Some of the possible impacts of over-supply and under-supply of airport terminals are summarized in Table 1.1.

Considering the undesirable consequences of over-sizing as well as under-sizing, it should be an important objective of airport planning to find an optimal way to balance supply and demand. Supply, also referred to as capacity, depends on the type, size, configuration, and most importantly, the conditions of such facilities, i.e., operational procedure and regulations. The term demand refers not only to the number of air passengers but also to those aspects of their behaviour that affect the ability of a functional component or a group of components to accommodate passengers. Passengers' behaviour consists of their arrival and departure over time, number of bags carried and checked, number of people accompanying the passenger, and whether the passenger has a ticket and boarding pass. Therefore, an improved knowledge of demand and supply characteristics is essential to achieve the optimum utilization of airport facilities. It should be noted that the concept of level of service should not be forgotten because it determines at what level of service demand and supply should be balanced.

The objective of this study is to optimize the utilization of PTB scarce resources. The utility of the PTB can be measured in terms of some indices such as; density,

Interest Group	Negative Impacts of Over-Supply	Negative Impacts of Under-Supply
Airport Authority	- Reduced revenues - Increased overhead costs	- Operational problems - Complaints from users - Loss of potential customers
Users	- Increased charges - Extra taxes	- Reduced LOS - Congestion, delays
Carriers	- Increased charges (fees, leases)	- Diversion of customers - Delay cost
Concessionaires	- Reduced revenue - Increased charges	- Loss of customers - Low level of service
Government	- Reduced Revenue	- Political Backlash

Table 1.1: Possible Impacts of PTB Over-supply and Under-supply

percentage of time used during a 24-hour period, percentage of space being utilized, volume/capacity ratio, etc . Although passengers under prevailing conditions on arrival at a component perceive the state of a component with other impacts such as waiting time, service time, and congestion, the use of density (number of occupants per unit space) as a measure of intensity of the usage level is appropriate. The rationale for the study was developed as a result of observations of the unequal temporal and spatial utilization of PTBs. Most passenger terminals provide enough space but the lack of an operational plan and flow management techniques causes congestion in some areas while other areas become under-utilized. Since individual functional components of an airport terminal interact to ease the transfer of passengers from the ground to the air or vice versa, lack of proper operation of one of these components could lead to an eventual functional breakdown of the whole terminal. Whether or not such

a breakdown occurs depends on the operation of all functional components and the demand placed upon them.

1.2 Problem Background

The most obvious factor causing the ineffective utilization of airport terminals is traffic peaking. When the demand for the use of an airport facility is plotted against time, the graph would look like a landscape of mountains and valleys. Peaking may be by hour of the day, day of the week, and season of the year. Figure 1.2 shows the demand curve for a typical day at ThunderBay, Ontario airport. As the figure shows, for two distinct periods of time, the PTB is used extensively while for the remainder of the day it is almost vacant.

Associated with airport peaking are costs. To accommodate peak demands, investment in airport facilities and airport operating costs are higher than they would be if demand were distributed over time more evenly. Moreover, peaking may also cause congestion and delays which imposes costs on air carriers and make travel less productive and less pleasant for airline passengers. In addition to the three aforementioned types of cost, i.e., larger capital cost, operating and maintenance cost, and quality of service to passengers, the cost of under-utilization should be considered. The under-utilization cost could be the marginal benefit obtained from utilizing the less utilized parts of the terminal building. Airport peaking is of course primarily caused by airlines concentrating flights at certain times of the day, days of the week or seasons of the year. The airline schedule is established based on several factors such as:

- The demand of the public to travel within social hours on short-haul operations, and in the case of long-haul flights to depart and/or arrive at reasonable local

Figure 1.2: Actual Traffic Counts for a Typical Day At ThunderBay Airport

Source: Transport Canada, 1992

times of the day at the main passenger points.

- The need for arranging connecting services specially those where long-haul international services link with short haul domestic networks.
- The utilization pattern of the aircraft fleet which tends to cause peaking in its own right. The utilization pattern of aircraft when related to the geography of large populations, channel much of air transport into fairly specific times of operation at key cities.
- Other constraints which contribute to peaking such as: night curfews, numerical limitation to night movements, or noise limitations that may restrict landings and take-offs.

The peaking of passengers may differ from the peaking of flights. In most cases both load factors and average aircraft size are larger during peak periods. The obvious consequence is that the passengers' peak is normally much more pronounced than aircraft peaks, particularly seasonal and hourly peaks.

Over the years several approaches have been initiated to deal with allocation of resources in such a way to overcome the problems of peaking. These approaches have been mostly developed for the airside part of the airport. Some of those approaches are: capacity expansion, demand management, and application of advanced technology. Recognizing that the idea of adding capacity for short periods of time is a difficult solution, methods of increasing the utility of airport facilities by more efficient allocation of resources have been developed (Fawcett, 1990). Some of the allocation methods are:

1. using airline scheduling committees to allocate slots among the air carriers vying for the slots.

2. allowing the buying and selling of slots in auction-type arrangements,
3. using lotteries to assign the slots, and
4. leveling the utilization of available resources through the use of a marginal cost pricing system based on the time of day, day of the week, or season of the year.

The goal behind these different approaches is to move traffic from the peak to the non-peak period and to use the airport resources more evenly. However, these approaches did not solve the overall problems of congestion and inefficient utilization of resources. Rather they shifted the congestion in some degree from airside to apron and landside area. An airport is a set of interconnected physical facilities and components. For it to operate efficiently, the capacities of each of those elements must be matched. Relief of a bottleneck in one part of the airport will not have the desired effect on the overall capacity unless other parts are able to absorb a greater influx of traffic. Measures to augment runway capacity or to increase the flow of traffic through the airspace may be of little or no practical benefit unless passengers are capable of moving expeditiously to and from the terminal building. If the movement of passengers inside the terminal building is constrained by poor terminal design or operational procedures, the effect ripples throughout the airport and delays accumulate.

1.3 Problem Definition

The current design procedure for airport terminals determines space requirement according to a broad criterion of average space per person. Given the traffic level, there is a corresponding space requirement. The traffic level is the forecast demand for a typical hour, i.e., Typical Peak Hour Passenger (TPHP). Derivation of the TPHP

from the existing or forecasted data varies among countries. For example, at Amsterdam Schiphol airport, the demand level during the 20th busiest hour is used, and in France, Aeroports de Paris uses the 40th busiest hour. The British Airports Authority defines the TPHP as the level such that 5.0 percent of the annual passenger volume occurs at higher hourly rates (Transportation Research Board, 1987). Transport Canada uses the 90th percentile peak hour passenger flow, but considers the variations in demand within this peak period (Transport Canada, 1986). Federal Aviation Administration (FAA) guidance materials uses the peak hour of an average day of the peak month as a basis for planning and design (Federal Aviation Administration, 1988). It is clear that there is no universally acceptable definition for the TPHP. Even with the standard TPHP, the problem still remains because, in the current practice space requirements are determined according to a broad criterion of average space per person instead of focusing on highly variable demand and trying to come up with a flexible space allocation for each component of the PTB. As a result, space which translates into a scarce resource, may be misallocated.

Assuming that the average peak as the 30th busiest hour, this means, in theory, that the PTB is fully utilized for one hour in the year, 29 hours in the year it is over utilized, and for the remainder of the time, i.e., 8730 hours, it is under utilized (there are 8760 hours in a 365 day year). In other words, according to this theory, the PTB is fully to over utilized 0.34 percent of the time each year. Although it is not possible to construct facilities based on the highly variable demand, it is possible to use and operate them more realistically. A flexible design concept will help to overcome some of the variabilities associated with the forecast data. However, favouring a flexible design without a variable operational plan cannot solve the problem entirely. Even with the concept of flexible design, the PTB reaches its capacity each year, still the PTB is utilized only 0.34 percent of the time. Clearly, then there is a need for

some tools and techniques to address the problems of the trade-offs between different ways of handling a given traffic volume and the trade-offs involved in operating a terminal to handle varying traffic flow. These may include trade-offs between capital and operating costs, between costs and levels of service, between costs incurred by operators and passengers, between using technology for more efficient operation and expanding existing facilities, and between multi or shared usage and single or exclusive utilization of PTB resources.

The total PTB system cost is often not entirely visible, particularly those costs associated with the operation and support. The visibility problem can be related to the “iceberg” effect in which, the visible part is the design and construction cost and the remainder (under the water) is operating and maintenance cost. Figure 1.3 illustrates the invisibility of operating and maintenance costs of PTBs by making an analogy between the total cost and iceberg effect. The operating and maintenance costs of passenger terminals has been largely ignored as a determinant of design, particularly with respect to the growth of operating costs as the terminal grows in scale and complexity.

The operating and maintenance costs of terminal buildings is between \$115 to \$860 per m^2 of the gross total area annually which is about one-tenth of the capital cost. Table 1.2 shows operating and maintenance costs for a wide range of airports. If the total operating cost were allocated to the passenger processing part of the PTB, then the average cost would be \$230 to \$1700 per m^2 per year. The range of variation is due to several factors such as the geographical location and type of services they provide.

An aware PTB designer realizes that these operating and maintenance ongoing costs can now represent more than 50 percent of the true total costs incurred during the

Airport	Total O & M Costs	Total PTB Gross Area	Annual Pax.	\$/m²	\$/Pax
Macdonald Cartier	4,143,969.7	35,042	2,495,700	118.25	1.66
Dorval	14,600,528	97,601	5,563,300	149.61	2.62
Mirabel	11,644,954	101,663	2,424,400	114.62	4.80
Pearson	50,688,322	N/A	19,118,900	N/A	2.65
Castlegar	772,000	1,423	84,200	542.51	9.16
North Bay	786,000	1,807	81,800	434.97	9.60
Penticton	771,000	1,565	69,700	492.65	11.06
Port Hardy	437,000	1,413	20,100	309.27	21.7
Prince Rupert	570,000	1,239	112,600	460.05	5.10
Smithers	349,000	814	51,500	428.74	6.77
Terrace	539,000	1,999	83,200	269.63	6.47
Timmins	801,000	925	159,600	865.94	5.01

Table 1.2: PTB Unit O & M Costs For Various Airports, Transport Canada, 1993

Figure 1.3: The Operating and Maintenance Cost "Iceberg"

economic life of the facility, and thus deserve as much attention as capital costs. Taking into account the energy shortages and unfavourable economic conditions predicted in the future, more attention should be focused on the long term impact of increasing operating and maintenance costs. The expensive operating cost will ultimately be paid by the traveller, either through higher fares, concession prices, or user charges. Therefore, it is also important, from users' point of view, to have a methodology that can establish the interaction between planning and design decisions and long term operating and maintenance costs.

Another deficiency of the current design practice is that in spite of a sensitive relationship between physical planning and operational planning, the analysis of these two is not done early enough. To increase the efficiency of the PTB, two main concepts should be considered; design and operation. The result of ignoring one of these two would be an inefficient terminal with the possible occurrence of aforementioned problems. The combination of a poorly designed PTB with an excellent operational

plan may operate well, while an excellently designed PTB with a poor operating plan may result in a terminal operating poorly. Despite the fact that almost everybody agrees with this concept, it has been considered neither in practice nor in research. In practice many terminals have been built as architectural monuments to the progress of regional and national aviation. As a result, air travellers, in some degree have become accustomed to lavish displays of design that have nothing to do with the functions the terminal is intended to perform. This would not be serious problem were it not for the need to design the PTB so that it can accommodate continually changing air passenger traffic demand.

Another problem associated with the airport PTB design and operation is the month to month uncertainty of the airline industry. This creates situations where terminals which have been designed for one type of operation, are now faced to operate under a completely different situation due to the bankruptcy of a major airline or replacement of another carrier with very different scheduling or type of passengers, i.e., international vs domestic or hub vs origin/destination operations. This uncertainty can sometimes render even a well-conceived design inefficient or inappropriate. There are many examples in which passenger terminals operate poorly as a result of the lack of an operational plan which causes the mis-estimation of traffic patterns, flow characteristics and local consideration. For instance, at O'Hare, Chicago, the need to use the concourses for passenger security screening has created long and circuitous routes for transferring passengers. Kennedy, Dallas-Forth-Worth, and Dulles airports were planned for origin/destination traffic, while since deregulation, the traffic pattern has been changed which made these airports very inconvenient for transfer passengers. The current specific problems facing the PTB operation in particular are as follows:

- There is not an accepted methodology to address issues involving PTB optimiza-

tion. Some of these issues are: early association of physical and operational plans, stochastic nature of airport demand, long term costs of over- and under-supply of PTB facilities, performance measures, and utilization of scarce resources.

- While the investment in the airport terminals is extensive in terms of capital, operating, and maintenance cost, the facility is being fully utilized for a very small percentage of its useful life, e.g., 0.34 percent based on the 30th busiest hour theory.
- There is no methodology to allocate resources based on the variable nature of demand placed upon the facility. Therefore, while in a very short period of time the PTB may experience congestion, it is under utilized for the remainder of its useful life.
- While the operating and maintenance costs of PTBs constitute a major portion of the total cost, they almost always have been ignored in the planning and design process. Also there is no methodology to take into account the variability of demand on the operations cost.
- While in other parts of the airport some flow management strategies have been developed to ease congestion and delay problems, there is no management and control technique developed for the passenger processing part of the airport, i.e., PTB.
- Mostly there is no operational plan developed with the PTB design. Even if there were any, there is no procedure to test the functionality of the combination of these two plans, i.e., operation and design. There is no tool, either analytical or simulation, developed in which the PTB operator would be able to interactively place the demand on the system and observe its operation.

More detailed discussion of these problems are given in the following chapters. However, with the cost and difficulties in modifying the infrastructure to keep pace with the air traffic changes, it would be necessary for airport planners to first, favour a flexible design, and second prepare an operational plan for different scenarios. Airport operators may also be required to first, allocate PTB resources based on the variable nature of demand, and second, in the case of scarcity, manage and control the traffic flow in such a way to obtain the best of what is exist, i.e., optimum utilization. This thesis explores one approach to this problem of mis-allocation of resources by investigating the application of both resource allocation and flow management and control theories to the operation of the PTB. The hypothesis is that if optimum required resources are obtained, by application of resource allocation theory, then the results can be implemented in the real world through a flow management and control technique.

1.4 Purpose of the Study

The main purpose of this research is to develop an optimum resource utilization plan for the PTB to provide a facility with minimum operating and maintenance cost. The specific objectives of the study are as follows:

- **Propose an optimum resource utilization methodology for a typical airport PTB.**
This methodology, if applied properly, will provide a facility with minimum operating and maintenance cost throughout its useful life.
- **Develop a simulated mathematical model for optimum resource utilization of the PTB.** This model is developed based on the proposed methodology for theoretical experimentation and analysis.

- Develop an object oriented simulation model which would perform as the real world airport PTB. The operator would be able to interactively run the model and collect the probability distributions of demand on different segments of the PTB as well as statistics about other performance measures.
- Develop an optimization model which will provide a list of optimum required resources for all predefined segments of the PTB. The optimization model is based on a mathematical relationship between over- and under-supply costs, stochastic demand, levels of service, and PTB resources.
- Propose a generic real-time flow management and control system for a large airport PTB with peak oriented traffic. The proposed system, when fully developed, would perform two main functions. First, it will implement the variable time-resource plan obtained from optimization model. Second, it will disseminate information to different segments of the PTB for the purpose of passenger traffic flow management and control.

1.5 Scope of the Study

This study focuses on the airport passenger terminal building from the landside curb entrance to the aircraft gate or vice versa. The main subject of the research would be on the planning, design and operational aspects of the existing airport PTBs. The type of traffic flow which is analyzed is passenger traffic flow. Baggage flows can be included as an extension of the work at a later date. In terms of operation, a single authority for the PTB operation is assumed. Although the methodology can be applied at any airport with peak oriented traffic, medium to large sized airports are the best candidates. The design implication of the methodology is useful only for new

PTBs. However, the methodology can be used in planning additions to existing PTBs if they are flexible enough to be incorporated with the new additions. The planning application of the research was limited to physical and operational planning, and administration and financial planning were not part of the research.

1.6 Organization of the Thesis

This thesis, is organized into eight chapters and several appendices. So far, the problem has been defined in this chapter. The airport passenger terminal building system and some of its basic components required for passenger processing are reviewed in Chapter 2. The review includes the current research and practice in the area of PTB planning, design, and operation. Chapter 3 presents the formulation of the research problem. This includes a discussion of the proposed methodology for optimum utilization of PTB resources, preliminary identification of complex issues related to the proposed methodology, and development of the resource utilization model. The Object-Oriented simulation model developed for the study is explained in Chapter 4. Chapter 5 presents the development of an optimization model. The presentation includes the development of the optimization theory, and a heuristic algorithm to solve the optimization problem. Chapter 6 brings all the components and submodels, developed in previous chapters, together to form the resource utilization model. Two case studies, to test the resource utilization model, are also presented in this chapter. Chapter 7 presents some of the major applications of the resource utilization model. A conceptual flow management and control model is also discussed in this chapter. Chapter 8 presents a summary of results, conclusions, and recommendations for future research on the methodology developed in this study. The appendices, A to I, covering supporting materials are also presented for further reference.

Chapter 2

Overview of Passenger Terminal Design and Operation

2.1 Overview

The airport has been considered by the air transport industry as being divided into the airside and the landside area. The airside consists of the runways, taxiways, apron, and other associated facilities that support the movement of aircraft into and out of airport. The landside area contains those facilities that are required to permit the handling of passengers and their baggage and their transfer on and off the aircraft. Components of the landside are mainly the passenger terminal building, (PTB), the curbside area, access roads, parking facilities, and gates. It is recognized that the airport airside and landside are integrated systems and airport planning and design efforts should be directed at planning an effective airport system which creates a balance between airside and landside performance. However it is possible to separate these subsystems for the purpose of analysis and design. It is also possible to

separate the PTB from the ground access at its interface, i.e., the curbside area. For the purpose of this research, the PTB was considered as the most important element of the landside system in which the physical act of transferring takes place.

The PTB consists of those facilities necessary and desirable for the handling of passengers and their baggage prior to and after a flight. It is the element which links the ground access system to the air transportation system and is designed to provide convenient, fast, and economical transfer of passengers and their baggage. To operate smoothly at a desirable level of service, several facilities are necessary. These facilities should be arranged in such a way as to expedite the handling of passengers and their baggage through the terminal.

Figure 2.1 shows a simplification of the flow process for passenger and baggage through an international PTB. Operation of the PTB depends on the behaviour of individual functional components and interactions among them. Although the PTB is a set of individual components, not all are likely to cause delays and crowding or become a bottleneck. Those components which are potentially critical to the PTB operation are as follows:

1. The airline ticket counter used for ticket transactions, seat assignments, baggage check-in, and flight information.
2. The baggage claim which is used for receiving baggage from an arriving flight.
3. Security screening used for inspection of passengers and baggage.
4. Customs and immigration facilities which are used for processing passengers arriving on international flights.
5. The departure lounge or hold room used for assembling passengers for a flight departure.

Figure 2.1: Passenger and Baggage Flow In An Airport PTB

Source: Modified From Ashford, and Wright, 1992

6. The lobby for circulation, passenger and visitor waiting.

It should be noted, although, each component will be considered separately, the relationship between them should not be forgotten because the delay and crowding of each component will have an effect on the following component. In the following sections, the basic characteristics of the aforementioned components such as: its function, relation with others, location, demand, operating characteristics, sizing and configuration, level of service, and criteria for level of service assessment are summarized.

2.2 Passenger Terminal Building Operation

The PTB is a complex collection of individual functional components which interact to provide service to air passengers. Basically the PTB performs three main functions:

1. Processing of passengers and baggage. This include ticketing, check-in, government checks, and security arrangements.
2. Facilitating a change of mode. To change from one mode to the other, the passenger physically moves through the PTB according to a prescribed pattern of movement. These movement patterns are accommodated in passenger circulation areas.
3. Change of movement type. The terminal functions on the departure side as a receiver that collects passengers continuously and process them in batches. On the arrival side the pattern is reverse. This function necessitate a holding space, e.g., holdrooms, lobbys.

Thus the primary function of the PTB is to provide processing, circulation, and holding space. Due to the complexity of the PTB, it is useful to describe its operation in terms of some flow route diagrams. Since the situations and requirements may vary at each airport, it is not possible to recommend any particular flow route. The mandatory activities, activities of which a passenger must partake if he/she wishes to complete his/her journey, are grouped in two distinct patterns, i.e., arrival and departure. Some typical departure and arrival flow patterns are shown in Figure 2.1. These illustrations are independent of any particular geometric configuration of the PTB. This type of representation is useful because it permits an operations model to be built for each of the two subsystems, i.e., arrival and departure. It also shows the interrelationships among the components especially the precedence-dependence relationships.

2.2.1 Ticket Counter and Baggage Check

Operation of the ticket counter and baggage check-in begins when a passenger enters the terminal to obtain a ticket and check his/her baggage and ends when that passenger leaves the area. Normally airlines rent the space from airport operators and manage this space on an exclusive-use basis. Thus airlines establish their own standard for this component on the basis of company policy and local competition. The demand for this component is produced by the rate of arrivals. The rate of arrivals depend on the time before a scheduled flight departure and it is not constant due to the behaviour of passengers and ground access facilities.

The operating characteristics which are the average processing time and waiting area per passenger at the ticket counter are different for each airport. From a recent survey, conducted at the Macdonald Cartier International Airport (MCA), in Ottawa, for the

purpose of this research, the average processing rate was observed to be 32 passengers per hour or the time per passenger was 1.86 minutes each. The Level Of Service (LOS) is influenced by such demand and operating factors as: number and type of positions, passenger characteristics, airline procedure and staffing, space and configuration, and type of flight. The criteria for assessing the LOS could be the average waiting time, the queue length, or the space per person.

2.2.2 Baggage Claim

Baggage claim areas are typically located adjacent to the direct route of deplaning passenger circulation. This area will provide service for passengers to claim their baggage. The capacity of this component is determined by the type of equipment and the space available to the passengers. The demand or the number of passengers waiting in the area depends on the rate of arrival from the gate, and bag/passenger ratio. Larger aircraft usually cause longer queues because large number of passengers arrive at the same time.

Operating characteristics depend on the number and type of baggage claim devices and the number of flights which they serve. Passengers have to wait in several rows of parallel queues to see and pick up their baggage. The waiting time in this process depends on the rate at which bags are transferred from aircraft to carts, from carts to feeding belts, and the time of transport. The LOS of this component depends on factors such as: equipment configuration and claim area, staffing practices, baggage load and passenger characteristics. The criteria for LOS determination could be the average waiting time, and the passenger density of the area.

2.2.3 Customs and Immigration

In international airports, international passengers should undergo customs and immigration services consisting of passport inspection, inspection of baggage, agricultural materials, drugs, and the collection of duties. This component is generally segregated from other parts of the terminal building. Foreign passengers must present their passport and other documents at several inspection booths, as a result several queues will form. The number, size, and load factor of arriving aircraft could be used to estimate passenger loads at this component. The distribution of passenger arrivals is determined by walking speed and distances from arrival gates to the inspection areas.

Operating characteristics and planning standards are specified by FAA guidance material which suggest the rate of 50 passengers per hour per agent (Transportation Research Board, 1987). Space standards are similar to those for other passenger waiting areas. The factors which influence the LOS and capacity are: No. of channels, space and personnel, passenger characteristics, flight and schedule load. The criteria for assessing the LOS could be the waiting time and queue length.

2.2.4 Passenger Departure Lounge

Waiting areas adjacent to aircraft gates are named departure lounge, gate lounge, or hold rooms. The number of passengers waiting for a flight departure depend on the number of aircraft served by the area, aircraft seating capacity, load factor, and the time of commencement of boarding a flight and its departure time. Therefore, demand is usually expressed as the percentage of departing passengers arriving at the waiting area in separate intervals of time before flight departure.

Direct observations have shown that almost 15 to 20 minutes before departure about

70 to 90 percent of passengers are in the vicinity of the gate, i.e., holding lounges. Some of the factors which influence the level of service could be: seating and waiting area geometry, number of seats, boarding method and airline service characteristics. However, the criteria for assessing the LOS could be density or congestion.

2.2.5 Passenger Security Screening

At entrances to terminal gate areas or at the entry to gate lounges, all originating passengers should pass through the security screening. The equipment consists of metal detecting devices through which passengers walk and X-ray devices for screening carry-on luggage. The number of passengers aiming for the aircraft determine the demand of security screening. The rate of arrival can be estimated from the passenger arrival times at the airport.

Operating parameters are the width of the corridor and the number of inspection channels. Processing time for security is not constant but an average service time can be obtained. The LOS depends on the number of channels, equipment sensitivity, space and personnel, flight schedule and load , and passenger characteristics. Also the criteria could be the waiting time, congestion or the length of queue.

2.2.6 Terminal Circulation

This component consists of corridors, lobbies, stairs, escalators, and all the important routes from the beginning of the walking trip to the end, inside the terminal building. These spaces frequently suffer from bottlenecks and excessive queues. The circulation of passengers in a terminal building is very complex because all of the above-mentioned factors plus the characteristics of individuals influence the number

of passengers which can circulate in the terminal. Although the terminal building designers determine what routes may be available to passengers, airport operators can use signs or other information tools to direct passenger traffic and improve overall terminal circulation in an attempt to optimize the path a passenger must take through the terminal building.

The demand for this component is determined by patterns of passenger arrival at the airport before scheduled flight departure, by the paths which both arriving and departing passengers take between gates and terminal curbs, and by the speeds passengers make during this trip. Level of service is influenced by terminal configuration, passenger characteristics, flight schedule and load. The criteria for level of service assessment can be the module (space per person), average speed, and volume over capacity ratio.

2.3 Critical Issues In the PTB Planning, Design and Operation

Before discussing the PTB resource utilization methodology proposed in this research, the present state of the art in the planning, design, and operation of PTBs is briefly reviewed. The major deficiencies associated with the current practices are also explained. There are mainly two sources of information on PTB planning and design. The first consists of works by both airport design practitioners and planning students in the form of textbooks, journal articles, and conference papers. The second consists of descriptive articles that describe particular projects. The former tend to concentrate on planning questions while the latter usually emphasizes design. There is however, frequently some overlap where design issues are addressed in planning literature or

vice versa. Exploring all the existing literature in detail regarding their strengths and weaknesses is not in the scope of this research. However, some examples from the planning, design, and operational area are addressed in the following sections.

2.3.1 Planning

Planning can be defined as the process of determining the future requirements of a facility and the time that those requirements should be met. This usually requires the preparation of reliable estimates of future demand and organizing supply to meet that demand on schedule. Airport planning as a discipline emerged in the early 1960s when Horonjeff published a textbook called *Planning and Design of Airports* (Horonjeff, 1994). In the second edition of this book, he designated a chapter on planning and design of the passenger terminal area. He described the determination of PTB space requirements in a three step process.

1. Annual passenger volumes and types are obtained from forecasts. The typical peak hour passengers was defined as a design index and proposed to be in the range of 0.03 to 0.05 percent of the annual volume.
2. The facility demand by each passenger type is identified by matching passenger types with various facilities in the PTB.
3. The space requirements are determined by multiplying the demands for various types of facility with space requirements per unit volume of traffic. A set of space standards was given and were claimed to provide a reasonable level of service.

Another source of information is the planning and design manuals developed by several organizations in the air transport industry. A manual produced for the FAA. *The*

Apron and Terminal Building Planning Manual, represents a comprehensive treatment of the subject of PTB planning (FAA, 1975). The manual provides detailed guidance on space required for different functions and includes typical layouts based on the existing conditions at U.S. airports. Since the analysis of existing conditions is not described or referenced, there is no way to establish the limits of confidence that can be placed on the recommendations. Moreover, the space requirements are given in charts and nomographs which give a unique result at any given set of conditions. This approach does not permit the planner to trade off facilities against level of service or to incorporate any local conditions into the analysis.

The Air Transport Association of America, ATAA, produced another manual entitled *Airline Aircraft Gates and Passenger Terminal Space Approximations* (ATAA, July 1977). This manual is a supplementary report to the FAA report and is intended to give detailed assistance in approximating future gate requirements and terminal space. A third manual of importance to PTB planning is the *Airport Terminals Reference Manual* produced by the International Air Transport Association (IATA, 1995). This manual discusses issues and list consideration to be taken into account in PTB design. It does not provide detailed guidance on sizing and layout. A more empirical approach to space requirements is adopted in a series of documents prepared by the Airport Services Branch of Transport Canada (1978).

These aforementioned manuals generally use a combination of rule-of thumb estimating techniques. Charts and graphs in planning manuals are based on current and past airport facility requirements. For most techniques, the peak hour or annual demand on the terminal component is estimated and PTB requirements are determined based on these estimates. Various airport planners and designers have computerized these rule of thumb charts and graphs. Although these techniques provide a starting point for determination of approximate facility needs, such techniques offer little in

formation as to the performance of either individual components within the terminal system or the performance of the system itself.

The planning manual approaches may not be applicable to newer technology introduced in the airport PTBs. Since new technology may encompass higher degrees of automation or alternative methods of facility orientation. Since facility requirements are determined based on a single design level of traffic, they fail to answer the question of what happens under other traffic conditions. However, the existing planning approaches are useful if they are used in their proper context and recognized as estimates subject to a high degree of variability.

2.3.2 Design and Operation

The literature on the design of airport PTBs is extensive. The existing information can be classified into two areas, i.e., conceptual definition and detailed design. The conceptual definition is concerned with selecting an overall configuration for the PTB. Although the design manuals provide the designer with the means to determine the floor space of individual elements of the terminal system, there still remains the problem of selecting an overall concept and fitting together the components within the framework of that concept. Since the performance of the system depends on how well the individual components interact, the concept selection and evaluation task is very important.

Airport PTBs can have very particular features that will differentiate one from each other. However, there are some common general features which may be used to classify the design concepts. Ashford and Wright (1992) used the degree of centralization as the most important factor to classify the design concepts. The PTB design

concepts can be classified into three main categories, i.e., centralized, decentralized, and Transporter. A centralized PTB is one in which the passenger processing facilities are located within a building while the aircraft are parked around it. Since all passenger and baggage processing is done in one area, duplication of facilities are avoided. In a decentralized PTB separate sets of facilities such as: Ticket check-in, baggage claim devices, and security checkpoints are provided for each aircraft parking position or a set of parking positions. The transporter concept is the one in which most of the airside interface is removed from the PTB and passengers are moved to and from the aircraft by *transporter* vehicles. The aircraft standing parking positions are located on the apron far from the PTB.

Although many authors have addressed the problem of concept selection, it has been mainly in the form of arguments for and against various concepts. Some authors even offer a different perspective noting that each concept serves different segments of the market and arguments about which concept is the best are sterile (deNeufville, 1976). Most large passenger terminals adopt a hybrid concept, incorporating characteristics of more than one concept.

The only analytical tool to address the problem of concept selection was proposed by Braaksma, and Shortreed, (1975). He proposed a method of three linked algorithms that sequentially size the facilities required based on a set of flight schedules, then assign the flights to the facilities in such a way that the transport cost is minimized, then recognize the layout of the facilities to further minimize the transport cost with the assignment of loads held constant. The second and third steps are iterated until an overall optimum is obtained. The output of the design method is a program of load assignments and a geometric configuration of airport PTBs.

In contrast to the limited literature on the theory of concept selection and evaluation,

the design of individual elements has been extensively covered in detail. The literature contains a wide range of information consisting of design, operation, analysis and modelling of individual elements of the PTB. Different modelling approaches, e.g., analytical, and simulation, are also covered. An analytical model is a mathematically derived approximate representation of a facility, either probabilistic or regression model, which determines average facility performance over a specified time period based upon some assigned average demand level and average service times. Probabilistic analytical models, based on queuing theory, determine delays and queue lengths from analytical solutions for queue problems(Ashford, O'Leary and McGinity, 1976; Ashford et al. 1976; McKelvey, 1988). The models are based on several assumptions such as: distribution of passenger arrivals, service time distribution, number of service channels, and the queue discipline.

For example, McKelvey (1988) describes a model in which the arrival process was assumed a Poisson distribution, and service times from either exponential or by random variable characterized by its mean and variance. The model uses the aggregate peak hour demand and assumes that the demand in each processor is a function of maximum peak hour demand. Application of analytical solutions to stochastic queuing networks has not been proven to be very effective due to violation of some of its assumptions in real life. For example, the model utilized by McKelvey assumes that the peak demand is steady and does not vary during the peak period, which is hardly true in any airport. Based on the design criteria, e.g., 30th busiest hour or 90th percentile traffic demand, PTBs allow periods of overload. Stochastic analytical queuing solutions cannot handle overload situation. When the congestion ratio, i.e., $\rho = \lambda/\mu$ where λ is the arrival rate and μ is the service rate, approaches 1.0, the queue length tends to infinity. To avoid the complexity, McKelvey has chosen to calculate a deterministic delay component.

Since analytical models consider the aggregate demand during peak hour, they would not be able to evaluate how individual flights influence the PTB. Any changes in the schedule must be expressed by recalculating the aggregated demand over the peak period. However, the analytical queueing models are adequate for the design of PTB processing facilities. Due to the assumption of steady-state, models are not able to analyze the PTB performance over a long period of time, as would be desirable for cost-effectiveness assessment.

Simulation models are classified into two main categories: i.e., accounting models and time-oriented models (McCabe and Canbery, 1975). Accounting models are macroscopic and deterministic in nature, that use pre-defined rules to describe the state of the system. Time-oriented models are microscopic and stochastic in nature that they use Monte Carlo method to describe the movement of passengers individually. Accounting models deal with batches of passengers. A model in this category developed by McCulloch and Robus (1979). The model, ACAP, describes the PTB as a network of interconnected components and deals with network flows during discrete time intervals. For each time interval, the user supplies the input flows into the system and the program then calculates the flow between two consecutive nodes of the network. Queue lengths and number of passengers served during the interval are calculated by expressions obtained through regression analysis. The regression models in this approach are valid only for the airports surveyed and cannot be used for other airports without proper verification. It is also difficult to accommodate changes in the passenger processing procedures, e.g., adoption of newer technology, or operational policy changes. To represent any new condition, a data collection to verify the regression equation is required.

In the time-oriented simulation models, the state of the system changes for each new event. These models allow for the determination of the performance of the processor

or a series of linked processors as individual units of demand move through the PTB system. Time-oriented models are basically discrete or continuous. Continuous-event simulation has not been applied to analyze airport PTBs since no set of equations can be derived to define the characteristics of the PTB system and its operation. Discrete-event stochastic simulation models have been developed over the years and used for planning, design, and analysis of one or groups of PTB components. More detailed description of some of the widely used simulation models are given in Section 4.2. of Chapter 4.

Moreover, a variety of other techniques, e.g., rules of thumb, time-space, nomographs, charts, etc. are used by planners and designers. In these techniques, an estimate is usually made of the peak hour demand on the PTB facilities and these techniques are used to determine facility requirements. For example, the time-space technique was used to analyze waiting and circulation areas in PTBs (Benz, 1986), subway station platforms (Grigoriadou and Braaksma, 1986). For more information about these modelling techniques, the reader is referred to the Bibliography section. The Bibliography does not claim to be exhaustive but is illustrative of some of the papers which were reviewed and consulted while writing the thesis. The detailed design deals with elements whose overall configuration has already been defined. The issues addressed are about the design of a component of the PTB to fit within a given space or reconfigure a certain segment of the PTB.

2.4 Criticism of Current Approaches

By reviewing the existing literature it seems that there are no widely accepted planning and design procedure for the PTB facilities. There are some empirical approaches

mainly derived from the accumulated knowledge of airport related organizations and consultants. However, in this research, the elements of a loosely knit planning and design process which have been evolved over the years were reviewed and the deficiencies are briefly discussed. The basic design variable most commonly used and the criterion for design is some form of peak hour flow. As was mentioned earlier, the definition of peak hour may vary. For example, the typical peak hour passenger (TPHP) is used by the FAA, the Standard Busy Rate (SBR) is used in some European countries, and the planning peak hour passenger (PPHP) used by Transport Canada. Despite the great influence of seasonal and daily changes in patterns of traffic on operational performance, the peak hour volume is the only demand that is considered for either planning or design purposes. While in reality, changing airline route structure, schedules, and aircraft sizes may place peak demand on particular components of the PTB at times that differ from one component to another and from those for the PTB as a whole.

The midday hour when many flights converge at an airline hub-and-spoke centre may represent the peak demand for hold room areas, whereas at the same airport, demand at ticket counters may peak before scheduled evening departures of several wide body aircraft. The peaks for different segments of the PTB may happen at different times of the day. Regardless of the time of the year and flight schedule, passenger demand varies from month to month, from day to day in a week, and during a day in a pattern that may be predictable from historic records. The criteria for demand should reflect realistic recurring and not the worst possible case at an airport. It should also take into account the interactions between components of the PTB, i.e., analysis of the PTB as a united system. The existing approach has averaging effects and is insensitive towards different demand levels. It also does not take into consideration the stochastic nature of operations and the time variant influence of demand on the performance

of facilities. The stochastic nature and the variation of demand are included in the planning and design procedure proposed in this research.

The second issue in the design process is specification of LOS standards. The LOS standard is the basis for translating the forecasted demand into an architectural design. The problem of defining LOS measures for the PTB is an interesting issue which will be discussed in Chapter 3. Standards in the form of single values for any specific activity inside the PTB have been developed by aviation organizations or individual researchers. The main problem with these standards is in the way they are applied in the planning and design process. It is a common practice to take the number of peak hour passengers for the design day, TPHP, and multiply by LOS space standards to obtain the required space (Transport Canada, 1986). For example, the FAA suggest a ratio of 150 ft^2 per design hour passenger and Horronjeff recommended a total of 25 m^2 per TPHP for a domestic PTB and 30 m^2 for an international PTB with 1.0 m^2 allocated for the ticket lobby, and 3.0 m^2 to customs, etc. (Horonjeff, 1994). These guidelines fail to consider the simultaneous number of occupants present in any particular segment of the PTB. Furthermore, passengers within the PTB do not disperse to make uniform use of the entire area. Rather, they congregate in specific places, e.g., check-in counters, baggage chute mouth, etc. Therefore, providing an overall space without an efficient allocation may result problems during operation.

The third problem in the traditional planning and design process is determination and analysis of passenger flow. Over the years, several approaches, e.g., mathematical, graphical, simulation have been used to analyze the PTB passenger flow. The mathematical approach is based on steady-state queueing theory (Lee, 1966). The queueing models determine delays and queue lengths by the use of analytical solutions for queue problems. A queueing system is typically determined by a distribution of customer arrivals, by a distribution of service times, by the number of service channels, and by

the discipline under which a facility is operating. Analytical queuing systems assume that the passenger arrival and service time distributions are known and parameters such as average delay and queue length are obtained from mathematical equations (Ashford, O'Leary, and McGinity, 1976; McKelvey, 1988).

The graphical approach based on the deterministic queueing was applied as an effective way of analyzing and designing the specific components of the PTB such as ticket counter (deNeufville, and Grillo, 1982) or departure lounges (Wirasinghe, and Shehata, 1988; Vandebona, and Allen, 1993). This approach analyzes each component of the PTB separately without taking into account the relationships of all components. Since the components of the PTB are inter-dependent, and any change in one is likely to effect others, this approach may not be very effective for the design of a complete terminal. Simulation models for the analysis of airport PTBs have been used for more than 25 years. Existing computer simulation models, either for the whole system or for one component, lag behind the state of the art in simulation, e.g., object oriented programming. In summary, they require extensive reprogramming for a specific configuration, take a long time to process, and require very detailed input data (McKelvey, 1989; Odoni, and Neufville, 1990).

To size terminals the specific passenger flow for a peak hour is taken from either graphical or simulation models and then converted to space by using LOS standards. The spaces for each segment are then fitted into an architectural concept. The result would be a design which will perform well for that particular scenario if everything goes the way it was assumed. With the existing design process there is no way to evaluate the performance of the proposed design during operation. So far, existing mathematical or simulation models do not support the idea of PTB optimization or operations management. The bottom line is that no matter at what level of detail and accuracy the PTB is modeled and designed, there should be an operational tool

which provides recommendations in real time on actions that need to be taken in response to unpredicted events. These events may be long delays to some aircraft, inclement weather, unusually heavy demand, equipment breakdown, etc.

In another words, a space plan consisting of space layout and management is required before any concept can be fully developed. Space layout, via physical planning, involves the determination of the size, shape, and relative location of spaces. Space management, via an operational plan, involves the utilization of these spaces. Therefore, to have an economic and efficient PTB a good degree of association should be established between physical and operational plans. If this association is provided at the early stages of planning and design and can be maintained throughout the PTB's life, then the goal of an economic and efficient PTB can be achieved. The goal of economy and efficiency means maximizing the use of PTB supplied spaces at a reasonable LOS. It is clear that the physical layout should be flexible enough to accommodate the unexpected changes due to the aforementioned reasons.

In conclusion, the conventional approaches of determining facility requirements by proceeding from an estimate of design level traffic fail to answer the question of what happens under other traffic conditions. They also fail to take into account the real traffic flow with all its uncertainties as well as the simultaneous number of occupants at each time period. They rather determine each facility's requirement based on its peak demand which is a percentage of total peak hour. Furthermore, at the operational level, the interaction of the physical plan and the operational plan are not taken into account. Since the actual levels and needs of future traffic may be quite different from those now anticipated due to such factors as deregulation, uncertain economy, etc., any proposed methodology should involve a range of possible temporal distributions and concentrations of airport users within the PTB, i.e., have a utilization plan. In another words, a more scientific approach should be developed

to incorporate a realistic appreciation of the dynamics and behaviour of passenger flows, and the way PTB users truly allocate the time they spend in different segments of the PTB.

Chapter 3

Formulation of the Research Problem

3.1 Overview

The main purpose of this research is to develop a methodology to optimize the resource utilization of the PTB, based on resource allocation theory, to yield a facility with minimum operating and maintenance costs at a desired level of service. The PTB is a collection of components to facilitate the transfer of passengers and their baggage from groundside to the airside or vice versa. The airport PTB also should provide both a comfortable environment, in which passengers and those accompanying them may wait, and certain supporting services, e.g., food, beverages, car rental, etc. that users of the PTB may need. This whole PTB operation can be conceived as a dynamic system consisting mainly of two set of entities, i.e., resources, and users. Resources of the system, e.g., space, labor, materials are deployed to produce certain services to users, e.g., passengers and companions.

The dynamic aspect of the system has been almost neglected in the current planning and design practices. The current practice does not address issues involving trade-offs in the design process. Given a traffic level, there is a corresponding space requirement, no more and no less. No check for optimality is made at any stage. While in the real world, there are always trade-offs between capital and operating costs, between costs and levels of service, equipment and fixed facilities, labor and automation, expansion of existing facilities or addition of new ones, and between costs incurred by airlines and by the passengers. Since the actual levels and needs of the future traffic are highly stochastic, the planning and design methodology should involve the most likely temporal distributions and spatial concentrations of airport users within the PTB, and an optimization process for utilization of resources, i.e., optimum utilization plan.

3.2 Philosophy of Optimum Utilization

The approach taken in this research was to consider the PTB as a transportation system in which resources, e.g., space, labor, equipment, are deployed to provide certain services to the users, e.g., passengers, companions. The philosophy of this thesis is to achieve early association of physical and operational plans. Based on this philosophy, the goal was to develop an optimization methodology which include some important issues such as; stochastic nature of airport demand, long term costs of over- and under-supply of PTB facilities, performance measures, and utilization of scarce resources.

The rationale for developing the optimum resource utilization philosophy is based on several factors such as:

- Airports are striving to attain maximum efficiency from existing resources. As

Reiss (1995) pointed, "the days of high-flying airport terminal projects are over". The dominant philosophy of "build it" and they will come has been replaced by a more conservative approach, "do not over build. but be prepared to change". This new philosophy of planning and design is more in agreement with the today's realities of consolidation of airlines, shared use of resources, slowed passenger growth, and high debt loads for carriers and airport operators.

- Airports are being required to become financially self-sufficient in terms of operating and capital cost. For example, under the new Canadian National Airport Policy (July 1994), all the potential subsidies for regional and local airports will be phased out over five years. Under the new policy all federally-owned, operational or subsidized airports will be commercialized. Commercialization gives community-based groups the power to introduce business discipline and run airports in a manner that reflects their economic development objectives. Once a local operator assumes the responsibility for an airport, there is greater potential to generate commercial opportunities and identify operational efficiencies, e.g., reduction in overhead costs, shared resource utilization, quick response to local commercial initiatives, etc.
- The tenuous financial conditions of other transportation modes, e.g., rail, bus, and eliminating the governmental subsidies may force these modes towards an overall integration of transportation planning, design, operation and management. The integration would encourage the shared use of resources, e.g., multi-modal terminals. The idea of modal integration would be more feasible in the era of which local authorities who are in charge of other transportation modes are going to control the operation of the airports as well (Bell, 1988).
- Application of advanced technology seems to be a necessity of today's life. This is more important if advanced technology can prevent the consumption of more

resources. As Ree (1990), has stated we have already breached the global carrying capacity in terms of resource consumption. Therefore, one has to use resources in a more efficient manner rather than consuming more resources, i.e., sustainable development. The advanced technology has already been applied to control the traffic flow, e.g., MLS in airside, IVHS in urban transportation. It also can be applied in airport PTBs to manage the existing resources in more effective way.

Based on the philosophy of optimum utilization, there should be a utilization plan associated with the most likely scenarios which can be predicted at the early stages of planning. The utilization plan would be fine tuned based on the real-time traffic data and operational policies.

3.2.1 Basic Definitions

Some of the basic terms which will be used throughout this research are defined as follows;

- **Physical plan; or space layout** involves the determination of the size, shape, and approximate location of spaces.
- **Operational plan; or space management** involves the utilization of spaces. A good degree of association between the two plans is required in order to yield an economic and efficient PTB.
- **Over-supply cost unit;** the costs associated with providing one supply unit more than is actually required.

- Under-supply cost unit; incurred costs if resources are provided one unit less than what is required.
- Traffic demand; the stochastic and variable loads of passenger and non-passenger traffic imposed on different segments of the PTB.
- Utilization of resources; the percentage of time during a 24 hour period which the facility is being used, or the percentage of resources, e.g., space being utilized.
- Optimum PTB operation; Optimum or the best was defined, in this research, as the least total extra cost. Extra cost was referred to as the sum of over- and under-supply costs.

3.3 PTB Resource Utilization Methodology

The objective of this research is to optimize the whole PTB operation in terms of minimizing its operating and maintenance cost. To optimize the PTB system, research can be done either in resources or traffic flow or both. Since the resources are to be utilized based on the traffic demand, both entities have been taken into account for system optimization. Thus, based on the concepts of resource allocation, flow management and control, and the dynamic function of the PTB, an optimization methodology is proposed.

The proposed optimization methodology, illustrated in Figure 3.1 is developed based on the premise that the decision maker, e.g., airport authority, has complete control over a real world PTB system. This premise is based on the assumption of single authority for the PTB operation which was mentioned in the scope of study. It is also assumed that the existing PTB has enough flexibility to cope with the decisions

Figure 3.1: Optimum PTB Resource Utilization Methodology

made by the decision maker.

The methodology consist of three basic parts, i.e., input, processing, and output. Input or real-time data is obtained from various sources including the curbside area, ground transportation counters, parking lots, airport or airline personnel in the field, or automated sensors installed upstream of the passenger traffic flow. Input will include the real-time demand, e.g., passenger, greeters, meeters, etc., placed upon the system as well as some physical characteristics and operational policies set for the PTB.

In the processing part, data received would be processed, i.e., the upstream collected data would be analyzed to predict the actual loads on different segments of the PTB. The optimum value of required resources to satisfy the traffic demand would be found based on the performance measures by using an optimization process. The objective function of the optimization process is to minimize the total costs associated with the allocation of resources. In another words, the required resources for the demand are found in such a way that the total cost of over- and under-supply is minimized.

One of the outputs of the methodology would be the dissemination of real-time information regarding the management and control of pedestrian traffic flow inside the PTB. A variable time-resource plan is another output which, if implemented, can provide an optimum PTB in terms of its operating and maintenance cost. The operating and maintenance cost of the PTB is calculated according to the unit cost of providing resources.

At the implementation stage some site specific techniques of flow management and control are required to allocate the resources to different segments of the PTB which perform different activities. In another words, the synthesis of optimum resource values depends on the site constraints. The site should be equipped with some tools

such as: sensors, actuators, variable sign displays, audio and video systems, remote and loop detectors, etc. Moreover, the flow management and control technique, by taking into account the stochastic nature of PTB demand, would be able to respond to some unpredicted events which may occur during the PTB operation. If the resources were allocated as they were found from the optimization process, then the output would be minimum operating and maintenance costs for the PTB at different levels of performance.

However, it was felt that the proposed methodology is difficult to apply in a real terminal for the time being. Furthermore, the traditional design concepts and operational policies do not have the flexibility required for the application of the proposed methodology. The PTB should not only be flexible but also be equipped in such a way to respond, in real time, to the events which are not pre-planned. Thus it was decided to mathematically model the proposed methodology of optimum resource utilization by using computer programming and simulation techniques. The process of converting a real world system to a mathematical or simulated model is the standard approach taken by all other branches of science. The real world sample is simulated in the laboratory and experiments or tests are performed on the simulated model. Then based on the results of the tests on the simulated model, the performance of the real system is evaluated. The mathematical approach is called the PTB Optimum Resource Utilization Model and is explained in Section 3.4.

3.4 PTB Optimum Resource Utilization Model

The PTB optimum resource utilization model is shown in Figure 3.2. As Figure 3.2 illustrates, an attempt was made to convert the real world elements of the proposed

Figure 3.2: The PTB Optimum Resource Utilization Model

optimization methodology to some mathematical and simulation submodels in which a wide range of scenarios can be analyzed. The PTB optimum resource utilization model consists of two parts: 1) analysis and 2) application. The analysis part is developed based on two submodels, i.e., simulation and optimization. The application part includes a flow management and control model. In the first step of the analysis part, the demand is obtained from the forecast, i.e., a range of nominal schedules. There may be a program to generate schedules based on historical data, market structure, growth rate, and site specific conditions. The physical layout of the PTB is simulated as a network of activities to perform as a real terminal. The historical or existing operational policies and guidelines, if any, are integrated into the simulation model. The "Object Oriented" simulation model of the PTB would run for a number of days or weeks, to provide a comprehensive list of statistics. It will also provides real-time interactive information about different segments of the PTB. The simulation model development and its evaluation are explained in Chapter 4. The main task of the simulation model is to provide inputs, in the form of a demand function, to the optimization submodel.

To develop the optimization submodel, a new approach based on the principles of resource allocation theory was taken. An attempt was made to include those variables in the optimization which the philosophy of optimum utilization was based on. Variables such as; stochastic demand, LOS, costs of over and under-supply and utilization of all PTB segments are included in the objective function of the optimization process. The optimization problem and its heuristic solution approach are explained in detail in Chapter 5. To be useful for optimization purposes, the PTB was divided into several segments and the statistics were collected for each segment during the whole running period. The population statistics were analyzed to get the Probability Mass Function (PMF) of demand for each PTB segment, assuming a discrete distri-

bution in which only integer values for the passenger flow can occur. Other statistics such as queue length, waiting time, etc. were used for performance assessment. To be as realistic as possible, each operating day was divided into short time periods, e.g., one hour, and the PMF for each time period was obtained. The PMFs and the relative values of over- and under-supply costs were used as input to the optimization submodel. Since the PTB is a people-serving facility, the level of service was also included.

The optimization submodel will output the optimum value of required resources for each segment of the terminal at each instant of time. This is called a *variable time-resource plan*. The associated costs with these resources based on the values of providing one unit of supply is also calculated. The optimum resource utilization model was tested on two different airports, i.e., McDonald Cartier International Airport (MCA) and Mirabel International Airport (MIA). The process of model testing on those two airports and the results are demonstrated in Chapter 6. In the application part, a flow management and control model was developed, based on the site constraints, to implement the results obtained from the analysis part. A generic PTB flow management and control model as one of the applications of resource utilization model in operational planning is discussed in Chapter 7. In the following sections of this chapter some other elements of the optimum resource utilization model, which unlike optimization and simulation submodels do not require extensive analysis and model development, are explained. Those elements are; demand forecasting, operational policies and guidelines, and levels of service.

3.5 Demand Estimation

Demand forecasting, shown in Box 1 of Figure 3.2, is usually the basis for any transportation facility design and operational planning. The objective of forecasting is to provide detail peak hour demand for the design day many years ahead. The level of detail depends on the sources, time and purpose of the forecast. The normal procedure is to find the global number of passengers for the target year for which a new or expanded PTB is being designed. This global number is then converted into peak or design period applying several coefficients. The global number may directly be converted to a peak hour traffic using a single coefficient (0.003 to 0.005) or it may sequentially be converted by using several coefficients. Some of these coefficients, i.e., conversion factors, are such as monthly/annual traffic, peak hour/annual traffic, daily/monthly traffic, peak period/peak day traffic, and peak day/average day traffic.

Over the years, several methods to estimate peak hour traffic were developed. These methods are mainly based on the *n-th* hour traffic volume, *n-th* percentile hourly traffic volume, or different ways to combine monthly, daily, and hourly volumes. Based on these methods, it is usually straight forward to predict future traffic levels for any airport within a stable regulatory framework. It is also possible to develop hourly traffic predictions for the design day, i.e., nominal schedule. A nominal schedule is a table listing the timing, routings, aircraft types, air carriers, and associated number of passengers of all scheduled flights forecast to use a particular airport on a particular day in the future.

A nominal schedule can be used as a point of departure for detailed facility planning and design. The information contained in a nominal schedule can be used to calculate the size and duration of peaks for determination of required resources, e.g., space,

staffing requirements. Furthermore, the approximate costs associated with providing and operating the facilities can be estimated. To develop a nominal schedule, several assumptions must be made concerning the type of aircraft involved, their origin and destination, load factors, percentage of transfer or transit, etc. Therefore, the level of accuracy of these assumptions are subject to the impact of political events, fluctuations of the economy, deregulation, privatization, etc.

Under the aforementioned circumstances, the detailed forecasts are inaccurate especially for long periods of time, e.g., fifteen to twenty years. In another sense, a forecast schedule is called nominal because it is one of the many possible schedules that can be generated, depending on the specific assumptions used and the uncertainties surrounding the assumptions. However, it is suggested in this research that a set of scenarios be generated with reasonable ranges for the traffic levels and the assumptions that effect the traffic. Instead of nominating one specific schedule for a particular day in the future, planning day, a range of traffic levels and parameters would be nominated. Then the professional effort should be concentrated in investigating the implications and effects of uncertainties, e.g., performing risk analysis.

The performance of the system can also be measured over a range of circumstances. Then a preliminary analysis can justify the ones that should be taken for further detailed analysis. Therefore, the problem with having a single scenario is relieved in some degree by having a set of most probable scenarios. However, the problem still remains with the prediction of detailed traffic on the components of the PTB. This is particularly important since the size estimation of PTB segments relies on the intensity and the magnitude of passenger traffic using the system. A simplistic method which was adopted in the detailed design, is to multiply a representative space standard by the number of potential users.

Figure 3.3: Passenger Arrival Time Before Flight Departure

Attempts have been made to find the pattern of passenger arrival to the PTB based on the flight departure time (Transportation Research Board, 1987). Even at this limited scope, no predefined mathematical function was found to properly illustrate the pattern. Graphs have been developed according to the average statistics collected at some airports. Figure 3.3 shows the cumulative distribution of arrivals at an airport before flight departure.

However, for the optimization process, the probability density function of demand at each segment of the PTB system is required. The demand is assumed to be discrete since it represents the individual number of passengers. The average demand distribution over a typical day and its variability at each instant of time is illustrated in Figure 3.4.

For example, at point A the probability density function is assumed to be an unknown distribution with mean μ . As the graph shows, it is possible to have any positive number, but the chance of having μ number of passengers is the highest. The average distribution function represents the mean of each probability distribution over a typical day. It is hardly possible to fit a mathematical equation on the

Figure 3.4: Actual and Average PTB Demand Function

highly stochastic demand. Therefore, its function may be found either through an exhaustive data collection exercise for a long period of time or using a simulation approach.

In this research, for the detailed design, the demand distribution at each instant of time is taken into account. The demand distribution, Box 4 of Figure 3.2, at each time period for each segment of PTB is calculated based on the outputs of the simulation model. The simulation would run for a number of days, or weeks and the population statistics will be collected for each segment of the PTB during the whole running period. These statistics would be analyzed to get the Probability Mass Function (PMF) of demand for each PTB segment. To be as realistic as possible, the operating day is divided into short time periods, e.g., one hour, and the PMF for each time period is obtained. For example, if time periods were chosen to be one hour, there would be 24 PMFs for one segment of the PTB.

3.6 Operational Policies and Guidelines

The existing operational policies and guidelines, Box 3 of Figure 3.2, are used to simulate the operation of a real airport PTB. As mentioned in the preceding sections, one of the problems associated with PTB design and operation is the uncertainty of the airline industry. This uncertainty sometimes causes a well-conceived design to be inefficient or inappropriate. Therefore, airport planners should favour a flexible design and more importantly prepare an operational plan for different possible scenarios. To be able to prepare an operational plan, one should have a real knowledge about the type of activities inside the PTB. PTB activities can be classified into two principal component groups as follows:

- **airport related passenger services**, these services are usually provided for the convenience of the air traveller. These services could be commercial or non-commercial. Some of the non-commercial services are: flight and general airport information, security, passenger information services, directional signs, seating, rest rooms, baggage trolleys, public phones, and post office. Some of the commercial activities are: car rental, duty-free shops, insurance, advertising, banks, and general concessions.
- **airline related passenger services**, These operations are usually handled entirely by airlines or their agents. Some of these activities are: Reservations and ticket purchase, baggage check-in and storage, baggage delivery and reclaim, and airline information services.

Moreover, there are some activities which are handled by neither airlines nor airport but the government; some of these activities are: customs, agriculture, and immigration. Although the basic operational procedures of airports as they relate to safety

are similar throughout the world, the way in which those procedures are operated can differ radically. PTB operations could be airport dominant, airline dominant, or be a mixed model. In the case of airport dominance, the airport authority itself provides the staff to run the terminal services, e.g., European airports. At the other end of the scale, airline dominance, much of the necessary operational equipment and staff are provided by airlines or concessionaires, e.g., U.S. airports.

Most airports around the world work on a mixed model, where the airport authority takes care of some terminal operations, and airlines operate other facilities. The final choice of the operational procedure depends on some factors such as: philosophy of the airport authority, financial constraints, and availability of local labour and skills. For example, commercial facilities inside the PTB may be either operated directly by the authorities or leased on a concessionary basis to other operators. Detailed information about types of services and the authority in charge of these services is not the intent of this research to explore. More information can be found in other references (Ashford et. al., 1984).

However, some basic operating policies should be clear to go along with the design concept. The judgement on the overall performance of the PTB can be made only after matching the physical design and the operational plan together and see how the PTB performs. For example, one should specify whether passenger check-in areas are designated permanently to airlines or assigned to airlines by computer on a need basis. In the latter case check-in areas are vacated by one airline and taken up by another based on departure demand. Since under this system of operation there is not any permanent presence of the airline, such a method can lead to substantial savings in space compared with the permanent presence case.

These two types of operation are applicable to other parts of the PTB as well, e.g., gates, loading bridges, baggage claim areas, etc. Another issue which should be clear in the operations plan is the commercial operation at the PTB. One may argue that commercial facilities produce unnecessary obstructions to the principal passenger processing function of terminals. While proponents of commercial facilities argue that there is a demand for such facilities generated by high volumes of passengers and it should be met. However, in the operations plan it should be clear how much commercial facility is required and who is going to operate those facilities. Moreover, the type of operations that should be handled entirely by airlines should be determined. In more detail, the staff allocation procedure among the service locations should be determined, e.g., the staff allocation would be variable based on demand change or would be constant throughout the day. This will affect not only the operational performance but the economic performance as well.

However, being involved in the afore-mentioned types of issues is not in the scope of this research. This study assumes that the general operational policies to run the PTB are given. It assumes that those issues have already been resolved among major interest groups. The guidelines given by the airport authority will be applied in the simulation and optimization process.

4.7 Performance and Service Measures

The performance of a facility is defined as the ability to carry out a task or fulfill some promise. In a PTB, this ability generally refers to moving passengers and their luggage from ground transportation to aircraft and vice versa. The assessment of this movement depends mostly on the parties involved with PTB operations such as;

users (passengers), airlines, operators, and employees. It is the interaction of these groups as well as other minor parties that keeps the PTB running to provide efficient, convenient, and safe transfer of air passengers and their baggage between ground and air transportation modes. Although the presence of these groups is essential to the PTB operation, they may assess performance and service in terms of their own factors. Moreover, each interest group, e.g., passengers, may be a mixed group and have a variety of ideas about performance and service levels. It is also possible that the concerns of one interest group about the performance be in conflict with another interest group. For example, some passengers' measures of performance may be viewed as constraining passenger flows by operators or airlines.

Therefore, the comprehensive term of performance is not limited only to the direct users of the PTB. A variety of interest groups such as: airlines, airport operators, passengers, visitors, businesses operating at the PTB, employees of the various activities, governments and the community at large have concern over the airport operation. They may have their own view and their own meaning of performance. It would be ideal to have a set of performance measures or develop a methodology so flexible to reflect the needs of all these varied and sometimes conflicting groups (the term performance and service is used interchangeably). As an example, among those groups, the viewpoints of the three major groups, i.e., passengers, airlines, and operators, about the PTB performance and service measures are summarized in Tables 3.1 to 3.3 (Lemer, 1990).

The factors of performance in each table includes all the spatial, operational, and economic measures which are important to the users of the PTB. As shown in these tables, each of these three interest groups have certain unique interest and others that overlap with those of the other groups. Some of these factors are impossible to quantify, or hardly possible to qualify. Moreover, a great deal of subjective judgement

<i>Performance Measures</i>	<i>Index of Measurement</i>
Compactness	curb-to-gate distance curb-to-gate time difficulty(level changes, choice points, etc.)
Delay	Service times waiting times wait variation
Comfort and convenience	crowding noise levels temperature, humidity levels visual interest choice of actions encourages sociability
Service reliability	service level variation required time before departure connecting time flight alternatives
Visibility	signing or sight-lines spatial logic directness or circuitry
Cost	departure fees food and drink connection fees other concession prices

Table 3.1: Performance from passengers' point of view

Source: Modified From Lemer, 1990

<i>Performance Measures</i>	<i>Index of Measurement</i>
Operational effectiveness	passengers served per unit time people accommodated per unit time passenger service levels over time baggage handled per unit time baggage service reliability over time flight ground delays
efficiency	gate utilization space utilization labor utilization
Flexibility and Expandability	operational(new airline services) architectural(space for new passenger demands)
Functionality	reliability maintainability
Finances	revenue yield operations, maintenance expenses debt coverage
Risk	security effectiveness life safety, public health crime(theft, smuggling)

Table 3.2: Performance from operator's point of view

Source: Modified From Lerner, 1990

<i>Performance Measures</i>	<i>Index of Measurement</i>
Operational effectiveness	aircraft turnaround, flight service time baggage transfer reliability passenger service times
Station cost	terminal fees labor fees equipment costs inventory costs
Corporate image	control of space, design maintenance of service levels market share
Flexibility	operational(new services, aircraft) architectural(image and passenger accommodation)

Table 3.3: Performance from airlines' point of view

Source: Modified From Lemer, 1990

or a good understanding of user attitudes is needed to identify the most appropriate set of factors from these tables that can be used to evaluate the performance of a given PTB. However, the large scale of investment in PTBs and public concern for the impact of these investments, forced airport professionals to develop a level of service framework. The levels of service concept, Box 5 of Figure 3.2, is explained in more detail in Section 3.7.1.

3.7.1 Levels Of Service Framework

Although it would be very useful to consider all the user's point of view to develop a basic understanding of performance, it is planners, engineers, and managers whose decisions determine the level of performance users are likely to experience. These are the decision makers who allocate the space, provide the staff, and determine the way that the PTB should be used by users. Such decisions in turn influence both the operations and the cost of the PTB. The currently accepted PTB evaluation criteria are based primarily on the classical theories of pedestrian movement that evolved from studies related to commuter rail and bus stations.

The Level Of Service (LOS) concept based on Fruin's (1971) idea underlies the existing techniques. Fruin attempted to apply the LOS methodology, developed in the area of highway capacity analysis, to the design of pedestrian spaces. In that work, he stated that in addition to traffic engineering principles, human convenience should be taken into consideration. Fruin showed that although the maximum capacity of pedestrian traffic streams can be attained when there is dense crowding of pedestrians, such crowding results in significant reduction in pedestrian comfort and convenience. This led him to define pedestrian LOS standards in terms of space per person (module).

Success with the use of the LOS concept for vehicle and pedestrian facilities granted considerable interest in the application of somewhat similar methodology to airport facilities. In the past two decades the most comprehensive approach was suggested by Transport Canada in (1977). They adopted a LOS framework used for the design of highways, from A, the best, through F, the worst. This approach was subsequently proposed by IATA (1989) as a method of determining airport PTB service levels. Both approaches rely on setting different levels of space provision with respect to the six LOS, A to F. Similarly Davis and Braaksma (1987) proposed LOS standards for platoon conditions at PTB arrival corridors. Others recommended using a LOS framework similar to that used in highway capacity assessment, but composed of three (good, tolerable, bad) rather than six levels (Mumayiz, and Ashford, 1986). They argue that it is relatively difficult for passengers to distinguish clearly among more than three levels and identify these levels with the values of service measures used.

Although each agency/authority responsible for the planning and design of PTBs has established its own space standards, the concept of LOS underlying these standards has essentially originated from the pioneering work on pedestrian movement almost two decades ago. The general agreement among all these developed standards is that the quality of service was assessed in terms of space provision per occupant. This idea, LOS standards based on space, was accepted among airport researchers and is used in the airport industry.

The space-based concept of LOS was criticized recently due to its deficiency to consider the pedestrian's perception (Ashford, 1988; Seneviratne, 1994). In this respect, researchers believed that the quality of service should be assessed in terms of factors other than only space. These should be parameters representing the overall quality of the transfer between transportation modes experienced by the passengers. These parameters are dependent on numerous basic quantitative factors such as walking

distance, waiting time, availability of space, and cost; and qualitative factors such as information system, simplicity of procedures, safety, comfort and convenience, etc. Although it would be very useful to consider all those factors summarized in Tables 3.1 to 3.3, it seems more ideal than practical. This is due to the fact that first, the interest and objectives of each party are not identical, second, some of these factors are impossible to quantify or hardly possible to qualify, third, a great deal of subjective judgement would be involved in the quality of service assessment, and fourth, statistics on some of these measures are not available and it is hardly possible to obtain a comprehensive and sufficiently rich set of statistics to reflect all aspects of the PTB performance. Efforts to characterize the performance of a PTB in a way to take all the views into consideration, are hampered by the lack of data.

However, decision makers responsible for planning, design or operation of a PTB need some tools to assist them to get the best possible performance from the terminal. Operators should be able to determine when new operating procedures or facilities may be needed to deal with problems, and to choose the best procedure or facility. Moreover, performance and service measures must be scaled to permit judgmental comparison of conditions in the terminal. From a planning and design perspective, there is a logical appeal to a reasonably wide gradation of conditions which can provide designers with sufficient flexibility. Airport authorities, mainly governments, in some countries have established limited absolute measures of performance for controlling crowding and delay. For example, the FAA's Advisory Circular 5360 (1988), Transport Canada's interim level of service standards (1977), and IATA's Airport Reference Manual (1995) are among those which have been widely used by planners and designers. These documents are mostly like building codes and structural design standards in which there are some standards to judge acceptable walking distance or space availability.

It should be mentioned that not one set of specific measures may be equally useful for describing performance at all airports. This is due to the variety of airport characteristics and versatility of community concerns that provide the content within which decisions about PTB performance are made. However, in this research, the LOS concept is involved in the PTB utilization procedure in terms of two variables. First, a variable (θ) is considered as the amount of resource required for each demand unit at each LOS. For example, the amount of space required per occupant at LOS A in the baggage claim area. The total expected over- and under-supply cost is calculated based on the values given to this variable. The operating and maintenance cost also can be calculated at each LOS target. It is clear that variable θ can include only the quantifiable attributes of LOS, e.g., space required per occupant at each LOS. Second, the under-supply cost unit variable (β), which is the impact of providing resources, to the user, less than what is required. This variable will include the passengers' reflection to the shortage of resources. Although it is extremely difficult to provide the absolute value of variable β , its relative value to the cost of providing services beyond what is required is not difficult to estimate.

For practical applications the under supply cost can be defined in terms of monetary value of perceived disutility of users, i.e., waiting time, congestion, etc. There has been some attempts to put a value on some of these items such as walking distance, waiting time (Shirazi, 1992). In those studies, users of the facility were asked, through a questionnaire, the amount of money that they willing to pay if discomfort of waiting time or walking distance is removed. The amount of money then was defined as the user cost attributed to perceived dis-utility of spent time and/or walking distance. This money is user cost/person corresponding to a certain level of service. A regression analysis can be done between the amount of money and the level of service indicated by the user. This approach, although very subjective, can be used to find

the subjective value of under-supply cost. An attempt has been made, in this study, to include both efficiency and human values in the optimization procedure. These two objectives, i.e., efficient utilization and LOS are not necessarily incompatible. Before going to the process of optimization model development, the simulation model as an input provider of the optimization model is explained in Chapter 4.

Chapter 4

Simulation Model Development

4.1 Overview

One of the major elements of the optimum resource utilization model, developed in Section 3.4, was the simulation model of the PTB, shown in Box 2 of Figure 3.2. This chapter presents the analysis and development of an object oriented simulation model. In this research, a simulation model is considered as the laboratory version of the system on which experiments can be performed as a first step to design, analysis, and performance assessment of the real world system. Outputs can be obtained and inferences can be drawn about the real system without the need to actually physically build, disturb, or destroy the system. One of the outputs of interest is the real time demand function for each segment of the PTB which is used in the development of the optimization submodel.

A comprehensive research was undertaken on the existing airport PTB simulation models to see whether they can be used in the resource utilization model. A wide

range of simulation models was found in the literature for the analysis of passenger flows in one segment of the the PTB or as a whole. None of the existing models has had wide utilization. Many factors can be credited for the failure of these models to be widely used and to be easily accessible. Some of the most important factors can be pointed as; lack of interaction with the user, complexity, lack of flexibility, and costs. These models were not accessible to the public. Even if they could be obtained, some modifications were required to satisfy the requirements of the resource utilization model. Therefore, it was decided to design a new model aimed for simplicity, speed, interactive, object oriented, and ease of use without compromising accurate representation of PTB facilities. Before going to the procedures of the simulation model development, a brief review of the existing simulation models is given.

4.2 Simulation Models

Airport terminal simulation models have been used for more than 25 years. The first attempt to analyze the airport PTB by developing analytical models can be traced back to the late 1960s' when deterministic queueing was utilized to model individual components of the PTB, e.g., baggage claim, hold room, etc. (Mumayiz, 1990). During 1970's and 1980's many researchers from universities, industry, and government studied the subject. For example, the FAA's Airport Landside Simulation Model, ALSIM, and Transport Canada's airport simulation package are among the most widely used and publicly available simulation models. ALSIM is macroscopic, discrete event simulation model capable of producing flow parameters and statistics of simulated facilities. ALSIM was originally developed by Betchel Corporation and subsequently acquired, enhanced and modified by the Transportation Systems Center of the U.S. Department of Transportation (McCabe and Gorstein, 1982) Four

different languages were used to design ALSIM. The operating system commands are executed with the use of JCL, i.e., Job Control Language, the main simulation environment is designed in GPSS-V, all I/O, data and report formatting are conducted in FORTRAN. The IBM/370 assembly language was used to tie together all the components as a single module. The operation system on IBM/370 is a batch processing type which requires the program, input data, and appropriate system commands to be submitted together as a single job. There is no interaction between the users and executing programs. Moreover, ALSIM requires an extensive set of input data as shown in Table 4.1. The input data is grouped into four categories, i.e., flight schedule, passenger characteristics, airport geometry, and facility information. Input data is supplied to the simulation environment before the execution of the simulation process.

The model creates transactions representing passengers and visitors going through a set of PTB facilities such as; gates, customs, immigration, ticketing, baggage claim, etc. There are no provisions for intervening activity modelling. The output of the model is a report which includes passenger and processing facility statistics, i.e., flow at servers, average waiting time, queue length, and average utilization of servers.

Another well-known simulation model is Transport Canada's airport simulation package consists of three separate models that run on an IBM-AT or compatible microprocessor (Transport Canada, 1980). These three models are gate assignment model, air terminal passenger flow model, and ground transportation model. Each of these individual models has front, middle, and end segments. Front and end segments programmed in BASIC/PASCAL, and middle segment programmed in FORTRAN IV.

The air terminal passenger flow model consists of three interrelated modules, i.e.,

1. Flight Schedule	Flight number Airline, Aircraft type, Flight load Arrival/departure time Flight type (domestic, international or commuter) Transferring passengers Baggage claim facility identification number
2. Passenger Characteristics	Percentage preticketed Percentage using express check-in Passenger routing in landside Ground transportation modal choice Passenger group size Well-wisher per group Originating passenger arrival time distribution Arrival distribution of greeters Arrival distribution of vehicles meeting passengers Car rental agency selection distribution Percentage of well-wishers or greeters proceeding to gate Percentage of greeters proceeding inside terminal
3. Airport Geometry	Point number, X - Y coordinates Number of bags distribution Facility type at point Facility number within type
4. Facility Information	Service time distribution Car/taxi loading and unloading times Number of servers or size of facility Baggage transport time from aircraft to claim area

Table 4.1: Input Data Required by ALSIM, Source: McCabe and Gorstein, 1982

input module, the simulator, and the report generator. The input file consists of two files, i.e., an airport file and a flight schedule file. The airport file includes twenty two worksheets representing the processing features and the use of PTB components. The schedule data file consists of all relevant information about airline flight schedule. The simulator performs a Monte Carlo simulation of enplaning and deplaning passengers movements through the terminal complex based upon user assigned paths, the processing rate distributions, and transit times. The report generator module outputs a range of statistical measures such as: number of users entered/exited, baggage device assignment, queuing, and delays. The terminal flow model operates on IBM compatible micro-computers, running under DOS and requires less than 640 kilobytes of RAM (Transport Canada, 1991)

A number of other discrete event simulation models have been developed by universities, government agencies, and private sectors. In all of the previously developed simulation models, the conventional general purpose languages, e.g., FORTRAN, BASIC, or simulation languages, e.g., GPSS, SLAM were used. Some of the simulation languages used are GPSS (Cheng and Gilmour, 1978), SLAM (Mumayiz and Ashford, 1986), or GASP (Olsen, 1973).

Research on PTB modelling was carried out in other parts of the world such as England (Ashford, O'leary and McGinty, 1976; Ashford et al., 1976; Mumayiz, 1985; Mumayiz and Ashford, 1986), Australia, (Cheng and Gilmour, 1978) Denmark (Bastiansen, Hviid and Matthiesen, 1980), and in Yugoslavia (Jovanovic, Jelaska and Janic, 1984), etc. Moreover, many airport planning firms have developed special purpose PTB simulation model for their own use (Mumayiz, 1990). More detailed information about types, features, and properties of the other simulation models can be found in other references mentioned in the simulation section of the Bibliography.

Through the literature review on existing and currently used simulation models, it was found that models available at the present time do not respond to the types of issues associated with the PTB operation and management. In summary, they require extensive programming to fit with any specific configuration of a terminal, take a long time to process any particular run, and require much detailed information for every run. None of these models has any provisions for interaction with the user, i.e., batch jobs are submitted to the computer and the output comes in the form of a print-out. A long time is required to set up the model and analyze the output in the case of changing some input variables. As reported by Geddes (1990), who pointed out that almost four months were required to set up the passenger terminal flow model of Transport Canada to analyze only one area of the Vancouver terminal. Moreover, ALSIM final report contains a section on input data preparation which discusses the cost and implications of the data collection and assesses of a typical data collection and preparation at a PTB in the range of \$ U.S. 40,000 to \$ U.S. 50,000 in 1982 values (McCabe and Gorstein, 1982).

An additional problem with simulating the PTB is that the PTB operation and management problems cannot be strictly formulated as is required by currently used simulation models. This means that the simulation should run based on the pre-defined input data file and generate an output file and any change in the data would require re-run of the model. While in a real life, the changes would occur during the PTB operation. It requires a model in which the changes in the input data can be made during run time. These types of problems can be avoided by using the object oriented programming.

4.3 Object Oriented Approach

Recently due to the aforementioned problems mentioned in Section 1.2 and new development in software technology, there has been a lot of interest to use Object Oriented Programming (OOP) in PTB simulation (McKelvey, 1989, Odoni, and deNeufville, 1990, Mumayiz, 1991). The Object-Oriented approach has some advantages over conventional languages used in simulation. In summary the OOP approach is capable of providing immense programming flexibility, greater reduction of input requirements, easier to operate, and is user friendly (Smith, 1991). OOP also provides fully interactive execution with a high degree of animation/graphics capabilities. An object oriented PTB simulation program is one in which the objects are physical facilities that compromise an airport terminal system. Instead of going through the sequential programming, the system can be defined by choosing the various objects to be studied. After choosing the objects, the behaviour of each object is defined by input data. Then the user can specify the output data required for each object forming the network. Once this is done, the program performs the simulation and outputs the results.

Simulation models based on the OOP concept have several advantages over conventional ones which include the ability to pass information from one object to another, the ability to redefine networks, and the ability to share modelling and programming techniques across many objects whose behaviour is similar. The models can be very user friendly through the use of graphical displays to allow the user to choose and link processors to form the study network and through the use of on-screen dialogue with the user to interactively generate the necessary information and desired outputs. In spite of all of its advantages and interest in the airport industry, a PTB simulation model using OOP is not available yet. Moreover, an object oriented simulation tool

specifically developed to simulate transportation facilities could not be found. The only exception to this was TRANSIM, the newly developed computer program by Merisson Hershfield (1993).

Firstly, it was decided to explore the use of TRANSIM for PTB simulation. TRANSIM is based on the concepts of OOP and is used to simulate the transportation systems. Models can be created by using abstract objects which represents the various components of a transportation system. To build a model TRANSIM makes use of three programs; Builder, Preproc, and Transim. The basic layout of the model is built by using the "Builder", "Preproc" is just a data base program, and "Transim" runs the simulation. The results of the simulation are saved in a file which is readable by any spreadsheet program. At the time of model development, the TRANSIM was still under development. After research on the TRANSIM it was found that the program was developed towards specific projects and it should be modified to be used for PTB simulation. Application of TRANSIM for PTB simulation was prevented by the magnitude of resources required for its modification. After months of investigating TRANSIM, it was decided to pursue other avenues, e.g., object oriented simulation languages in other branches of engineering.

A search was undertaken in the area of systems and computer engineering to find the most recent and state of the art object oriented simulation tool. A new object oriented graphical modeling environment, *SES/workbench*, from Scientific and Engineering Software Inc. was investigated for simulating the PTB operation (SES, Reference manual, 1992). *SES/workbench* is an integrated collection of software tools for simulation and evaluation of complex systems such as: large software systems, data communication networks, and microprocessors. Although *SES/workbench* was mainly used in systems and computer engineering, its use in the transportation engineering as a state of the art in simulation languages was appeared to be very

attractive. It has several advantages over other simulation languages, e.g., GPSS, SLAM, such as: object oriented, user friendly, interactive, graphical illustration, animation, and ease in application. SES/workbench consists primarily of SES/design, SES/sim, and SES/scope. The graphical representation of the system is built by using the design interface module, "SES/design", in which objects are created to represent the various components of the system. The graphical representation is converted to an executable simulation model by "SES/sim", a translation and simulation module based on the C and C++ programming languages. Finally "SES/scope" is an animation module that provides the ability to observe and debug an executing simulation model.

SES/workbench is founded on the premise that complex systems cannot be effectively designed and evaluated by traditional methods. It also provides a variety of features, including object oriented programming, parallel programming, hierarchical model specification, and modular specification and compilation (SES Reference Manual, 1992). Designers and analysts of the PTB usually think about the system in terms of pictures: graphs, block diagrams, flow charts, and so on. SES/workbench allows the modeler to specify his/her design in the way he/she thinks about the system pictorially. Non-visual designs can rapidly become unmanageable as the complexity of a system grows. In addition to the built-in functions, SES/workbench is extensible, i.e., programmable. One can specify arbitrary C or C++ declarations, expressions, statements, and functions almost anywhere in the model, thereby extending the expressiveness of the system. After many months of investigating SES/workbench, it was decided that it was the best simulation tool available for this research.

In summary, an SES/workbench model is composed of one or more submodels, each represented by an extended directed graph. The basic components of a graph are nodes, arcs, transactions, and resources. Transactions are entities that flow from

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node to node along the arcs, e.g., passengers going through different segments of the PTB. Each transaction represents a process to be executed. Each transaction may carry with it an arbitrary user-defined data structure. Each node in a model represents the manipulation, e.g., allocation, or release of a physical or logical resource or some other processing step in a transaction's life. In a PTB model, a node might represent the ticket counter area, baggage claim area, holdroom, corridor, gate, etc. SES/workbench provides twenty-four built-in node types, each of which represent a different node icon, as shown in Figure 4.1. A simplified description of each node type is given in Table 4.2.

Each arc connects two nodes and is directed from one node to the other. It represents a path along which a transaction may flow from one node to another, e.g., PTB corridors. Each resource represents some physical or logical component for which transactions compete. In a PTB, a resource node might represent a baggage claim device, a server, processing space, etc. Each node, arc, and resource has a form attached to it specifying its characteristics. Normally, these forms are invisible, and one may display them by clicking the mouse on the corresponding object, as shown in Figure 4.2. The user can draw the graphs by using arcs and nodes, and fill out the forms to build his/her own model. The user may attach arbitrary C declarations and statements to any node in a graph. these statements will be executed by transactions passing through that node. Moreover, SES/workbench provides comprehensive support for building models as a collection of separately developed and compiled modules.

Figure 4.1: SES/workbench Built-in Node Icons

Node	Description
<i>service</i>	queuing for a processor
<i>delay</i>	pure time delay
<i>resource</i>	pool of passive resources
<i>allocate</i>	allocate zero or more resources
<i>release</i>	release zero or more resources
<i>create</i>	create zero or more resources
<i>destroy</i>	destroy zero or more resources
<i>block</i>	block on an arbitrary condition
<i>set</i>	adjust a node's characteristics.e.g. change a nodes' speed
<i>source</i>	create transactions periodically
<i>sink</i>	destroy transactions
<i>fork</i>	spawn children transactions
<i>join</i>	join children together with parent
<i>split</i>	split off transactions without need for joining
<i>loop</i>	loop through a portion of a graph
<i>branch</i>	a do nothing node
<i>interrupt</i>	interrupt other transactions
<i>resume</i>	resume processing after an interrupt
<i>enter</i>	enter a submodel
<i>call</i>	call one or more submodels
<i>reference</i>	reference, i.e., call, a submodel
<i>return</i>	return to calling submodel
<i>user</i>	user defined declarations and statements
<i>declaration</i>	variable and parameter declarations

Table 4.2: Description of SES/workbench Nodes, SES Reference Manual, 1992

Figure 4.2: Detailed Representation of a Typical Node Structure

4.3.1 Model Development Procedure

The PTB simulation model, PTBSIM, is designed to predict the movement of passengers, greeters, and well wishers for a given terminal design and a candidate commercial aircraft schedule. Throughout the model development every attempt was made to keep the model as simple and user friendly as possible. Although the model is developed based on a given terminal design, it is very easy to adjust the model for any type of PTB due to its object oriented aspect. One can easily change, delete, copy any node, arc, or sub-model to get the desired design.

The only required input to the model is an aircraft schedule which can be entered using any text editor. The aircraft schedule is used to generate passengers and non passengers entering the PTB. The operating day is divided into equal time increments, e.g., one minute long. It should be noted that the size of increments can be any value, e.g., from milliseconds to hours.

The PTBSIM was developed as one main module, consists of six submodels: *generate_planes*, *generate_arrive_pax*, *generate_depart_pax*, *process_arrive_pax*, *process_depart_pax*, and *concourse*. The main module and its six submodels are graphically illustrated in Appendix A. In addition, several functions, in C programming language, are developed to define the workload and transaction routing. These functions and some parameters are declared in the three declaration nodes. A brief description of declaration nodes and submodels is as follows:

In the main declaration node, two data structures are declared as PLANE and PASSENGER. These two structures consist of a collection of variables (information) which each plane or passenger should carry throughout the model. For example, each member of structure PLANE contains information such as; flight number, flight sector,

arrival/departure time, flight capacity, load factor, and gate used. This information comes from the aircraft schedule. Each member of the PASSENGER structure will receive that information from the associated member of the PLANE structure. In another words, the passengers are recognized based on their own flight information, e.g., flight number. The structures are declared unshared meaning that each passenger will preserve his/her own copy of data including flight number, gate, arrival/departure time, while passing through different sections of the PTB.

The function `load_data` reads the airport schedule from an input file and calculates the event time of the planes. The event time is the time when the passengers of each aircraft start to enter the PTB. The event time for arrivals is the arrival time of the aircraft at the gate. For departures, the event time is based on the arrival time of enplaning passengers at the airport before flight departure. Based on the historical and observed data, the lead time was assumed to be 60-90 minutes for domestic and 120-180 minutes for international departures. Depending on the aircraft size, the calculated event time is an extra piece of information that each member of the structure PLANE would contain. The planes are then sorted into an increasing order according to their event time.

In summary, the `load_data` function is somewhat a pre-processor which reads the aircraft schedule, checks for any error and arranges the schedule based on the event-time of airplanes. In the `param_declaration` node, several variables are declared as parameters for future use to parameterize the model. Some variables may be declared as run-time or compile-time parameters. In the case of run-time parameters, the modeler can interactively change the values of variables while the model is running and observe the consequences. In the `function_decs` node, two general purpose functions, i.e., `sort` and `carrier_comp` have been declared. The `sort` function sorts any given set of values and the `carrier_comp` function compares the flight number strings, e.g.,

USA1235, and routes passengers to their own carrier for service.

The *generate_planes* submodel is the plane-load generator submodel. A transaction, "seed" is generated and opens the load-data function from the main declaration node. The seed transaction reads each line of the sorted data file and generates another transaction called "plane" by the split node. The plane transaction is routed to either *generate_arrive_pax* or *generate_depart_pax* according to its sector, i.e., arrival or departure. After all the plane transactions are generated and routed to their own section through a loop, the seed transaction is destroyed in a sink node. The walking times from gates to the first processing facility of the PTB, based on the average pedestrian walking speed are also calculated. It should be noted that all of these events happen in a simulation time zero, i.e., there is no time elapsed for the initialization process.

The *generate_arrive_pax* submodel generates arriving passengers. The plane transaction enters the submodel and waits in the delay node for its event time. When the transaction reaches its event time, it moves to the user node *gen_arrive_dist_function* and generates an array of passengers through a user defined function. In this function the number of passengers each aircraft generates is equal to the capacity of the plane times its load factor. The number of passengers are then distributed in one minute time increments according to a user defined average aircraft dis-embarking rate or exit-rate from historical data. The accumulated number of passengers generated for each increment is compared with the total number of passengers. Once the array of passenger transactions are generated, the plane transaction send them to the submodel *process_arrive_pax* by looping through the split node. Since the movement of aircraft is not in the scope of this research, the plane transaction goes to the sink node to be destroyed after it unloads all its passengers.

The submodel *generate_depart_pax* generates the enplaning passengers and sends them for processing. The plane transaction enters the submodel and wait for its event time. Upon reaching its event time, the plane transaction leaves the delay node and performs the methods defined in the user defined node *gen_dept_dist_function*. After analyzing some historical as well as observed data, it was found that the flow of passengers to the PTB is a function of time before departure. Several distributions were tested on the collected data and the triangular distribution was found to be the best fit. The distribution is defined as follows:

$$f(t) = \begin{cases} \frac{2(t-first)}{(mode-first)(last-first)} & first \leq t \leq mode \\ \frac{2(last-t)}{(last-mode)(last-first)} & mode < t \leq last \\ 0.0 & \text{otherwise} \end{cases} \quad (4.1)$$

where,

$f(t)$ = percentage of passengers generated at each time increment,

t = time before flight departure,

$first$ = time when the first passenger arrives at the PTB,

$last$ = time when the last passenger arrives at the PTB, and

$mode$ = time when the maximum number of passengers arrive at the PTB.

In the above-mentioned equation (4.1), $first$ and $last$ are defined based on the flight section, i.e., domestic, international, etc. The $mode$ was calibrated based on historical data and its value was found to be as:

$$mode = first + \sigma(last - first) \quad (4.2)$$

The value of variable σ is based on the type of the flight, e.g., scheduled, charter, long or short haul, etc. Table 4.3 contains the data collected by Transport Canada Airport Planning Division of Toronto at Pearson International airport.

The numbers in the table represent the percentage of passenger arrivals in various time intervals. As shown in the table, passenger and greeter arrival distributions vary between the flight sector and time of the day. Therefore, the value of σ may be calibrated based on the flight sector, e.g., domestic, international, or time of the day, etc. Figure 4.3 illustrates the distribution of passenger arrivals at the airport as a function of time before flight departure.

The arrival times of passengers are generated from the triangular probability distribution. Each passenger has his/her own arrival time. The passengers generated are accumulated and compared with the total number of passengers to make sure that all passengers are generated. Then the passengers are sorted according to their arrival time at the airport. The plane transaction then leaves the user node and enters a loop in which it sends the passengers to the submodel *process_depart_pax* through a split node. The passengers are sent according to their arrival time at the airport. The plane transaction finally leaves the loop and vanishes in the sink node.

The submodel *process_arrive_pax* deals with deplaning passengers. Passengers unloaded from the plane go to the submodel *concourse*, to be explained later. Passengers coming out of the submodel *concourse* will be routed according to their section, i.e., domestic, international, etc. Upon arrival of domestic passengers to the baggage claim area meters will be generated according to the following Poisson distribution.

$$f(m) = \begin{cases} \frac{e^{-\lambda} \lambda^m}{m!} & m = 0, 1, 2, 3, \dots \\ 0.0 & \text{Otherwise} \end{cases} \quad (4.3)$$

Flight sector	Period	Time before flight departure (min)			
	of day	0-45	45-120	120-180	More than 180
Domestic sectors					
Short-haul	A.M.	23.81	66.67	9.52	0.00
	P.M.	3.42	52.14	27.35	17.39
Rapid Air	A.M.	63.89	30.56	5.56	0.00
	P.M.	20.21	51.06	7.45	21.28
Long-haul	A.M.	49.12	43.86	7.02	0.00
	P.M.	10.90	51.66	18.48	18.96
Transborder sectors					
Short-haul	A.M.	25.66	66.37	6.19	1.77
	P.M.	9.59	67.81	13.70	8.90
Holiday	A.M.	6.06	93.94	0.00	0.00
	P.M.	3.57	64.29	14.29	17.86
Long-haul	A.M.	40.00	60.00	0.00	0.00
	P.M.	8.7	56.52	19.57	15.22
International sectors					
Britain	P.M.	0.00	60.00	8.0	32.00
Europe	P.M.	0.72	65.47	22.30	11.51
Others	P.M.	0.00	45.83	53.33	0.83
Charter sectors					
Domestic	A.M.	5.56	82.22	12.22	0.00
Transborder	A.M.	0.96	84.03	15.02	0.00
Others	A.M.	1.19	85.71	7.14	5.95

Table 4.3: Percentage of Passenger Arrivals At Terminal One, PIA

Source: Modified From Setti, 1990

Figure 4.3: Triangular Illustration of Passenger Arrival Before Flight Departure

where,

m = number of meeters/greeters associated with each passenger,

ω = average number of meeters/greeters with each passenger, and

$f(m)$ = the probability of having m number of meeters or greeters.

Previous analysis on the collected data showed that the meeter/passenger ratio (mean in Poisson distribution) varies based on the flight sector and period of the day (Setti, 1990). Figure 4.4 and 4.5 show the result of recent survey on meeter and greeter ratios at MCA. The survey was carried out in two different days, one at the deplaning section for meeter and one at the enplaning section for greeter. The number of people accompanying the passenger, i.e., meeter or greeter, were recorded. Analysis on the sample of collected data showed that a Poisson distribution can represent both meeter and greeter distribution functions with two different means (mean = 1.1 for greeter and mean = 0.9 for meeter). To be able to visually compare the survey results with the predicted values, probabilities from Poisson distribution were multiplied by the total sample size.

Figure 1.1: Observed and Predicted Number of Meeters at MCA

Figure 1.5: Observed and Predicted Number of greeters at MCA

Then passengers as well as meeters proceed to the baggage claim area to pick up their luggage. Passengers in the baggage claim area experience a delay equal to the sum of waiting time for bags to arrive after flight arrival and queuing time to retrieve their baggage. A percentage of passengers who do not have luggage may bypass the baggage claim area and go directly to the arrival lobby. Passengers and meeters then proceed to the dom_arrival_lobby node where they experience a delay in preparation time to leave the PTB.

International passengers should pass through the Primary Inspection Lines, PIL, which is represented by a service node. A service node is a single queue, multi server, first in first out system. Upon passing the PIL process, a fraction of passengers who do not have any luggage to pick up may go directly to the arrival lobby. Those who have baggage go through to the baggage claim processing area. After claiming their baggage, a percentage of passengers who have something to declare go to the custom inspection node. Some international passengers may need to go through immigration before going to the customs area.

Table 4.4 summarizes typical service times observed at various processors at the deplaning section of the PTB. As shown in the table, a wide range of discrepancies exist between service time of processors of the same type. Several factors can be attributed for the wide range of service times such as: flight sector, airline, equipment type, passenger type, etc. For example, the average service time at PIL were found to be 15 seconds for passengers arriving in Transborder short haul flights and 25 seconds for those arriving in transborder long-haul (Transport Canada, 1985). Passengers arriving in flights classified as holiday sector had an average service time of 30 seconds at the PIL. The service time for international flights, at PIL, ranged from 40 to 60 seconds. It was also observed that passengers arriving in international flights operated by foreign carriers had longer average service times than those arriving in

flights operated by Canadian carriers. Previous studies show that the service time of processors can be drawn from the following negative exponential distribution.

$$f(z) = \begin{cases} \frac{e^{-z/\nu}}{\nu} & z > 0 \\ 0.0 & \text{Otherwise} \end{cases} \quad (4.4)$$

where,

z = service time associated with each passenger.

ν = average service time of passengers, and

$f(z)$ = the probability of having z units of service time.

Passengers then proceed to the arrival lobby where they meet the meeters. After spending a preparation delay time, passengers and the meeters leave the PTB. To account for the variabilities involved in the number of servers in each service node over time, a "set" node is introduced to this submodel. The set node, called, *staff_manager*, allows the user to define the number of personnel that may be present at each instant of time for each service node. In another words, the user can set the power of service nodes to any real number in the set node. For example, if the power of service node PHL is changed from 1.0 to 0.5, it means either the number of servers has been reduced to half or the service time of the node has been doubled. One may have a predefined schedule for staff management throughout the day.

The *process_depart_pax* submodel models the behaviour of enplaning passengers and greeters. Departure passenger transactions are accompanied with the greeters. Greeters are generated by a split node from a Poisson probability function. Almost all the passengers and greeters go through the ticket lobby in which they experience the delay

Processor	Processing Rate	Source
Disembarking Rate	25-29 pax/min/door	TC Doc AK-62-10-000
Primary Inspection	65-100 pax/hour/processor 1.32 pax/min, Edmonton 1.33 pax/min, Vancouver(TB) 1.45 pax/min, Vancouver(Int)	TC Doc AK-62-10-000 TC Doc AK-14-06-008
Baggage Claim	4.6 pax/min, Edmonton 9.2 pax/min, Thunder Bay	TC Doc AK-14-06-008 CASE, Thunder Bay
Baggage Device	26-30 bags/min	IATA, Airport Terminals Reference Manual
First Bag at Claim Device	5-7 minutes from time pax enter baggage claim area	TC Doc AK-62-10-000
Secondary Immigration	8-12 pax/hour	Doc AK-62-10-000
Secondary Customs	12-18 pax/hour	Doc AK-62-10-000
Loading at Curb (Dwell Time)	2-4 min, Automobile 1-3 min, Taxi 2-5 min, Limousine 5-10 min, Bus	TRB Special Report 215
Walk speeds	1.0-1.3 m/s	TRB Special Report 215

Table 4.4: Processing Rates for Deplaning Processors of the PTB

time equal to the walking distance over the walking speed. A percentage of passengers pre-ticketed go to the express check-in. About 80 percent of passengers go to the ticket counters which are represented by service nodes. Each major airline and its allied carriers is represented by a service node with some number of servers. Passengers are directed to the service nodes according to their flight number. The first three letter of their flight number is checked to route them to their designated carriers. Average service times of these processors are drawn from Table 4.5, which is developed based on the historical data and other published documents. The passengers and well-wishers then proceed to the public waiting and concession area.

Depending on how much time is left for each passenger before departure, the passenger may stay in the waiting and concession area, represented by the delay node of `wait_and_concession`. If the time left for the passenger is too short, then the passenger will experience only the walking time delay. Passengers and their companions proceed to the security booths through corridors or some vertical transportation facilities such as: escalators, elevators, etc. These vertical transportation facilities are represented by service nodes in which their service time is drawn from their capacity. Passengers and greeters proceed to the `greet_area` just before the security booths. Only passengers are allowed to pass security and go to the concourse. Greeters would return from the security and leave the PTB. The variability of servers in the service nodes, i.e., staff allocation, is reflected in the `set` node, `staff_manager`. The number of airline and security personnel can be changed over time through the `set` node.

The *concourse* submodel is a waiting area with several number of gates. The arrival passengers experience a delay time in `walking_time` node equal to their walking distance over their walking speed. The walking distance is the distance between the deplaning gate and the first processing facility. The departure passengers enter the concourse and wait until the final boarding call. Therefore, each passenger will expe-

Processor	Processing Rate	Source
Unloading at Curb (Dwell Time)	1-3 min, Automobile 1-2min, Taxi 2-4 min, Limousine 2-5 min, Bus	TRB Special Report 215
Ticket Sales/ Reservations	20-60 pax/hour 60 pas/hour, Vancouver	TC Doc AK-62-10-000 TC Doc AK-14-06-031
Check-in, Baggage Drop	45-60 pax/hour 60 pas/hour, Vancouver	TC Doc AK-62-10-000 TC Doc AK-14-06-031
Full Service Check-in	10-43 pax/hour	TRB Special Report 215
Express Check-in	15-50 pax/hour	TRB Special Report 215
U.S. Pre-clearance	50-60 pax/hour	TC Doc AK-62-10-000
Security; X-Ray Machine	400-500 pax/hour 500-600 pax/hour 60-120 pax/hour(hand-checked) 90-120 pax/hour(automated) 78-400 pax/hour (La Guardia)	TC Doc AK-62-10-000 Hart, The Airport PTB TRB Special Report 215 TRB Special Report 215 TRB Special Report 215
Loading at Gate, Ticket Lift	12-14 pax/min/door	TC Doc AK-62-10-000

Table 4.5: Processing Rates for Deplaning Processors of the PTB

rience a different amount of delay time. There is another delay node for the possible use by connecting passengers, if any. In summary, the rationale for developing the PTBSIM in different submodels is that it can be easily adjusted for different airports without immense code restructuring. The only segment of the PTB which may differ from the one developed here, can easily be modified to reflect those differences. The source list of the PTBSIM is included in Appendix B.

4.4 Model Evaluation

The PTB simulation model was developed as a tool for the dynamic prediction of certain parameters, e.g., flows, queues, congestion, utilization, as a result of passenger processing inside the terminal building. The evaluation process consists of calibration and validation. Calibration is the process of adjusting some input data to establish a baseline for modeling a specific airport. Validation is a process of evaluation to test the model's performance over a range of operating conditions. To evaluate the model the following steps were required:

1. Planning for and obtaining required data at existing airports,
2. Incorporating the collected data into the model,
3. Simulating the operations of the PTB for the observation time period using the demand placed upon the system, and
4. Comparing the model outputs with observed data in the form of time series of flow and queue lengths observed at PTB components.

To complete each of the afore-mentioned steps, several subtasks were required. For example, the data collection task required the specification of data items to be ob-

tained, the desired amount of data, the location of data collection, the time, and the personnel to conduct the survey. In the following sections, the calibration and validation process is briefly discussed.

4.4.1 Model Calibration

The PTB at the Macdonald Cartier International Airport at Ottawa, MCA, was selected as a basis for model evaluation. Factors involved in choosing this site were as follows:

- The terminal is a typical all-sector airport with all required arrival and departure facilities. MCA process also domestic and international passengers, as a result providing a diversity of operational characteristics.
- Medium-large passenger volumes, MCA is the fifth largest airport in Canada with 2.5 million passengers in 1992 (Jones, et al., 1992).
- Design characteristics, MCA has a single PTB with almost independent enplaning and deplaning sections. Passengers transfers are accomplished by walking, i.e., no mechanical devices were used.
- Proximity of the MCA to the research area, Carleton University, made it easier for frequent data collection and testing the results.

The floor plans of the two floor levels of the PTB are illustrated in Figures 4.6 and 4.7. The first floor, Figure 4.6, consists of ticket lobby, ticket counter, baggage claim area, concession, PILL, and customs and immigration for international arrivals. The second floor, Figure 4.7, consists of security, departure lounge, gates, and administration.

Figure 4.6: Ground Floor plan of PTB at MCA

Source: Modified From MCA, 1991

Figure 4.7: Second Floor plan of PTB at MCA

Source: Modified From MCA, 1991

The operating schedule was obtained from the PTB manager. The schedule consists of flight numbers, arrival times, departure times, type of aircraft, gate numbers, origins, and destinations. Having the air carrier and the type of aircraft, the number of seats were obtained from the Official Airline Guide, OAG (Nelson, 1993). The type of passengers, i.e., domestic or international, was assumed based on their origin and destination city. The load factor for each aircraft was impossible to get, therefore, the average load factor was obtained from the Aviation Section of Statistics Canada (Statistics Canada, 1993). All those actual parameters were synthesized into an input file which is illustrated in Appendix C. Other information such as the walking distance and the area of each component was obtained from the PTB physical layouts and was incorporated into the model.

When the basic layout of the model was constructed, the SES/scope was used to calibrate the model. SES/scope allows the modeller to interact with, control, and debug the model while it is running. It also allows one to watch an animated display of the model's execution and to debug the model should it behave in unexpected ways. For example, one may check the current transaction to see the paths it follows, its category, the number of greeters or meeters it generate, and the information that it carries when transferring between submodels. One can interact with the animation of a running model through the SES/scope window below the SES/design window. An example of both windows, SES/design in top and SES/scope in bottom, are shown in Figure 4.8.

All the trace messages and other information about the model's state are displayed in the SES/scope window. One can enter the control commands at the SES/rli command line prompt below the SES/scope window. At the top of SES/scope window is a banner containing several buttons that are used to control various animation parameters, and fields that display information about the current state of the model.

Figure 4.8: Illustration of SES/design and SES/scope Window

While SES/scope is active, one may examine specification forms, defined for the nodes in the graph, displayed in the SES/design window. In the case of any unexpected behaviour of the model, the specification form may be checked for tracing the problem. After the debugging process, one may calibrate the model using animation capability. SES/scope provides a detailed animation of the model events as the model runs. The modeller also has control over the events that he/she chooses to see animated. Some of the events that can be animated are: transaction movement, transaction tracking, transaction creation and destruction, service and delay nodes, and queue entry and exit.

As a passenger (transaction) flows through the PTB, e.g., traverses arcs, enters nodes, it is represented by a rectangle containing a "T" (for transaction) followed by the transaction identification number as shown in Figure 4.9. The most recently traversed arc is thickened considerably. This permits one to observe visually the paths that specific transactions follow as they flow through the model. The modeller has control over the scope of animation by using the buttons and defining them according to his/her own needs. One may choose to animate a specific category of passengers, or a specific service node, or submodel. For example, modeller may want to observe and follow the departure passengers while they are going through different submodels and nodes. More specifically, one can visually investigate the queue length at the security. In this case it is required to animate only the submodel *process_depart_pax* and observe *security* node.

Moreover, a specific node or path can be investigated in more detail by using "inspect" command while running the model. SES/scope provides inspectors that allow the modeller to monitor the status of nodes, resources, transactions and statistics. A small window in Figure 4.9 shows the characteristics of the animated current transaction. As shown in the figure, the transaction is a greeter (transaction number 1601) which

Figure 4.9: Illustration of Animation Capability of the Model

has traversed the path through ticket lobby to the stand-up service node. The detail of transaction movement also is shown in the bottom window, i.e., SES/scope window. However, using the SES/scope, the debugging process was done and the PTBSIM was fine-tuned based on the data obtained from the MCA passenger terminal building.

4.4.2 Model Validation

The general objective of the validation procedure for PTBSIM is the demonstration of the extent of agreement between model outputs and corresponding data obtained at the airport. Data observed for this purpose are time series of flow and queue length at passenger processing facilities. The model is also capable of producing time series data for direct comparison with field observation.

Data was collected by stationing observers at several locations throughout the PTB for simultaneous observation of the terminal's population at each processing unit. The survey was conducted on Friday December 3, 1993. Since it was not allowed to do the survey at restricted areas, data was collected at public areas such as: baggage claim area, ticket lobby, ticket counters, concession, and security checkpoints. The number of people present at each node was counted and recorded during each time interval. The time interval during which the data was collected and recorded was different among survey nodes. Some survey areas such as baggage claim, concessions, and ticket lobby included a large amount of space as a result, large number of occupants. It took more than one minute to count total number of people present at those locations. Therefore, the count was repeated every two to four minutes depend on the number of occupants. For other small areas, e.g., ticket counters, and security, the traffic count was recorded every minute during the survey period. For some time periods, the service rate as well as the number of servers were also recorded. The

survey period was chosen to be the busiest time of the day, i.e., 1400 to 1700 hours.

The PTBSIM reports all the events happening at each node if requested. Whenever a passenger enters or exits the node its population will change. Therefore, for a single one minute time interval there would be several population statistics. A sample of outputs is illustrated in Appendix D. For the purpose of comparison, a C' computer program was written to collect one number representing the node population at each one minute time period.

The model was validated in a three step procedure. First the population values from the PTBSIM versus time and the field values versus time were plotted on the same pair of axes for visual comparison. Second, if visual agreement was fairly good, the regression analysis between the field data and simulation outputs were performed to evaluate the degree that model can replicate the actual field. Third for those segments who were about 70 percent in agreement, a more in depth statistical analysis was performed. The third step consists of producing a series of five model replications with different random number streams and determining if the simulated mean was in agreement with the field data during the survey period. The three steps of the model validation is summarized in the following sections.

4.4.3 Visual Comparison of Field and Simulated Data

The comparison was made in terms of passenger/non-passenger accumulation in some segments of the PTB over a certain period of time, Friday afternoon, December 3, 1993. This comparison was made only for those segments on which data were collected. It should be noted that the time unit is in minutes, for example, 1500 hours is represented by $15 \times 60 = 900$. The simulation ran for a 24 hours period, i.e.,

from 0.0 to 1440. Observed values obtained during the data collection period are connected by solid lines and simulated outputs by dashes.

Ticket Lobby

The ticket lobby at MCA is used as a holding and queueing area for passengers that want to go through ticket and baggage check-in. It consists queueing area for two major airlines in Canada, i.e., Air Canada, and Canadian Airlines, and few other U.S. or chartered carriers, e.g., USA. Canada 3000. Passengers are entered to this area through one entrance only and are assumed to leave the area after check-in. Due to longitudinal layout of the area, the observer had to walk through the whole area thus occupant counts of less than two minutes were impossible. Since the simulation outputs are in one minute intervals, the field data were interpolated to find the missing numbers.

Figure 4.10 compares the observed passenger and greeter accumulations in the ticket lobby area against the PTBSIM outputs. Except few points, the shape of the two curves suggest a good level of similarity. Although it seems reasonable to attribute these differences to the assumptions made with regard to the number of servers and service times, several runs with changes in these parameters showed that the results were sensitive to the load factor and passenger arrival distribution at the PTB as shown in sensitivity analysis section, i.e., Section 4.5.

Concessions and Waiting Area

Figure 4.11 shows plots of passenger and greeter accumulations in the concessions area by PTBSIM and field observations. The area includes all concessions which are

Figure 4.10: Comparison of the Observed and Simulation Outputs, Ticket Lobby

Figure 4.11: Comparison of the Observed and Simulation Outputs, Concessions

located in the central waiting area. Passengers have to pass this area to get to the security at the second floor. Car rental agencies are in separate location and were not included in the concessions area. The number of occupants were counted at each three minute interval and were interpolated to get the counts for each one minute time interval.

Air Canada and Canadian Airlines

Figure 4.12 and 4.13 illustrate the comparison of simulation outputs and field observations for two major airlines and their allied. The air carriers operating at MCA were grouped into three main categories, i.e., Air Canada, Canadian Airlines, and others. Each category include some small regional airlines, e.g., Air Canada consists of Air Ontario, Air Nova, Air Alliance, Air Schefferville, and Bearskin. The Air Atlantic and Dutch Royal were considered as the Canadian airline allied since they used the same space. The sharp afternoon peak in the Canadian Airline plot is due to the KLM flight 676 (international flight with more than 200 passengers) with the departure time of 16:40 P.M.

Queuing Area Before Security

The graph in Figure 4.14 shows the comparison of passenger and greeter accumulations in front of the security booths for the survey period. The field counts includes total number of occupants which were present at this area. This include passengers waiting in the queue and those who were waiting for the last good bye to the greeters before passing through security. PTBSIM consistently generated a larger number of persons, but the shape of the curves are in reasonable agreement.

Figure 4.12: Comparison of the Observed and Simulation Outputs, Air Canada

Figure 4.13: Comparison of the Observed and Simulation Outputs, Canadian Airlines

Figure 4.14: Comparison of the Observed and Simulation Outputs, Security

Baggage Claim Area

Figure 4.15 compares the total number of passengers/meeters obtained from the PTBSIM against field observations. There are some discrepancies between the two values for a specific time interval. The difference may be due to the way that the area was modeled. Since the baggage flow was not in the scope of this research, the baggage claim segment was considered as an area where passengers experience a delay time equal to the sum of waiting time for bags to arrive and time to retrieve their baggage. While at the MCA, the baggage area is integrated with the arrival lobby and car rental agencies. Therefore, the observations may not necessarily represent those which belong only to the baggage claim area.

However, these plots permit a visual examination of agreement or disagreement between the two time series. PTBSIM would probably reproduce the observed data

Figure 4.15: Comparison of the Observed and Simulation Outputs. Baggage Claim

more accurately if some fine tuning in the input data were done. This was not done due to the lack of a comprehensive data base on PTB performance. Comprehensive data on all aspects of PTB operation and passenger characteristics were required to do more detailed analysis of simulation outputs. The collection of more data for model validation was prevented by the magnitude of resources required for a comprehensive survey. The graphs illustrate a reasonable agreement between the field and model outputs. The magnitude of this agreement is further investigated in the following section.

4.4.4 Statistical Analysis of PTBSIM Outputs

Regression Analysis

Although the visual approach shows a reasonable agreement between model outputs and observations, the extent to which the model can replicate the existing situations is another important aspect. PTBSIM also outputs a list of statistics, e.g., mean, standard deviation, maximum, and minimum for some parameters defined throughout the model such as: population, queue length, waiting time, utilization. A sample of these statistics are included in Appendix E. These statistics are very useful for the overall performance evaluation of the model.

The model can be validated in some degree through SES/scope. Running in SES/scope, one can visually see the graphic illustration of some statistics such as population, queue length, etc. Figure 4.16 shows the population statistics against time for several segments of the PTB. The graphs can be zoomed in for more detailed illustration. Another application of these real time statistical graphs is in performance assessment of the system. By looking at these graphs, the operator would be able to locate the areas in which the LOS is below the pre-specified standards.

The second step of model validation was performing a regression analysis test and finding the degree of correlations between the field and observed values. The Statistical Package for Social Science, SPSS, program utilizing the least squares method was used to do the linear regression between the observed and simulated values (Norman, 1985). The output of the SPSS package is included in Appendix F. The results are summarized in Table 4.6. The critical values for the t and F with a 5.0 percent level of significance were found from the statistical tables (Gugarati, 1988). The t and F tests are for rejecting the null hypothesis about the slope of the regression equation.

Figure 4.16: Real-Time Graphic Illustration of Statistical Results

Component	r	r ²	t	F	t-critical*	F-critical**
Ticket Lobby	0.66	0.44	11.01	121.21	1.96	3.84
Baggage Claim	0.52	0.27	7.62	57.80	1.96	3.84
Concession Area	0.79	0.62	16.12	259.89	1.96	3.84
Security Area	0.66	0.44	10.94	119.56	1.96	3.84
Air Canada	0.64	0.41	10.45	109.11	1.96	3.84
Canadian airline	0.79	0.62	16.65	277.29	1.96	3.84
* at 5 percent level of significance and (n-1) degree of freedom						
** at 5 percent level of significance and (1, n-2) degree of freedom						

Table 4.6: Summary of the Regression Analysis Results

High t and F values substantiate the existence of good agreement between observed and simulation outputs. The coefficient of correlation r is by definition an estimate of the strength of the linear association between the variables. In this particular case, the correlation coefficient was evaluated as the degree which simulation outputs compared to the observed values. Graphically, this is a linear comparison of theoretical values versus observed values. By looking at the table and taking into account the reasons of discrepancy between the observed data and simulation outputs, the results are reasonably good.

Chi-Square Goodness of Fit

The problem associated with validating models such as PTBSIM is that the model is neither fully deterministic nor fully probabilistic. Although the airport facilities are simulated in the probabilistic fashion, the model is driven by a deterministic input stream of aircraft arrivals and departures, i.e., aircraft schedule. Therefore, this precludes the use of some schemes normally used to compute the measures of

validity for simulation models. For example, the length of the simulation run is predetermined, e.g., one operating day, and one would not be able to run the model until certain confidence levels were obtained. Moreover, the inputs are deterministically time varying, e.g., passenger arrival and departure distributions based on time. As a result the comparison of individual statistics such as mean and variance are not a measure of validity if not associated with the specific time period.

In the case of purely probabilistic simulation (Monte Carlo) input variables are drawn from prespecified input probability distributions and the output variable is also characterized by a probability distribution; once the model has reached steady-state. It is assumed that each output observation is randomly and independently drawn from output distribution (Hsu, and Hunter, 1977). Based on this assumption, the sample mean provides an unbiased estimate of the true output mean, and the standard error of the estimate of the mean can be computed. In the case of Monte Carlo simulation whose inputs are deterministically time varying, each observation is drawn from a different underlying distribution with different mean and variance. While in purely probabilistic case each observation is drawn from the same assumed input distribution. It does not make sense to compare the daily mean of population of a node obtained from simulation with an instantaneously observed value, because there are several peak and off-peaks according to the demand distribution. For example, the observation of mean queue length at a processor at simulation time 9:00 A.M. sheds no light on the distribution of queue lengths one would expect at the same processor at the simulated time 2:00 P.M.

As a result, without several observations for each time period, it is impossible to estimate the variance of the individual observations, and thus it is difficult to estimate the variance of the sample mean. Therefore, the proper technique for validating some segments of the PTB is to run the PTBSIM for several times using different random

number streams. Thus there would be several observations for each point in time. The observations at each run can be used to obtain an unbiased estimate of both mean and variance of the observations at each time interval. Then a goodness of fit test can be established for testing the hypothesis that simulation means follow the distribution of observed data. The chi-square goodness of fit test has been recommended for large sample sizes (Banks, and Carson, 1984). The test procedure begins with arranging the n observations into a set of k class intervals . The test statistic is given by,

$$X_0^2 = \sum_{i=1}^k \frac{(O_i - E_i)^2}{E_i} \quad (4.5)$$

where,

O_i = observed frequency in class interval i ,

E_i = expected frequency in class interval i , and

X^2 = the chi-square distribution value.

The X^2 follows the chi-square distribution with $k - s - 1$ degrees of freedom, where s represents the number of parameters of the hypothesized distribution estimated by the sample statistics. The critical value $\chi^2_{\alpha, k-s-1}$, where s is the number of parameters estimated from the data and α is the level of significance, is obtained from the table and compared with the calculated X^2 . If the calculated X^2 is greater than the critical one , then the two distributions do not conform.

However, for the purpose of this research, five subsequent runs of the PTBSIM with the same input data by using different random number streams were performed. For the three segments of the PTB, whose r value was about 0.7, expected flow values for each 10 minutes interval were collected. Values obtained from the five runs were

averaged at each time point. The mean of the observed data for each 10 minute interval was also calculated. The χ^2 value was calculated for each segment. The critical value $\chi^2_{\alpha, k-s-1}$ was found from the chi-square table. In this case $s=0.0$ since no parameter was estimated from the data. Summary of the analysis result for three segments of the PTB are shown in Tables 4.7, 4.8, and 4.9. At $\alpha=0.05$, the critical value $\chi^2_{0.05,15}$ is 25.0. Therefore, based on the analysis, observed data for the three segments of the PTB, i.e., Ticket lobby, security, and concessions, conform to the simulation outputs at level of significance 0.05, i.e., the calculated value is less than the critical value.

The comprehensive validation of models such as PTBSIM requires a great deal of data collection. The data should be collected on all aspects of the PTB. Some of the very basic required data are such as: service characteristics of all PTB components, passenger accumulation and queue length at processors, passenger arrival distribution for different flight sectors, baggage characteristics, flight schedule, greeters, meeters, etc. The survey methods for collecting the data may include; time-stamping (Braaksma, 1976), flash-card survey (Dunlay, 1981), interview, tailing, videotaping, direct observations, etc. It would be extremely resource consuming to perform a comprehensive survey for a complex PTB system for extended period of time. Moreover, data collection by itself is prone to observation errors and random variance. The aforementioned factors have prevented a full validation of the PTBSIM. It should be pointed that PTBSIM was designed to be an easy-to-use planning tool rather than a detailed component design tool. However, the PTBSIM modularity allows the modeller to expand the modules to whatever level of detail is required with relative ease.

Time (min)	Run 1	Run 2	Run 3	Run 4	Run 5	Mean (E)	Std.	Obs. (O)	$(O - E)^2/E$
870	117	107	104	123	116	113.4	6.9	95	3.0
880	102	88	93	96	102	96.2	5.4	87	0.9
890	81	61	81	71	61	71	8.9	70	0.0
900	69	70	67	55	57	63.6	6.3	56	0.9
910	67	81	67	62	59	67.2	7.5	65	0.1
920	76	85	85	78	82	81.2	3.7	79	0.1
930	107	99	100	110	117	106.6	6.7	95	1.3
940	112	109	122	128	123	118.8	7.1	109	0.8
950	125	126	109	119	108	117.4	7.7	107	0.9
960	121	116	126	105	129	119.4	8.5	113	0.3
970	133	126	115	114	121	121.8	7.1	105	2.3
980	114	143	143	127	133	132	10.9	112	3.0
990	121	127	132	115	123	123.6	5.7	109	1.7
1000	110	89	113	99	110	104.2	9	87	2.8
1010	73	62	73	59	68	67	5.7	70	0.1
1020	61	54	59	47	64	57	6	74	5.1
Σ									23.3

Table 4.7: Summary of the Chi-square Analysis For Concessions Area

Time (min)	Run 1	Run 2	Run 3	Run 4	Run 5	Mean (E)	Std.	Obs. (O)	$(O - E)^2/E$
870	77	60	67	66	74	68.8	6.0	73	0.3
880	59	50	56	57	66	57.6	5.2	70	2.7
890	39	37	36	42	35	37.8	2.5	46	1.8
900	11	34	36	41	48	40.6	5.1	44	0.3
910	17	39	38	45	47	43.2	3.9	46	0.2
920	46	38	49	46	54	46.6	5.2	57	2.3
930	67	53	56	58	67	60.2	5.8	68	1.0
940	74	59	65	71	68	67.4	5.2	80	2.4
950	66	68	67	61	60	64.4	3.3	77	2.5
960	61	91	64	84	63	72.6	12.4	70	0.1
970	96	94	78	78	83	85.8	7.8	77	0.9
980	91	84	82	74	93	84.8	6.8	74	1.4
990	83	67	96	85	104	87	12.6	86	0.0
1000	68	43	58	60	75	60.8	10.8	67	0.6
1010	47	37	39	35	48	41.2	5.3	52	2.8
1020	38	44	35	42	43	40.4	3.4	53	3.9
Σ									23.2

Table 4.8: Summary of the Chi-square Analysis For Ticket Lobby Area

Time (min)	Run 1	Run 2	Run 3	Run 4	Run 5	Mean (E)	Std.	Obs. (O)	$(O - E)^2/E$
870	31	22	27	24	32	27.2	3.9	16	1.6
880	27	24	26	21	20	23.6	2.7	19	0.9
890	24	21	22	20	18	21	2.0	15	1.7
900	22	18	19	20	17	19.2	1.7	17	0.3
910	17	16	19	17	14	16.6	1.6	13	0.8
920	18	16	19	17	14	16.6	1.6	13	0.3
930	24	22	23	21	17	21.4	2.4	18	0.5
940	31	27	28	29	29	28.8	1.3	23	1.2
950	34	27	29	31	32	30.6	2.4	29	0.1
960	31	28	33	24	32	29.6	3.3	22	2.0
970	35	34	31	36	27	32.6	3.3	25	1.8
980	41	32	41	28	31	34.6	5.4	27	1.7
990	35	33	34	36	26	32.8	3.5	32	0.0
1000	27	32	31	29	31	30	1.8	22	2.1
1010	16	12	17	15	14	14.8	1.7	7	4.1
1020	14	12	15	11	13	13	1.4	7	2.8
Σ									24.9

Table 4.9: Summary of the Chi-square Analysis For Security Area

4.5 PTBSIM Sensitivity Analysis

Sensitivity analysis is the study of how model outputs change in response to change in input parameters. The sensitivity analysis can be used to estimate the implications of alternative operational policies or to evaluate the trade offs between level of service and capacity in the PTB system. It may also be used to determine how accurately the input variables should be determined. Sensitivity analysis may be performed on any of the model inputs depending on what question the modeller is trying to answer or what problems is going to be solved. Some of the variables for sensitivity analysis are as load factor, percent pre-ticketed, greeter distribution, meeter distribution, passenger arrival distribution, service times, number of servers, etc.

The sensitivity analysis approach on the current simulation models is to vary the input variable of interest and to do as many runs for each value of the variable as is necessary to obtain statistical bounds on the outputs of interest. For example, a variable requires four to six values to cover the range of interest and a minimum of five runs are needed for each value of variable. Thus between 20 to 30 runs are needed (may be more) to perform sensitivity analysis on even one variable. Although single run of these models may not be expensive, analysis of so many runs is tedious and expensive.

An attempt was made to overcome the aforementioned problem in the PTBSIM. The model has been parameterized by declaring some of the input variables as run-time parameters. Parameterizing the model permits the modeller to experiment more freely with various values of the parameters, e.g., service time, number of servers, interarrival time, and so on, without recompiling and rerunning the model every time he/she want to make a change. This feature is especially useful when performing

“what if” and trade off analysis, i.e., sensitivity analysis.

The modeller would be able to change some of the parameters of interest and see the outcome of these changes. For example, the queue population and power of the node “security_booths” are shown in Figure 4.17.

Power of the node is a parameter which can be used to increase or decrease either the service time or the number of servers in a specific node. The default value for the power was set to be 1.0 in the param_declaration node. At time 953, the power was changed to 0.5, i.e., service time doubled or number of servers was decreased to half. As a result a queue starts to build up. At time 989 the power was again changed to 1.5, i.e., the number of servers increased three times, and queue decreased significantly. It should be noted that the inclined line in the power graph connects only the two power changes and does not mean that power was changed continuously. This interactive operation can be performed for several service nodes at the same time. Therefore, the PTBSIM can be used as an operational tool in which the sensitivity analysis can be performed interactively.

However, the effect of one of the input variables, i.e., average load factor, on the population of some of the PTB components is graphically illustrated in Figure 4.18, 4.19, and 4.20. In this example, the time series population of three segments of the PTB, i.e., concessions, security, and ticket lobby, based on the three different load factors are shown. The solid line represent the load factor which was used for the model validation, and the upper and lower dashed lines represent the maximum and minimum values assumed. For the purpose of clarity only three load factors within a wide range, i.e., 0.43 to 0.96, was assumed.

As shown in Figures 4.18 to 4.20, the PTB system is very sensitive to the load factor. There is a positive relationship between the load factor and the population

Figure 4.17: Illustration of the Interactive Operation of the PTBSIM

tion on different segments of the PTB. The effect of the load factor on increasing the population of PTB segments is more significant at peak periods than the off peaks. This is due to the fact that the number of flights during peak periods is greater than the number of flights during off peaks. Then by increasing the average load factor, the number of passengers as well as meeters/greeters is also increased. The sensitivity of the model to the load factor shows that a good knowledge about the actual demand on the system is essential. However, except for comparison purposes in reports, this type of analysis can be done interactively within the PTBSIM. For the purpose of this research, PTBSIM can provide the population statistics over time for different segments of the PTB. These statistics will be used to develop the probability mass functions of populations for the optimization model which is discussed in Chapter 5.

Figure 4.18: Effect of Different Load Factors on the Population of Concessions Area

Figure 4.19: Effect of Different Load Factors on the Population of Ticket Lobby Area

Figure 4.20: Effect of Different Load Factors on the Population of Security Area

Chapter 5

Optimization Model

5.1 Overview

The main component of the resource utilization model is the optimization model, shown in Box 7 of Figure 3.2. The most obvious problem facing airport passenger terminal operators is the lack of an accepted methodology to address issues involving optimization. According to the current planning and design practices, for a given demand level there is a corresponding space requirement. While in practice, there are always trade-offs between cost and levels of service, between labor and automation, between equipment and fixed facilities, and between expansion of existing facilities and the addition of new ones.

For example, operating and maintenance costs which constitute a major portion of the total cost, has been almost always neglected in the current planning and design procedures. Operating and maintenance costs can be reduced by a reduction in level of service, especially at peak periods, but at some cost to the passenger. The least cost

solution may not be always the best solution for the passenger. On the other hand terminal configurations that supposedly offer high levels of service may be expensive to operate. Those costs will be ultimately paid by the traveller either through higher fares, or other user charges. All of these issues should be taken into account in the process of PTB planning, design, and operation.

There has been little research to involve optimization theory in the planning, design, and operation of airport PTBs. The only exception is development of a design methodology, based on the heuristic modelling technique, to produce an optimum terminal design (Braaksma, 1973). The methodology is composed of three major algorithms: facility sizing algorithm, the load assignment algorithm, and the facility layout algorithm. This methodology determines the minimum amount of areal spaces first, and second the loads are assigned to the facilities in such a way that transport cost, expressed as the sum of the products of passenger flow times distance, is at minimum. Then the facilities are located relative to each other in such a manner that the transport cost is also at a minimum. The second and third steps are iterated until an optimum design has been obtained. The methodology is very useful in planning and design in terms of optimum concept selection. It does not deal with the PTB components in detail in terms of operating characteristics and stochastic demand.

A methodology for optimizing the resource utilization of a real world PTB was proposed in Section 3.3. The proposed real system methodology was converted to a resource utilization model using a mathematical and simulation approach as discussed in Section 3.4. The optimum PTB resource utilization model, illustrated in Figure 3.2, consists of some submodels and elements. Some of those elements such as demand estimation, operational policies, and performance measures were briefly discussed in Chapter 3. In this chapter the optimization problem, its theory, and model development, are discussed.

5.2 PTB As A Functional system

As mentioned in Chapter 2, the PTB is the interface between the air mode and the ground access mode. Its main function is to facilitate the processing of passengers and their baggage prior to boarding and after leaving the aircraft. To perform this main function, the PTB houses airline operational facilities required to process passengers and their baggage. In addition, the PTB provides a comfortable environment, in which passengers and those accompanying them may wait, or receive certain supporting services such as food, car rental, and so forth.

In this research, the whole PTB is considered as a system in which labor, capital, and services are deployed to produce certain services to passengers. Although it may be argued that the PTB is an architectural space as well, this research is concerned only with the functional aspect of the building. This is due to the fact that if aircraft operated like buses, one could just drive to the airport, park beside the apron, and walk to the aircraft. In this case, PTBs would be limited to providing shelter for waiting passengers, i.e., this was how air travel began. However, as the number of passengers to be loaded and un-loaded at each aircraft movement increased, and the cost of aircraft required that they spend as little time as possible waiting at airports, it necessitates the organization of passengers and their baggage in advance of the aircraft's scheduled departure. In addition, government's requirements for controlling international travellers has increased the PTB to its present complexity. The function of this complex system may be seen as taking a passenger and providing some services to that passenger. This provision of services is associated with some cost to operators as well as passengers. Optimizing the associated costs with the PTB operation is the subject of the optimization model.

5.3 Optimization Theory

The research problem addressed in the optimization process is that given a fixed amount of resources, e.g., PTB space, the process should determine the allocation of all or part of the resources to a series of activities, with variable demand, in such a way that the objective function under consideration is optimized. The PTB can be divided into several segments. These segments perform different services to the users of the PTB. Each segment has its own set of characteristics such as: unit operational and maintenance cost, LOS standards, and variable traffic demand pattern. The optimization model determines the optimum required resources for each segment of the PTB to perform its activity taking into account the operational and maintenance cost involved and the LOS provided to users. The problem addressed here is a resource allocation problem with a series of constraints. The resource allocation problem is generally formulated as follows:

$$\begin{aligned}
 &\text{Minimize} && f(x_1, x_2, \dots, x_n) \\
 &\text{subject to:} && \sum_{j=1}^n x_j = N, \\
 &&& x_j > 0, \quad j = 1, 2, 3, \dots, n
 \end{aligned} \tag{5.1}$$

That is, given one type of resource whose total amount is equal to N , it is desired to allocate it to n segments (components of the PTB system) which serve an uncertain number of customers so that the objective value $f(x_1, x_2, \dots, x_n)$ becomes as small as possible. The objective value may be interpreted as the cost or loss, or the profit or reward, incurred by the resulting allocation. In the case of profit or reward the objective value of $f(x_1, x_2, \dots, x_n)$ should be maximized. The variable x_j in Equation 5.1 represents the amount of resource allocated to segment j . If the resource is not divisible, e.g., persons, processors, then the variable x_j is a discrete variable that takes nonnegative integer values. In this case, the constraint $x_j = \text{integer}, j = 1, 2, 3, \dots, n$ is added to Equation 5.1. The objective function in general form, i.e.,

Equation 5.1, cannot be used for airport PTBs due to the fact that one may have more resources than what is required. A special objective function for this problem should be developed in such a way that the allocated resources may be smaller or equal to the total resource available. The objective function for this research problem is as follows:

$$\begin{aligned} &\text{Minimize} \quad \sum_{j=1}^n c_j(x_j) \\ &\text{subject to:} \quad \sum_{j=1}^n x_j \leq N, \\ &\quad \quad \quad x_j > 0, \quad j = 1, 2, 3, \dots, n \end{aligned} \quad (5.2)$$

where,

$c_j(x_j)$ = expected over- and under-supply cost of allocating x_j to segment j .

x_j = resource allocated to segment j , e.g., space.

n = total number of PTB segments.

N = total amount of available resource, e.g., PTB passenger processing area.

The main objective in Equation 5.2 is to minimize the expected over- and under-supply cost function. The difference is that not all of the resources need be allocated. The resource is allocated based on the demand placed upon the system. The expected cost at each segment is a function of allocated resources. There are two types of costs associated with the allocation of resources, i.e., over- and under-supply cost. Moreover, allocation of resources depends on the demand placed upon the facility. As a result, the expected cost is also a function of demand. The demand at each segment is also uncertain and depends mainly on the flight schedule. Taking all the variables into consideration, the expected over- and under-supply cost function for the PTB is found as follows:

Assume that y is the demand variable at each segment and $p_j(y)$ is the probability mass function for variable y at segment j . This means that the probability of having y units of demand at segment j is $p_j(y)$. It is also assumed that each unit of demand needs θ_j units of resource at segment j , e.g., the amount of space that each passenger occupies. If x_j is the amount of resource supplied to segment j , then the expected amount of over-supply resources would be:

$$\sum_0^{\delta_j} (x_j - \theta_j y) p_j(y) \quad (5.3)$$

where,

x_j = the amount of resource supplied,

y = demand variable, i.e., number of passengers,

$p_j(y)$ = probability of having y units of demand at segment j ,

θ_j = the amount of resource needed by each demand unit, LOS,

δ_j = integer (x_j/θ_j) .

To calculate the cost associated with the amount of over-supply resources, the unit cost of over-supply at segment j should be found. If α_j is assumed to be the unit cost of over-supply at segment j , then the over-supply cost at this segment is as follows:

$$\alpha_j \sum_0^{\delta_j} (x_j - \theta_j y) p_j(y) \quad (5.4)$$

As was mentioned, if the resources supplied to segment j were less than required then there would be an under-supply cost. Following the same process and assuming β_j to be the unit cost of under-supply, the expected under-supply cost would be:

$$\beta_j \sum_{\delta_j}^Y (\theta_j y - x_j) p_j(y) \quad (5.5)$$

where,

Y = maximum expected demand for segment j .

β_j = the unit cost of under-supply.

Therefore, the total cost associated with the allocation of x_j resources to segment j is the sum of the two preceding cost elements,

$$c_j(x_j) = \alpha_j \sum_0^{\delta_j} (x_j - \theta_j y) p_j(y) + \beta_j \sum_{\delta_j}^Y (\theta_j y - x_j) p_j(y) \quad (5.6)$$

By solving Equation 5.6 for different values of x_j , the optimum resource value associated with the minimum total cost, for one specific segment, can be found. Since the PTB system consists of several segments for which resources should be allocated, the total expected over- and under-supply cost for the whole system would be as follows:

$$C_T = \sum_{j=1}^n c_j(x_j) = \sum_{j=1}^n \left[\alpha_j \sum_0^{\delta_j} (x_j - \theta_j y) p_j(y) + \beta_j \sum_{\delta_j}^Y (\theta_j y - x_j) p_j(y) \right] \quad (5.7)$$

where,

C_T = total expected over- and under-supply cost of the PTB system,

n = maximum number of PTB segments.

It is hardly possible to find an absolute mathematical solution for the preceding equation in which the resources and demand were assumed indivisible. It is possible to solve this equation numerically or by computer programs and provide the values of x_j for all predefined segments of the PTB.

However, if the resources and demand were assumed to be divisible, then x_j and y are continuous variables that can take any nonnegative real values. In this case following

the same procedure of indivisibility, the total over- and under-supply cost function for segment j would be as follows:

$$c_j(x_j) = \alpha_j \int_0^{\delta_j} (x_j - \theta_j y) dF_j(y) + \beta_j \int_{\delta_j}^{\infty} (\theta_j y - x_j) dF_j(y). \quad (5.8)$$

where,

$F_j(y)$ = cumulative distribution function of demand at segment j which is continuous and increasing,

θ_j = constant representing the amount of required resource for each unit of demand function,

α_j = unit cost of over supply at segment j ,

β_j = unit cost of under supply at segment j .

The cost function for the continuous case, Equation 5.8, can be rewritten as follows:

$$\begin{aligned} c_j(x_j) = & \alpha_j(x_j) \int_0^{\delta_j} dF_j(y) - \alpha_j \theta_j \int_0^{\delta_j} y dF_j(y) + \beta_j \theta_j \int_0^{\infty} y dF_j(y) \\ & - \beta_j \theta_j \int_0^{\delta_j} y dF_j(y) - \beta_j(x_j) \int_0^{\infty} dF_j(y) + \beta_j(x_j) \int_0^{\delta_j} dF_j(y) \end{aligned} \quad (5.9)$$

If μ_j is defined as the mean of $F_j(y)$, then by using the principles of probability theory such as: $\int_0^{\infty} y dF_j(y) = \mu_j$ and $\int_0^{\infty} dF_j(y) = 1.0$ the preceding equation would simplify to the next equation, i.e:

$$\begin{aligned} c_j(x_j) = & \beta_j \theta_j \mu_j - (\alpha_j + \beta_j) \theta_j \int_0^{\delta_j} y dF_j(y) \\ & + (\alpha_j + \beta_j) x_j \int_0^{\delta_j} dF_j(y) - \beta_j x_j \end{aligned} \quad (5.10)$$

since $\int_0^{\delta_j} dF_j(y) = F_j(\delta_j)$, Equation 5.10 would be further simplified to,

$$\begin{aligned} c_j(x_j) = & \beta_j(\theta_j \mu_j - x_j) + (\alpha_j + \beta_j) x_j F_j(\delta_j) \\ & - (\alpha_j + \beta_j) \theta_j \int_0^{\delta_j} y dF_j(y) \end{aligned} \quad (5.11)$$

Therefore, the only integral left in Equation 5.11 is analyzed as;

$$\int_0^{\delta_j} y dF_j(y) = \int_0^{\infty} y dF_j(y) - \int_{\delta_j}^{\infty} y dF_j(y) \quad (5.12)$$

The first part of Equation 5.12 is equal to μ_j and the second part can be solved by using the following expected value theory (Billingsley, 1986):

$$\int_{(x>\alpha)} X dF(x) = \alpha(1 - F(\alpha)) + \int_{\alpha}^{\infty} (1 - F(x))dx \quad (5.13)$$

Replacing X with y , α_j with δ_j , and $F(x)$ with $F_j(y)$ leads to,

$$\int_{\delta_j}^{\infty} y dF_j(y) = \delta_j(1 - F(\delta_j)) + \int_{\delta_j}^{\infty} (1 - F_j(y))dy \quad (5.14)$$

The integral in Equation 5.14 is analyzed to,

$$\int_{\delta_j}^{\infty} [1 - F_j(y)]dy = \int_0^{\infty} [1 - F(y)]dy - \int_0^{\delta_j} [1 - F(y)]dy \quad (5.15)$$

Since $\int_0^{\infty} (1 - F(y))dy = \int_0^{\infty} y dF(y) = \mu_j$, and the second integral can be broken into two parts, Equation 5.15 would simplify as;

$$\int_{\delta_j}^{\infty} (1 - F_j(y))dy = \mu_j - \left(\int_0^{\delta_j} dy - \int_0^{\delta_j} F(y)dy \right) = \mu_j - \delta_j + \int_0^{\delta_j} F(y)dy \quad (5.16)$$

Finally by substituting Equation 5.16 into 5.12 and substituting Equation 5.12 into 5.11, the total cost function would be simplified to a determinate function in which all of its elements can be calculated,

$$c_j(x_j) = \beta_j \theta_j (\mu_j - \delta_j) + (\alpha_j + \beta_j) \theta_j \int_0^{\delta_j} F_j(y) dy \quad (5.17)$$

Considering that $\delta_j = x_j/\theta_j$, then the preceding equation can be written with respect to x_j ,

$$c_j(x_j) = \beta_j \theta_j (\mu_j - x_j/\theta_j) + (\alpha_j + \beta_j) \theta_j \int_0^{x_j/\theta_j} F_j(y) dy \quad (5.18)$$

If the demand function is known the absolute value for x_j can be found by solving this equation mathematically. To find the optimum value for x_j , the derivative of

the final equation with respect to x_j should be taken, i.e:

$$c'_j(x_j) = -\beta_j + (\alpha_j + \beta_j)\theta_j F_j(x_j/\theta_j) \quad (5.19)$$

If the value of derivative is substituted by zero, i.e., $c'_j(x_j) = 0.0$, and then by solving the derivative with respect to x_j , the absolute value of x_j is found.

From the Equation 5.18 and its derivative (F_j is increasing) it is also clear that the cost function is convex with respect to variable x_j which means that there is a minimum point in the cost function. Figure 5.1 shows the approximate shape of the cost function based on the resource variable of x_j . The exact shape of the cost function can be found by obtaining the value of coefficients and the range of variables.

So far, the equation for finding the optimum resource value for one typical segment of the PTB based on the minimum over- and under-supply cost was found. The objective function was to minimize the expected total cost of operating the whole PTB system consisting several segments. Therefore, the problem would be a resource allocation problem with a separable convex objective function. There are few approaches to solve the allocation problems of type Equation 5.1 in which the total amount of resources, N , would be allocated among the segments, i.e., $\sum_{j=1}^n x_j = N$. If the demand function and the values for α_j and β_j are known, then Equation 5.1 can be written as a series of nonlinear separable convex functions which have to be optimized. In another words the values of x_j should be found in such a way as to minimize the expected cost function. Then knowing all the variables and constants, algorithms have been developed, e.g., RANK or RELAX, to find the optimal values for x_j (Ibaraki, Toshihide, 1988). It should be noted that several assumptions are inherent in these algorithms. For example, these algorithms minimize the sum of convex objective functions of one variable under a simple constraint that all variables sum to a given constant, i.e., maximum resource available. They also assume that each objective

Figure 5.1: Typical Cost Function of PTB Segments With Respect to x_j

function (f_j) is strictly convex, i.e., has a defined mathematical function that its derivation is increasing in x_j . These assumptions are not supported for airport PTBs in which hardly all resources are fully utilized and the demand function cannot be defined mathematically.

The objective function of this research problem is more complex due to the fact that the sum of allocated resources could be less than or equal to the maximum resource available. Except for some approximation procedures, no formal, computationally mathematical solutions exist for optimally solving Equation 5.2. In addition, more complexities exist within the equation such as the exact demand function, and the unit costs for over- and under-supply. Due to the stochastic nature of passenger arrival and departure at the PTB, no specific mathematical function can represent the actual demand on the system at each instant of time. More detailed discussion about the complexities involved in the demand estimation was given in Section 3.5. Another difficulty associated with the mathematical approach is finding values for α_j and β_j . The value of α_j depends on the unit cost of over-supply of a facility or activity which is going to be performed, e.g., design, construction, operation and maintenance. The value of α_j can be obtained by going through a cost allocation process. First all the cost items associated with the PTB's operation should be estimated. Second the sum of these costs should be divided by the total amount of resources available. Then the cost of providing one unit of extra resource can be obtained. For example, the procedure for the estimation of the operational cost of over-supply, α_j , is summarized as follows:

$$\alpha_j = OPS_{total} / RES_{total} \quad (5.20)$$

where,

OPS_{total} = total PTB operational and maintenance cost

RES_{total} = total resource available such as space, labor.

The value of β_j is the most difficult to estimate. The question to be answered is how much would be the cost to the operator if resources are provided one unit less than what is required? In the case of multiple airports, the operator at one airport may lose customers due to the availability of better service at another location. One approach is to put monetary values on the amount of discomfort such as: congestion, delay, walking distance, etc. experienced by passengers. This approach is interpreted as a social cost estimation which would give an impression of the under-supply cost from a users' point of view. Although this may not be the same cost from an operators' point of view, the operator is required to provide some level of care and comfort to passengers. Therefore, it is necessary to incorporate some measures for the assessment of quality of service provided for the passenger.

5.3.1 Optimization Model Development

Existing optimization algorithms, e.g., RANK, RELAX developed in combinatorial optimization (Ibaraki, 1988) were examined to see if they could be used to solve the developed optimization problem. The results were negative due to the fact that in an airport PTB not all resources need be allocated and no mathematical function can represent the variable demand distribution on the PTB segments. Since the assumptions of these algorithms are not supported by the real life PTB operation, an algorithm was developed from first principles. A simplified flow chart of optimization program is shown in Figure 5.2. The source list of the main optimization program is given in Appendix G.

In this flowchart an attempt has been made to solve the optimization problem numer-

Figure 5.2: Heuristic Algorithm of the Optimization Program

ically since the requirements for an analytical solution, e.g., demand function, α_j , β_j , etc. does not exist. The PTB is divided into several processing or service segments and the probability distributions of the population are obtained from the simulation. The modeller can define the unit costs of over- and under-supply for each segment of the PTB. The LOS standards are also defined by the operator. The algorithm of the program consists of mainly two parts, i.e., optimization and sub-optimization. In the optimization part no constraint has been set for the maximum amounts of available resources, while in the sub-optimization part the maximum amounts of available resources are limited. The mechanism of the optimization program is summarized as follows:

The only inputs to the program are the PMFs, Box 4 of Figure 3.2, obtained from the simulation model and variables of α_j , β_j , and θ_j . The PMFs for different segments of the PTB are saved in separate data files. Each data file contains the population distribution function for 24 hour time periods of a typical day for a specific segment of the PTB. The relative values of α_j and β_j , Box 6 of Figure 3.2, are assumed based on engineering judgement or historical data. From the analysis it was found that the absolute values of α_j and β_j do not change the final results if the relative value, α/β , remains constant. It is clear that the larger the values of α_j and β_j , the larger is the total over- and under-supply cost. However, the obtained optimum required resources do not change since the relative value remains constant.

The variable θ_j will represent the level of service concept within the optimization. In another words, θ_j represents the required resource value for each demand unit at each LOS. The most common quantitative factors that influence level of service in PTBs are congestion which is measured in terms of number of passengers per unit area, queue length, and waiting time (TRB, 1975; Transport Canada, 1979; McCullough and Roberts, 1979; TRB, 1987; Ashford, 1988; Omer and Khan, 1988; Seneviratne and

Martel, 1994). Transport Canada (1979) proposed a comprehensive level of service assessment method based on providing "space" at different PTB components. The method which was subsequently adopted by International Air Transport Association (IATA, 1981), established six different levels of service based on space provision. The boundaries for the various PTB facilities are shown in Table 5.1. The six levels of service are described in Table 5.2.

Data files containing the PMFs are opened and scanned into the program. The time of the day is divided into equal time periods, e.g., one hour long. Within one time period, the procedure will find the optimum required resources for different segments of the PTB. The program calculates the over- and under-supply costs associated with each resource value. Then the resource value associated with the minimum total over- and under-supply cost is called optimum required resource.

The sum of optimum resource values for all PTB segments during first time period is compared with the maximum existing resources, e.g., total PTB processing area. If the sum of resources is smaller than the maximum value, then the time is incremented and the same process is repeated for all other time periods. If the sum of resources for all segments at a specific time period is greater than the maximum existing resource, the process will start to sub-optimize the system. The optimization process will find the optimum resources without any constraint at a global minimum total cost. Having the constraint of limited total resources, the optimum values will be adjusted at a price of increased total cost.

The sub-optimization process will be done in such a way to minimize the increased cost to the total expected over- and under-supply cost. Therefore, the process will find the optimum resource value of the segment associated with the minimum value of under-supply unit cost, β_j . The optimum resource value of the segment will be

Terminal Component	Level of Service				
	A to B	B to C	C to D	D to E	E to F
Check-in	1.6**	1.1	1.2	1.0	0.8
waiting areas	2.7	2.3	1.9	1.5	1.0
Holdroom	1.4	1.2	1.0	0.8	0.6
Baggage claim*	1.6	1.4	1.2	1.0	0.8
PIL area	1.4	1.2	1.0	0.8	0.6
* without baggage device					
** space requirements in m ² /person					

Table 5.1: LOS Targets for PTB Components, (Transport Canada, 1979)

LOS	Definition
A	Excellent level of service, condition of free flow, no delays, direct routes, excellent level of comfort.
B	High level of service, condition of stable flow, high level of comfort.
C	Good level of service, condition of stable flow, provides acceptable throughput, related subsystems in balance.
D	Adequate level of service, condition of unstable flow, delays for passengers, conditions acceptable for short time periods.
E	Unacceptable level of service, condition of unstable flow, sub-systems not in balance, represents limiting capacity of the system.
F	System breakdown, unacceptable congestion and delays.

Table 5.2: LOS Definitions for PTB Components, (Transport Canada, 1979)

decremented until the sum of resources for all segments is equal to the maximum existing resource. It should be noted that the resource value of any segment cannot be decremented lower than its minimum value. The minimum resource value for each segment could be the required resources at the lowest operating service level, e.g., E or D. Omer and Khan (1988) suggest that level of service C is the most cost effective level of service for the design of airport landside facilities. Level of service D was suggested to be as a trigger point for capacity expansion. Transport Canada (1979) also recommends level of service C as a design standard, as it provides good level of service at a reasonable cost. However, the minimum level of service can be defined by the user.

The sum of the new optimum resources of various segments will be compared with the maximum existing resources and if it is still higher than the maximum, another segment with the second lowest β_j will be chosen for sub-optimization. If the values of β_j for two segments are equal, then the segment with the higher unit cost of over-supply, α_j , will be chosen. The rationale is choosing the segments for sub-optimization which have the least impact in the total cost increase. As mentioned earlier, the cost of operating different segments of the PTB may be different due to the type and the cost of facilities involved in their operation. From the analysis, it was found that the lowest β_j and the highest α_j have the minimum impact on the total over- and under-supply cost. This process is repeated until the sum of the optimum required resources are equal to the maximum available resources.

The output of the optimization program would be the optimum resource values in a variable time-space plan format, Box 8 of Figure 3.2. The program will also provide the associated supply costs of resources for a 24-hour period, Box 9 of Figure 3.2. Figure 5.3 shows the theoretical variable time-space plan as well as the practical plan compared with the existing one. How close one can bring the practical plan

Figure 5.3: Comparison of Theoretical, Practical, and Existing Time-Space Plan

to the theoretical plan depends on the flexibility of the physical layout and other constraints, e.g., traffic demand pattern.

The sum of optimum resource values from various segments multiplied by the unit cost of providing resources is the total cost of operating the PTB at each instant of time. If all the conditions are met, the operational and maintenance cost would be a function of demand distribution. Therefore, one of the objectives of this research, which was to produce a variable time-cost plan as opposed to a fixed cost plan, is achieved. This optimization procedure, if applied properly, will result in significant savings on the operation and maintenance costs of PTBs over long time periods. However, for the short term, it is recommended that the results of the optimization program be implemented on the site by a flow management and control model which will be discussed in Chapter 7. In another words, the existing resources and the traffic flow could be managed in such a way to provide a diagram as close to the optimum time-resource plan as possible. It should be noted that short time implementation is more difficult due to the existence of various constraints, e.g. physical layout, lack of flexibility, established traffic pattern, etc. Chapter 6 brings all the components of the resource utilization model together and demonstrates two case studies.

Chapter 6

Component Synthesis and Model Testing

6.1 Overview

A methodology for optimum resource utilization of a typical airport passenger terminal was proposed in Section 3.3. Due to some difficulties in application of the methodology to a real world terminal, the methodology was converted to a resource utilization model using mathematical simulation approach as shown in Figure 3.2. The PTB optimum resource utilization model, discussed in Section 3.4., consists of a set of components and submodels. Issues associated with some of the components such as: stochastic demand, operational policies, and levels of performance, were discussed in Chapter 3. The airport PTB was simulated using an object oriented simulation tool. The simulation model and its evaluation were discussed in Chapter 4. The optimization submodel consists of the theory and a heuristic solution algorithm was developed in Chapter 5. This chapter re-assembles all the components and

submodels developed in the previous chapters. Figure 6.1 illustrates the synthesis of all components and submodels which constitute the optimum resource utilization model. The final stage of the model development includes a testing procedure to assess its potential for application. To illustrate the application of the overall model, two case studies are given.

6.2 PTB Case Studies

This section demonstrates the application of the PTB optimum resource utilization model by examining two medium sized Canadian airports, i.e., Macdonald Cartier International Airport. (MCA) and Mirabel International Airport (MIA). PTBs of these two airports process almost equal number of passengers annually, i.e., 2.5 million in 1992 (Jones, J., et al, 1992). However, the operating cost of the PTB at MIA is more than two times higher than that of MCA, as shown in Table 1.2. Since the case studies are intended to be illustrative of the resource utilization model, some simplification of the process is not only acceptable but desirable. It is also necessary to make some assumptions concerning parameter values, since their accurate determination would require extensive data gathering. The collection of data was prevented by the magnitude of resources, e.g., time, staff, money, required for a comprehensive survey. The implementation part of the model, i.e., allocation of resources using flow management and control techniques was excluded from the case studies and is discussed in Chapter 7.

Figure 6.1: The PTB Optimum Resource Utilization Model

6.2.1 MCA Case Study

The weekly schedule of MCA was analyzed in seven separate daily schedules for seven days of the week. The daily flight schedule represents the immediate and current 24 hour period of flights planned. The load factors were estimated based on the average values obtained from Statistics Canada. The operational policies used were based on the information obtained from the PTB manager. The simulation model was calibrated for MCA and was run for each of the seven daily schedules. The PTB area was divided into eleven segments of passenger processing and handling. These segments include: ticket lobby, security, departure and arrival lounges, domestic baggage claim, international baggage claim, Primary Inspection Lines (PIL), customs and immigration, arrival lobby, greeting area, and concessions. The population statistics were collected for each of those ten segments, for every day of the week while the simulation was running.

The PMFs were developed by writing a computer program which read the files containing the population statistics at any instant of time. The program then calculated the probability of having any number of passengers according to its frequency within each time period, e.g., one hour. The output of this program would be another file containing the population and its probability for each segment, i.e., PMF distributions of demand. Figure 6.2 and 6.3 illustrate an example of PMF for two different segments of PTB, i.e., queues at security and population at concessions, during one peak hour period. The PMF distribution varies among segments of the PTB from time to time.

The PMF files were used as input to the optimization program. The accurate determination of real values of α_j and β_j require a comprehensive survey and data collection. The value of α_j is based on the airport location, types of services the airport offers,

Figure 6.2: Typical PMF of Queue Length at Security Area of PTB at MCA

Figure 6.3: Typical PMF of Population at Concessions Area of PTB at MCA

and its value can be found by going through a cost allocation procedure as described in Section 5.3. The value of β_j is also depends on such factors as: passengers type, airport monopoly, geographical location, operational policies, etc, and its value can be obtained by different types of surveys, e.g., interviews, questionnaires, etc. For the purpose of this case study the relative value of α_j over β_j was assumed. For example, assuming $\alpha_j/\beta_j = 2.0$, means that the cost of providing one unit resource more than what is required is twice as much as providing one unit less than what is required.

The level of service criteria was assumed to be the quantitative measures such as congestion and queue length. These criteria were further translated to space provision criterion as an indicator of service quality. The value of θ_j , i.e., space provision, was obtained from LOS standards, developed by Transport Canada (1979), for different segments of the PTB. Since the *available space* was recognized, by most of the researchers, to be a good quantitative criteria for LOS assessment, it was used as the required resource for passenger processing (TRB, 1975; Transport Canada, 1979; McCullough and Roberts, 1979; TRB, 1987; Ashford, 1988; Omer and Khan, 1988; Seneviratne and Martel, 1994). Other resources such as; staff, utility, etc., are also based on the available space. Moreover, most of the operating expenses can be converted in terms of $\$/m^2$.

Figure 6.4 illustrates the variable time-space diagram for the whole PTB. This is only the optimum required space for passenger processing. The space for facilities and equipment are not taken into account. To get the total required space for the PTB, the equipment and facilities space should be added to get the values obtained from optimization model.

It should be noted that the available total passenger processing and equipment space at MCA is about 14,000 m^2 . Moreover, for each segment of the PTB, the population

Figure 6.4: Weekly Time-Space Diagram of PTB at MCA

statistics of seven days were combined into a single file to develop a weekly PMF. The thick line in Figure 6.2 shows the optimum required spaces for a weekly PMF. This line represents the optimum time-space diagram if the analysis period were assumed to be one week. One can develop time-resource plans for as short as one hour, to as long as one year depending on the accuracy of the desired results. Appendix E illustrates a sample of computer output of the resource utilization model for each segment of the PTB during each time period. This output includes the time period, segments of the PTB, minimum total over- and under-supply cost, optimum occupied space, and a hypothetical supply cost of the optimum space.

The profile of the traffic for a typical day, month, and year are illustrated respectively in Figures 6.5, 6.6, 6.7. In all these graphs, the horizontal axis shows the time and the vertical axis represents the number of passengers present at that time period. The daily profile of the traffic is similar to the time-resource diagram developed by the optimum resource utilization model. It shows that the required resource is a reflection of demand placed upon the system. The philosophy of the optimization is also to balance the demand and supply in such a way to minimize the extra cost of over- and under-supply.

6.2.2 MIA Case Study

Although the total volume of passenger traffic at the MIA is about the same as at MCA, the distribution of traffic is significantly different. The passenger traffic at MIA is more peak oriented than that at MCA. The PTB operation at MIA is also different due to the use of Passenger Transfer Vehicles (PTVs) instead of loading bridges. Since the PTBSIM was calibrated using MCA data, minor changes were required in the two submodels to account for the change in PTB operation at MIA. The change in

Figure 6.5: Daily Profile of PTB Passenger Traffic, MCA

Source: Transport Canada, 1992

Figure 6.6: Monthly Profile of PTB Passenger Traffic, MCA

Source: Transport Canada, 1992

Figure 6.7: Annual Distribution of PTB Passenger Traffic, MCA

Source: Transport Canada, 1992

the passenger processing was modified in the simulation model and the outputs were validated against field data collected at the PTB for two consecutive days (August 6 to 7, 1994). Due to the large size of the PTB, a comprehensive survey requires great effort, e.g., staff, time, and financial support. The lack of comprehensive data on PTB segments has prevented an attempt to validate PTBSIM against behaviour of PTB as a whole.

Therefore, it was decided to observe certain parts of the PTB for some periods of time and compare them with the simulation outputs. A sample of simulation outputs and data collected at the PIL on Sunday (August 7, 1994) and at the international baggage claim on Saturday (August 6, 1994) are shown in Figures 6.8, 6.9 respectively.

Although the survey was very limited, the graphs illustrate a reasonable agreement between the field data and model outputs. Although the PTBSIM generated different number of persons, the shape of the two curves suggest a good level of similarity. These differences are attributed to the assumptions made with regard to PTV travel time from aircraft parking slot to the doors of the PTB, and the variability of the number of servers in the processing areas, greeter and meeter/passenger ratio, passenger arrival distribution, load factor, service time, etc. None of these assumptions were validated against field data due to the lack of comprehensive data base.

It is also reasonable to attribute the discrepancies between the two curves to differences in the actual and planned arrival/departure times. The input data for the simulation was based on the planned time while the observed data were based on the actual arrival/departure time. However, a regression analysis, utilizing the least square method, on the simulated outputs and observed data at those two segments, e.g., PIL, baggage area, were performed. The correlation between the observed and simulated data was about sixty percent, ($r = 0.61$ for baggage area and $r = 0.57$ for

Figure 6.8: Comparison of Observed Data and Simulation Outputs, PIL Area, MIA

Figure 6.9: Comparison of Observed Data and Simulation Outputs, Baggage Claim Area, MIA

PIL area). Taking into account that the PTBSIM was not developed to specifically simulate the MIA, the results were assumed reasonable for the case study.

The weekly aircraft schedule was obtained from the airport authorities. The original schedule contained both cargo and passenger flights. The schedule was then modified to include passenger flights only for different days of the week. The PTB area was divided into eleven segments such as: PIL, international baggage claim, customs, immigration, the "points", arrival lobby, greet area, ticket lobby, security, departure lounge, and concessions. Some of the PTB segments in MIA differ from the segments of the PTB in MCA. This is due to the type of passengers that each airport processes, i.e., MIA mainly international and MCA mainly domestic passengers. For example there were only two domestic flights with a small aircraft at MIA. As a result, the domestic baggage claim area was almost vacant and was not considered as a main segment of the PTB. In contrast to the MCA, the PIL area and immigration area of MIA were busy most of the time and were taken as one of the main segments for analysis.

Population statistics were collected for eleven segments for each day of the week. In addition to a separate data file for each segment, on each day, statistics of seven days were combined to get a weekly PMF for each segment. The PMFs were developed from the passenger flow outputs of the simulation, as previously explained in the MCA case study. The value of θ_j which indicates the LOS criteria was obtained from Transport Canada documents. The relative value of α_j over β_j was also assumed. These data were used as input to the optimization model. The output of the optimization model is variable time space diagram for different days of the week. Figure 6.10 shows the optimum required resources, i.e., passenger processing space, for the PTB for different days of the week. The fixed facility and equipment spaces should be added to the spaces obtained from optimization. At present, the existing spaces for passenger

Figure 6.10: Weekly Time-Space Diagram of PTB at MIA

processing and equipment is about 45,000 m^2 . The thick line shows the weekly diagram as a result of weekly PMF. The time period depends on the level of detail and accuracy one may require from the analysis. Figure 6.11, 6.12, 6.13 show the passenger traffic profile for a typical day, month, and year respectively. The traffic pattern at MIA will be significantly different in winter from summer. In MCA also the winter schedule would change from the summer schedule.

Using the optimum resource utilization model, one can optimize the PTB resources according to the variable demand placed upon the components of the PTB. As shown in Figure 6.8, the MIA time-space plan can represent the daily profile of passengers at the PTB. It should be noted that the space obtained from the optimization is passenger processing space and does not contain the facility or equipment space. It can be easily adjusted since the equipment space is a fixed space according to the equipment type. Using the ratio of staff/passenger as the LOS criteria, one can find the variable time-resource plan in terms of optimum number of staff required. However, one can convert the resources to cost values and compare with the existing condition at the PTB to see the savings as a result of optimization. Moreover, since the simulation and optimization models are stochastic, then the most probable conditions and scenarios can be taken into account while performing the analysis. Therefore, one may manage the available resources in such an efficient way so as to minimize the under and over-supply cost.

So far, the two submodels of the PTB optimum resource utilization model, i.e., the simulation model, and optimization model have been developed. Major issues involved in other components of the overall model have also been discussed. The overall model was tested for two different airports. The results of the analysis part of the model would be a theoretical time-resource plan based on the minimum under- and over-supply cost. It should be noted that no judgement on the operation of these

Figure 6.11: Summer Daily Profile of PTB Passenger Traffic, MIA

Source: Transport Canada, 1992

Figure 6.12: Monthly Profile of PTB Passenger Traffic, MIA

Source: Transport Canada, 1992

Figure 6.13: Annual Distribution of PTB Passenger Traffic, MIA

Source: Transport Canada, 1992

two airports should be made at this stage. This is due to the fact that the values of variables included in the optimization process are hypothetical. The intent here was to demonstrate how the model can perform under different conditions and what the results look like. The application part of the model deals with the implementation of the theoretical outputs. The implementation of the analysis part as well as some other potential applications of the overall model are discussed in Chapter 7.

Chapter 7

Applications of the Resource Utilization Model

7.1 Overview

The primary objective of this research was to develop an optimum resource utilization plan for an airport PTB. The mathematical resource utilization model, developed in Section 3.4, consists of a set simulation and optimization models that can be used to supplement the existing analysis for the planning and design of airport PTBs. The resource utilization model was developed for application in airport PTBs, which typically handle the largest pedestrian flow in transportation terminals. The general rationale and structure of the model is adaptable to other passenger terminals, e.g., bus, train, etc. through the development and substitution of the appropriate input requirements such as LOS criteria and calibration factors. The optimum resource utilization model can also be applied in air cargo terminals. Application of the model in cargo terminals may be more effective due to the fact that cargo traffic can be

managed and controlled better than the passenger traffic.

Two broad applications of the resource utilization model are presented in this chapter, i.e., 1) planning and design, and 2) operational planning. The first case involves the determination of design requirements for an airport PTB planning scenario. The second case is a new approach to operational planning for resource allocation. The model is one of determining the optimum required resources for a variable traffic demand at the desired operating LOS.

7.2 Planning and Design

The resource utilization model may be used for determining design requirements when planning a new or expanded PTB. In the literature, planning was defined as the process of determining the future requirements of the facility and the time that these requirements should be met. Design is the process of translating a planning concept into a realizable form, usually expressed in the form of engineering drawings, graphic illustrations, and specification models. Although there is a good source of information on the planning and design of PTBs, this information mainly includes the widely used design manuals from various sources as well as more detailed consideration of individual elements of the PTB system. Some of the design manuals are; *The Apron and Terminal Building Planning Report* by the Federal Aviation Administration (FAA, 1975), *Airport Terminal Reference Manual* by the International Air Transport Association (IATA, 1995), *Airline Aircraft Gates and Passenger Terminal Space Approximation* by the Air Transport Association of America, (ATAA, 1977), and Transport Canada documents (Transport Canada, 1982, 1986).

The design manuals provide the planner with the means to determine the total space

required, the number of gates, or even the floor space for each component. In general, the space requirements are given in charts and nomographs that give a unique result to any given set of conditions. In terms of cost, only construction costs are addressed in one of those manuals (FAA, 1975). The manuals do not permit the planner to take into consideration the operating cost and to trade off facilities against LOS, or indeed to incorporate any local conditions into the analysis. However, the manuals mentioned that consideration should be given to cost savings and energy conserving when designing the PTBs

The current planning approach is based on a single measure of traffic, i.e., peak hour volumes. The flaws with this peak hour concept were discussed in Section 1.3. Therefore, the determination of the likely variation and characteristics of the future demand on the system should be taken into consideration when developing methods for determining space requirements. Moreover, from a different perspective, it should be determined how well the planning and design process will serve the ultimate users of the PTB system, namely the passengers. These two perspectives, i.e., efficient use of resources, and levels of performance are not necessarily incompatible. These two aspects are included in the optimization model while the final output is based on the minimum over- and under-supply cost. The application of the resource utilization model in the planning process is shown in Figure 7.1.

In the proposed planning and design process, a range of nominal schedules, based on a set of scenarios, with reasonable ranges both for the traffic levels and for variables which may affect the design, are produced to generate the demand placed upon the PTB system. The PTB is defined in terms of various service segments and flow paths connecting these segments with the landside and airside parts of the airport. When the layout of the simulation model is built, the simulation model is then run to provide the user with a range of information on the estimated behaviour of the

Figure 7.1: Proposed Planning and Design Procedure

PTB in terms of passenger accumulations and delays in desired segments of the PTB. This information is collected and stored in different data files and the PMFs are built based on these files for each segment during the 24 hour period for any given schedule. These PMFs associated with unit costs of over- and under-supply and LOS criteria would be input to the optimization model.

The optimization model is then run to provide the theoretical time-resource diagrams for each set of inputs. For instance, the user will find the optimum required passenger processing space throughout the operating day or week for some typical aircraft schedules. These typical aircraft schedules will represent the most likely scenarios within the planning horizon. The planner may divide the planning horizon to several time periods, e.g., one to five years each, and perform the analysis for each time period. For example, daily PMFs can be developed instead of hourly PMFs, and the variable time resource diagram can be found for a typical month or year. The length of time periods depends on the level of detail and accuracy required by the planner.

After calculating the theoretical time-space diagrams for the most probable alternatives, a probabilistic cost benefit analysis, e.g., risk analysis approach, may be applied to find the optimum alternative for each time period. By using risk analysis, airport planners can contemplate and confront the future uncertain environment in which airports should operate. Instead of analyzing for one scenario, several scenarios with associated probability of occurrence are taken into account. Thus a probability distribution of alternatives with associated costs and benefits would be analyzed and the least total cost scenario can be found. The essence of this exercise is to provide a means by which the decision maker can review the most likely possible future scenarios and choose the optimum ones for further adjustment. The adjustment includes adding facility and equipment spaces and taking into account the possible site constraints.

The facility and equipment spaces are fixed spaces which can be added to the processing spaces. After adjusting the theoretical time-space requirements for local conditions, type of facilities, and equipment, a more practical time-space diagram is obtained. There may be several time-resource plans for various stages of development. For example, an optimum time-space plan can be found for say every four year period. These time-resource plans need not necessarily be the same. The PTB should be designed in such a way that it can be operated according to different practical time-space plans. For example, instead of designing a fixed amount of space for each activity inside the PTB, the PTB can be designed as one block of space with movable partitions. In this concept the overall space would be managed among various service segments based on the real-time traffic demand placed upon these segments. The aforementioned concept can be used more effectively in air cargo terminals. However, further research is needed to investigate more innovative approaches for flexible PTB design and operation.

Although the economy of operation falls into the realm of operational planning, the design concept should have the capability of accommodating variable operations plans. The PTB may be built based on the maximum required spaces, its design concept should be flexible enough to permit for a time variable operations plan. It should be noted that the maximum required spaces from the time-space diagram is different from the existing peak hour design maximum. According to the existing peak hour approach, each element is designed based on its peak load and the sum of spaces for all elements would be the total required space. Since the peak loads for all segments do not occur at the same time, the PTB is under utilized most of the time. While in the proposed process the time dimension is taken into account and an optimum space value for each time period is obtained taking into account the simultaneous demand on all segments of the PTB. In another words, the resources are found in proportion

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PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISION^{SM} RESOLUTION TARGETS

to the number of persons who are simultaneously present in all parts of the PTB.

For an existing PTB, the same aforementioned process can be applied to find the areas which require improvement. By examining different alternatives, it may not be necessary to expand the facility, but by re-arranging the time space activities, e.g., multi-purpose utilization of space, the problem may be resolved. To clarify the time-space concept, an example from real life, i.e., PTB at MIA, is given.

The PTB at the MIA was designed to provide a short travel distance between the passenger entry and exit points. It was believed that this concept would result in a shorter travel time for passengers in the PTB. Unfortunately, the PTB has experienced delays and congestion in the deplaning segments for many years. Although the queuing and delay problems can be attributed to the peaking characteristics of the airline schedule, these problems are exacerbated by the physical layout as reported by J. P. Braaksma & Associates Ltd. (1994).

Figure 7.2 shows the deplaning section of the PTB at MIA. As shown in the figure, the initial surge of passengers quickly fills the available space in the pre-PIL area. The queues in the pre-PIL area grow so quickly that they block other passengers disembarking from the PTVs. These queues quickly move to the baggage claim area. Since passengers have to wait for their baggage to arrive, the baggage claim area becomes very congested while there is almost nobody in the pre-PIL area. After claiming their baggage, passengers move through the "point" which is located between the boundary of the baggage claim area and the secondary inspection area. The queue at the point also extends past and around carousels. The queues become longer since passengers loaded their baggage onto carts.

The passengers and their baggage move to the secondary inspection area. The queue for the secondary inspection area is long enough to conflict with passengers passing

Figure 7.2: Deplaning Section of PTB At MIA, Source: Braaksma, J.P., 1994

through the point. Since the processing time at customs is longer than at the PIL, the queue moves much slower. This causes the customs area to become so congested that considerable amount of jockeying is required to clear the counter area. This is at the time where there is no queue at either pre-PIL or baggage claim area. Studies undertaken to identify the problem conclude that the overall space for the traffic volume is more than required. The problem is with the space management rather than overall space. Several design principles were suggested such as; good use of space, good operational capabilities, flexibility, simple flow lines and reasonable cost. Based on these criteria, several concepts were developed to streamline the passenger flow and mitigate the queuing and delay problems. All the concepts were space management rather than capacity expansion.

This example reaffirms the thesis idea of multi-purpose utilization of space and taking time dimension into the design process. One solution based on the thesis philosophy could be to design the PTB with mobile PIL and custom booths in such a way that they can be moved around. It is clear that these mobile booths can still function and keep whatever equipment they require, thanks to the telecommunication technology. In this concept the space can easily be adjusted based on the traffic loads on different segments of the PTB. In another words, the space would be managed in such a way to accommodate the variable demand at each segment of the PTB. This will be discussed more in the operational application of the model.

7.3 Operational Planning

A potential application of the optimum resource utilization model is to develop a variable time-resource plan based on the demand placed upon the PTB system. The

model suggests the optimum resource value to be supplied at any time for each segment of the PTB. Then the operator would be able to control the allocation of its resources among different segments of the PTB. The whole resource utilization model can be used to provide an operational plan one day in advance, given the airline schedule.

Since the simulation model provides a real-time interactive information about different segments of the PTB, it may be used as an educational tool for new staff. One can observe the consequences of changing some of the variables which will play an important role in the PTB operation. The simulation model may be used as an operations tool for the PTB manager or operating staff to help them maintain a reasonable LOS throughout the PTB. This can be done through either PTB resource allocation or passenger flow management and control or both, Box 10 and 11 of Figure 3.2. In the first scenario the operator may take space from under-utilized segments and allocate it to the over-utilized areas, i.e., dynamic allocation of resources. It will require the PTB to be equipped with some sensors and actuators with which, the operator can control the allocation of space, e.g., close some areas and open others.

The overall optimum resource utilization model can be used as a tool to estimate the total number of personnel required to run the PTB. In other words, a hiring policy can be developed based on the variable time resource diagram obtained from the optimization model. Since the number of personnel to run the PTB is different from time to time based on the traffic volume, it may be economically cost effective to hire multi-skilled personnel which can perform two or more tasks. It should be noted that multi-skilled personnel may be more expensive to hire. However, the marginal cost of cross utilization of personnel should be taken into consideration when performing the cost benefit analysis.

Although the implementation of dynamic resource allocation associated with capital cost, it will be justified over long term especially in large airports with peak oriented traffic. While in the second scenario, i.e., flow management and control, the operator may control the movement of passengers within the PTB. This also can be done by an information dissemination technique throughout the PTB. Information dissemination could be through visual, verbal, thermal, auditory, olfactory signs or messages. This subject is discussed in more detail in the PTB flow management and control section, i.e., 7.5.

7.4 Flow Management and Control Theory

One of the objectives of the study was to propose a real-time flow management and control system, Box 10 of Figure 3.2, which can implement the results of the analysis part of the resource utilization model. Before proposing the PTB flow management and control model, some preliminary initiatives of the flow management and control application in the landside section of the airport is briefly discussed. Other areas in which this theory has been applied are: Aircraft traffic, urban transportation, water and waste water treatment and distribution, computer communications, etc. These applications of the theory are discussed in Appendix I.

7.4.1 Flow Management and Control In Airport Landside Area

Unlike the airside part of the airport, current knowledge about landside operation is poorly developed. Reliable comparative statistics on operating conditions in the

landside are scarce. For example, PTB utilization and staffing statistics are often not available. The design aspects of the PTB are well researched and approaches for conceptual and detailed design have been developed over the years (references are listed in the planning and design section of the Bibliography).

In contrary, the operational aspects of the landside has not been developed so far. A few airline and airport operators have tried to develop some computer models in support of management of day to day operations of large scale terminals. For example, a gate assignment display system has been developed by United Airlines to help manage the assignment of aircraft to gates at Chicago/O'Hare airport (Odoni, and deNeufville, 1990). These existing tools are of limited scope due to the fact that they deal with only one component of the PTB and very specific aspects of its operation. However, they may presage a future generation of models with wider scope. Mathematical models useful in portraying landside operations have not been developed or not available for the public use. Quite recently the Port Authority of New York and New Jersey is planning to develop a traffic management and control system for the landside portion of the Newark International Airport (Carris, 1992).

At present, a control desk located in the airport administration building of JFK International Airport serves as a control centre of the whole landside area. The development of this control desk has been a response to put all incoming information into the same location for coordinated action by the staff. The existing system controls the operation of shuttle buses, parking, the roadways, and sign services. The new proposed traffic management and control system will use IVHS technology as a part of an overall traffic management strategy. Strictly speaking, the traffic management and control in a systematic fashion is very limited or may not exist. In the PTB area, a few computer simulation models have been developed for detailed design process. These models also require a high level of detail in representing terminal operations.

However, there is a strong need for management and control models which combine the detailed design simulation models with optimization algorithms and/or expert systems.

7.5 PTB Flow Management and Control Model

The PTB system consists of mainly two category of entities, i.e., resources, and passengers. To optimize the system's operation, these two entities should be involved. The optimum required resources are found through the optimization model and a flow management and control technique is needed to allocate the optimum resources based on the variable demand on the system. The analysis part of the research takes into account the probabilistic nature of the demand, cost of over- and under-supply, and LOS criteria, to provide a list of required resources for each segment at any instant of time. The application part of the research is developing techniques to apply the theoretical numbers in the field. By having flow management and control techniques, the PTB operator, would also be able to respond to pre-planned or spontaneous events. The spontaneous events may be equipment breakdown, urgent landing, inclement weather, sudden schedule change, early arrival or late departure, etc. Since each airport has its own specific characteristics and set of constraints for model application, it was decided to develop a generic model which can be adjusted for any airport.

Figure 7.3 illustrates the generic form of an integrated PTB flow management and control model. The proposed PTB management and control model has been separated into two sections, the management section and the control section. The structure of each section could be one person or a team depending on the PTB size.

The management section assumes prior knowledge of any event. This section has

Figure 7.3: PTB Flow Management and Control Model

also access to the available historical and existing physical and operational data. It utilizes support activities such as planning, data base design, scenario generation, modelling, and evaluation. The main task of this section is to provide long term operational planning schemes and procedures. By obtaining the required information and a seasonal or daily flight schedule, initial planning is performed. As a result of this initial planning, different scenarios may be generated. These scenarios can be modeled using the simulation model. The optimization process is performed using outputs of the simulation model and some cost items. Finally the management section will evaluate the alternatives according to some performance measures and forwards the best alternative to the control section as the PTB Utilization Plan.

The PTB control section works on the basis of a given optimum utilization plan in which different segments of the PTB would function in an efficient manner. This section is also activated by an unanticipated event such as; inclement weather, sudden schedule change, early arrival or late departure, equipment breakdown, urgent landing, terrorism, etc. The control section will be notified about the event by its support elements in the field. There may be some preliminary analysis regarding the type, location, and severity of the event. The control support system may consists of personnel, actuators, and sensors present in the field to transfer the information. The control section using real-time information from its support system makes the decision and activates the revised utilization plan. The revised utilization plan is implemented through the information system which is connected to different segments of the PTB. Some segments of the PTB may be monitored, by the control section, at the same time to observe the impact of decisions already made. In addition to the PTB segments, information will also be disseminated to other major parts of the landside area such as; ramp and apron management, airline system, etc. The decisions of the control section are also forwarded to the management section as a feed back for the

analysis of another possible event. These decisions and analysis results may be stored in the data file for future use.

Although all parts of the PTB management and control model, illustrated in Figure 7.2, are in separate blocks, it does not mean that they are temporally or spatially separated. Some of these functions can be performed at the same time or at the same place. The whole model is based on the management and control concepts which permits complex systems to function in a coordinated way during predicted or unpredicted situations. The model has mainly two central functions: information collection and dissemination, and resource allocation. Information is collected, through support systems, e.g., sensors, detection loops, actuators, etc., installed in major segments, processed, and disseminated to where ever they are needed. Resource allocation is a decision making process to take resources from where they are no longer needed and direct them to wherever the need arises. To clarify the concept of a PTB management and control center, an application case is given as an hypothetical example.

7.5.1 An Operational Example

Suppose a weekly schedule is given for a peak oriented passenger traffic airport. The management section will revise the weekly schedule to provide daily schedules which are the heart of PTB day to day operations. Scenarios are generated and modeled using the data base and the simulation model. Applying the performance measures and cost items, the optimization model is activated. As a result, a resource utilization plan for each day of the week is given to the control section. Therefore, the control section has knowledge about the type and the magnitude of resources required for each segment at each instant of time. If everything occurs as it were planned by the management section in their analysis, the utilization plan can be programmed and

be implemented automatically. However, in the airport industry, not everything goes the way it was planned. To clarify the problem, a hypothetical example is given.

Consider aircraft AC'100 scheduled to unload its passengers at time t_1 . Due to some unpredicted reasons aircraft AC'200 has to unload its passengers at the same time, i.e., t_2 . Assume that the passengers' walking time from AC'100 to the first processing facility is t_w . At time $t = t_a$, the control section is faced with an over-loaded segment of the PTB which was not expected by the management section. The control section must decide whether to allow the unloaded passengers to go to the first processing facility, e.g., PIL, or take resources, e.g., space from unutilized areas and allocate them to the overloaded area, or keep the passengers in a hold room until some later time t_1 , ($t_1 > t_a$). The graphical illustration of this example is shown in Figure 7.1. The controller's decision is based on the following factors:

- the capacity of the corridors and processing unit at time t_a ,
- the number of passengers waiting in queues in front of the processing facility,
- the degree of congestion in the corridors as well as in the processing area, and
- the time at which passengers from other aircraft are already unloaded and are walking towards the processing facility.

If at time t_a it were possible to have all the aforementioned information, then one could decide whether to send the passengers ahead or keep them until the condition at the processing facility gets better. It should be noted that some of this information such as the capacity of the corridors, or the walking time to the processing area are already available. The only real-time information that should be sent to the controller is the number of passengers or the degree of congestion. This can easily be done by

Figure 7.4: Illustration of Passenger Flow Control Example

installing sensors or counters at some points of interest and reporting the data through cable to the control section. The control section can also use the same equipment to implement their decisions regarding resource allocation or flow control. For instance, in the case of over crowding, it may be necessary to keep the passengers of aircraft AC'100 in an ancillary area and postpone the release time to t_i ,

$$t_i = t_a + w_i - t_w \quad (7.1)$$

where,

t_i = time to release the passengers towards processing unit

t_a = arrival time of passengers from the aircraft to the gate area

w_i = queue dissipation time at the next processing unit

t_w = walking time from hold room to the next processing unit

The same process can be repeated for the next service area, e.g., baggage claim. If all of the baggage claim areas are already occupied, sending more passengers ahead will make the situation worse. Therefore, the control section would decide, based on the information from the baggage area, whether to allocate more space from underutilized areas and then release passengers or keep them in a less congested place, e.g., ancillary hold area. The criterion for the decision maker in the baggage area may be density. Density of the area can be defined as follows:

$$MOD = \frac{NPI_t - NPO_t}{A_t} \quad (7.2)$$

where,

MOD = module of the specified area, m^2/pax .

NPI_t = number of passengers entering the area at time t

NPO_t = number of passengers exiting the area at time t

A_t = space available at time t .

Therefore, the controller can decide to send the passengers to the area if the density is lower than a pre-specified value or rearrange the space to bring the density down. On a real-time basis the operator has the number of passengers present at any area at each instant of time. The same process can be repeated for the next processing unit, e.g., customs. Passengers are allowed to go to secondary inspection customs whenever one of the two conditions are met, i.e., waiting time is less than a certain time or density is smaller than a pre-specified value. There are other options that the controller may chose, e.g., activation of back-up servers or reassignment of allocated space.

The same unanticipated event may happen in the enplaning section of the PTB. Assume that the control section is implementing the resource utilization plan developed by the management section. If due to some reasons, e.g., problems in the airside, one or more aircraft cannot take off, the control section is faced to change the utilization plan. For example the resources in the less utilized areas may be taken and allocated to the over loaded segments. If the resources in the departure lounge are utilized to its maximum value, passenger flow control may be applied to prevent the LOS deterioration or system breakdown.

Passengers arrive at the PTB sometime before flight departure. The lead time depends on the type of passengers, e.g., international, domestic, business, recreational. Since the departure lounges are already congested due to the delay in the aircraft take off, the departing passengers can be sent to other segments of the PTB or to a more pleasant area, e.g., ancillary hold area, concessions, etc. The boarding time and the security clearance time will be announced or displayed, through variable signs or messages, later by the control centre. At the same time the density and queue clearance time at each facility can be checked against level of service criteria. If those criteria are violated, the controller will consider some control options to maintain the desired level of service. Some of the actions which the control section may take are as follows:

- re-deployment of some employees,
- reassignment of space,
- activation of back-up servers,
- modification of passengers' flow by assigning them different routes
- change in gate assignment, and

- utilization of less utilized spaces.

Another application of the PTB management and control center would be in airports with two distinct and temporally separated passenger traffic peaks for arrivals and departures. For example, airports which experience a morning arrival peak and afternoon departure peak. In these cases the arrival resources, e.g., space, equipment, could be converted to serve the departure passengers in the afternoon. If the philosophy of resource management and shared use is accepted, the PTB utilization can be significantly increased in those airports. In this example, instead of having a fixed space allocation for the enplaning and deplaning section of the PTB, the space would dynamically be allocated based on the passenger traffic load on each section. This management technique can also be expanded to other airports with monthly or seasonal peak traffic. There are capital and operating costs associated with the feasibility concept. However, the associated costs would be much lower than the benefit gained throughout the PTB life.

It should be mentioned that at present most of the Canadian airports are underutilized, i.e. 94 percent of all air passenger use only 26 of 726 airports (Transport Canada, 1994). It became clear that considerable amount of resources were used to support a large network of airports that serve only six percent of the air passengers. Under the National Airports Policy of 1994, all the operational subsidies for regional and local airports will be phased out over five years. In addition, ownership of regional, local and other smaller airports will be transferred to interested regional groups such as provincial/local governments, airport commissions, private business and others. The new owners will be able to make arrangements about the operation and management of the airport that can serve the community in a more commercial and cost-efficient manner. Moreover, other transportation modes can be

locally adjusted to air transportation requirements making easier overall integration of transportation planning, design, operation and management.

The idea of integration and shared use of resources is more practical if both airports and facilities of other modes are being built and operated by a single authority. Single authority of different modes of transportation may provide an opportunity in which transportation resources can be managed and utilized more efficiently. The result of the resource management and shared use application would be savings in operations and maintenance cost, Box 12 of Figure 3.2. The saving would be noticeable if the procedure applied properly and the savings accumulated over long periods of time. The details of operations and maintenance cost savings are discussed in Section 7.6.

7.6 Operations and Maintenance Cost Savings

There are many organizations that contribute to the functioning of the airport PTB. They may be private firms or public agencies . The type and the duties of each of those groups may be different at each airport. The administration of the airport is done by the airport authority which may be a public agency such as a city department, federal government, or special purpose regional agencies or private ventures. Although other groups become involved at the PTBs in the execution of their normal functions, operation of the PTB from a property management point of view is the responsibility of the airport authority. The airport authority would like to get the best of what exists and to obtain an increasing rate of return from the capital invested. Although airport operators may not participate in those aspects of passenger handling such as ticketing, checking and sorting baggage, they will provide the space and equipment which is required for the job. Therefore, this research will focus on the operating

expenses incurred by the airport authorities.

In order to determine the variables to be included in the operations cost function, it is necessary to examine the operating expenses of PTBs. The problem with this type of analysis is the lack of suitable data which are not publicly available. In general, airport authorities record their accounts in two different ways. The first is the object or nature of the expense, e.g., salaries, and second is the function or purpose, e.g., maintenance. These are called objective and functional accounts respectively. However, suitable data has been obtained for a number of airports through comprehensive search and requests from authorities in condition that the details of the data be kept confidential.

Table 7.1 shows the total and unit operations and maintenance costs for a number of selected airports. In order to obtain an understanding of the costs associated with the operation of PTBs, a finer division is needed. Table 7.2 shows the PTB cost items for a typical airport throughout the years. The O & M costs are categorized from a property management point of view. To obtain the total operations costs, depreciation, and cost of capital should also be included. The airline's passenger processing costs are not included in these categories. Joint costs such as insurance and personnel overhead are not specifically recorded for the PTB unless an allocation has already been made by the airport authorities. Table 7.3 illustrates cost items of a typical PTB in more detail. There is no unique way of classifying the cost items in such detail as shown in Table 7.3. These detail costs are case sensitive and vary from airport to airport.

By analyzing the cost items it can be concluded that the O & M costs are generally more influenced by the amount of space provided than by the passenger volume. For instance, the staff levels and equipment required to clean and maintain the PTB is a function of the size of facilities. Security costs will be effected more by the facility size

Airport	Total O & M Costs	Total PTB Gross Area	Annual Pax.	\$/m²	\$/Pax
Macdonald Cartier	4,143,969	35,042	2,495,700	118.25	1.66
Dorval	14,600,528	97,601	5,563,300	149.61	2.62
Mirabel	11,644,954	101,663	2,424,400	114.62	4.80
Pearson	50,688,322	N/A	19,118,900	N/A	2.65
Castlegar	772,000	1,423	84,200	542.51	9.16
North Bay	786,000	1,807	81,800	434.97	9.60
Penticton	771,000	1,565	69,700	492.65	11.06
Port Hardy	437,000	1,413	20,100	309.27	21.7
Prince Rupert	570,000	1,239	112,600	460.05	5.10
Smithers	349,000	814	51,500	428.74	6.77
Terrace	539,000	1,999	83,200	269.63	6.47
Timmins	801,000	925	159,600	865.94	5.01

Table 7.1: PTB Unit O & M Costs For Various Airports

Source: Transport Canada, 1993

Cost Elements	1990/91	1991/92	1992/93
Heating & Air Conditioning	290,500.0	292,500.0	308,987.0
Cleaning	522,839.0	553,800.0	632,190.0
Water and Power	600,400.0	674,200.0	597,872.0
Maintenance	851,500.0	855,000.0	937,273.0
Security	503,625.0	395,800.0	406,400.0
Site Administration	413,828.5	415,695.0	432,408.3
Grants in lieu of Taxes	501,500.0	535,636.0	588,660.6
Land Rent	239,905.8	239,405.8	239,405.8
Total O & M Costs	4,102,172.8	3,962,536.8	4,143,696.7

Table 7.2: Operation and Maintenance Costs For MCA in Different years

Source: Transport Canada, 1993

than the passenger flow, since it may be necessary to patrol infrequently used areas more thoroughly than busy areas. Utilities, heating, air conditioning and ventilation are also a function of facility size. There is a direct and positive relationship between the PTB area and the cost of utilities, e.g., heating, air conditioning, etc. The total O & M costs which consists of the aforementioned items would be a function of facility size rather than the passenger volume. The data in Table 7.1 shows that the total operation cost of MIA is much higher than the MCA in spite of processing less traffic volume.

Therefore, the O & M cost from the operators' point of view can be translated into providing space. It is clear that providing large size facilities will require not only more space, but more labor and equipment as well. As a result, the operating and maintenance costs will also increase. However, the cost measurement criterion can be $\$/M^2$ of space provided. As a result, PTBs which process higher traffic volumes in

Cost Elements	Cost	Cost Elements	Cost
Total Maintenance	937,273	-Plants and pest	9,407
-Salaries	515,343	-Mats and Deodorizer	6,891
-Non-salaries	399,410	Total Hydro	535,600
-Vehicle Costs	22,520	Total Security	406,400
Heating, Ventilation, AC	308,987	-Salaries	263,418
-Steam	119,177	-Overtime	13,746
-Contracts	49,746	-Allowances	2,955
-Hydro	59,046	-Non-salary	126,281
-Labour	75,018	Total Water	62,272
-Materials	6,000	Total Sewage	64,476
Total Cleaning	637,451	Land Rent	239,905.8
-Bldg Cleaning	560,559	Total Site Administration	415,695
-Garbage Removal	31,242	Grants-in-lieu of Taxes	535,636
-Toilets (paper, soap)	26,383	Total O and M	4,143,696.7

Table 7.3: Breakdown of Operation and Maintenance Costs For MCA, 1992

Source: Transport Canada, 1993

less space, are better utilized and are more efficient.

By looking at Table 7.3, there are some cost items which are beyond the control of PTB operator. Cost items such as depreciation, and land rent will occur whether one uses the space or not. These cost items are called *indirect costs* in this research. There are some other cost items which can be controlled by the PTB operator. Some expenses such as cleaning, heating, air conditioning, maintenance, security, and utilities are based on the utilization of the space. It means that if space is not used these cost items could be reduced. Such cost items are called *direct costs* in this research. If the space is going to be used from time to time, some minimum services are required during vacant periods to keep the space available for busy periods. Therefore, the spaces which are not being used still take a small percentage of direct cost. The total operating cost is formulated as follows:

$$TOMC = \gamma(Gspace) + \lambda(Aspace) \quad (7.3)$$

where,

$TOMC$ = total operations and maintenance cost,

$Gspace$ = total gross area of the PTB,

$Aspace$ = active passenger processing area,

γ = unit cost of maintaining the PTB, and

λ = unit cost of active PTB operation.

The total operation and maintenance cost consists of two basic parts is illustrated in Figure 7.6. The first part is the cost of maintaining the PTB if it is not being used for passenger processing. The second part is the cost of providing the environment

Figure 7.5: Relationship Between PTB Resources and O & M Costs

and services for passenger processing. The first part of the equation is a constant value depending on the size and location of the PTB. There is a direct and positive relationship between the total cost and processing space. It means that if one can allocate the processing space in a more efficient way, there would be some savings on the total operating cost. In another words, the savings on the operating cost depend on the efficient use of the available space. This will signify the importance of the concept of time variable resource utilization model developed in this research.

The aforementioned savings are from operational point of view. There are also savings from a planning and design point of view. For example, in the long term, there would be savings on capital cost consisting of the PTB itself, together with the associated mechanical and electrical plant, furnishing and fixtures, mobile and fixed equipment, and the land area occupied. Depreciation or the net book value of these capital costs are also related to the facility size. This would be a significant amount if it were calculated throughout the years. It should be mentioned that almost all the capital expenses are provided by the airport authorities, unless the individual airlines erect their own unit terminals. In common practice, airport authorities build the PTB and

lease its space to airlines. The financing of the PTB is a complicated exercise which is beyond the scope of this research.

Chapter 8

Conclusions and Recommendations

8.1 Summary

The current constraint on public funding and expenditure will require that airport professionals investigate strategies which will balance the airport resources and demand placed upon them. This means that first, new facilities should be designed as realistically as possible to avoid inadvertent over-sizing and under sizing, and second, the most efficient use of existing facilities should be achieved. The goal of this research, real time resource management and passenger traffic flow control of airport PTB, was achieved through developing an optimum resource utilization model. The rationale for developing such a model was based on a thorough investigation of current PTB design and operational practices.

In the course of this research, it was found that the current planning and design

guidelines, e.g., determining facility requirements by proceeding from an estimate of some design level, fails to answer what happens under other traffic conditions. The existing practices also fail to incorporate the interaction between physical planning and operational planning at the early stages. The stochastic nature of air transport demand, long term costs of over- and under-supply, performance measures, and variable utilization of scarce resources are among other issues which were not addressed in the current practice.

Moreover, the operating and maintenance costs which constitute a major portion of the total cost have almost always been ignored in the planning and design process. Using the current design guidelines, the PTB is being fully to over utilized for less than half a percentage of its useful life. However, with the cost and difficulties in modifying the infrastructure to keep pace with the air traffic changes, it would be necessary for airport planners to first, favour a flexible design, second prepare an operational plan for different scenarios, and third, allocate the resources based on the variable nature of demand.

This thesis explored one approach to this problem of mis-allocation of resources by investigating the application of both *resource allocation* and *flow management and control* theories to the operation of the PTB. Therefore, to achieve the purpose of this research, a facility with minimum operating and maintenance cost at a desired level of service, an optimization methodology for the utilization of resources was proposed. The proposed optimization methodology, is developed based on the premise that the decision maker, e.g., airport authorities, have complete control over a real world PTB system. It is also assumed that the existing PTB has enough flexibility to cope with the decisions made by the decision maker.

The proposed methodology took into account the real-time changes in passenger

traffic flow conditions to optimize the utilization of resources. The PTB should be equipped with sensors, located upstream of each segment, e.g., processing, waiting, circulation. The characteristics of passenger traffic flow are measured in real-time and the optimum required resources are found by optimization model. The optimum required resources are then allocated to different segments of the PTB by using some flow management and control techniques. Within the system, the time period for the resource optimization is set by the operator while information is collected and updated at each time period. When properly set up, this system would be able to anticipate any congestion or grid-lock on the basis of conditions of the upstream traffic.

The optimization part of the methodology was developed based on resource allocation theory in which a fixed amount of resources are allocated to a series of activities, with variable demand, in such a way that the objective function under consideration is optimized. A mathematical model to predict the optimum resources, based on the minimum total over- and under-supply cost was developed.

The proposed methodology was based on such assumptions as, a single authority of the PTB, flexible design, and real time data collection sensors which are not available at present. It was felt that the methodology is difficult to apply in a real terminal, for the time being, for testing and evaluation. Therefore, the methodology was mathematically modeled to an optimum resource utilization model. The PTB resource utilization model was developed in two parts, i.e., analysis, and application. The analysis part was developed based on two submodels, i.e., simulation and optimization. The application part was mainly based on the flow management and control model.

The physical layout of the PTB was simulated using the state of the art simula-

tion tool, SES/workbench. The object oriented simulation model of the PTB was developed to provide a list of statistics required for the optimization purpose. The simulation outputs were used by the optimization submodel to provide the optimum value of required resources for each segment of PTB at each instant of time. The output of optimization model, a variable time resource plan, would be implemented by the flow management and control model developed in the application part.

To illustrate the applicability of the resource utilization model, two airport PTBs, MCA, MIA were studied. The two PTBs were simulated and the outputs of the simulation associated with some parameters were used as input to the optimization model. The variable time-space diagram was compared against the actual demand for each PTB case. Several applications of the resource utilization model in planning, design, and operation were briefly discussed. A flow management and control model was proposed as one of the operational applications of the resource utilization model.

8.2 Conclusions

This research has initiated a new approach to solving problems in airport PTBs that is based upon resource utilization and flow management and control rather than conventional capacity expansion. The practical usefulness of this approach depends upon the integration of advanced technology to capture and disseminate real-time information.

- A methodology was proposed to assist PTB operator to optimize the utilization of available resources. It comprises a set of steps which its final product would be a facility with minimum total operating and maintenance cost.

- The proposed methodology addressed some important issues involving PTB optimization. Some of these issues are such as: early association of physical and operational plans, stochastic nature of airport demand, long term costs of over- and under-supply of PTB facilities, performance measures, and utilization of scarce resources.
- An optimum resource utilization model was developed as a more practical version of proposed methodology. As parts of the resource utilization model three sub-models, i.e., simulation, optimization, and flow management and control model, were developed.
- The object oriented simulation model can perform as a real world airport terminal. The simulation comprises a set of simple submodels and nodes which can easily be explored and modified to fit any airport PTB. The PTB operator would be able to interactively run the model and collect the probability distributions of demand on different segments of the PTB as well as statistics about other performance measures.
- The simulation model provides a real-time interactive information about different segments of the PTB. It may be used as an educational tool for the new staff. One can observe the consequences of changing some of the variables which will play an important role in the PTB operation. The simulation model may be used as an operations tool for the PTB manager or operating staff to help them to maintain a reasonable LOS throughout the PTB.
- The optimization model will provide a list of optimum required resources for all predefined segments of the PTB. The optimization model is based on a mathematical relationship between over- and under-supply costs, stochastic demand, levels of service, and PTB resources.

- A real-time flow management and control model was proposed in which the PTB operator would be able to respond to preplanned or spontaneous events. The management section will provide long term operational planning schemes and procedures. The control section works on the basis of a given optimum utilization plan in which all segments of the PTB would function in an efficient and orderly manner.
- The suggested flow management and control model in this research is one of the demand management strategies which have been successfully applied in other fields of science and engineering. In the proposed model, the operator may control the movement of passengers by some techniques such as information dissemination. The model will also help to respond quickly to some unpredicted events which may otherwise cause chaos in the PTB. Since each PTB must meet the needs of a unique situation and it is unlikely that a standard flow control technique can take account of all variation in circumstances, the control strategy should be an integral part of the design process.
- Although the resource utilization model was developed for application in airport PTBs, which typically handle the largest pedestrian flow in transportation terminals, the general rationale and structure of the model is adaptable to other passenger terminals, e.g., bus, train, through the development and substitution of the appropriate input requirement such as LOS criteria and calibration factors.
- The resource utilization model was incorporated into the planning and design process and a new planning and design process was proposed. In the proposed process, all the possible variabilities of the demand were taken into account to provide a set of scenarios rather than one specific scenario.

- The proposed planning and design process has the potential for designing good functional space plans using the variable demand function and optimization model. The output of the process would be one or more flexible design concepts to be operated according to the optimum time-space plan.
- The operating and maintenance costs, which so far were ignored in the planning process, were taken into account in the proposed process. The optimization model is based on minimizing the total over- and under-supply cost which will include the operations and maintenance cost.
- Although the external envelope of the functional plan is based on the maximum required spaces, the maximum was found according to the number of occupants who are simultaneously present in all parts of the PTB rather than the sum of peaks loads on all segments.
- The whole resource utilization model can be used to provide an operational plan one day in advance, given the airline schedule. The user would be able to place the demand on the system and observe its operation. One can also test the PTB operation under different load conditions, and operational plans, interactively.
- Based on a preliminary analysis on the operations and maintenance costs it was found that a major portion of total operating and maintenance costs is a function of facility size rather than the passenger volume. A time variable resource utilization plan will significantly decrease the total operating and maintenance costs. Furthermore, in the long term, there would be savings on the capital cost consist of mechanical and electrical plant, furnishing, fixtures, mobile and fixed equipments, depreciation, etc.

8.3 Recommendations

This thesis initiated an opportunity for a very wide and fruitful area of research. Since this work is more conceptual than analytical, a lot of detailed research can be done to explore the vagueness of any assumption used at each step of the model development. Some of those are as follows:

- The integration of the resource utilization model into the planning and decision making process and development of techniques for investment timing, concept generation and selection, etc. This will not only satisfy the need for an optimum framework in which to take planning decisions but also will satisfy the users' need, i.e., good level of service and saving spending.
- To be able to experiment with the idea of flow management and control for optimum cost, research is required to devise new design concepts. The interior design concept should be so flexible to accommodate the possible instantaneous changes that may be required due to stochastic nature of demand.
- The PTB is located between two other subsystems of the airport complex, i.e., airside and groundside. Any change in the operation of these two subsystems will affect the PTB operation and vice versa. Research is required to integrate the PTB flow management and control model with the traffic management and control efforts in other parts of the airport complex.
- More research is required to adjust the simulation model in such a way as to integrate the concept of the flow management and control model. If this were done, the operator would be able to interactively experiment with different PTB operation scenarios by applying different flow control techniques depending on the nature and magnitude of the problem.

- Another area of research would be the integration of all parts of the resource utilization model into one program with a single input and output. At present, within the resource utilization model there are three models which should be run separately. In a real-time scenario, all three models should be run at the same time. By integration, the real-time statistics would be collected and the optimization process would be done to provide a list of required resources at each time period. In the case of PTBs, it seems to be more theoretical than practical due to the fact that it is hardly possible to adjust resources perfectly to the highly variable demand. However, it would be practical if time periods for performing optimization are assumed longer, e.g., one hour.
- In order to use the proposed methodology, certain data must be available to calibrate some variables used in the process, e.g., unit values of over- and under-supply costs, level of service standards. Data specially should be collected to estimate the under-supply cost variable which is based on the users' satisfaction. Data should also be collected on the causes, effects, and the amount of savings of different operational plans, e.g., fixed resource utilization vs. time variable utilization, and exclusive use vs. shared use of resources.
- In the long term new and innovative approaches should be found to increase the utilization of airport resources. In the short term options such as shared use of resources, multi-modal terminal, multi skilled personnel, or multi phasing development should be studied in more detail.

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Appendix A: Graphical Illustration of the Simulation Model, PTBSIM

This model simulates the movement of passengers (enplaning and deplaning), greeters, and well-wishers for a given terminal design and a candidate commercial aircraft schedule. It consists of six submodels and two declaration nodes.

SES/design 2.1
Index What How

macdonald
generate_planes

This submodel will open and read the aircraft schedule. It also separate and send the arrival and departure planes to their own submodels.

declare_local_vars

This submodel will generate enplaning
 passengers from the departure aircraft.
 It will also route passengers to their
 own submodel for processing.

SIS/design 2.1
Index What Now

Macdonald
process arrive par

This submodel will process deplaning passengers. Passengers arriving from the submodel concourse proceed to different components of terminal building according to their origins, i.e., domestic or international.

This submodel will process both
 enplaning and deplaning passengers.
 Since concourse is the common area,
 it has been treated as a separate
 submodel. The waiting time for each
 passenger is different.

Appendix B: Source List of the PTBSIM

B: Source List of Simulation Model, macdonald.sim

*****

```
#include "sessim.h"
```

```
module macdonald;
```

```
#include "macdonald.inc"
```

```
/* ..... */
```

```
/* ..... */
```

```
/* ..... Type Declarations ..... */
```

```
/* ..... */
```

```
/* ..... */
```

```
/*
    This model simulates the movement of
    passengers (enplaning and deplaning),
    greeters, and well-wishers for a given
    terminal design and a candidate
    commercial aircraft schedule.
    It consists of six submodels and two
    declaration nodes.
```

```
*/
```

```
static category const seed;
```

```
static category const planes;
```

```
static category const arrival_pass;
```

```
static category const departure_pass;
```

```
static category const greeters;
```

```
static category const meeters;
```

```
static category const greeters_back; /* returning greeters */
```

```
/* main_declarations */
```

```
static {
```

```
#include <stdio.h>
```

```
#include <string.h>
```

```
#define LF load_factor
```

```
#define exit_rate 20.
```

```
#define max_plane 248
```

```
#define dom_leadtime 75.
```

```
#define int_leadtime 110.
```

```
unshared int indx ; // index into plane array
```

```
unshared float pass_dist[200]; //array of departure passengers of each plane
```

```
unshared int pax_dist[50]; // array of arrival passengers
```

```

unshared char greeter_id[10];
unshared char meeter_id[10];
typedef struct {
char    cat[10], // flight number
        type[10], // domestic or international
        sector[10]; // arrival or departure
float    time, // arrival or departure time
        cap, // capacity of airplane
        LF; // load factor of airplane
int    gate; // gate number for airplane
float    etime; // event time of airplanes
} PLANE;
PLANE plane[max_plane];

unshared struct PASSENGER {
char    flight[10], //flight number
        region[10], //domestic or international
        section[10]; //arrival or departure
int    gate, //gate number
        baggage; //baggage claim device
float    time; //arrival or departure time
}passenger;

int    pass, sorted;
PLANE    temp;
int load_data () {
int i;
FILE *outp, *inp;
inp = fopen("friday", "r");
outp = fopen("RESULT", "w"); /* read raw data from a file*/

for (i=0; i< max_plane; i++)
    fscanf(inp, "%s%s%s%f%f%f%d", plane[i].cat, plane[i].type,
        plane[i].sector, &(plane[i].time), &(plane[i].cap),
        &(plane[i].LF), &(plane[i].gate) );

/* calculate the event time of planes,e.g., time planes start to generate pass*/
for (i=0; i<max_plane; i++)
{
    if ( strcmp(plane[i].sector, "arrive") == 0)
        plane[i].etime = plane[i].time;
    else {
        if ( strcmp(plane[i].type, "dom") == 0)
            plane[i].etime = plane[i].time - dom_leadtime;

```

```

        else
            plane[i].etime = plane[i].time - int_leadtime;
        }
    fprintf(outp, "%10s %15s %10s %10.1f %10.1f %10.1f %3d %10.1f\n",
        plane[i].cat, plane[i].type,
        plane[i].sector, plane[i].time, plane[i].cap, plane[i].LF,
        plane[i].gate, plane[i].etime);
    }
    /* sort airplanes according to their event times*/
    pass = 1;
    do {
        sorted = 1;
        for (i= 0; i<(max_plane - pass); ++i)
            { if (plane[i].etime > plane[i+1].etime)
                { temp = plane[i];
                  plane[i] = plane[i+1];
                  plane[i+1] = temp;
                  sorted = 0;
                }
            }
        ++pass;
    } while(!sorted);
    for (i=0; i<max_plane; ++i)
        fprintf(outp, "%10s %15s %10s %10.1f %10.1f %10.1f %3d %10.1f\n",
            plane[i].cat, plane[i].type,
            plane[i].sector, plane[i].time, plane[i].cap, plane[i].LF,
            plane[i].gate, plane[i].etime);

    fclose(outp);
    fclose(inp);
}
}

/* param_declarations */
static {

parameter double pil_power =1.0; //default power of service nodes
parameter double sec_power =1.0; //1.0 means full utilization 0.0 = nothing
parameter double cus_power =1.0;
parameter double aca_power =1.0;
parameter double cdn_power =1.0;
parameter double oth_power =1.0;

int pil_servers=8; //immigration personnel

```

```

int cus_servers= 3; //custom personnel
int aca_servers= 10; //air canada ticket agents
int sec_servers= 3; //security personnel
int cdn_servers=8; //canadian airline ticket agents
int other_servers=8; //other airline personnel
#define walk_speed 60.

```

```

int num = 0; //user defined
double crowd; //statistics
//distances from gates to baggage claim area
float d34 = 360;
float d6 = 350;
float d8 = 330;
float d10 = 320;
float d32 = 300;
float d12 = 280;
float d14 = 270;
float d30 = 240;
float d16 = 230;
float d18 = 220;
float d28 = 180;
float d20 = 160;
float d26 = 120;
float d24 = 110;
float d22 = 100;
double t34, t32, t30, t28, t26, t24, t22, t20, t18, t16, t14, t12, t10, t8, t6;
}

```

```

/* functions_decs */
static {

```

```

sort(float v[], int n)
{
    int pas, sorts, i;
    float tem;
    pas = 1;
do {
    sorts = 1;
    for (i=0; i<(n-pas); i++)
    {
        if (v[i] > v[i+1])
        { tem =v[i];
          v[i] = v[i+1];
          v[i+1] = tem;

```

```

    sorts = 0;
    }
}
++pas;
} while (!sorts);
}

int carrier_comp(char *a, char *b)
{
    int i;
    for (i=0; i<3; i++)
    { if (*a++ != *b++)
        return 0;
    }
    return 1;
}

static submodel generate_planes {
    /*
        This submodel will open and read
        the aircraft schedule. It also
        separate and send the arrival and
        departure planes to their own
        submodels.
    */

    /* declare_local_vars */

    int icount = 0;
    source_node seed_plane {

        default port m_26 ();
    } seed_plane;

    split_node process_plane {

        default port m_28 ();
    } process_plane;

    sink_node di_29 {

    } di_29;

```



```

user_node read_record {

    default port m_30 () ;
} read_record;

user_node open_n_read_schedule {

    default port m_94 () ;
} open_n_read_schedule;

user_node calculate_walk_times {

    default port m_200 () ;
} calculate_walk_times;

default static port m_1 () ;
} generate_planes;

static submodel generate_arrive_pax {
/*
    This submodel will generate deplaning
    passengers from the arrival aircraft.
    It also route deplaning passengers to
    their own submodel for processing.
*/

/* local_variables */

unshared int current_increment;
unshared int lag_time;
unshared int sum;
delay_node wait_for_arve_etime {

    default port m_113 () ;
} wait_for_arve_etime;

enter_node di_114 {

} di_114;

user_node gen_arve_dist_function {

    default port m_115 () ;
} gen_arve_dist_function;

```

```

split_node create_arve_passengers {

    default port m_116 () ;
} create_arve_passengers;

delay_node lag_time_increment {

    default port m_117 () ;
} lag_time_increment;

sink_node di_119 {

} di_119;

default static port m_112 () ;
} generate_arrive_pax;

static submodel concourse {
    /*
        This submodel will process both
        enplaning and deplaning passengers.
        Since concourse is the common area,
        it has been treated as a separate
        submodel. The waiting time for each
        passenger is different.
    */

    enter_node di_137 {

    } di_137;

    delay_node wait_till_depart {

        default port m_138 () ;
    } wait_till_depart;

    return_node di_139 {

    } di_139;

    delay_node walking_time {

        default port m_186 () ;
    } walking_time;

```

```

delay_node connection_time {

    } connection_time;

    collect population pop;
    collect response ;

    default static port m_136 () ;
} concourse;

static submodel generate_depart_pax {
    /*
        This submodel will generate enplaning
        passengers from the departure aircraft.
        It will also route passengers to their
        own submodel for processing.
    */

    /* local_variables */

    unshared int pax;
    unshared int sum;
    enter_node di_142 {

    } di_142;

    split_node create_dept_passengers {

        default port m_144 () ;
    } create_dept_passengers;

    delay_node lead_time_increment {

        default port m_145 () ;
    } lead_time_increment;

    sink_node di_147 {

    } di_147;

    delay_node wait_for_dept_etime {

        default port m_149 () ;
    } wait_for_dept_etime;

```

```

user_node gen_dept_dist_function {

    default port m_151 () ;
} gen_dept_dist_function;

default static port m_141 () ;
} generate_depart_pax;

static submodel process_arrive_pax {
    /*
        This submodel will process deplaning
        passengers. Passengers arriving from
        the submodel concourse proceed to
        different components of terminal
        building according to their origins,
        i.e., domestic or international.
    */
    /* total_deplaning_time */

    enter_node begin_arrival {

        } begin_arrival;

    branch_node di_157 {

        } di_157;

    delay_node arrival_lobby {
        collect population ;
        collect response ;

        default port m_158 () ;
    } arrival_lobby;

    service_node pil {
        collect population ;
        collect response ;
        collect utilization ;

        default port m_170 () ;
    } pil={pil_servers, 1};

    delay_node dom_baggage_claim {
        collect population pop;

```

```

    collect response ;

    default port m_171 () ;
} dom_baggage_claim;

delay_node int_baggage_claim {
    collect population ;
    collect response ;

    default port m_172 () ;
} int_baggage_claim;

split_node dom_meeters {

    default port m_177 () ;
} dom_meeters;

split_node int_meeters {

    default port m_178 () ;
} int_meeters;

sink_node end_arrival {

} end_arrival;

set_node staff_manager {

    default port m_201 () ;
} staff_manager;

service_node custom_booths {
    collect population ;
    collect response ;
    collect utilization ;

    default port m_204 () ;
} custom_booths={cus_servers, 1};

collect {arrival_pass} begin_arrival => end_arrival tot_arrive_time;

default static port m_154 () ;
} process_arrive_pax;

```

```

static submodel process_depart_pax {
  /* total_enplaning_time */
  /*
    This submodel will process enplaning
    passengers. Passengers will go to
    different components of the terminal
    building for processing and finally go
    to the concourse submodel
  */

  enter_node begin_depart {

    } begin_depart;

  delay_node ticket_lobby {
    collect population ;
    collect response ;

    default port m_162 () ;
  } ticket_lobby;

  sink_node end_depart {

    } end_depart;

  service_node others {
    collect population ;
    collect response ;
    collect utilization ;

    default port m_167 () ;
  } others={other_servers, 1};

  branch_node di_169 {

    } di_169;

  split_node generate_greeters {

    default port m_179 () ;
  } generate_greeters;

  service_node stairs_up {

```

```

    default port m_180 () :
} stairs_up;

sink_node di_181 {

} di_181;

service_node cdn_and_allied {
    collect population ;
    collect response ;
    collect utilization ;

    default port m_182 () :
} cdn_and_allied={cdn_servers, 1};

branch_node distribute {

} distribute;

service_node aca_and_allied {
    collect population ;
    collect response ;
    collect utilization ;

    default port m_185 () :
} aca_and_allied={aca_servers, 1};

delay_node wait_n_concessions {
    collect population ;
    collect response ;

    default port m_190 () :
} wait_n_concessions;

service_node security_booths {
    collect population ;
    collect response ;
    collect utilization ;

    default port m_205 () :
} security_booths={sec_servers, 1};

set_node staff_manager {

```

```

    default port m_210 () :
  } staff_manager;

service_node stairs_down {

    default port m_214 () :
  } stairs_down;

delay_node greet_area {
  collect population ;
  collect response ;

    default port m_215 () :
  } greet_area;

collect {departure_pass} begin_depart => end_depart tot_depart_time;

default static port m_160 () :
} process_depart_pax;

/* .....*/
/*                                     */
/*           Method Declarations           */
/*                                     */
/* .....*/

/* method m_1 for generate_planes */

static port m_1 :: generate_planes ()
{

    /* method m_26 for seed_plane */

    port m_26 :: seed_plane ()
    {
        source_once 0.0 {category seed} ;
    }

    /* method m_28 for process_plane */

    port m_28 :: process_plane ()
    {

        split { category planes , quantity 1 , auto , unshared } ;

```



```

}

/* method m_30 for read_record */

port m_30 :: read_record ()
{
    indx = icount++ ;
    /*printf ("%f%f%s%s\n", plane[indx].time,
    * plane[indx].cap, plane[indx].sector, plane[indx].type);*/
}

/* method m_94 for open_n_read_schedule */

port m_94 :: open_n_read_schedule ()
{
    load_data ();
}

/* method m_200 for calculate_walk_times */

port m_200 :: calculate_walk_times ()
{
    t34 =d34/walk_speed;
    t32 =d32/walk_speed;
    t30 =d30/walk_speed;
    t28 =d28/walk_speed;
    t26 =d26/walk_speed;
    t24 =d24/walk_speed;
    t22 =d22/walk_speed;
    t20 =d20/walk_speed;
    t18 =d18/walk_speed;
    t16 =d16/walk_speed;
    t14 =d14/walk_speed;
    t12 =d12/walk_speed;
    t10 =d10/walk_speed;
    t8 = d8/walk_speed;
    t6 = d6/walk_speed;
}

node di_133 = generate_arrive_pax;
node di_153 = generate_depart_pax;

topology {
    seed_plane => calculate_walk_times ();
}

```

```

    }
    topology {
        process_plane { category seed } => read_record () ;
        process_plane { category planes , if (strcmp(plane[indx].sector, "arrive") == 0)
    } => di_133 () ;
        process_plane { category planes , if (strcmp(plane[indx].sector, "depart") == 0)
    } => di_153 () ;
    }
    topology {
        read_record => process_plane () ;
        read_record { category seed , if icount == (max_plane) } => di_29 () ;
    }
    topology {
        open_n_read_schedule => read_record () ;
    }
    topology {
        calculate_walk_times => open_n_read_schedule () ;
    }
}

```

/* method m_112 for generate_arrive_pax */

```

static port m_112 :: generate_arrive_pax ()
{

```

/* method m_113 for wait_for_arve_etime */

```

port m_113 :: wait_for_arve_etime ()
{
    delay plane[indx].etime;
}

```

/* method m_115 for gen_arve_dist_function */

```

port m_115 :: gen_arve_dist_function ()
{

```

```

    int i = 0;

```

```

    int total = 0;

```

```

    /* do function and assign pass_dist array values */

```

```

    //printf ("%f%f\n",plane[indx].cap, plane[indx].LF);

```

```

    sum =(int) (plane[indx].cap * plane[indx].LF);

```

```

    //printf ("%d\n", sum);

```

```

while(sum - total > 0)
{ if ((sum -total)> ex.t_rate )
pax_dist[i] = (int)normal(exit_rate,10,1);
else
pax_dist[i] = sum - total;
total += pax_dist[i];
//printf("%d\n", pax_dist[i]);
i++;
}
lag_time = i;
current_increment = 0;
}

/* method m_116 for create_arve_passengers */

port m_116 :: create_arve_passengers ()
{
passenger.gate = plane[indx].gate;
passenger.time = plane[indx].time;
strcpy(passenger.flight, plane[indx].cat);
strcpy(passenger.region, plane[indx].type);
strcpy(passenger.section, plane[indx].sector);
//printf("%d %f %s %s %s\n", passenger.gate, passenger.time,
//passenger.region, passenger.flight, passenger.section);

split { category arrival_pass , quantity pax_dist[current_increment] , auto ,
unshared } :
}

/* method m_117 for lag_time_increment */

port m_117 :: lag_time_increment ()
{
current_increment = current_increment + 1;

delay 1.0;
}

node di_135 = process_arrive_pax:

topology {
wait_for_arve_etime => gen_arve_dist_function () :
}
topology {

```

```

        di_114 => wait_for_arve_etime ();
    }
    topology {
        gen_arve_dist_function => lag_time_increment ();
    }
    topology {
        create_arve_passengers { category planes } => lag_time_increment ();
        create_arve_passengers { category planes : if c_time >= (plane[indx].etime +
lag_time) } => di_119 ();
        create_arve_passengers { category arrival_pass } => di_135 ();
    }
    topology {
        lag_time_increment => create_arve_passengers ();
    }
}

/* method m_136 for concourse */

static port m_136 :: concourse ()
{

    /* method m_138 for wait_till_depart */

    port m_138 :: wait_till_depart ()
    {

        float wt;
        wt = passenger.time - c_time;
        if(wt<0.0)
            printf("%s %f %f %s\n", passenger.flight,
                    passenger.time, v, "lost his flight");
        else
            delay wt;
    }

    /* method m_186 for walking_time */

    port m_186 :: walking_time ()
    {
        select {
        case {if(passenger.gate == 34)}: delay t34; break;
        case {if(passenger.gate == 32)}: delay t32; break;
        case {if(passenger.gate == 30)}: delay t30; break;
        case {if(passenger.gate == 28)} :delay t28; break;

```

```

        case {if(passenger.gate == 26)} :delay t26; break;
        case {if(passenger.gate == 24)} :delay t24; break;
        case {if(passenger.gate == 22)} :delay t22; break;
        case {if(passenger.gate == 20)} :delay t20; break;
        case {if(passenger.gate == 18)} :delay t18; break;
        case {if(passenger.gate == 16)} :delay t16; break;
        case {if(passenger.gate == 14)} :delay t14; break;
        case {if(passenger.gate == 12)} :delay t12; break;
        case {if(passenger.gate == 10)} :delay t10; break;
        case {if(passenger.gate == 8)} :delay t8; break;
        case {if(passenger.gate == 6)} :delay t6; break;
        default: delay normal(7,3,1);
    }
}

//

topology {
    di_137 { category departure_pass } => wait_till_depart ();
    di_137 => connection_time ();
    di_137 { category arrival_pass } => walking_time ();
}
topology {
    wait_till_depart => di_139 ();
}
topology {
    walking_time => di_139 ();
}
topology {
    connection_time => di_139 ();
}
;
//get_population(concourse.pop,.....crowd);
//collect_sample congestion = crowd/concourse_area;
}

/* method m_141 for generate_depart_pax */

static port m_141 :: generate_depart_pax ()
{

    /* method m_144 for create_dept_passengers */

    port m_144 :: create_dept_passengers ()

```

```

{
    passenger.gate = plane[indx].gate;
    passenger.time = plane[indx].time;
    strcpy(passenger.flight, plane[indx].cat);
    strcpy(passenger.region, plane[indx].type);
    strcpy(passenger.section, plane[indx].sector);
    //printf("%d %f %s %s %s\n", passenger.gate, passenger.time,
    //passenger.region, passenger.flight, passenger.section);

    split { category departure_pass , quantity 1 , auto , unshared } ;
}

/* method m_145 for lead_time_increment */

port m_145 :: lead_time_increment ()
{

    delay pass_dist[pax+1] - pass_dist[pax];
    ;
    pax = pax +1;
}

/* method m_149 for wait_for_dept_etime */

port m_149 :: wait_for_dept_etime ()
{

    delay plane[indx].etime;
}

/* method m_151 for gen_dept_dist_function */

port m_151 :: gen_dept_dist_function ()
{

int i=0;
int total = 0;
float min, mode, max;
    /* do function and assign pass_dist array values */
    //printf ("%f%f\n",plane[indx].cap, plane[indx].LF);
    sum = (int)(plane[indx].cap * plane[indx].LF);
    //printf ("%d\n", sum);
    min = plane[indx].etime;

```

```

    if(strcmp(plane[indx].type, "dom") == 0)
        max =(plane[indx].time -15);
    else
        max = (plane[indx].time -20);
    mode =(min + 2./3.*(max-min));

    while((sum - total) > 0)
    {
        pass_dist[i] = triangular(min, mode, max);

        total += 1;
        //printf("%f\n", pass_dist[i]);
        i++;
    }
    //printf("%d\n",total);
    sort(pass_dist, total);
    for (i=0; i<total; i++)
        //printf("%f\n", pass_dist[i]);
    pax = 0;
}

node di_166 = process_depart_pax;

topology {
    di_142 => wait_for_dept_etime ();
}

topology {
    create_dept_passengers { category planes } => lead_time_increment ();
    create_dept_passengers { category planes , if pax == sum-1 } => di_147 ();
    create_dept_passengers { category departure_pass } => di_166 ();
}

topology {
    lead_time_increment => create_dept_passengers ();
}

topology {
    wait_for_dept_etime => gen_dept_dist_function ();
}

topology {
    gen_dept_dist_function => lead_time_increment ();
}
}

/* method m_154 for process_arrive_pax */

```

```

static port m_154 :: process_arrive_pax ()
{

    /* method m_158 for arrival_lobby */

    port m_158 :: arrival_lobby ()
    {

        delay normal(4,2,1);
    }

    /* method m_170 for pil */

    port m_170 :: pil ()
    {
        //if(c_time<300 || c_time >1380)
        //employees =(double)(1.0/pil_servers);
        //else
        //if((c_time>=300 && c_time<590) ||(c_time>=720 &&
        // c_time<1140))
        //employees =(double)(4.0/pil_servers);
        //else
        //employees = (double)(2.0/pil_servers);

        service expo(1.0);
    }

    /* method m_171 for dom_baggage_claim */

    port m_171 :: dom_baggage_claim ()
    {
        //

        delay normal(4.5,3,1);
        ;
        //get_population(dom_baggage_claim.pop,,,,,crowd);
        //collect_sample congestion = (crowd/dom_bag_area);
    }

    /* method m_172 for int_baggage_claim */

    port m_172 :: int_baggage_claim ()
    {

```



```

        delay normal(4,3,1);
    }

/* method m_177 for dom_meeters */

port m_177 :: dom_meeters ()
{
    strcpy(meeter_id, passenger.flight);

    split { category meeters , quantity poisson(0.9) , unshared } :
}

/* method m_178 for int_meeters */

port m_178 :: int_meeters ()
{
    strcpy(meeter_id, passenger.flight);

    split { category meeters , quantity poisson(1.5) , unshared } :
}

/* method m_201 for staff_manager */

port m_201 :: staff_manager ()
{
    if(c_time<300 || c_time>=1380)
    {
        set pil.power = pil_power/8;
        set custom_booths.power = cus_power/3;
    }
    else
        if((c_time>= 300 && c_time <600) || (c_time>=840 && c_time<1140))
        { set pil.power = pil_power/1.2;
          set custom_booths.power = cus_power/1.2;
        }
    else
        { set pil.power = pil_power/2;
          set custom_booths.power = cus_power/1.4;
        }
}

/* method m_204 for custom_booths */

port m_204 :: custom_booths ()

```

```

{
    //if(c_time<300 || c_time >1380)
    //employees =(double)(1.0/cus_servers);
    //else
    //if((c_time>=300 && c_time<590) ||(c_time>=720 &&
    // c_time<1140))
    //employees =(double)(2.0/cus_servers);
    //else
    //employees = (double)(1.0/cus_servers);

    service expo(2.5);
}

node di_156 = concourse;

topology {
    begin_arrival => di_156 ();
}
topology {
    di_156 { category arrival_pass , if (strcmp(passenger.region, "dom")==0) } =>
dom_meeters ();
    di_156 { category arrival_pass , if (strcmp(passenger.region, "inter") == 0) }
=> staff_manager ();
}
topology {
    di_157 => arrival_lobby ();
}
topology {
    arrival_lobby => end_arrival ();
}
topology {
    pil => int_baggage_claim ();
    pil { prob 0.1 } => int_meeters ();
}
topology {
    dom_baggage_claim => di_157 ();
}
topology {
    int_baggage_claim => int_meeters ();
    int_baggage_claim { prob 0.5 } => custom_booths ();
}
topology {
    dom_meeters => dom_baggage_claim ();
    dom_meeters { prob 0.10 } => di_157 ();
}

```

```

    }
    topology {
        int_meeters => arrival_lobby ();
    }
    topology {
        staff_manager => pil ();
    }
    topology {
        custom_booths => int_meeters ();
    }
}

/* method m_160 for process_depart_pax */

static port m_160 :: process_depart_pax ()
{

    /* method m_162 for ticket_lobby */

    port m_162 :: ticket_lobby ()
    {
        if((passenger.time - c_time)<15){
            //printf("%f %d\n", (passenger.time-c_time), 1);
            delay 1; }
        //get_population(ticket_lobby.pop,,,,,,crowd);
        //collect_sample congestion = (crowd/tlb_area);

        delay normal(2.45,1.5,1);
    }

    /* method m_167 for others */

    port m_167 :: others ()
    {
        //if(c_time<300 || c_time >1380)
        //employees =(double)(1.0/other_servers);
        //else
        //if((c_time>=300 && c_time<590) ||(c_time>=720 &&
        // c_time<1140))
        //employees =(double)(6.0/other_servers);
        //else
        //employees = (double)(4.0/other_servers);

        service expo(1.5);
    }
}

```

```

}

/* method m_179 for generate_greeters */

port m_179 :: generate_greeters ()
{
    strcpy(greeter_id, passenger.flight);

    split { category greeters , quantity poisson(1.1) , auto , unshared } ;
}

/* method m_180 for stairs_up */

port m_180 :: stairs_up ()
{
    service 0.025;
}

/* method m_182 for cdn_and_allied */

port m_182 :: cdn_and_allied ()
{
    //if(c_time<300 || c_time >1380)
    //employees =(double)(2.0/cdn_servers);
    //else
    //if((c_time>=300 && c_time<590) ||(c_time>=720 &&
    // c_time<1140))
    //employees =(double)(6.0/cdn_servers);
    //else
    //employees = (double)(4.0/cdn_servers);

    service expo(1.6);
}

/* method m_185 for aca_and_allied */

port m_185 :: aca_and_allied ()
{
    //if(c_time<300 || c_time >1380)
    //employees =(double)(2.0/aca_servers);
    //else
    //if((c_time>=300 && c_time<590) ||(c_time>=720 &&
    //c_time<1140))

```

```

//employees =(double)(8.0/aca_servers);
//else
//employees = (double)(5.0/aca_servers);

service expo(1.48);
}

/* method m_190 for wait_n_concessions */

port m_190 :: wait_n_concessions ()
{

float slack =0.;
if(c_category == greeters_back)
    delay normal(0.6, 0.5,1);
else
{
    slack =(passenger.time - c_time)/2;
    if (slack <= 8.)
        delay 1;
    else
        delay normal(slack/2, 3,1);
}
//get_population(wait_n_concessions.pop,.....crowd);
//collect_sample congestion = (crowd/concession_area);
}

/* method m_205 for security_booths */

port m_205 :: security_booths ()
{
    //if(c_category == departure_pass)
    //service expo(0.2);
    //else
    //service (0.000);

    //if(c_time<300 || c_time >1380)
    //employees =(double)(1.0/sec_servers);
    //else
    //if((c_time>=300 && c_time<590) ||(c_time>=720 &&
    // c_time<1140))
    //employees =(double)(3.0/sec_servers);
    //else
    //employees = (double)(2.0/sec_servers);

```

```

        service expo(0.17);
    }

/* method m_210 for staff_manager */

port m_210 :: staff_manager ()
{
    if(c_time<300 || c_time>=1380)
    {
        set others.power = oth_power/8;
        set aca_and_allied.power = aca_power/5;
        set cdn_and_allied.power = cdn_power/6;
        set security_booths.power = sec_power/3;
    }
    else
        if((c_time>= 300 && c_time <600) || (c_time>=840 && c_time<1140))
        { set others.power = oth_power/1.25;
          set aca_and_allied.power = aca_power/1.25;
          set cdn_and_allied.power = cdn_power/1.25;
          set security_booths.power = sec_power/1.0;
        }
    else
        { set others.power = oth_power/2;
          set aca_and_allied.power = aca_power/2;
          set cdn_and_allied.power = cdn_power/2;
          set security_booths.power = sec_power/1.3;
        }
    }

/* method m_214 for stairs_down */

port m_214 :: stairs_down ()
{

    service 0.025;
}

/* method m_215 for greet_area */

port m_215 :: greet_area ()
{
    if((passenger.time - c_time)<5){
        //printf("%f %d\n", (passenger.time-c_time), 1);
        delay 1; }
}

```

```

//get_population(ticket_lobby.pop.....crowd);
//collect_sample congestion = (crowd/tlb_area);

delay normal(1.2, 1,1);
}

node di_164 = concourse;

topology {
    begin_depart => generate_greeters ();
}
topology {
    ticket_lobby => di_169 ();
    ticket_lobby { prob 0.1 } => stairs_up ();
    ticket_lobby { category departure_pass , prob 0.8 } => distribute ();
}
topology {
    di_164 => end_depart ();
}
topology {
    others => di_169 ();
}
topology {
    di_169 { if ((passenger.time - c_time)>20) , prob 0.40 } => wait_n_concessions
();
    di_169 => stairs_up ();
}
topology {
    generate_greeters => staff_manager ();
}
topology {
    stairs_up => greet_area ();
}
topology {
    cdn_and_allied => di_169 ();
}
topology {
    distribute => others ();
    distribute { if (carrier_comp(passenger.flight, "aca") ||
carrier_comp(passenger.flight, "ont") || carrier_comp(passenger.flight, "aaq") ||
carrier_comp(passenger.flight, "am") || carrier_comp(passenger.flight, "asf") ||
carrier_comp(passenger.flight, "bls") ) } => aca_and_allied ();
    distribute { if (carrier_comp(passenger.flight, "cdn") ||
carrier_comp(passenger.flight, "klm") || carrier_comp(passenger.flight, "atl") ) } =>

```

```

cdn_and_allied () :
{
    topology {
        aca_and_allied => di_169 () ;
    }
    topology {
        wait_n_concessions => stairs_up () ;
        wait_n_concessions { category greeters_back } => di_181 () ;
    }
    topology {
        security_booths { category departure_pass } => di_164 () ;
    }
    topology {
        staff_manager => ticket_lobby () ;
    }
    topology {
        stairs_down { category greeters } => { category greeters_back }
wait_n_concessions () :
    }
    topology {
        greet_area { category departure_pass } => security_booths () ;
        greet_area { category greeters } => stairs_down () ;
    }
}

```

```

/* ..... */
/*                                     */
/*           Main Function           */
/*                                     */
/* ..... */

```

```

#ifndef FALSE
#define FALSE 0
#endif
#ifndef TRUE
#define TRUE 1
#endif

```

```

extern double    di_warmUp_d;

```



```

extern int      di_trace_d;
extern double   di_goTime_d;
extern double   di_goInterval_d;
extern int      di_interactive_d;
extern const char* di_reportTitle_d;

main (int argc, char *argv[])
{

    void di_interactor_f () , di_defmain_f ();
    reserve (0) strcpy, di_interactor_f, di_defmain_f;

    di_warmUp_d      = 0.0;
    di_trace_d       = FALSE;
    di_goTime_d       = 1000.0;
    di_goInterval_d  = 0.0;
    di_interactive_d = FALSE;

    di_reportTitle_d =
    """;

    //c_stream.reseed(6436);
    go(860);
    //report();
    clear();
    go(1020);
    report();
    //go(1440);
    //report();
} /* main function */

```

**Appendix C: Input Data File for Simulation Model, Typical
Schedule, MCA.**

4

OF/DE

4

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

PRECISION^{SM} RESOLUTION TARGETS

C: PTBSIM Typical Input Data File:

```

*****
Flight      Flight      Flight      Time(min)  A/C      Load      Gate
Number      Sector      Type      Arr/Dep    Cap.      Factor     No.
-----
usa1776      inter      depart      365        100       0.83       26
atl1488      dom        depart      385         88       0.73       30
usa65        inter      depart      385        100       0.83       28
aca198      dom        arrive       47         95       0.73       16
aca602      dom        depart      390         95       0.83       16
asfpl       dom        arrive      390         18       0.73        8
asf101      dom        depart      400         18       0.73        8
ont408      dom        depart      400         37       0.83       12
blspl       dom        arrive      375         18       0.73       16
bls371      dom        depart      405         18       0.73       16
aca441      dom        depart      405        137       0.83       20
cdn923      dom        depart      420        110       0.83       22
ont341      dom        depart      420         37       0.83       12
exp4301     dom        depart      420         35       0.73       34
aca123      dom        depart      420        137       0.83       18
aaq106      dom        depart      420         37       0.73        8
acatow      dom        depart      420         95       0.83        6
ont343      dom        depart      435         37       0.73       10
aca570      dom        arrive      384         37       0.73        6
acaf029     dom        depart      440         37       0.73        6
arn892      dom        depart      440         88       0.73       14
exp4687     dom        depart      446         19       0.73       34
exp4778     dom        depart      465         35       0.73       35
fabtow      dom        arrive      450        126       0.73       16
fab864      dom        depart      470        126       0.73       16
cdn803      dom        depart      480        105       0.83       24
acatowl     dom        arrive      420         95       0.83       20
aca443      dom        depart      480         95       0.83       20
asf200a     dom        arrive      475         19       0.73       10
asf200      dom        depart      495         19       0.73       10
cnn407      dom        arrive      450         80       0.73       28
cnn408      dom        depart      495         80       0.73       28
cdn407      dom        arrive      450        100       0.83       28
cdn408      dom        depart      495        100       0.83       28
ont340      dom        arrive      482         37       0.83       12
ont345      dom        depart      500         37       0.83       12
exp4307     dom        depart      510         35       0.73       35
cdn901a     dom        arrive      490        137       0.83       22
cdn901      dom        depart      520        137       0.83       22
aaq171      dom        arrive      510         37       0.73       10
aaq105      dom        depart      525         37       0.73       10
aca301a     dom        arrive      492        137       0.83       20
aca301      dom        depart      535        137       0.83       20
aca440      dom        arrive      477        137       0.83       18
aca119      dom        depart      540        137       0.83       18
cdn800      dom        arrive      475        105       0.83       26
cdn806      dom        depart      540        105       0.83       26

```

asf102	dom	arrive	535	19	0.73	12
asfpl	dom	depart	555	19	0.73	12
ont400	dom	arrive	509	37	0.83	8
ont410	dom	depart	560	37	0.83	8
aca177a	dom	arrive	531	95	0.83	16
aca177	dom	depart	560	95	0.83	16
aaq170	dom	arrive	560	37	0.73	10
aaq114	dom	depart	580	37	0.73	10
fabtow	dom	arrive	540	126	0.73	14
fab860	dom	depart	590	126	0.73	14
aca442	dom	arrive	552	137	0.83	18
aca447	dom	depart	600	137	0.83	18
cdn802	dom	arrive	530	105	0.83	24
cdn807	dom	depart	600	105	0.83	24
exp4310	inter	arrive	577	37	0.73	30
exp4313	inter	depart	600	37	0.73	30
bls370	dom	arrive	596	18	0.73	10
blspl	dom	depart	615	18	0.73	10
atl1481	dom	arrive	590	88	0.73	26
atl1482	dom	depart	620	88	0.73	26
exp4656	inter	arrive	593	19	0.73	32
exp4681	inter	depart	626	19	0.73	32
ont344	inter	arrive	613	37	0.83	12
ont349	inter	depart	630	37	0.83	12
aca174a	dom	arrive	624	95	0.83	16
aca174	dom	depart	660	95	0.83	16
aca444	dom	arrive	615	137	0.83	18
aca191	dom	depart	660	137	0.83	18
cdn804	dom	arrive	595	105	0.83	22
cdn809	dom	depart	660	105	0.83	22
exp4741	inter	arrive	628	35	0.73	30
exp4746	inter	depart	660	35	0.73	30
aaq103	dom	arrive	645	37	0.73	10
aaq107	dom	depart	665	37	0.73	10
exp4300	dom	arrive	662	35	0.73	32
exp4303	dom	depart	690	35	0.73	32
usa603	inter	arrive	623	105	0.73	28
usa1693	inter	depart	700	105	0.73	28
ont348	dom	arrive	674	37	0.83	12
ont351	dom	depart	720	37	0.83	12
aca446	dom	arrive	668	95	0.83	18
aca517	dom	depart	720	95	0.83	18
atl1493	dom	arrive	715	88	0.73	26
atl1484	dom	depart	745	88	0.73	26
ont348	dom	arrive	728	37	0.83	12
ont353	dom	depart	750	37	0.83	12
cdn808	dom	arrive	716	105	0.83	22
cdn813	dom	depart	780	105	0.83	22
exp4312	inter	arrive	747	35	0.73	30
exp4315	inter	depart	780	35	0.73	30
aca448	dom	arrive	731	137	0.83	18
aca147	dom	depart	780	137	0.83	18

aaq124	dom	arrive	725	37	0.73	10
aaq120	dom	depart	785	37	0.73	10
ont411	inter	arrive	750	37	0.83	32
ont414	inter	depart	800	37	0.83	32
exp4658	inter	arrive	765	19	0.73	34
exp4671	inter	depart	806	19	0.73	34
ont360	dom	arrive	780	37	0.83	12
ont365	dom	depart	810	37	0.83	12
cdn920	dom	arrive	769	105	0.83	20
cdn929	dom	depart	840	105	0.83	20
aca450	dom	arrive	789	95	0.83	18
aca455	dom	depart	840	95	0.83	18
exp4318	inter	arrive	807	35	0.73	28
exp4319	inter	depart	840	35	0.73	28
aaq113	dom	arrive	825	35	0.73	10
aaq122	dom	depart	845	35	0.73	10
exp4787	inter	arrive	808	35	0.73	30
exp4748	inter	depart	870	35	0.73	30
ont404	dom	arrive	850	37	0.83	12
ont357	dom	depart	870	37	0.83	12
cdn411	dom	arrive	835	105	0.83	34
cdn410	dom	depart	880	105	0.83	34
asfpl	dom	arrive	860	19	0.73	8
asf103	dom	depart	885	19	0.73	8
cdn812	dom	arrive	832	105	0.83	24
cdn817	dom	depart	900	105	0.83	24
aca452	dom	arrive	850	137	0.83	18
aca159	dom	depart	900	137	0.83	18
aca113a	dom	arrive	860	137	0.83	20
aca113	dom	depart	900	137	0.83	20
aaq115	dom	arrive	885	37	0.73	10
aaq162	dom	depart	905	37	0.73	10
aca619	dom	arrive	755	95	0.83	14
aca179	dom	depart	920	95	0.83	14
exp4302	inter	arrive	880	35	0.73	30
exp4305	inter	depart	930	35	0.73	30
ont413	inter	arrive	880	35	0.73	32
ont369	inter	depart	995	35	0.73	32
aca046	inter	arrive	816	200	0.83	26
aca044	inter	depart	940	200	0.83	26
cdn814	dom	arrive	895	105	0.83	22
cdn819	dom	depart	960	105	0.83	22
aca454	dom	arrive	909	95	0.83	18
aca519	dom	depart	960	95	0.83	18
aaq117	dom	arrive	955	35	0.73	10
aaq174	dom	depart	980	35	0.73	10
exp4682	inter	arrive	948	19	0.73	30
exp4665	inter	depart	980	19	0.73	30
aca176	dom	arrive	879	95	0.73	16
aca618	dom	depart	985	95	0.73	16
asf203a	dom	arrive	970	18	0.73	6
asf203	dom	depart	990	18	0.73	6

ont356	dom	arrive	945	35	0.83	8
ont363	dom	depart	990	35	0.83	8
klm575	inter	arrive	895	200	0.75	28
klm676	inter	depart	995	200	0.75	28
usa467	inter	arrive	896	105	0.73	26
usa1239	inter	depart	996	105	0.73	26
blspl	dom	arrive	960	18	0.73	6
bls373	dom	depart	996	18	0.73	6
aaq181	dom	arrive	985	35	0.73	6
aaq130	dom	depart	1000	35	0.73	6
arn893	dom	arrive	975	88	0.73	14
arn882	dom	depart	1005	88	0.73	14
fab861	dom	arrive	990	126	0.73	12
fabtow	dom	depart	1010	126	0.73	12
cdn902a	dom	arrive	970	105	0.83	22
cdn902	dom	depart	1020	105	0.83	22
cdn816	dom	arrive	955	105	0.83	24
cdn821	dom	depart	1020	105	0.83	24
fab861	dom	arrive	990	126	0.73	12
fabtow	dom	depart	1020	126	0.73	12
aca456	dom	arrive	979	200	0.83	18
aca145	dom	depart	1020	200	0.83	18
exp4642	inter	arrive	995	35	0.73	32
exp4311	inter	depart	1020	35	0.73	32
cdn904	dom	arrive	969	105	0.83	20
cdn905	dom	depart	1035	105	0.83	20
asf104	dom	arrive	1020	15	0.73	10
asf106	dom	depart	1040	15	0.83	10
ont368	dom	arrive	1022	35	0.83	12
ont365	dom	depart	1050	35	0.83	12
aca139a	dom	arrive	1025	137	0.83	16
aca139	dom	depart	1065	137	0.83	16
aca136	dom	arrive	1039	137	0.83	18
aca463	dom	depart	1080	137	0.83	18
cdn818	dom	arrive	1015	105	0.83	28
cdn823	dom	depart	1080	105	0.83	28
cdn907a	dom	arrive	1043	105	0.83	24
cdn907	dom	depart	1085	105	0.83	24
aca865	dom	arrive	1004	200	0.83	28
aca866	dom	depart	1085	200	0.83	28
aca181a	dom	arrive	1068	95	0.83	14
aca181	dom	depart	1100	95	0.83	14
ont360	dom	arrive	1098	37	0.83	12
ont407	dom	depart	1120	37	0.83	12
exp4968	inter	arrive	1105	35	0.73	30
exp4309	inter	depart	1135	35	0.73	30
cdn926	dom	arrive	1074	105	0.83	22
cdn826	dom	depart	1140	105	0.83	22
aca460	dom	arrive	1091	137	0.83	18
aca465	dom	depart	1140	137	0.83	18
arn895	dom	arrive	1120	88	0.73	14
arn888	dom	depart	1150	88	0.73	14

ont417	inter	arrive	1125	37	0.83	32
ont418	inter	depart	1155	37	0.83	32
fab867	dom	arrive	1150	126	0.73	16
fabtow	dom	depart	1170	126	0.73	16
ont362	dom	arrive	1166	37	0.73	12
ont369	dom	depart	1185	37	0.73	12
asf106	dom	arrive	1170	15	0.73	8
asfpl	dom	depart	1190	15	0.73	8
aca126	dom	arrive	1151	137	0.83	18
aca467	dom	depart	1200	137	0.83	18
bls372	dom	arrive	1190	18	0.73	8
blspl	dom	depart	1210	18	0.73	8
cdn824	dom	arrive	1198	105	0.83	22
cdn831	dom	depart	1260	105	0.83	22
arn897	dom	arrive	1260	35	0.73	14
arntow	dom	depart	1290	35	0.73	14
aca464	dom	arrive	1211	137	0.83	18
aca473	dom	depart	1320	137	0.83	18
cdn908a	dom	arrive	1314	137	0.83	22
cdn908	dom	depart	1350	137	0.83	22
aca138a	dom	arrive	1317	137	0.83	20
aca138	dom	depart	1350	137	0.83	20
aca466	dom	arrive	1331	137	0.83	18
acatow	dom	depart	1380	137	0.83	18
aca124a	dom	arrive	1370	137	0.83	20
aca124	dom	depart	1400	137	0.83	20
ont419	dom	arrive	1390	37	0.73	32
onttow	dom	depart	1420	37	0.73	32
atl1467	dom	arrive	1370	35	0.73	30
exp4308	inter	arrive	1322	35	0.73	34
exp4304	inter	arrive	1230	35	0.73	34
arntow	dom	arrive	1260	82	0.73	6
usa372	inter	arrive	1227	105	0.73	28
aca468	dom	arrive	1419	137	0.73	20
exp4747	inter	arrive	1203	35	0.73	34
cdn930	dom	arrive	1405	105	0.83	22
aca178	dom	arrive	1219	95	0.83	18
ont368	dom	arrive	1288	37	0.73	12
exp4864	inter	arrive	1128	19	0.73	34
usa1840	inter	arrive	1301	105	0.73	26
acatow	dom	arrive	1380	137	0.73	6
cdn822	dom	arrive	1135	105	0.73	24
onttow	dom	arrive	1420	37	0.73	8
aaq129	dom	arrive	1190	37	0.73	10
ont364	dom	arrive	1215	37	0.73	8

Appendix D: Sample of Time Series Flow Outputs of the Simulation Model.

D: Sample of Time Series Flow Outputs

*****

Time	Flow	Time	Flow	Time	Flow
859	36	860	35	861.144	44
859	37	860	36	861.292	43
859	38	860	37	861.339	42
859	39	860	38	861.409	41
859	40	860	39	861.427	40
859	41	860	40	861.456	39
859	42	860	41	861.63	38
859	43	860	42	861.696	37
859	44	860	43	861.75	36
859	45	860	44	861.758	35
859	46	860	45	861.929	34
859	47	860	46	862	33
859	48	860	47	862	32
859	49	860	48	862	33
859	50	860	49	862	34
859	51	860	50	862	35
859	52	860	49	862	36
859	51	860	50	862	37
859	52	860	51	862	38
859	53	860.018	5	862	39
859	54	860.019	4	862	40
859	55	860.032	4	862	41
859	56	860.067	4	862	42
859	57	860.239	4	862	43
859	58	860.307	4	862	44
859	59	860.367	4	862	45
859	60	860.44	43	862	46
859.001	59	860.476	4	862	47
859.021	58	860.52	41	862	48
859.084	57	860.543	4	862	49
859.086	56	860.559	3	862	50
859.138	55	860.768	3	862	51
859.139	54	860.877	3	862	52
859.196	53	860.929	3	862	53
859.236	52	861	35	862	54
859.239	51	861	36	862	55
859.288	50	861	37	862	56
859.305	49	861	38	862	57
859.314	48	861	39	862	58
859.324	47	861	40	862	59
859.367	46	861	41	862	58
859.427	45	861	42	862.004	57
859.447	44	861	43	862.022	56
859.457	43	861	44	862.061	55
859.606	42	861	45	862.139	54
859.633	41	861	46	862.205	53
859.652	40	861	47	862.27	52
859.709	39	861	48	862.279	51

Appendix E: Detailed Output Statistics of The PTBSIM

E: Summary of PTBSIM Statistics Report:

*****
 *****

MODEL NAME (from name of main module): macdonald

DATE AND TIME OF COMPLETION OF THIS BATCH: Mon Jul 3 19:56:29 1995

SIMULATION PERIOD COVERED BY THIS REPORT: 160 (from 860 to 1020)

NUMBER OF EVENTS SINCE LAST RESET: 108866

*****
 ***** Initializing Parameters *****
 *****

Parameter:

    pil_power = 1

Parameter:

    sec_power = 1

Parameter:

    cus_power = 1

Parameter:

    aca_power = 1

Parameter:

    cdn_power = 1

Parameter:

    oth_power = 1

*****
 ***** DETAILED STATISTIC REPORT *****

**Statistic Report:

POPULATION of submodel concourse
 (user-assigned name = pop)

In module: macdonald

category: arrival_pass

MEAN:	26.592	variance:	1229.9	stdev:	35.07
minimum:	0	maximum:	160	ending value:	6

category: departure_pass
 MEAN: 474.92 variance: 19731 stdev: 140.47
 minimum: 229 maximum: 813 ending value: 383

category: ALL
 MEAN: 501.52 variance: 24696 stdev: 157.15
 minimum: 232 maximum: 947 ending value: 389

****Statistic Report:**

RESPONSE TIME of submodel concourse

In module: macdonald

category: arrival_pass
 MEAN: 3.2187 variance: 0.9365 stdev: 0.96773
 minimum: 1.6667 maximum: 5.8333
 sample count: 1343

category: departure_pass
 MEAN: 41.055 variance: 315.46 stdev: 17.761
 minimum: 0 maximum: 106.13
 sample count: 1717

category: ALL
 MEAN: 24.449 variance: 530.05 stdev: 23.023
 minimum: 0 maximum: 106.13
 sample count: 3060

****Statistic Report:**

POPULATION of node arrival_lobby

In module: macdonald

In submodel: process_arrive_pax

category: arrival_pass
 MEAN: 32.134 variance: 391.45 stdev: 19.785
 minimum: 0 maximum: 75 ending value: 70

category: meeters
 MEAN: 32.683 variance: 353.85 stdev: 18.811

minimum:	0	maximum:	79	ending value:	75
category: ALL					
MEAN:	64.817	variance:	1434.9	stdev:	37.88
minimum:	1	maximum:	146	ending value:	145

****Statistic Report:**

RESPONSE TIME of node arrival_lobby

In module: macdonald

In submodel: process_arrive_pax

category: arrival_pass					
MEAN:	3.8775	variance:	3.9814	stdev:	1.9953
minimum:	0	maximum:	8		
sample count:	1304				

category: meeters					
MEAN:	4.0184	variance:	3.758	stdev:	1.9386
minimum:	0	maximum:	8		
sample count:	1280				

category: ALL					
MEAN:	3.9473	variance:	3.8742	stdev:	1.9683
minimum:	0	maximum:	8		
sample count:	2584				

****Statistic Report:**

POPULATION of node pil

In module: macdonald

In submodel: process_arrive_pax

category: arrival_pass					
MEAN:	15.839	variance:	1495.6	stdev:	38.673
minimum:	0	maximum:	169	ending value:	0

category: ALL					
MEAN:	15.839	variance:	1495.6	stdev:	38.673
minimum:	0	maximum:	169	ending value:	0

**Statistic Report:

RESPONSE TIME of node pil

In module: macdonald

In submodel: process_arrive_pax

category: arrival_pass

MEAN:	11.164	variance:	54.961	stdev:	7.4136
minimum:	0.0045329	maximum:	25.613		
sample count:	227				

category: ALL

MEAN:	11.164	variance:	54.961	stdev:	7.4136
minimum:	0.0045329	maximum:	25.613		
sample count:	227				

**Statistic Report:

UTILIZATION of node pil

In module: macdonald

In submodel: process_arrive_pax

category: arrival_pass

MEAN:	1.609	variance:	9.9642	stdev:	3.1566
minimum:	0	maximum:	8	ending value:	0

category: ALL

MEAN:	1.609	variance:	9.9642	stdev:	3.1566
minimum:	0	maximum:	8	ending value:	0

**Statistic Report:

POPULATION of node dom_baggage_claim

(user-assigned name = pop)

In module: macdonald

In submodel: process_arrive_pax

category: arrival_pass

MEAN:	26.752	variance:	740.54	stdev:	27.213	
minimum:	0	maximum:	111	ending value:		78

category: meeters

MEAN:	23.246	variance:	564.63	stdev:	23.762	
minimum:	0	maximum:	91	ending value:		58

category: ALL

MEAN:	49.998	variance:	2559.9	stdev:	50.595	
minimum:	0	maximum:	190	ending value:		136

Statistic Report:RESPONSE TIME of node dom_baggage_claim**

In module: macdonald

In submodel: process_arrive_pax

category: arrival_pass

MEAN:	4.4391	variance:	6.9957	stdev:	2.6449
minimum:	0	maximum:	9		
sample count:	955				

category: meeters

MEAN:	4.4728	variance:	6.9385	stdev:	2.6341
minimum:	0	maximum:	9		
sample count:	827				

category: ALL

MEAN:	4.4548	variance:	6.9655	stdev:	2.6392
minimum:	0	maximum:	9		
sample count:	1782				

Statistic Report:POPULATION of node int_baggage_claim**

In module: macdonald

In submodel: process_arrive_pax

category: arrival_pass

MEAN:	4.9617	variance:	79.041	stdev:	8.8905

minimum: 0 maximum: 30 ending value: 0

category: ALL

MEAN: 4.9617 variance: 79.041 stdev: 8.8905
minimum: 0 maximum: 30 ending value: 0

**Statistic Report:

RESPONSE TIME of node int_baggage_claim

In module: macdonald

In submodel: process_arrive_pax

category: arrival_pass

MEAN: 4.0157 variance: 7.0361 stdev: 2.6526
minimum: 0 maximum: 8
sample count: 199

category: ALL

MEAN: 4.0157 variance: 7.0361 stdev: 2.6526
minimum: 0 maximum: 8
sample count: 199

**Statistic Report:

POPULATION of node custom_booths

In module: macdonald

In submodel: process_arrive_pax

category: arrival_pass

MEAN: 28.133 variance: 367.52 stdev: 19.171
minimum: 0 maximum: 62 ending value: 0

category: ALL

MEAN: 28.133 variance: 367.52 stdev: 19.171
minimum: 0 maximum: 62 ending value: 0

**Statistic Report:

RESPONSE TIME of node custom_booths

In module: macdonald
In submodel: process_arrive_pax

category: arrival_pass

MEAN:	37.346	variance:	115.55	stdev:	10.749
minimum:	19.685	maximum:	59.919		
sample count:	133				

category: ALL

MEAN:	37.346	variance:	115.55	stdev:	10.749
minimum:	19.685	maximum:	59.919		
sample count:	133				

**Statistic Report:

UTILIZATION of node custom_booths

In module: macdonald
In submodel: process_arrive_pax

category: arrival_pass

MEAN:	2.4832	variance:	1.2216	stdev:	1.1053	
minimum:	0	maximum:	3	ending value:		0

category: ALL

MEAN:	2.4832	variance:	1.2216	stdev:	1.1053	
minimum:	0	maximum:	3	ending value:		0

**Statistic Report:

ARC RESPONSE TIME for nodes begin_arrival=>end_arrival (user-assigned name = tot_arrive_time)

In module: macdonald
In submodel: process_arrive_pax

category: arrival_pass

MEAN:	17.565	variance:	294.23	stdev:	17.153
minimum:	1.8333	maximum:	96.332		
sample count:	1304				

category: ALL

MEAN: 19.157 variance: 345.01 stdev: 18.574
 minimum: 1.8333 maximum: 99.022
 sample count: 2584

**Statistic Report:

POPULATION of node ticket_lobby

In module: macdonald

In submodel: process_depart_pax

category: departure_pass

MEAN: 26.949 variance: 120.34 stdev: 10.97
 minimum: 8 maximum: 60 ending value: 22

category: greeters

MEAN: 29.941 variance: 157.55 stdev: 12.552
 minimum: 10 maximum: 79 ending value: 23

category: ALL

MEAN: 56.89 variance: 530.33 stdev: 23.029
 minimum: 21 maximum: 139 ending value: 45

**Statistic Report:

RESPONSE TIME of node ticket_lobby

In module: macdonald

In submodel: process_depart_pax

category: departure_pass

MEAN: 2.4391 variance: 2.0066 stdev: 1.4165
 minimum: 0 maximum: 4.9
 sample count: 1780

category: greeters

MEAN: 2.4984 variance: 1.8862 stdev: 1.3734
 minimum: 0 maximum: 4.9
 sample count: 1928

category: ALL

MEAN: 2.4699 variance: 1.9444 stdev: 1.3944

minimum: 0 maximum: 4.9
sample count: 3708

**Statistic Report:

POPULATION of node others

In module: macdonald
In submodel: process_depart_pax

category: departure_pass
MEAN: 4.5275 variance: 42.104 stdev: 6.4888
minimum: 0 maximum: 26 ending value: 0

category: ALL
MEAN: 4.5275 variance: 42.104 stdev: 6.4888
minimum: 0 maximum: 26 ending value: 0

**Statistic Report:

RESPONSE TIME of node others

In module: macdonald
In submodel: process_depart_pax

category: departure_pass
MEAN: 2.8078 variance: 4.9311 stdev: 2.2206
minimum: 0.016364 maximum: 11.837
sample count: 258

category: ALL
MEAN: 2.8078 variance: 4.9311 stdev: 2.2206
minimum: 0.016364 maximum: 11.837
sample count: 258

**Statistic Report:

UTILIZATION of node others

In module: macdonald
In submodel: process_depart_pax

category: departure_pass
 MEAN: 2.8792 variance: 8.815 stdev: 2.969
 minimum: 0 maximum: 8 ending value: 0

category: ALL
 MEAN: 2.8792 variance: 8.815 stdev: 2.969
 minimum: 0 maximum: 8 ending value: 0

**Statistic Report:

POPULATION of node cdn_and_allied

In module: macdonald
 In submodel: process_depart_pax

category: departure_pass
 MEAN: 13.255 variance: 207.86 stdev: 14.417
 minimum: 0 maximum: 55 ending value: 6

category: ALL
 MEAN: 13.255 variance: 207.86 stdev: 14.417
 minimum: 0 maximum: 55 ending value: 6

**Statistic Report:

RESPONSE TIME of node cdn_and_allied

In module: macdonald
 In submodel: process_depart_pax

category: departure_pass
 MEAN: 4.746 variance: 20.28 stdev: 4.5033
 minimum: 0.0020187 maximum: 23.2
 sample count: 449

category: ALL
 MEAN: 4.746 variance: 20.28 stdev: 4.5033
 minimum: 0.0020187 maximum: 23.2
 sample count: 449

**Statistic Report:

UTILIZATION of node cdn_and_allied

In module: macdonald

In submodel: process_depart_pax

category: departure_pass

MEAN:	5.5595	variance:	7.8066	stdev:	2.794	
minimum:	0	maximum:	8	ending value:		6

category: ALL

MEAN:	5.5595	variance:	7.8066	stdev:	2.794	
minimum:	0	maximum:	8	ending value:		6

**Statistic Report:

POPULATION of node aca_and_allied

In module: macdonald

In submodel: process_depart_pax

category: departure_pass

MEAN:	26.964	variance:	576.45	stdev:	24.009	
minimum:	0	maximum:	85	ending value:		7

category: ALL

MEAN:	26.964	variance:	576.45	stdev:	24.009	
minimum:	0	maximum:	85	ending value:		7

**Statistic Report:

RESPONSE TIME of node aca_and_allied

In module: macdonald

In submodel: process_depart_pax

category: departure_pass

MEAN:	5.7888	variance:	20.497	stdev:	4.5274
minimum:	0.0013401	maximum:	23.807		
sample count:	752				

category: ALL

MEAN:	5.7888	variance:	20.497	stdev:	4.5274
minimum:	0.0013401	maximum:	23.807		
sample count:	752				

**Statistic Report:

UTILIZATION of node aca_and_allied

In module: macdonald

In submodel: process_depart_pax

category: departure_pass

MEAN:	8.5719	variance:	4.9843	stdev:	2.2326	
minimum:	0	maximum:	10	ending value:		7

category: ALL

MEAN:	8.5719	variance:	4.9843	stdev:	2.2326	
minimum:	0	maximum:	10	ending value:		7

**Statistic Report:

POPULATION of node wait_n_concessions

In module: macdonald

In submodel: process_depart_pax

category: departure_pass

MEAN:	44.395	variance:	283.14	stdev:	16.827	
minimum:	11	maximum:	74	ending value:		30

category: greeters

MEAN:	52.08	variance:	271.25	stdev:	16.47	
minimum:	18	maximum:	90	ending value:		28

category: greeters_back

MEAN:	7.2461	variance:	11.767	stdev:	3.4303	
minimum:	0	maximum:	18	ending value:		4

category: ALL

MEAN:	103.72	variance:	1145.2	stdev:	33.841	
minimum:	33	maximum:	163	ending value:		62

**Statistic Report:

RESPONSE TIME of node wait_n_concessions

In module: macdonald

In submodel: process_depart_pax

category: departure_pass

MEAN: 11.357 variance: 24.388 stdev: 4.9384
 minimum: 0 maximum: 27.198
 sample count: 636

category: greeters

MEAN: 12.52 variance: 25.759 stdev: 5.0753
 minimum: 0.50942 maximum: 31.136
 sample count: 687

category: greeters_back

MEAN: 0.58928 variance: 0.15705 stdev: 0.3963
 minimum: 0 maximum: 1.2
 sample count: 1974

category: ALL

MEAN: 5.1524 variance: 41.366 stdev: 6.4316
 minimum: 0 maximum: 31.136
 sample count: 3297

**Statistic Report:

POPULATION of node security_booths

In module: macdonald

In submodel: process_depart_pax

category: departure_pass

MEAN: 3.8019 variance: 22.363 stdev: 4.729
 minimum: 0 maximum: 26 ending value: 6

category: ALL

MEAN: 3.8019 variance: 22.363 stdev: 4.729
 minimum: 0 maximum: 26 ending value: 6

**Statistic Report:

RESPONSE TIME of node security_booths

In module: macdonald

In submodel: process_depart_pax

category: departure_pass

MEAN: 0.33506 variance: 0.11077 stdev: 0.33282
 minimum: 0.00044802 maximum: 1.9295
 sample count: 1811

category: ALL

MEAN: 0.33506 variance: 0.11077 stdev: 0.33282
 minimum: 0.00044802 maximum: 1.9295
 sample count: 1811

**Statistic Report:

UTILIZATION of node security_booths

In module: macdonald

In submodel: process_depart_pax

category: departure_pass

MEAN: 1.8813 variance: 1.2089 stdev: 1.0995
 minimum: 0 maximum: 3 ending value: 3

category: ALL

MEAN: 1.8813 variance: 1.2089 stdev: 1.0995
 minimum: 0 maximum: 3 ending value: 3

**Statistic Report:

POPULATION of node greet_area

In module: macdonald

In submodel: process_depart_pax

category: departure_pass

MEAN: 13.977 variance: 26.268 stdev: 5.1252
 minimum: 2 maximum: 29 ending value: 10

category: greeters

MEAN: 15.193 variance: 36.165 stdev: 6.0137
 minimum: 0 maximum: 37 ending value: 10

category: ALL

MEAN: 29.17 variance: 95.514 stdev: 9.7731
 minimum: 7 maximum: 60 ending value: 20

**Statistic Report:

RESPONSE TIME of node greet_area

In module: macdonald

In submodel: process_depart_pax

category: departure_pass

MEAN: 1.2337 variance: 0.62472 stdev: 0.79039
 minimum: 0 maximum: 3.002
 sample count: 1816

category: greeters

MEAN: 1.2358 variance: 0.62151 stdev: 0.78836
 minimum: 0 maximum: 2.4
 sample count: 1969

category: ALL

MEAN: 1.2348 variance: 0.62288 stdev: 0.78923
 minimum: 0 maximum: 3.002
 sample count: 3785

****Statistic Report:**

ARC RESPONSE TIME for nodes begin_depart=>end_depart
 (user-assigned name = tot_depart_time)

In module: macdonald

In submodel: process_depart_pax

category: departure_pass

MEAN: 52.747 variance: 285.31 stdev: 16.891
 minimum: 19.675 maximum: 109.98
 sample count: 1717

category: ALL

MEAN: 52.747 variance: 285.31 stdev: 16.891
 minimum: 19.675 maximum: 109.98
 sample count: 1717

*****
 ***** **NODE SUMMARY STATISTIC REPORT** *****
 *****

In module: macdonald

In submodel: process_arrive_pax

	SAMPLE COUNT	MEAN POPULATION	MEAN RESPONSE	MEAN UTILIZATION
Node: arrival_lobby				
category: arrival_pass				
	1304	32.134	3.8775	
category: meeters				

	1280	32.683	4.0184	
category: ALL	2584	64.817	3.9473	
Node: pil				
category: arrival_pass	227	15.839	11.164	1.609
category: ALL	227	15.839	11.164	1.609
Node: dom_baggage_claim				
category: arrival_pass	955	26.752	4.4391	
category: meeters	827	23.246	4.4728	
category: ALL	1782	49.998	4.4548	
Node: int_baggage_claim				
category: arrival_pass	199	4.9617	4.0157	
category: ALL	199	4.9617	4.0157	
Node: custom_booths				
category: arrival_pass	133	28.133	37.346	2.4832
category: ALL	133	28.133	37.346	2.4832
Node: begin_arrival=>end_arrival				
category: arrival_pass	1304		17.565	
category: ALL	2584		19.157	

In submodel: process_depart_pax

	SAMPLE COUNT	MEAN POPULATION	MEAN RESPONSE	MEAN UTILIZATION
Node: ticket_lobby				
category: departure_pass	1780	26.949	2.4391	
category: greeters	1928	29.941	2.4984	
category: ALL	3708	56.89	2.4699	
Node: others				
category: departure_pass	258	4.5275	2.8078	2.8792

category: ALL	258	4.5275	2.8078	2.8792
Node: cdn_and_allied				
category: departure_pass	449	13.255	4.746	5.5595
category: ALL	449	13.255	4.746	5.5595
Node: aca_and_allied				
category: departure_pass	752	26.964	5.7888	8.5719
category: ALL	752	26.964	5.7888	8.5719
Node: wait_n_concessions				
category: departure_pass	636	44.395	11.357	
category: greeters	687	52.08	12.52	
category: greeters_back	1974	7.2461	0.58928	
category: ALL	3297	103.72	5.1524	
Node: security_booths				
category: departure_pass	1811	3.8019	0.33506	1.8813
category: ALL	1811	3.8019	0.33506	1.8813
Node: greet_area				
category: departure_pass	1816	13.977	1.2337	
category: greeters	1969	15.193	1.2358	
category: ALL	3785	29.17	1.2348	
Node: begin_depart=>end_depart				
category: departure_pass	1717		52.747	
category: ALL	1717		52.747	

*****
 ***** END REPORT 1 FOR BATCH 2 OF REPLICATION 1 *****
 *****

Appendix F: Detailed Output of The Statistical Program, SPSS

F: Detailed Output of the SPSS. MCA Data:

*****

03 Jul 95 SPSS Release 4.0 for Sun 4

20:01:03 SPSS -- Carleton University Sun-4

SunOS 4.0

For SunOS 4.0 SPSS -- Carleton University

License Number 21295

This software is functional through August 31, 1999.

Try the new SPSS Release 4.0 features:

- * LOGISTIC REGRESSION procedure
- * EXAMINE procedure to explore data
- * FLIP to transpose data files
- * MATRIX Transformations Language
- * CATEGORIES Option:
  - * conjoint analysis
  - * correspondence analysis
  - * GRAPH interface to SPSS Graph

See the new SPSS documentation for more information on these new features.

```

1 0 DATA LIST FILE='data.all'
2 0 /time 1-7 bag 8-14 tlb 15-21 aca 22-28 cdn 29-35 sec 36-42 con 43-49
3 0 bags 50-56 tlbs 57-63 acas 64-70 cdns 71-77 secs 78-84 cons 85-91.
```

This command will read 1 records from data.all

Variable	Rec	Start	End	Format
TIME	1	1	7	F7.0
BAG	1	8	14	F7.0
TLB	1	15	21	F7.0
ACA	1	22	28	F7.0
CDN	1	29	35	F7.0
SEC	1	36	42	F7.0
CON	1	43	49	F7.0
BAGS	1	50	56	F7.0
TLBS	1	57	63	F7.0
ACAS	1	64	70	F7.0
CDNS	1	71	77	F7.0
SECS	1	78	84	F7.0
CONS	1	85	91	F7.0

```

4 0 SAVE OUTFILE='sps.sys'.
5 0
```

Time stamp on saved file: 03 JUL 95 20:01:05

File contains 13 variables, 104 bytes per case before compression

161 cases saved

Preceding task required .44 seconds CPU time; .97 seconds elapsed.

6 0 GET FILE='sps.sys'.

File sps.sys

Created: 03 JUL 95 20:01:05 - 13 variables

7 0 REGRESSION VARIABLES = bag bags

8 0 /DEPENDENT = bag

9 0 /ENTER bags.

03 Jul 95 SPSS Release 4.0 for Sun 4

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20:01:06 SPSS -- Carleton University Sun-4 SunOS 4.0

There are 203,464 bytes of memory available.

The largest contiguous area has 202,824 bytes.

1348 bytes of memory required for REGRESSION procedure.

0 more bytes may be needed for Residuals plots.

03 Jul 95 SPSS Release 4.0 for Sun 4

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20:01:07 SPSS -- Carleton University Sun-4 SunOS 4.0

***** MULTIPLE REGRESSION *****

Listwise Deletion of Missing Data

Equation Number 1 Dependent Variable.. BAG

Block Number 1. Method: Enter BAGS

Variable(s) Entered on Step Number 1.. BAGS

Multiple R	.51633	Analysis of Variance			
R Square	.26659		DF	Sum of Squares	Mean Square
Adjusted R Square	.26198	Regression	1	67385.26972	67385.26972
Standard Error	34.14537	Residual	159	185379.14022	1165.90654
		F =	57.79646	Signif F =	.0000

----- Variables in the Equation -----

Variable	B	SE B	Beta	T	Sig T
BAGS	.406806	.053510	.516327	7.602	.0000
(Constant)	27.655507	3.804353		7.269	.0000

End Block Number 1 All requested variables entered.

03 Jul 95 SPSS Release 4.0 for Sun 4

Page 4

20:01:07 SPSS -- Carleton University Sun-4 SunOS 4.0

Preceding task required .22 seconds CPU time; 1.40 seconds elapsed.

10 0 regression variables = tlb tlbs

11 0 /dependent = tlb

12 0 /enter tlbs.

There are 203,528 bytes of memory available.

The largest contiguous area has 202,824 bytes.

1348 bytes of memory required for REGRESSION procedure.

0 more bytes may be needed for Residuals plots.

03 Jul 95 SPSS Release 4.0 for Sun 4

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20:01:07 SPSS -- Carleton University Sun-4 SunOS 4.0

***** MULTIPLE REGRESSION *****

Listwise Deletion of Missing Data

Equation Number 1 Dependent Variable.. TLB

Block Number 1. Method: Enter TLBS

Variable(s) Entered on Step Number 1.. TLBS

Multiple R	.65771	Analysis of Variance			
R Square	.43258	DF	Sum of Squares	Mean Square	
Adjusted R Square	.42901	Regression	1	13543.53287	13543.53287

Standard Error   10.57021   Residual   159   17764.96402   111.72933

F =   121.21734   Signif F = .0000

----- Variables in the Equation -----

Variable	B	SE B	Beta	T	Sig T
TLBS	.403499	.036649	.657711	11.010	.0000
(Constant)	42.289520	2.229311		18.970	.0000

End Block Number 1 All requested variables entered.

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20:01:07 SPSS -- Carleton University Sun-4 SunOS 4.0

Preceding task required .08 seconds CPU time; .13 seconds elapsed.

13 0 regression variables = con cons

14 0 /dependent = con

15 0 /enter cons.

There are 203,528 bytes of memory available.

The largest contiguous area has 202,824 bytes.

1348 bytes of memory required for REGRESSION procedure.

0 more bytes may be needed for Residuals plots.

03 Jul 95 SPSS Release 4.0 for Sun 4

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20:01:08 SPSS -- Carleton University Sun-4 SunOS 4.0

***** MULTIPLE REGRESSION *****

Listwise Deletion of Missing Data

Equation Number 1 Dependent Variable.. CON

Block Number 1. Method: Enter CONS

Variable(s) Entered on Step Number 1.. CONS

Multiple R	.78767	Analysis of Variance			
R Square	.62042		DF	Sum of Squares	Mean Square
Adjusted R Square	.61804	Regression	1	37423.41219	37423.41219
Standard Error	11.99995	Residual	159	22895.79278	143.99870

F = 259.88716   Signif F = .0000

----- Variables in the Equation -----

Variable	B	SE B	Beta	T	Sig T
CONS	.450594	.027951	.787669	16.121	.0000
(Constant)	41.470536	3.043478		13.626	.0000

End Block Number 1 All requested variables entered.

03 Jul 95 SPSS Release 4.0 for Sun 4

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20:01:08 SPSS -- Carleton University Sun-4 SunOS 4.0

Preceding task required .08 seconds CPU time; .13 seconds elapsed.

16 0 regression variables = aca acas

17 0 /dependent = aca

18 0 /enter acas.

There are 203,528 bytes of memory available.

The largest contiguous area has 202,824 bytes.

1348 bytes of memory required for REGRESSION procedure.

0 more bytes may be needed for Residuals plots.

03 Jul 95 SPSS Release 4.0 for Sun 4

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20:01:08 SPSS -- Carleton University Sun-4 SunOS 4.0

***** MULTIPLE REGRESSION *****

Listwise Deletion of Missing Data

Equation Number 1 Dependent Variable.. ACA

Block Number 1. Method: Enter ACAS

Variable(s) Entered on Step Number 1.. ACAS

		Analysis of Variance			
		DF	Sum of Squares	Mean Square	
Multiple R	.63793				
R Square	.40696				
Adjusted R Square	.40323				
Standard Error	9.24541				
		Regression	1	9326.48989	
		Residual	159	13590.93868	
				85.47760	

F = 109.11034   Signif F = .0000

----- Variables in the Equation -----

Variable	B	SE B	Beta	T	Sig T
ACAS	.318739	.030514	.637935	10.446	.0000
(Constant)	22.009026	1.096745		20.068	.0000

End Block Number 1 All requested variables entered.

03 Jul 95 SPSS Release 4.0 for Sun 4

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20:01:08 SPSS -- Carleton University Sun-4 SunOS 4.0

Preceding task required .08 seconds CPU time; .13 seconds elapsed.

19 0 regression variables = sec secs

20 0 /dependent = sec

21 0 /enter secs.

There are 203,528 bytes of memory available.

The largest contiguous area has 202,824 bytes.

1348 bytes of memory required for REGRESSION procedure.

0 more bytes may be needed for Residuals plots.

03 Jul 95 SPSS Release 4.0 for Sun 4

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20:01:08 SPSS -- Carleton University Sun-4 SunOS 4.0

**** MULTIPLE REGRESSION ****

Listwise Deletion of Missing Data

Equation Number 1 Dependent Variable.. SEC

Block Number 1. Method: Enter SECS

Variable(s) Entered on Step Number 1.. SECS

Multiple R	.65515	Analysis of Variance			
R Square	.42922		DF	Sum of Squares	Mean Square
Adjusted R Square	.42563	Regression	1	4712.21608	4712.21608
Standard Error	6.27782	Residual	159	6266.34292	39.41096

F = 119.56613   Signif F = .0000

----- Variables in the Equation -----

Variable	B	SE B	Beta	T	Sig T
SECS	.544741	.049818	.655149	10.935	.0000
(Constant)	1.503865	1.553170		.968	.3344

End Block Number 1 All requested variables entered.

03 Jul 95 SPSS Release 4.0 for Sun 4

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20:01:08 SPSS -- Carleton University Sun-4 SunOS 4.0

Preceding task required .08 seconds CPU time; .13 seconds elapsed.

22 0 regression variables = cdn cdns

23 0 /dependent = cdn

24 0 /enter cdns.

There are 203,528 bytes of memory available.

The largest contiguous area has 202,824 bytes.

1348 bytes of memory required for REGRESSION procedure.

0 more bytes may be needed for Residuals plots.

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20:01:08 SPSS -- Carleton University Sun-4 SunOS 4.0

***** MULTIPLE REGRESSION *****

Listwise Deletion of Missing Data

Equation Number 1   Dependent Variable..   CDN

Block Number 1. Method: Enter   CDNS

Variable(s) Entered on Step Number 1..   CDNS

Multiple R	.79722	Analysis of Variance			
R Square	.63556		DF	Sum of Squares	Mean Square
Adjusted R Square	.63327	Regression	1	6037.06516	6037.06516
Standard Error	4.66601	Residual	159	3461.69261	21.77165

F =   277.29018   Signif F = .0000

----- Variables in the Equation -----

Variable	B	SE B	Beta	T	Sig T
CDNS	.426841	.025633	.797222	16.652	.0000
(Constant)	11.229662	.500445		22.439	.0000

End Block Number 1   All requested variables entered.

03 Jul 95   SPSS Release 4.0 for Sun 4

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20:01:08   SPSS -- Carleton University   Sun-4   SunOS 4.0

Preceding task required .05 seconds CPU time; .13 seconds elapsed.

25 0 correlations bag bags tlb tlbs con cons.

PEARSON CORR problem requires 816 bytes of workspace.

03 Jul 95   SPSS Release 4.0 for Sun 4

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20:01:08   SPSS -- Carleton University   Sun-4   SunOS 4.0

- - Correlation Coefficients - -

BAG	BAGS	TLB	TLBS	CON	CONS

BAG	1.0000	.5163**	.1118	.2355**	.0820	.2705**
BAGS	.5163**	1.0000	-.0059	.0540	-.0733	-.0359
TLB	.1118	-.0059	1.0000	.6577**	.7905**	.8310**
TLBS	.2355**	.0540	.6577**	1.0000	.7134**	.8286**
CON	.0820	-.0733	.7905**	.7134**	1.0000	.7877**
CONS	.2705**	-.0359	.8310**	.8286**	.7877**	1.0000

* - Signif. LE .05   ** - Signif. LE .01   (2-tailed)   " . " printed if a coefficient cannot be computed

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20:01:08 SPSS -- Carleton University Sun-4 SunOS 4.0

Preceding task required .11 seconds CPU time; .35 seconds elapsed.

26 0 correlations sec secs aca acas cdn cdns.

PEARSON CORR problem requires 816 bytes of workspace.

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20:01:08 SPSS -- Carleton University Sun-4 SunOS 4.0

- - Correlation Coefficients - -

	SEC	SECS	ACA	ACAS	CDN	CDNS
SEC	1.0000	.6551**	.2309**	-.0079	.1704*	.0871
SECS	.6551**	1.0000	-.0549	-.0975	.3020**	.1920*
ACA	.2309**	-.0549	1.0000	.6379**	-.0481	-.0600
ACAS	-.0079	-.0975	.6379**	1.0000	-.4595**	-.3728**
CDN	.1704*	.3020**	-.0481	-.4595**	1.0000	.7972**
CDNS	.0871	.1920*	-.0600	-.3728**	.7972**	1.0000

* - Signif. LE .05   ** - Signif. LE .01   (2-tailed)   " . " printed if a coefficient cannot be computed

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20:01:08 SPSS -- Carleton University Sun-4 SunOS 4.0

Preceding task required .09 seconds CPU time; .10 seconds elapsed.

27 0 descriptives bag tlb sec aca cdn con bags tlbs acas cdns secs cons.

There are 203,848 bytes of memory available.

The largest contiguous area has 202,840 bytes.

912 bytes of memory required for the DESCRIPTIVES procedure.

48 bytes have already been acquired.

864 bytes remain to be acquired.

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20:01:09 SPSS -- Carleton University Sun-4 SunOS 4.0

Number of valid observations (listwise) = 161.00

Variable	Mean	Std Dev	Valid		N	Label
			Minimum	Maximum		
BAG	48.10	39.75	3	152	161	
TLB	65.06	13.99	36	92	161	
SEC	17.60	8.28	1	39	161	
ACA	30.57	11.97	10	63	161	
CDN	16.88	7.71	6	39	161	
CON	88.11	19.42	50	129	161	
BAGS	50.25	50.45	0	177	161	
TLBS	56.42	22.80	23	121	161	
ACAS	26.86	23.95	2	82	161	
CDNS	13.24	14.39	0	52	161	
SECS	29.55	9.96	9	60	161	
CONS	103.50	33.94	33	161	161	

03 Jul 95 SPSS Release 4.0 for Sun 4

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20:01:09 SPSS -- Carleton University Sun-4 SunOS 4.0

Preceding task required .11 seconds CPU time; .31 seconds elapsed.

28 0 finish.

28 command lines read.

0 errors detected.

0 warnings issued.

2 seconds CPU time.

6 seconds elapsed time.

End of job.

Appendix G: Source List of the Main Optimization Program

G: Source List of Optimization Algorithm:

```
*****
```

```
#include <stdio.h>
#define MAXTIME 23
#define SEGMENTS 10
#define MAXRESOURCE 5000
#define MAXDEMAND 2000

typedef struct {
float cost;
int space;} MIN;

MIN min[MAXRESOURCE];

int y[MAXTIME+1][SEGMENTS+1][MAXDEMAND+1];
float py[MAXTIME+1][SEGMENTS+1][MAXDEMAND+1];
int count[MAXTIME+1][SEGMENTS+1];

float alpha[SEGMENTS+1], beta[SEGMENTS+1], theta[SEGMENTS+1],
delta[SEGMENTS+1], bx[SEGMENTS+1], ax[SEGMENTS+1], minb, lastmin;
int t, j, x, num, k, i, totalx[MAXTIME +1], xopt[MAXTIME +1][SEGMENTS+1],

DELTA, kk, coef;
char minutes[10], tempstring[15];
float c1[MAXRESOURCE], c2[MAXRESOURCE], c[MAXRESOURCE],
opcost[MAXTIME +1][SEGMENTS+1],
segcost[MAXTIME +1][SEGMENTS+1], totalc[MAXTIME +1],
cmin[SEGMENTS+1], MINCOST;

main()
{
FILE *fo, *fp;

FILE *map[SEGMENTS+1];
map[0] = fopen("wktic.dat.out", "r");
map[1] = fopen("wkdombag.dat.out", "r");
map[2] = fopen("wksec.dat.out", "r");
map[3] = fopen("wkcon.dat.out", "r");
map[4] = fopen("wkpil.dat.out", "r");
map[5] = fopen("wkintbag.dat.out", "r");
map[6] = fopen("wklob.dat.out", "r");
map[7] = fopen("wkcus.dat.out", "r");
map[8] = fopen("wkholddp.dat.out", "r");
map[9] = fopen("wkholdar.dat.out", "r");
```

```

map[10] = fopen("wkgrt.dat.out", "r");

fo = fopen("fin7", "r");
fp = fopen("wkoutput", "w+");

for (j=0; j<= SEGMENTS; j++)
    { fscanf(fo, "%f %f %f", &alpha[j], &beta[j], &theta[j]);
      fprintf(fp, "segment= %d, alpha= %f, beta= %f, theta= %f \n \n", j,
              alpha[j], beta[j], theta[j]);
      /*printf("%f %f %f\n", alpha[j], beta[j], theta[j]);*/ }
for (t=0; t<=MAXTIME; t++)
    { j = 0;
label:  while(j <= SEGMENTS)
        {
            k = 0;
            while(feof(map[j])==0)
                {
                    fscanf(map[j], "%s", tempstring);
                    if (strcmp(tempstring, "minutes") != 0)
                        {
                            y[t][j][k] = atoi(tempstring);

                            /*printf("%d %d %d \n", t,j,k);*/

                            if ((fscanf(map[j], "%f", &py[t][j][k])) !=1)
                                printf("number missing =%d %d\n", y[t][j][k], j);
                            else

                                k++;
                                continue;
                        }
                    else
                        /* printf( "%s\n", tempstring);*/
                        count[t][j] = k;
                    /* for (i=0; i< count[t][j]; i++); */
                    /* printf( "%d %f\n", y[t][j][i], py[t][j][i]);*/
                    j++;

                    goto label;
                }
        }
    }
/* optimization procedure */

```

```

for (t=0; t<=MAXTIME; t++)
{
    minb = 1000;
    lastmin = 0;
    for (j=0; j<= SEGMENTS; j++)
    { bx[j] = beta[j];
      ax[j] = alpha[j]; }

    totalx[t] = 0;
    totalc[t] = 0.0;
    for (j=0; j<=SEGMENTS; j++)
    {
        MINCOST = 100000.;
        num = 0;

        for (x=0; x<MAXRESOURCE; x++)
        { c1[x] = 0;
          c2[x] = 0;
          delta[j] = (int)(x/theta[j]);
          for (k=0; k < count[t][j]; k++)
          {
              if ( y[t][j][k] <= delta[j])
                  c1[x] += alpha[j]*(x - theta[j]*y[t][j][k])*py[t][j][k];
              else
                  c2[x] += beta[j]*(theta[j]*y[t][j][k] - x)*py[t][j][k];
          }
          min[x].cost = c1[x] + c2[x];
          min[x].space = x;
          /*fprintf(fp,"%f, %d\n",min[x].cost, min[x].space );*/
          if(MINCOST > min[x].cost)
          {
              MINCOST = min[x].cost;
              continue;
          }
          else
              break;
        }
        cmin[j] = MINCOST;
        xopt[t][j] = min[x-1].space;
        opcost[t][j] = min[x-1].cost;
        segcost[t][j] = alpha[j]*xopt[t][j];
        totalc[t] += segcost[t][j];
    }
}

```

```

    totalx[t] += xopt[t][j];

    fprintf(fp, " time = %d, segment = %d, min. extra cost = %.2f, optimum space =
%d, supply cost = %.1f.\n", t, j, opcost[t][j], xopt[t][j], segcost[t][j]);
}
fprintf(fp, "\n time = %d, total optimum space = %d, total supply cost = %.1f\n\n",
t, totalx[t], totalc[t]);

if(totalx[t]*2/3 > MAXRESOURCE)
    fprintf(fp, "\n Resources Are Lower Than Minimum Level\n\n");
else

    for(k=0; k<=SEGMENTS; k++)
/*fprintf(fp, "\n %d\n", xopt[k]);*/
        while(totalx[t] > MAXRESOURCE)
        { /*fprintf(fp, "\n beta= %f\n", bx[coef]);*/

            for(k=0; k<=SEGMENTS; k++)
            {
                if(minb > bx[k] && bx[k] > lastmin)
                { minb = bx[k];
                  kk = k;
                }
            }
/*fprintf(fp, "\n minimum beta= %f\n", minb);*/
            coef = kk;

            if(minb == bx[k])
            { if(ax[kk] <= ax[kk-1])
              coef = kk-1; }

            DELTA = totalx[t] - MAXRESOURCE;
            if(DELTA <= xopt[t][coef]/3)
            {
                xopt[t][coef] = xopt[t][coef]-DELTA;
                segcost[t][coef] = xopt[t][coef] *alpha[coef];
                totalx[t] = totalx[t] - DELTA;
                totalc[t] = totalc[t] - alpha[coef]*DELTA;
            }
            else
            {
                totalx[t] = totalx[t] - (xopt[t][coef])/3;
                totalc[t] = totalc[t] - (xopt[t][coef]*alpha[coef])/3;
                xopt[t][coef] = (2*xopt[t][coef])/3;
            }
        }
    }

```

```

    segcost[t][coef] = xopt[t][coef] *alpha[coef];
}

for(k=0; k<=SEGMENTS; k++)
    fprintf(fp," time = %d, segment = %d, sub-optimum space = %d, supply cost=
    %.1f\n",
    t, k, xopt[t][k], segcost[t][k] );
    fprintf(fp," \n time = %d, available space = %d, supply cost= %.1f\n",
    t, totalx[t], totalc[t]);
    lastmin = minb;
    minb= 100;

}
}

for (t=0; t<=MAXTIME; t++)
    { for(j=0; j<=SEGMENTS; j++)
        fprintf(fp," time = %d, segment = %d, min. extra cost = %.2f, optimum space
        = %d, supply cost =%.1f,\n", t, j, opcost[t][j], xopt[t][j], segcost[t][j]);

        fprintf(fp," \n time = %d, total optimum space = %d, total supply cost = %.1f\n
        \n",
        t, totalx[t], totalc[t]);

    }
for (t=0; t<=MAXTIME; t++)
    fprintf(fp," \n %d\n", totalx[t]);

    for(k=0; k<=SEGMENTS; k++)
        fclose(map[k]);

    fclose(fv);
    fclose(fp);
}

```

Appendix H: Sample Output of The Optimization Model

H Typical Optimization Model Output:

*****

a. Input Parameters:

-----

segment= 0, alpha= 1.500000, beta= 1.500000, theta= 1.600000

segment= 1, alpha= 1.100000, beta= 1.100000, theta= 1.600000

segment= 2, alpha= 1.200000, beta= 1.200000, theta= 1.400000

segment= 3, alpha= 1.300000, beta= 1.300000, theta= 2.700000

segment= 4, alpha= 1.400000, beta= 1.400000, theta= 1.400000

segment= 5, alpha= 1.500000, beta= 1.500000, theta= 1.600000

segment= 6, alpha= 1.600000, beta= 1.600000, theta= 2.700000

segment= 7, alpha= 1.700000, beta= 1.700000, theta= 1.600000

segment= 8, alpha= 1.800000, beta= 1.800000, theta= 1.400000

segment= 9, alpha= 1.900000, beta= 1.900000, theta= 1.400000

segment= 10, alpha= 1.900000, beta= 1.900000, theta= 1.600000

*****

b: Output for A User Defined Resource Type, MCA:

-----

time = 0, segment = 0, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 0, segment = 1, min. extra cost = 22.02, optimum space = 52, supply cost =57.2,

time = 0, segment = 2, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 0, segment = 3, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 0, segment = 4, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 0, segment = 5, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 0, segment = 6, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 0, segment = 7, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 0, segment = 8, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 0, segment = 9, min. extra cost = 21.97, optimum space = 23, supply cost =43.7,

time = 0, segment = 10, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 0, total optimum space = 75, total supply cost = 100.9

time = 1, segment = 0, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 1, segment = 1, min. extra cost = 3.96, optimum space = 6, supply cost =6.6,

time = 1, segment = 2, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 1, segment = 3, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 4, segment = 10, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 4, total optimum space = 15, total supply cost = 25.8

time = 5, segment = 0, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 5, segment = 1, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 5, segment = 2, min. extra cost = 2.04, optimum space = 2, supply cost =2.4,

time = 5, segment = 3, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 5, segment = 4, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 5, segment = 5, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 5, segment = 6, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 5, segment = 7, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 5, segment = 8, min. extra cost = 188.98, optimum space = 235, supply cost =423.0,

time = 5, segment = 9, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 5, segment = 10, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 5, total optimum space = 237, total supply cost = 425.4

time = 6, segment = 0, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 6, segment = 1, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 6, segment = 2, min. extra cost = 2.25, optimum space = 3, supply cost =3.6,

time = 6, segment = 3, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 6, segment = 4, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 6, segment = 5, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 6, segment = 6, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 6, segment = 7, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 6, segment = 8, min. extra cost = 102.24, optimum space = 560, supply cost =1008.0,

time = 6, segment = 9, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 6, segment = 10, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 6, total optimum space = 563, total supply cost = 1011.6

time = 7, segment = 0, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 7, segment = 1, min. extra cost = 113.59, optimum space = 143, supply cost =157.3,

time = 7, segment = 2, min. extra cost = 2.74, optimum space = 3, supply cost =3.6,

time = 7, segment = 3, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 7, segment = 4, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 7, segment = 5, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 7, segment = 6, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 7, segment = 7, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 7, segment = 8, min. extra cost = 207.58, optimum space = 361, supply cost =649.8,

time = 7, segment = 9, min. extra cost = 114.65, optimum space = 72, supply cost =136.8,

time = 7, segment = 10, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 7, total optimum space = 579, total supply cost = 947.5

time = 8, segment = 0, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,

time = 8, segment = 1, min. extra cost = 90.34, optimum space = 175, supply cost =192.5,

time = 8, segment = 2, min. extra cost = 2.36, optimum space = 3, supply cost = 3.6,
 time = 8, segment = 3, min. extra cost = 0.00, optimum space = 0, supply cost = 0.0,
 time = 8, segment = 4, min. extra cost = 0.00, optimum space = 0, supply cost = 0.0,
 time = 8, segment = 5, min. extra cost = 0.00, optimum space = 0, supply cost = 0.0,
 time = 8, segment = 6, min. extra cost = 137.15, optimum space = 289, supply cost = 462.4,
 time = 8, segment = 7, min. extra cost = 0.00, optimum space = 0, supply cost = 0.0,
 time = 8, segment = 8, min. extra cost = 121.66, optimum space = 516, supply cost = 928.8,
 time = 8, segment = 9, min. extra cost = 70.32, optimum space = 84, supply cost = 159.6,
 time = 8, segment = 10, min. extra cost = 0.00, optimum space = 0, supply cost = 0.0,

time = 8, total optimum space = 1067, total supply cost = 1746.9

time = 9, segment = 0, min. extra cost = 0.00, optimum space = 0, supply cost = 0.0,
 time = 9, segment = 1, min. extra cost = 47.32, optimum space = 100, supply cost = 110.0,
 time = 9, segment = 2, min. extra cost = 1.93, optimum space = 3, supply cost = 3.6,
 time = 9, segment = 3, min. extra cost = 81.87, optimum space = 224, supply cost = 291.2,
 time = 9, segment = 4, min. extra cost = 8.36, optimum space = 12, supply cost = 16.8,
 time = 9, segment = 5, min. extra cost = 4.86, optimum space = 6, supply cost = 9.0,
 time = 9, segment = 6, min. extra cost = 65.45, optimum space = 154, supply cost = 246.4,
 time = 9, segment = 7, min. extra cost = 1.63, optimum space = 2, supply cost = 3.4,
 time = 9, segment = 8, min. extra cost = 121.90, optimum space = 424, supply cost = 763.2,
 time = 9, segment = 9, min. extra cost = 52.86, optimum space = 39, supply cost = 74.1,
 time = 9, segment = 10, min. extra cost = 0.00, optimum space = 0, supply cost = 0.0,

time = 9, total optimum space = 964, total supply cost = 1517.7

time = 10, segment = 0, min. extra cost = 7.68, optimum space = 22, supply cost = 33.0,
 time = 10, segment = 1, min. extra cost = 42.78, optimum space = 87, supply cost = 95.7,
 time = 10, segment = 2, min. extra cost = 1.88, optimum space = 3, supply cost = 3.6,
 time = 10, segment = 3, min. extra cost = 60.88, optimum space = 165, supply cost = 214.5,
 time = 10, segment = 4, min. extra cost = 28.96, optimum space = 42, supply cost = 58.8,
 time = 10, segment = 5, min. extra cost = 10.72, optimum space = 24, supply cost = 36.0,
 time = 10, segment = 6, min. extra cost = 70.39, optimum space = 173, supply cost = 276.8,
 time = 10, segment = 7, min. extra cost = 12.22, optimum space = 18, supply cost = 30.6,
 time = 10, segment = 8, min. extra cost = 129.76, optimum space = 302, supply cost = 543.6,
 time = 10, segment = 9, min. extra cost = 66.50, optimum space = 81, supply cost = 153.9,
 time = 10, segment = 10, min. extra cost = 9.66, optimum space = 12, supply cost = 22.8,

time = 10, total optimum space = 929, total supply cost = 1469.3

time = 11, segment = 0, min. extra cost = 17.74, optimum space = 38, supply cost = 57.0,
 time = 11, segment = 1, min. extra cost = 34.37, optimum space = 67, supply cost = 73.7,
 time = 11, segment = 2, min. extra cost = 1.57, optimum space = 2, supply cost = 2.4,
 time = 11, segment = 3, min. extra cost = 37.23, optimum space = 119, supply cost = 154.7,
 time = 11, segment = 4, min. extra cost = 0.00, optimum space = 0, supply cost = 0.0,
 time = 11, segment = 5, min. extra cost = 0.00, optimum space = 0, supply cost = 0.0,
 time = 11, segment = 6, min. extra cost = 53.04, optimum space = 70, supply cost = 112.0,
 time = 11, segment = 7, min. extra cost = 9.52, optimum space = 10, supply cost = 17.0,

time = 11, segment = 8, min. extra cost = 62.01, optimum space = 220, supply cost = 396.0,
time = 11, segment = 9, min. extra cost = 34.47, optimum space = 34, supply cost = 64.6,
time = 11, segment = 10, min. extra cost = 10.16, optimum space = 18, supply cost = 34.2,

time = 11, total optimum space = 578, total supply cost = 911.6

time = 12, segment = 0, min. extra cost = 22.27, optimum space = 45, supply cost = 67.5,
time = 12, segment = 1, min. extra cost = 49.25, optimum space = 98, supply cost = 107.8,
time = 12, segment = 2, min. extra cost = 1.71, optimum space = 2, supply cost = 2.4,
time = 12, segment = 3, min. extra cost = 51.93, optimum space = 140, supply cost = 182.0,
time = 12, segment = 4, min. extra cost = 7.27, optimum space = 8, supply cost = 11.2,
time = 12, segment = 5, min. extra cost = 4.74, optimum space = 8, supply cost = 12.0,
time = 12, segment = 6, min. extra cost = 64.71, optimum space = 132, supply cost = 211.2,
time = 12, segment = 7, min. extra cost = 3.43, optimum space = 3, supply cost = 5.1,
time = 12, segment = 8, min. extra cost = 90.86, optimum space = 289, supply cost = 520.2,
time = 12, segment = 9, min. extra cost = 51.67, optimum space = 42, supply cost = 79.8,
time = 12, segment = 10, min. extra cost = 12.02, optimum space = 23, supply cost = 43.7,

time = 12, total optimum space = 790, total supply cost = 1242.9

time = 13, segment = 0, min. extra cost = 19.47, optimum space = 53, supply cost = 79.5,
time = 13, segment = 1, min. extra cost = 48.71, optimum space = 79, supply cost = 86.9,
time = 13, segment = 2, min. extra cost = 1.83, optimum space = 2, supply cost = 2.4,
time = 13, segment = 3, min. extra cost = 37.91, optimum space = 146, supply cost = 189.8,
time = 13, segment = 4, min. extra cost = 65.73, optimum space = 73, supply cost = 102.2,
time = 13, segment = 5, min. extra cost = 6.41, optimum space = 21, supply cost = 31.5,
time = 13, segment = 6, min. extra cost = 68.19, optimum space = 116, supply cost = 185.6,
time = 13, segment = 7, min. extra cost = 14.33, optimum space = 16, supply cost = 27.2,
time = 13, segment = 8, min. extra cost = 112.91, optimum space = 221, supply cost = 397.8,
time = 13, segment = 9, min. extra cost = 33.76, optimum space = 40, supply cost = 76.0,
time = 13, segment = 10, min. extra cost = 11.48, optimum space = 24, supply cost = 45.6,

time = 13, total optimum space = 791, total supply cost = 1224.5

time = 14, segment = 0, min. extra cost = 33.45, optimum space = 88, supply cost = 132.0,
time = 14, segment = 1, min. extra cost = 69.00, optimum space = 104, supply cost = 114.4,
time = 14, segment = 2, min. extra cost = 2.04, optimum space = 3, supply cost = 3.6,
time = 14, segment = 3, min. extra cost = 51.06, optimum space = 275, supply cost = 357.5,
time = 14, segment = 4, min. extra cost = 26.60, optimum space = 25, supply cost = 35.0,
time = 14, segment = 5, min. extra cost = 11.63, optimum space = 16, supply cost = 24.0,
time = 14, segment = 6, min. extra cost = 103.37, optimum space = 213, supply cost = 340.8,
time = 14, segment = 7, min. extra cost = 17.37, optimum space = 45, supply cost = 76.5,
time = 14, segment = 8, min. extra cost = 207.54, optimum space = 528, supply cost = 950.4,
time = 14, segment = 9, min. extra cost = 88.84, optimum space = 79, supply cost = 150.1,
time = 14, segment = 10, min. extra cost = 14.60, optimum space = 42, supply cost = 79.8,

time = 14, total optimum space = 1418, total supply cost = 2264.1

time = 15, segment = 0, min. extra cost = 23.07, optimum space = 99, supply cost =148.5,
 time = 15, segment = 1, min. extra cost = 41.41, optimum space = 88, supply cost =96.8,
 time = 15, segment = 2, min. extra cost = 2.92, optimum space = 3, supply cost =3.6,
 time = 15, segment = 3, min. extra cost = 50.80, optimum space = 326, supply cost =423.8,
 time = 15, segment = 4, min. extra cost = 74.56, optimum space = 160, supply cost =224.0,
 time = 15, segment = 5, min. extra cost = 9.35, optimum space = 36, supply cost =54.0,
 time = 15, segment = 6, min. extra cost = 107.68, optimum space = 205, supply cost =328.0,
 time = 15, segment = 7, min. extra cost = 24.85, optimum space = 75, supply cost =127.5,
 time = 15, segment = 8, min. extra cost = 169.24, optimum space = 521, supply cost =937.8,
 time = 15, segment = 9, min. extra cost = 48.10, optimum space = 44, supply cost =83.6,
 time = 15, segment = 10, min. extra cost = 19.64, optimum space = 50, supply cost =95.0,

time = 15, total optimum space = 1607, total supply cost = 2522.6

time = 16, segment = 0, min. extra cost = 57.39, optimum space = 133, supply cost =199.5,
 time = 16, segment = 1, min. extra cost = 57.02, optimum space = 163, supply cost =179.3,
 time = 16, segment = 2, min. extra cost = 9.53, optimum space = 10, supply cost =12.0,
 time = 16, segment = 3, min. extra cost = 91.15, optimum space = 381, supply cost =495.3,
 time = 16, segment = 4, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,
 time = 16, segment = 5, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,
 time = 16, segment = 6, min. extra cost = 93.06, optimum space = 273, supply cost =436.8,
 time = 16, segment = 7, min. extra cost = 27.20, optimum space = 31, supply cost =52.7,
 time = 16, segment = 8, min. extra cost = 177.37, optimum space = 906, supply cost =1630.8,
 time = 16, segment = 9, min. extra cost = 60.12, optimum space = 66, supply cost =125.4,
 time = 16, segment = 10, min. extra cost = 24.76, optimum space = 59, supply cost =112.1,

time = 16, total optimum space = 2022, total supply cost = 3243.9

time = 17, segment = 0, min. extra cost = 37.87, optimum space = 97, supply cost =145.5,
 time = 17, segment = 1, min. extra cost = 76.93, optimum space = 163, supply cost =179.3,
 time = 17, segment = 2, min. extra cost = 3.29, optimum space = 3, supply cost =3.6,
 time = 17, segment = 3, min. extra cost = 56.84, optimum space = 270, supply cost =351.0,
 time = 17, segment = 4, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,
 time = 17, segment = 5, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,
 time = 17, segment = 6, min. extra cost = 103.89, optimum space = 243, supply cost =388.8,
 time = 17, segment = 7, min. extra cost = 0.00, optimum space = 0, supply cost =0.0,
 time = 17, segment = 8, min. extra cost = 237.56, optimum space = 477, supply cost =858.6,
 time = 17, segment = 9, min. extra cost = 59.64, optimum space = 64, supply cost =121.6,
 time = 17, segment = 10, min. extra cost = 17.50, optimum space = 44, supply cost =83.6,

time = 17, total optimum space = 1361, total supply cost = 2132.0

time = 18, segment = 0, min. extra cost = 19.98, optimum space = 59, supply cost =88.5,
 time = 18, segment = 1, min. extra cost = 46.02, optimum space = 86, supply cost =94.6,
 time = 18, segment = 2, min. extra cost = 1.75, optimum space = 2, supply cost =2.4,
 time = 18, segment = 3, min. extra cost = 42.61, optimum space = 191, supply cost =248.3,
 time = 18, segment = 4, min. extra cost = 17.21, optimum space = 18, supply cost =25.2,
 time = 18, segment = 5, min. extra cost = 11.43, optimum space = 13, supply cost =19.5,

time = 18, segment = 6, min. extra cost = 106.93, optimum space = 156, supply cost = 249.6,
time = 18, segment = 7, min. extra cost = 2.16, optimum space = 3, supply cost = 5.1,
time = 18, segment = 8, min. extra cost = 172.17, optimum space = 326, supply cost = 586.8,
time = 18, segment = 9, min. extra cost = 47.16, optimum space = 42, supply cost = 79.8,
time = 18, segment = 10, min. extra cost = 15.22, optimum space = 30, supply cost = 57.0.

time = 18, total optimum space = 926, total supply cost = 1456.8

time = 19, segment = 0, min. extra cost = 16.05, optimum space = 26, supply cost = 39.0,
time = 19, segment = 1, min. extra cost = 111.01, optimum space = 154, supply cost = 169.4,
time = 19, segment = 2, min. extra cost = 1.72, optimum space = 2, supply cost = 2.4,
time = 19, segment = 3, min. extra cost = 36.31, optimum space = 113, supply cost = 146.9,
time = 19, segment = 4, min. extra cost = 0.00, optimum space = 0, supply cost = 0.0,
time = 19, segment = 5, min. extra cost = 4.16, optimum space = 5, supply cost = 7.5,
time = 19, segment = 6, min. extra cost = 176.20, optimum space = 221, supply cost = 353.6,
time = 19, segment = 7, min. extra cost = 4.08, optimum space = 5, supply cost = 8.5,
time = 19, segment = 8, min. extra cost = 58.39, optimum space = 242, supply cost = 435.6,
time = 19, segment = 9, min. extra cost = 99.54, optimum space = 111, supply cost = 210.9,
time = 19, segment = 10, min. extra cost = 10.09, optimum space = 16, supply cost = 30.4,

time = 19, total optimum space = 895, total supply cost = 1404.2

time = 20, segment = 0, min. extra cost = 12.29, optimum space = 16, supply cost = 24.0,
time = 20, segment = 1, min. extra cost = 51.10, optimum space = 117, supply cost = 128.7,
time = 20, segment = 2, min. extra cost = 1.10, optimum space = 1, supply cost = 1.2,
time = 20, segment = 3, min. extra cost = 24.03, optimum space = 54, supply cost = 70.2,
time = 20, segment = 4, min. extra cost = 17.91, optimum space = 22, supply cost = 30.8,
time = 20, segment = 5, min. extra cost = 11.15, optimum space = 19, supply cost = 28.5,
time = 20, segment = 6, min. extra cost = 89.74, optimum space = 114, supply cost = 182.4,
time = 20, segment = 7, min. extra cost = 4.45, optimum space = 7, supply cost = 11.9,
time = 20, segment = 8, min. extra cost = 61.65, optimum space = 68, supply cost = 122.4,
time = 20, segment = 9, min. extra cost = 40.39, optimum space = 45, supply cost = 85.5,
time = 20, segment = 10, min. extra cost = 8.37, optimum space = 9, supply cost = 17.1,

time = 20, total optimum space = 472, total supply cost = 702.7

time = 21, segment = 0, min. extra cost = 20.19, optimum space = 50, supply cost = 75.0,
time = 21, segment = 1, min. extra cost = 50.13, optimum space = 51, supply cost = 56.1,
time = 21, segment = 2, min. extra cost = 1.82, optimum space = 2, supply cost = 2.4,
time = 21, segment = 3, min. extra cost = 37.39, optimum space = 138, supply cost = 179.4,
time = 21, segment = 4, min. extra cost = 21.05, optimum space = 34, supply cost = 47.6,
time = 21, segment = 5, min. extra cost = 6.27, optimum space = 21, supply cost = 31.5,
time = 21, segment = 6, min. extra cost = 49.35, optimum space = 54, supply cost = 86.4,
time = 21, segment = 7, min. extra cost = 4.05, optimum space = 9, supply cost = 15.3,
time = 21, segment = 8, min. extra cost = 135.19, optimum space = 151, supply cost = 271.8,
time = 21, segment = 9, min. extra cost = 33.55, optimum space = 38, supply cost = 72.2,
time = 21, segment = 10, min. extra cost = 12.32, optimum space = 24, supply cost = 45.6,

time = 21, total optimum space = 572, total supply cost = 883.3

time = 22, segment = 0, min. extra cost = 17.31, optimum space = 39, supply cost = 58.5,
 time = 22, segment = 1, min. extra cost = 63.11, optimum space = 157, supply cost = 172.7,
 time = 22, segment = 2, min. extra cost = 1.72, optimum space = 2, supply cost = 2.4,
 time = 22, segment = 3, min. extra cost = 30.48, optimum space = 105, supply cost = 136.5,
 time = 22, segment = 4, min. extra cost = 5.62, optimum space = 7, supply cost = 9.8,
 time = 22, segment = 5, min. extra cost = 6.03, optimum space = 8, supply cost = 12.0,
 time = 22, segment = 6, min. extra cost = 112.62, optimum space = 206, supply cost = 329.6,
 time = 22, segment = 7, min. extra cost = 6.59, optimum space = 8, supply cost = 13.6,
 time = 22, segment = 8, min. extra cost = 127.98, optimum space = 249, supply cost = 448.2,
 time = 22, segment = 9, min. extra cost = 42.97, optimum space = 50, supply cost = 95.0,
 time = 22, segment = 10, min. extra cost = 10.12, optimum space = 21, supply cost = 39.9,

time = 22, total optimum space = 852, total supply cost = 1318.2

time = 23, segment = 0, min. extra cost = 3.52, optimum space = 5, supply cost = 7.5,
 time = 23, segment = 1, min. extra cost = 52.66, optimum space = 96, supply cost = 105.6,
 time = 23, segment = 2, min. extra cost = 1.58, optimum space = 2, supply cost = 2.4,
 time = 23, segment = 3, min. extra cost = 12.92, optimum space = 25, supply cost = 32.5,
 time = 23, segment = 4, min. extra cost = 0.00, optimum space = 0, supply cost = 0.0,
 time = 23, segment = 5, min. extra cost = 0.00, optimum space = 0, supply cost = 0.0,
 time = 23, segment = 6, min. extra cost = 62.25, optimum space = 135, supply cost = 216.0,
 time = 23, segment = 7, min. extra cost = 0.00, optimum space = 0, supply cost = 0.0,
 time = 23, segment = 8, min. extra cost = 90.39, optimum space = 111, supply cost = 199.8,
 time = 23, segment = 9, min. extra cost = 52.90, optimum space = 42, supply cost = 79.8,
 time = 23, segment = 10, min. extra cost = 5.20, optimum space = 6, supply cost = 11.4,

time = 23, total optimum space = 422, total supply cost = 655.0

Appendix I: Applications of Flow Management and Control Theory

Flow Control In Airport Airside

When air traffic control began about fifty years ago, the main original reasons were to keep aircraft safely separated from each other, to help flights be efficient, and to bring order, rules, and pattern out of potential chaos and arbitrariness, particularly near airports and other regions with dense traffic. All of these needs were recognized when the air traffic was light and slow. Today air traffic is growing at the rate that outstrips the capacity of the airport and Air Traffic Control (ATC) system, resulting in mounting congestion and delay. Congestion has begun to affect severely air traffic in the U.S. and Western Europe on a network wide basis. Although this congestion is limited to the busiest commercial airports and to a few sectors of air traffic control network, the distribution of traffic is such that the effects are felt by a large fraction of air travellers.

To overcome this problem, some approaches are suggested. As already mentioned, the capacity expansion approach, i.e., building new facilities, is not always feasible. Demand restriction approaches, e.g., imposition of quotas, are difficult to implement. Therefore, the next approach would be to optimize operations for a given demand and capacity through flow control procedures. This approach will control the flow of air traffic so as to best match the demand with available capacity over time and across the various components of the airports network.

Until recently, flow control in air traffic was only a local problem limited to some major airports. The emphasis was on ATC technologies for the management of traffic so as to maintain a smooth flow of aircraft to and from the airport with minimum delay. This is done by the technologies of metering, sequencing and spacing. Until recently these are largely matters of controller art that depend heavily on the individual's skill and experience. As part of the modernization of the ATC system, some government

agencies are developing new software packages that will assist in traffic management at and around airports. For example, the FAA has developed a software called the Traffic Management System (TMS), which will perform several important functions to increase the efficiency of airport and airspace utilization. Some of its functions are such as; airspace configuration management, dynamic planning and computation of acceptance rate, tactical execution of control strategy, runway configuration management, and departure flow metering. Further information about airport-aircraft flow control and technology can be found in other references [1, 2].

Quite recently, as a response to the air traffic growth problem, researchers have begun to examine the air traffic congestion as a network wide problem. The network was defined as a set of elements such as; airports, airways, way-points, and sectors. The purpose was to find a flow management strategy to minimize the cost of the whole system through a tradeoff between ground holding and airborne delay. In the area of analytical models, a number of researchers studied the flow management and control problem from a network wide perspective and offered several valuable insights [3, 4]. Due to the complexity of the problem a number of organizations and researchers have initiated the development of computer based simulation programs whose purpose would be to provide an environment for experimenting and evaluating alternative flow management strategies and algorithms. In practical terms, a Central Flow Control Facility (CFCF) has been operated for several years by the FAA in Washington, D.C. [1]. Its responsibility is to carry out strategically-oriented flow management functions, e.g., ground holds, metering, and rerouting for the ATC system in the US. The CFCF is very well equipped with the information-gathering capabilities including regional and local weather data, up-to-the-minute data on the status of airborne traffic throughout the country and projections of traffic levels over a time horizon of several hours.

However, much of the ongoing research on the flow controls aimed toward developing algorithms and automation aids to manage more effectively the flow of air traffic. It should be noted that the hardware technology for air traffic control has been well developed but the state of the art in software and algorithms lags behind significantly.

Flow Control in Urban Transportation

The serious congestion problems facing many urban areas around the world and the dramatic increase in congestion predicted for the future have created an intense interest in finding new ways for cities to manage the flow of traffic. The field of flow control in urban areas is very well established. It has been widely used in such applications as network equilibration, planning of investment in urban highway infrastructure, and setting of traffic signals. Research in this general area has made important contributions to the development of algorithms for large scale, non-linear optimization.

An efficient use of available capacity of urban networks implies a smooth flow of traffic, permitting vehicles to reach their destinations with fewer stops and reduced delays. The capacity of each part of the transportation network should be in balance with the existing and projected demand to the extent possible. To achieve that goal, two types of solutions are offered; capacity expansion, and demand management. Due to the limited capacity of existing roadways and infeasibility of building new facilities because of space, money, time, environmental and social constraints, transportation professionals are initiating transportation system management strategies aimed at improving the traffic handling capability of existing facilities. Some of those applied strategies are: spreading the peak demand over time of day or over space, i.e., travel routes, flexible and variable work hours, encouraging public transit and

high occupancy vehicles, road pricing, auto-free areas, etc.

Advanced Technology Application

Quite recently with the availability of new technology, efforts are being made on strategies based on traffic management and control technologies. Traffic management and control measures include direct control of road traffic and driver information services. Traffic management and control systems, consisting of diverse basic technologies, encompass a variety of capabilities. For example, in one system vehicles on the road are detected by sensors, then processors analyze the information and transmission to other parts of the system. This information is provided to the communication infrastructure for transmittal to a traffic management and control centre. Information obtained through the traffic management and control centre can be used to create aids to drivers in the form of changeable message signs, traffic signal settings, freeway ramp metering, and providing information to the road users [5].

Hence, some countries are considering such systems in which real-time changes in traffic conditions are taken into account. These systems collect their own traffic data in order to respond to changing conditions in real time, i.e., provide flow control and traffic management information. Examples include SCOOT (Split, Cycle, and Offset Optimization Technique) from UK., PRODYN from France, and SCTS from Australia. The SCOOT system started as a joint government-industry research project whose aim was to produce a traffic adaptive control strategy which could be more efficient than those based on fixed time plans. The success of the SCOOT control strategy led to its use in a number of cities and the delay reduction has been favourable (23% in some cases). Further description of the control methodology of these projects can be found in other references [6, 7].

Another advanced state of the art technology developed to manage traffic flow has been called the Intelligent Vehicle-Highway System (IVHS). The purpose of IVHS development is to improve transportation network efficiency by combining the characteristics of vehicles, drivers, and highways. Four categories of IVHS are: Advanced Traffic Management System (ATMS) Advanced Traveller Information System (ATIS) Commercial Vehicle Operation (CVO) and Advanced Vehicle Control Systems (AVCS). The detail of IVHS technology and its function can be found in other references [7, 8, 9]. However, the main purpose of IVHS is to monitor, control, and manage the traffic flow by adjusting traffic signals, altering incident management personnel, displaying current traffic conditions to automobile and commercial vehicle drivers and transit. However, a better utilization of the capacity of existing systems is made possible by diverting traffic from overloaded routes to under utilized routes. As a result, ATMS can produce smoother traffic flows with significantly reduced delays.

Flow Control in Computer Networks

A computer communication network consist of a number of facilities (processors, and links between processors) shared by competing users (messages or packets). Senders generate messages which are subsequently transmitted over the network to receivers. The acceptance of a message by a receiver usually consists of; storing the message in a buffer, and sending an acknowledgement (ACK) back to the sender. As soon as the sender received this ACK, he/she knows that there is no longer any need to store a copy of that message, i.e., a buffer space can be emptied. However, when the sender has not received an ACK within a certain period of time or receives a negative ACK, he/she will retransmit that message in order to prevent endlessly long waiting times.

The finite capacities of network facilities cause conflicts between the message. Queues

of messages are formed in front of certain facilities and finite buffers are filled to capacity so that packets are lost or have to be retransmitted. This may lead to a drastic reduction of the performance of the system, i.e., long waiting times, or decrease of network throughput. Thus flow control and management procedures are needed to prevent the system from becoming overloaded. Several flow control procedures which have been developed over time are: global, local, and isorhythmic flow control.

The principle of global flow control is to shift congestion from the interior of the network to the points of traffic admittance. This flow control procedure regulates the externally offered traffic to the network. In the simplest, the total number of packets that may be present at any time in the network is limited. New packets may only enter the network when the number present drops below the number specified. This is indicated by control messages received at the source acknowledging reception of one or more packets at the destination.

Local flow control is the collection of procedures that regulate traffic within the network, e.g., between two nodes. In this control procedure, the number of packets at any single node is determined and blocked packets are assumed dropped from the network. New packets are allowed to enter at each node so that the total traffic rate is always a fixed quantity.

In isorhythmic permits are assigned to each node of network, and packets may enter, on arrival, only if a permit is available. If a node is allowed to transmit a packet only when it has acquired a special permit from the network, then the total number of packets in the network at any one time can be restricted by ensuring that the number of permits in existence is limited. This guarantees that the network as a whole cannot become congested, although congestion can still occur in localized regions. Further detailed information about flow control procedures can be found in other references

[10, 11, 12].

Flow Control In Environmental Engineering

Flow management and control has been extensively used in environmental engineering, e.g., water and waste water treatment, water distribution, and water resources. The development of any of those systems is accomplished in two phases. The first one comprises the planning, design, and construction of the system which needs enterprise and judgement. The second phase, the operation of the system is equally important as the first one. It is only by means of efficient operation that the system can fulfill its expected purpose with respect to technical, economical, social, and political criteria. Treatment plants consist of various pools into which fluid (water or waste water) enters, goes through certain processes, and then exits with desired quality. These processes require the measurement of a number of parameters which depend on many factors, such as the type of process, operation policy, and effluent standards. Although such parameters vary from plant to plant, some of them e.g., flows, liquid levels, pressure, temperature, are common to all treatment systems [13].

From the aforementioned explanation, it is interesting to note that a number of parallel aspects exist between systems in environmental and transportation engineering, although the two are related to completely different field of application. Both deal with systems which require controlled operation. Recently with the existence of modern technology, most of the water and waste water plants are automatically operated and controlled. In the case of treatment plants, these operations consist mainly of closing or opening electrically actuated valves and starting or stopping pumps. Recently some modern plants have incorporated automated equipment which monitors and controls both machines and processors [14]. This facility is provided by pro-

grammable automatic units, extending from electro-mechanical units via static logic control devices to systems employing mini-computers.

The flow control theory is not limited to the treatment plants. It has been applied in water distribution, irrigation, and hydroelectric power production systems. A water distribution system comprises pipelines, reservoirs, storage tanks, and pumping stations. Due to the complexity of the system, control has been applied automatically. The automation control in the system consists of such functions as follows:

- Supervisory control of pipeline, flow pressure, reservoir level, pump operation, storage tanks,
- Monitoring of quality and flow of water,
- Remote operator control of all elements (valves, pumps, etc.),
- Optimization of water procurement and distribution according to predetermined economic criteria,
- On line calculation of valve settings based on reservoir filling rates and expected demand,
- Calculation of reservoir filling rates, hourly reserves, demand and supply predictions,
- Daily, weekly, monthly printout of reports of all events and operating values.

A good example for an automated control irrigation system is the Salt river project in Tucson, Arizona, where a 220 kilometers canal network can be monitored and controlled by a single operator. Detailed information about this project can be found in other references [15]. However, the growing complexity of water and waste water

treatment and distribution systems, and the need to economize steadily-declining water resources, have led to the continuous and automatic monitoring and control of these processes.

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