A DECISION PROBLEM INVOLVING THE INTRODUCTION OF RTOL AIRCRAFT INTO COMMERCIAL AIR TRANSPORTATION SYSTEMS

by

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CHAPTER 1

INTRODUCTION

In the very near future, it will be necessary to make several important decisions concerning the air transportation industry in order to meet increasing air traffice demand [34]. These decisions will be concerned with increasing the capacity and efficiency of the present air traffic system to meet air traffic demand that is expected to reach 500 million passengers per year by 1980 and to double again during the 1980's [34]. In resolving this problem, it will be necessary for the decision-maker(s) to consider many different factors such as the costs involved, the environment, customer satisfaction and limited resources. This study will consider a set of three decisions that must be made by the decision-maker(s) and suggest a procedure to assist him in making them.

Problem Description

The research presented in this thesis was actuated by the development of the concept of a reduced takeoff and landing (RTOL) aircraft. The RTOL aircraft, as presently conceptualized, would have some characteristics such as reduced noise levels,

which would possibly be superior to those of conventional takeoff and landing (CTOL) aircraft in increasing the capacity of the present air traffic system.

The problem itself is one of determining whether it would be advantageous to introduce RTOL aircraft into the air traffic system in light of its various attributes, and, if it is used, on which flight routes should RTOL replace CTOL. The tradeoffs between RTOL and CTOL that will be considered in this study will involve fuel usage, noise levels produced and delay encountered at the airports in each itinerary. (An itinerary is defined as a series of connecting flights made by one aircraft between an origin airport and a final destination airport.) The constraints that will be placed upon the use of these aircraft will include operating costs, purchase price of the aircraft, seating capacity and demand, runway lengths, and individual airport noise restrictions.

The problem can then be stated concisely as follows:

> Find the itineraries of an air traffic system for which each type of aircraft being considered is assigned such that each of the following criteria are minimized: (a) the amount of fuel used, (b) the noise levels created at each of the airports in an itinerary, and (c) the total delay encountered on each of the itineraries. These aircraft assignments are subject to the following constraints: (a) the runway lengths of each city in an itinerary must meet or exceed the necessary length for takeoff and landing requirements of the assigned aircraft, (b) the total seating on the aircraft must meet or exceed the demand for air service between all cities on an itinerary, (c) the total direct operating

cost and indirect operating costs must not exceed a specified bugetary restriction, (d) the noise restrictions placed on any airport in an itinerary must not be exceeded, (e) the total purchase price of all aircraft needed to meet the requirements of the demand in the air traffic system must not exceed specified bugetary restrictions, and (f) only one kind of aircraft may be used for each itinerary.

In solving this problem, the following quantities are assumed to be given: (a) the available budgets, (b) the itineraries that are to be flown in the air traffic system, (c) the characteristics of the airports in the air traffic system (e.g. runway length), and (d) the characteristics of the aircraft to be flow in the system (e.g. passenger capacity).

Purpose of Study

The purpose of this study is to provide the decision-makers of such organizations as commercial airlines, aircraft manufacturers and regulatory agencies with a decision-making aid to determine the applicability of RTOL or other nonconventional aircraft in a commercial air carrier system. The value of such a decision-making process can be seen in a quote of Mr. R. Lee of the Operational Research Branch of British Airways: "Given a set of commercially desirable schedules which are to be operated by one of two similar aircraft types it is often very difficult to obtain a satisfactory allocation, if indeed it is possible at all."[27].

In addition to presenting the decision-making tool mentioned above, this study will also have the purpose of demonstrating whether or not the RTOL aircraft would be viable in a given georgraphic area.

Scope of Research

The scope of this particular study will be limited to one geographic area of the country. The reason for this is the necessity to consider each individual hub area[1] to determine which satellite airports[2] can be utilized and what effect their utilization will have on the major airport. It will also be necessary to determine airports in the area that are not presently being served by CTOL but could be served by an RTOL aircraft. Due to the large number of such hub areas and airports nationwide, the geographic scope of this research will be restricted to the northeast region of the United States.

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[1]An airport hub is generally regarded as a major metropolitan area serving 1.00 percent or more of the total enplaned passengers in scheduled service of the fixed-wing operations of the certified air carriers in the 48 contiguous states and the District of Columbia [38]. It usually consists of one or more major commercial airports and several smaller or satellite airports.

[2]A satellite airport is any airport in a metropolitan area which receives less than 25 percent of all air carrier operations.

In addition to the restrictions mentioned above, the possible savings in airport real estate will not be expicitly considered in this study due to the unavailablity of data. Although this factor could be a very important consideration in the utilization of RTOL in suburban areas [39], no airports have been designed explicitly for RTOL air traffic and no estimate of savings can be made at this time.

Solution Approach

In developing a solution procedure for the problem under consideration, the first step was to clearly define the problem. The second step was to take the problem definition and develop a mathematical model of it. The model that was developed in this thesis is based on information obtained through contacts with the airline industry [20,26,41].

After a mathematical model of the problem had been developed, the third step in the solution approach was to formulate a solution procedure. Several different methods of multicriterion optimization were considered as a possible basis for the solution of the model. Of these techniques, one developed by Monarchi [31] was chosen because of its use of aspiration levels set by the decision-maker. It was felt that this makes the use of the procedure somewhat more comprehensive for the actual decision-maker than using other methods requiring the definition of the decision-maker's utility function.

In the present research, the technique developed by Monarchi is altered so that 0-1 variables are used in place of continuous variables. This is done by replacing the Griffith-Stewart approximation programming technique by a 0-1 algorithm developed by Balas [1]. In addition, other minor changes were made to accommodate the specific mathematical model being solved.

Thesis Organization

The second chapter of this thesis describes the RTOL aircraft, the air transportation system it would operate in and the decision problems that must be considered in the utilization of RTOL. In this discussion, the decision-makers for each of the decision problems are identified and their particular goals are described.

The third chapter of this study is concerned with the development of the decision model. In this chapter, a discussion is presented dealing with data collection that was required to determine values for the various parameters used in the mathematical model. The parameters used in the model are then explicitly defined along with their function in the model itself in Chapter 4. The mathematical model is then presented and a discussion is given concerning its various components and their purpose.

The solution procedure is presented in Chapter 5. Previous developments in multicriterion optimization are discussed and a

detailed presentation of the Monarchi procedure is presented. This is followed by a discussion of the changes that were made to the Monarchi procedure in order to make it compatible with the decision problem being solved in this study. The computer code written to perform the solution procedure is also discussed.

The sixth chapter in this study describes the solution of an example problem that involves a geographic area in which RTOL could possibly be used. The area considered, the associated data (such as runway lengths, itineraries, etc.) and the solution results are presented.

The seventh chapter of this thesis is devoted to a discussion of the results obtained in the study and to a discussion of further uses of the solution procedure that was developed, and to further study in this particular area. It should be noted that the literature dealing with each of the previously mentioned chapters is included in that chapter itself. The appendices that are included in this thesis contain information concerning, (a) a questionnaire sent to airline executives, (b) aircraft categories, (c) airport identification symbols, (d) the Monarchi procedure, and (e) the computer program used in the solution procedure.

CHAPTER 2

BACKGROUND

Demand for air transportation has increased greatly over the past twenty years. Since 1955, demand has increased over 500 percent nationwide [34]. However, the estimated demand for air carrier service is expected to increase at a rate even greater than that of air transportation in general. The problem that will be faced is evident from an examination of Figure 1 [34]. This figure shows that the growth in capacity (made up of the two factors of increased passengers per aircraft and increased number of aircraft), will only be able to meet expected growth in demand until 1980. (Increased passengers per aircraft assumes the exclusive use of wide-body aircraft and a load factor of 65 percent as opposed to today's 55 percent, and an increased number of aircraft assumes the reduction of separation distances between aircraft with the advent of more sophisticated aircraft guidance systems.)

Therefore, by 1980, or earlier if these assumptions cannot be met, the growth in air traffic demand will increase faster than the present capacity to meet it. Even at the present time, congestion has become a common charactertistic at the nation's major airports [11]. This congestion has many causes, the major

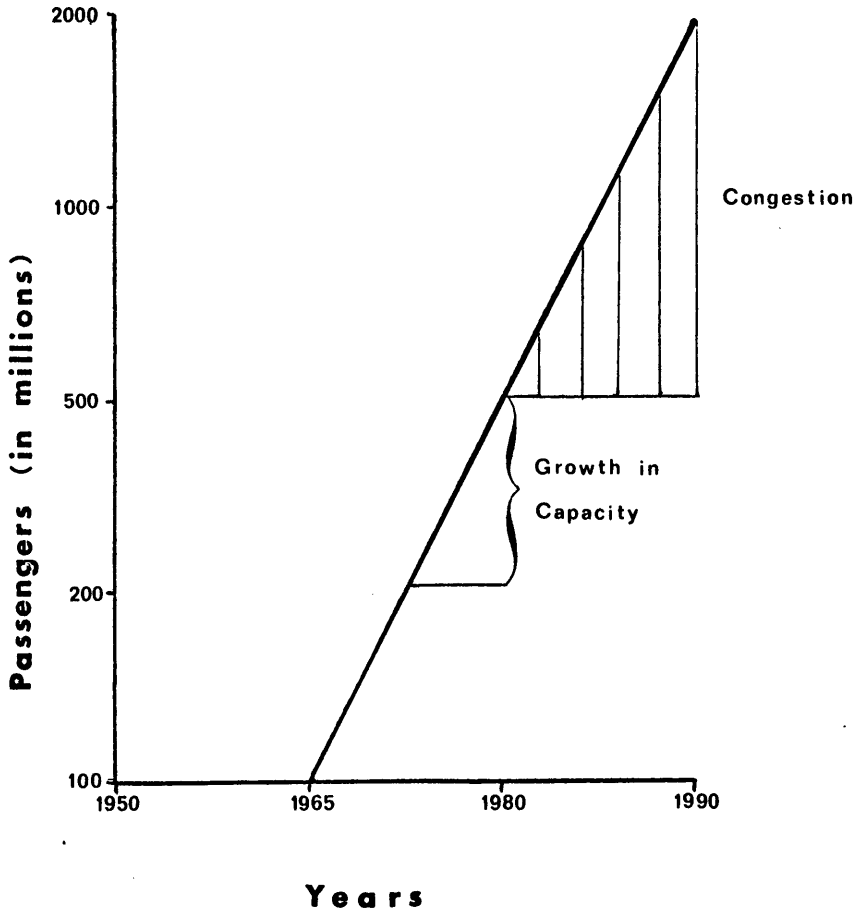

Figure 1

Passenger Demand and the Corresponding Congestion

ones being: (a) runway saturation, (b) noise restrictions imposed by environmental regulations, (c) insufficient turnoffs from runways, (d) lack of aprons and holding areas, and (e) an insufficient number of gates [13].

For the purpose of this study, it is important to note the congestion created by restrictions and runway saturation. Congestion caused by noise restrictions is due largely to the fact that such restrictions dictate the runway on which a particular type of aircraft may depart or land (a large aircraft is generally not allowed to use runways which will bring the approaching aircraft directly over residential areas). This in turn could lead to longer taxi times, holding times and waiting times, all contributing to excessive delay [38]. Saturated runways (caused by the inability to service aircraft operations expeditiously) cause aircraft demanding service to encourter ground congestion and long waiting periods [13].

The cost of congestion has become one of the major concerns of the airlines [11]. It has been estimated that congestion in the United States has cost the airlines over $195 million in 1973 alone [11]. When this cost is coupled with other costs such as the lost opportunity cost of the passenger's time spent circling an airport and that of additional airport personnel, it is apparent from an economic standpoint that congestion should be alleviated.

As previously discussed, it will be necessary to consider several possible solutions concerning ways to meet the anticipated increase in demand and the corresponding increase in congestion in the air traffic system. One of the possible solutions to this problem is the introduction of a new type of aircraft with the characteristics which will allow it to be used in place of conventional takeoff and landing (CTOL) aircraft. In some instances, this may lead to an increase in the capacity of the air traffic system. This study will concentrate on the possible utilization of a recently proposed reduced takeoff and landing (RTOL) aircraft.

The RTOL Aircraft

The RTOL aircraft is generally considered to represent a class of aircraft whose takeoff and landing capacity lies between that of CTOL and V/STOL (vertical/short takeoff and landing) aircraft. The characteristics of these aircraft are summariezed in Table 1 [3,24,39]. Although the field lengths shown in Table 1 can vary slightly depending on the takeoff and landing conditions and individual aircraft, they serve to show the differences found among aircraft types on relation to runway requirements.

The RTOL aircraft is under consideration by commercial airlines as a future air carrier vehicle because of its potential to [20]: (a) supply commercial air service to areas not presently

TABLE 1

RELATIVE CAPABILITIES OF RTOL

Aircraft Type	Example	Minimum Field Length Requirement
Large CTOL	Boeing 747	11,000 ft.
Small CTOL	DC-9	6,500 ft.
RTOL	Under Consideration	4,500 ft.
STOL	de Havilland Twin Otter	1,500 ft.
VTOL	Helicopter	< 100 ft.

being served, (b) reduce air traffic congestion and delay in metropolitan areas served by one major airport by extending air carrier service to smaller airports in the area with medium to short runways, (c) reduce the usage of fuel by decreasing flight time through a reduction in delay, and (d) provide improvements in community noise characteristics by reason of decreased noise propagation paths and reduced emission of noise energy by the aircraft.

There are two different types of RTOL presently being considered for use in the United States. One has been designed by Boeing [3]. This aircraft would have a takeoff and landing capability of 5000 feet. The configuration developed for this version of RTOL was designed with the following objectives in mind [3]: (a) noise improvements created by increased takeoff heights (greater altitude before the cruise mode is started), increased approach gradients (steepness of descent) and reduced power used in descent; (b) emission improvement caused by reduced engine emissions, reduced main engine operation and reduced airplane operation (due to reduced ground delay by congestion relief); and (c) congestion relief directly attributed to aircraft characteristics including reduced approach speeds, reduced air-to-air separation, increased ground deceleration, higher turnoff speeds, and improved path accuracy (maintaining an assigned flight path).

The second RTOL design has been proposed by the Lockheed Corporation [39]. This aircraft would have a takeoff and landing requirement of 4000 feet. It was designed with major considerations given to sound levels and fuel usage. The major characteristics of this aircraft as compared to those of the Boeing RTOL and a composite wide-body aircraft developed by Boeing [3] are shown in Table 2 [3,39].

In addition to the physical properties given in Table 2, it is also important to consider the differences in direct operating cost (DOC)[1] of RTOL as opposed to CTOL. The RTOL aircraft will tend to have a higher DOC than the CTOL aircraft for direct flights between city pairs (assuming no delay) [20]. This results from the fact that RTOL is designed for shorter landings and a reduction in noise levels. The penalty RTOL incurs because of such operating characteristics will occur in the cruise mode [26]. However, it has been stated that savings in congestion relief and in airport real estate (due to reduced runway requirements in new

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[1]Operating expenses for air carriers are broken down between aircraft operating expenses and servicing, sales and general expense. Aircraft operating expenses are commonly referred to as 'direct operating costs' or DOC's while servicing, sales and general expenses are synonymous with 'indirect operating cost' or IOC [8].

TABLE 2

CHARACTERISTICS OF ALTERNATIVE RTOL DESIGNS

	Lockheed RTOL		Boeing RTOL		CTOL[a]	
Runway Requirements	4,000	ft.	5,000	ft.	8,300	ft.
Passenger Capacity	148		196		196	
Range	1,500	n. mi.	3,000	n. mi.	3,000	n. mi.
Cruising Speed	.75	Mach.	.90	Mach.	.85	Mach.
Altitude Capacity	30,000	ft.	40,000	ft.	40,000	ft.
Noise Goal (EPNDB Below FAR-36)[b]	-15.0		-10.3		-3.6	
Operating Weight (Empty)	124,480	lb.	185,290	lb.	194,000	lb.

[a]The CTOL aircraft used here is a composite of a present day wide-body aircraft as determined by Boeing [3].

[b]Effective Perceived Noise in Decibels (EPNdB) below Federal Air Requirement--Part 36.

airports and existing suburban airports) will more than offset the DOC penalty [39].

Other versions of RTOL type aircraft that have been considered both here in the United States and in Europe include:

1. An RTOL aircraft based on a modified DC-9 which would have a passenger capacity of 100 people and a runway capacity of less than 5000 feet (although not a quiet aircraft, it was suggested that it may be an economically viable for a large national air system) was presented in the 1972 National Transportation Report [40] as an alternative to CTOL for short haul flights of under 500 miles.

2. A quiet takeoff and landing aircraft (QTOL) with a field length requirement of 1250 meters (4100 ft.), a passenger capacity of 191, a noise level of at least 10 EPNDB below FAR-36 (Federal Air Regulation-Part 36) requirements is being developed in Europe by the Europlane Marketing Group for short haul operations of between 250 and 500 n. mi. [5].

3. Other RTOL aircraft have also been considered which would be modifications of such aircraft as France's Mercure, West Germany's VFW 614, the A-300B Airbus (designed through the cooperation of several European nations) and the Soviet Union's YAK-40. These aircraft would have to be altered to meet minimum runway restrictions and noise levels [42].

RTOL and the National Aviation System

The RTOL aircraft has been mentioned for possible utilization in both long-haul and short-haul situations in the national aviation system. However, due to the limited potential of RTOL in a long-haul system [3], this research will deal with the short-haul.

The present short-haul air system is a complex, integrated system that serves both local passengers and long-haul passengers making short connecting flights on the same aircraft and at the same airports as the long-haul air system. As a result, there are two disadvantages when short-haul passengers for local origins and destinations are processed through major airports in large metropolitan areas [40]. The first disadvantage is that many major airports are located far from the central business district, thereby forcing local short-haul travelers to spend a large percentage of their trip time traveling to and from airports. The second disadvantage is that mixing short-haul and long-haul air traffic and passengers adds to airport congestion both in the air and on the ground.

In a study prepared in 1972 for the Department of Transportation, it was shown that a short-haul air system independent of the long-haul air system would have a very pronounced effect on the reduction of airport congestion in the United States. Table 3 [40] shows the anticipated savings that would be accured

TABLE 3

EFFECTS OF INDEPENDENT SHORT-HAUL AIR SYSTEMS ON AIRPORT CONGESTION

City	Airport/Hub	Long-Haul Passenger time savings		Long-Haul Airline cost savings	
		Millions of min. per year		Millions of dollars per year	
		1975	1985	1975	1985
New York	JFK/LGA/EWR	6.9	15.8	1.0	1.8
Washington	DCA/IAD/BAL	1.0	1.7	0.2	0.3
Philadelphia	PHL	0.9	0.9	0.2	0.2
Chicago	ORD	22.3	19.0	3.2	2.2
Detroit	DTT	0.7	1.1	0.1	0.2
Los Angeles	LAX	11.0	8.7	1.4	1.0
San Francisco	SFO	9.0	12.6	1.3	1.6
Miami	MIA/FLL	0.2	0.4	0.0	0.1
Atlanta	ATL	4.8	5.5	0.7	0.7
Boston	BOS	0.6	0.7	0.1	0.1
Dallas	DFW	1.2	5.4	0.2	0.2
St. Louis	STL	0.9	2.1	0.2	0.2
Denver	DEN	0.5	1.1	0.1	0.1
Cleveland	CLE	0.3	0.6	0.0	0.1
Total		60.3	69.7	8.7	8.8

if secondary airports were used for the short-haul system. In the discussion of a short-haul system, the RTOL aircraft was mentioned as a possible vehicle to provide sufficient service and still be economically viable.

To demonstrate the viability of a short-haul system using RTOL, a study was done by Charles Rivers Associates [6]. In this study, it was estimated that traffic in city pairs separated by a distance of 185 to 500 miles would support at least two RTOL aircraft of 100 passengers operating full-time in a satellite airport service in 1977. The results of their study are shown in Table 4. A total of 66 city pairs were shown to have sufficient demand to allow at least one aircraft to operate on a full-time basis at a profit in a satellite airport service. Of these city pairs, an estimated 41 would support the use of only one or two aircraft, but the number of aircraft used per city pair would go as high as 23 for the Boston-New York City pair. This is a strong indication that there is potentially a substantial market for RTOL aircraft for short-haul satellite airport service.

Another possible aspect of the desirability of introducing RTOL aircraft into air transportation service is the applicability of RTOL to various new sectors of the national aviation system. It has been shown that there are over 2000 airports with runways of 4000 feet or longer in the United States [6]. Of these, only 510 or approximately one-fourth are presently being served by

TABLE 4

SUMMARY OF AIRCRAFT DEMAND ESTIMATES FOR SHORT-HAUL SATELLITE AIRPORT SERVICE

	Intercity 185 Miles	Distance 500 Miles
Flights per day, each way, assuming two aircraft operate the route	13	7
Passengers per year, both ways, assuming 50 percent load factor	407,000	219,000
Demand index for satellite service (original demand on conventional service = 100)	121	127
Required non-connecting demand for conventional service to support new service in 1977 (passengers per year)	336,000	172,000
Required total demand to support new service in 1977 (assuming connecting passengers are 28 percent of the total)	460,000	234,000
Implied total demand required in 1968 (assuming 9 percent annual growth in passenger traffic)	212,000	98,000

Number of city pairs that could support at least one aircraft in full time service = 66

Aircraft required to provide new service in 1977 = 207

scheduled air carriers. These figures would tend to indicate a vast number of available airports that could be put into service for use by RTOL that are not presently being served by CTOL because of RTOL's reduced runway requirements (assuming, of course, that there is sufficient demand to support air carrier service). The breakdown of airports in the United States is given in Table 5 [6].

The introduction of RTOL as an air carrier into many of these airports would allow a large segment of the American public to obtain air carrier air transportation at a location much closer to their homes than at the present time. This would bring about an obvious savings in ground transportation costs. It is also possible that since air transportation is more readily accessible, the demand for air service would increase.

In summary, there are both advantages and disadvantages to the use of RTOL in the commercial air transportation system. In considering its possible utilization, it will be necessary for a decision-maker to weigh these factors depending upon his own utility and make a final decision. The thesis will be concerned with this decision problem involving these tradeoffs and the development of a methodology to assist in its optimization.

TABLE 5

TOTAL NUMBER OF AIRPORTS

(January 1, 1972)

Type	Number
Airports[1]	10,639
Heliports	966
Seaplane ports	465
	12,070
Paved Runway Airports	3,632
Paved Heliports	544
	4,176

RUNWAY LENGTH BREAKDOWN

Length in Feet	Airports
0-2999	6,365
3000-3999	2,274
Subtotal	8,639
Over 4000	2,000
Total	10,639

[1]Includes private and public airports. Scheduled air carriers serve 510 of this total.

CHAPTER 3

THE DECISION PROBLEM

Decision making is basically a process whereby a choice is made by a decision-maker (who may be an individual, a group or committee, or any number of independent individuals dedicated to one particular purpose) among different alternatives. In multi-criterion decision-making each of these alternatives has multiple objectives. The associated criteria represent different attributes of the alternatives. An example of this would be in selecting a new automobile from several alternatives; criteria such as comfort, gas milage and safety would be considered.

Multiple criteria decision methods can be grouped into four main categories:

1. Mathematical Programming Methods. In these methods, a large set of alternatives is considered through the use of an objective function that is subject to a set of constraints. An algorithm is used to converge to a final solution.

2. Weighting Methods. These methods are based on a process of comparing criteria by first numerically scaling the criteria (intra-criteria preferences) and then giving numerical

weights across the attributes (inter-criteria preferences). An objective function is then developed for aggregating the criteria into a single number for each alternative and a rule is developed for choosing the alternative on the basis of the highest weight.

3. Sequential Elimination Methods. Sequential elimination methods are characterized by scalings of criteria values (intra-criteria preferences), a set of constraints (which may be empty across attributes) and a process for dequentially comparing alternatives on the basis of attribute values so that alternatives can be eliminated or retained. The alternatives may also be compared to a predetermined standard.

4. Spatial Proximity Methods. These methods require the construction of a graphical representation and the identification of ideal configurations and the choice rule based on the proximity of alternatives to these ideal configurations.

Table 6 presents these four major categories and the different methods associated with each of these. This study will deal with the method of interactive multicriterion programming. However, for an excellent overview of all of these methods, see Cochrane [9, P. 18]. The development of a multicriterion programming procedure for the decision problem concerning RTOL will be presented in Chapter 5. However, first a discussion of the selection of alternatives and criteria will be given in this chapter followed by the formulation of the model in Chapter 4.

TABLE 6

MULTIPLE CRITERIA DECISION PROCEDURES

I. Mathematical Programming Methods

1. Global objective function
   -Linear programming

2. Goals in constraints
   -Goal programming

3. Local objective functions, interactive
   -Interactive, multicriteria programming

II. Weighting Methods

1. Inferred preferences
   -Linear and curvilinear regression
   -Analysis of variance

2. Directly assessed preferences
   -Tradeoffs
   -Additive and multiplicative weighting
   -Hierarchical additive weighting
   -Maximin
   -Minimax

III. Sequential Elimination Methods

1. Alternative versus standard
   -Disjunctive and conjunctive constraints

2. Alternative versus alternatives
   -Dominance
   -Lexicography
   -Elimination by aspects

IV. Spatial Proximity Methods

1. ISO-preference graphs
   -Indifference map

2. Ideal points
   -Multi-dimensional, non-metric scaling

3. Graphical preferences
   -Graphical overlays

Formultion of Decision Situation

In determining an exact decision situation concerning the use of RTOL aircraft in an air transportation system, several different decision situations must be considered. These situations may have several different decision-makers with potentially dissimilar viewpoints and objectives must be considered. The various components of these decisions situations faced by the decision-makers are discussed below:

Service Areas

The first consideration in describing the decision situation concerns the geographical areas RTOL would serve. It is possible that RTOL could only be used in certain sectors of the country such as the California Corridor or the Northeast Corridor because of the associated establsihed short-haul markets; or, it is possible that RTOL could provide savings over CTOL for a majority of short-haul flights in larger areas, such as the entire east coast. It is also necessary to look at individual hub areas to determine which satellite airports could be utilized and what effect their utilization would have on the major airports. For this reason, in the examples presented in Chapter 6, the scope of this study will be limited to one particular area of the country, namely the Northeastern United States.

One group of decision-makers who will be concerned with the areas serviced by RTOL is the officials of the airlines.

Their decisions will determine the areas within their service regions where RTOL will be instituted as an air carrier. A second group of decision-makers will be the regulatory agencies such as the Civil Aeronautics Board and the Federal Aviation Administration. They will be concerned with regulating the regions serviced by the airlines and determining the impact of airline operation in various areas of the country.

Scheduling of Itineraries

A second consideration for the decision situation is that of scheduling RTOL flights relative to CTOL flights. Specifically, decisions must be made as to the number of itineraries that will be flown with RTOL and which airports these itineraries will include. This consideration is facilitated by the fact that it is possible that a CTOL aircraft may not be able to land at one or more of the airports in an itinerary because of the restrictions on runway length and noise. It is also possible that use of a satellite airport at a hub city instead of the use of the major airport may present a considerable savings due to delay reduction.

The decision-makers in this case would be the management of the particular airline or airlines who decide to consider using RTOL and Civil Aeronautics Board members interested in regulating the airlines. Their decisions would determine routing of RTOL in its capacity as an air carrier.

Number of Aircraft Purchased

In addition to determining the scheduling of RTOL, it will also be necessary to determine the number of RTOL that should be purchased. Due to the high purchase price of RTOL, the number of RTOL could be very critical in determining the feasibility of its wide spread usage. As pointed out in [6], a small number of RTOL aircraft (less than 200) is not likely to be sufficient for the manufacturers to decide to produce it. On the other hand, if the suggested region of RTOL utilization requires too many RTOL to be financially practical, the size of the region or the number of flights will have to be decreased.

The group of decision-makers who will be concerned with the number of RTOL purchased will be the airline executives who must determine the airline's fleet size. It will be their decision that will determine how many RTOL should be purchased to meet passenger demand.

Therefore, it can be seen that several different decisions with different decision-makers should be considered in the RTOL usage issue. The situations under consideration in the examples presented later in the thesis will be clearly defined and other possible situations will be discussed in Chapter 6.

Possible Alternatives and Criteria

The possible alternatives in this decision problem involve choosing among several different types of aircraft with different characteristics for assignment to a given set of airline itineraries. A discussion of the different type of aircraft that will be considered in this study and their relative characteristics was given in Chapter 2. In addition to the RTOL and CTOL aircraft previously mentioned, this particular decision problem could also involve other types of aircraft such as STOL or VTOL. However, since this particular study involves the possible utilization of RTOL aircraft in place of CTOL aircraft, only these two types of aircraft will be considered.

In order to ascertain which attributes of these aircraft would be included for possible consideration by a decision-maker a survey was sent to executives associated with the major airlines (see Appendix A for a copy of this survey). The results of the responses received along with the viewpoints of the aircraft manufacturers are shown in Table 7. These responses show that the major factors considered by the airlines and aircraft manufacturers include such things as: (a) fuel usage and possible fuel penalties, (b) direct and indirect operating costs, (c) noise characteristics, (d) purchase price, (e) congestion relief and delay reduction, and (f) runway requirements.

TABLE 7

IMPORTANT AIRCRAFT USAGE CONSIDERATIONS

American Airlines [20]	Boeing Aircraft Co.[3]	Continental Airlines [41]	Eastern Airlines [26]	Lockheed Aircraft Co. [39]
1. Air Transportation System[a]	1. Noise Levels	1. Direct Operating Cost	1. Fuel Penalties	1. Fuel Penalties
2. Runway Length	2. Runway Length	2. Runway Length	2. Type of Service	2. Noise Levels
3. Noise Levels	3. Congestion Relief	3. Capacity	3. Purchase Price	3. Congestion Relief
4. Congestion Relief	4. Purchase Price	4. Noise Levels	4. Pollution Levels	4. Runway Length
5. Operating Cost	5. Type of Service[b]	5. Pollution Levels	5. Air Transportation System	5. Operating Cost
6. Purchase Price	6. Air Transportation System	6. Facility Requirements		
		7. Purchase Price		

[a]Air transportation system refers to geographical areas served by the air transportation system.

[b]Type of service refers to whether the service is long-haul, short-haul or a combination of the two.

After analyzing these responses and related literature dealing with airline decision-making [3,39], it was determined that the dominant considerations by an airline decision-maker appear to be: (a) fuel usage, (b) noise characteristics, and (c) congestion relief. Therefore, these attributes were used as the criteria for the problem and will appear expicitly in the objective function of the model. Other attributes such as operating cost and purchase price will be included as constraints. Presented in the next section is a discussion of each of these criteria with respect to their importance in present day air carrier service.

Criteria for Decision-Making

The following criteria were chosen for inclusion in the decision-making model based on information from various industry decision-makers (see questionnaire, Appendix A):

Fuel Usage

The effects of the energy crisis have been felt in all areas of transportation and the airline industry is no exception. Fuel allocation cutbacks have caused schedule cuts that have eliminated many low demand flights. Other methods have been used to reduce fuel usage in the present system include, (a) reduced throttle settings, (b) holding a departing flight at the gate until clearance to takeoff is obtained, thereby conserving

fuel in ground operations, and (c) holding flights at the point of origination until clearance is obtained at the point of destination to reduce airborne delays [39]. However, even though several methods have been used to conserve fuel, the continued fuel cost increases and lower fuel allocations are still a major concern with all airlines [39].

In order to ascertain the concern being expressed by the airlines in regard to future fuel consumption, it is important to compare the anticipated use of fuel and the anticipated availability of fuel in the future. The problem can be discerned by comparing Figure 2 [29] which shows the total anticipated use of fuel given in 10^{15} BTU per year for all leading forms of transportation with Figure 3 [29] which shows the projected world oil production. Although Figure 3 does not show the production of all fuel types, it does give a good indication of the anticipated shortage since jet fuel is produced from oil.

Therefore, with the anticipated increase in demand and the decrease in supply, increased prices and decreased allocations are a distinct possibility in the future. Since the RTOL aircraft will use more fuel than the CTOL in the cruise mode, fuel usage is a very important criterion in determining the utilization of RTOL aircraft.

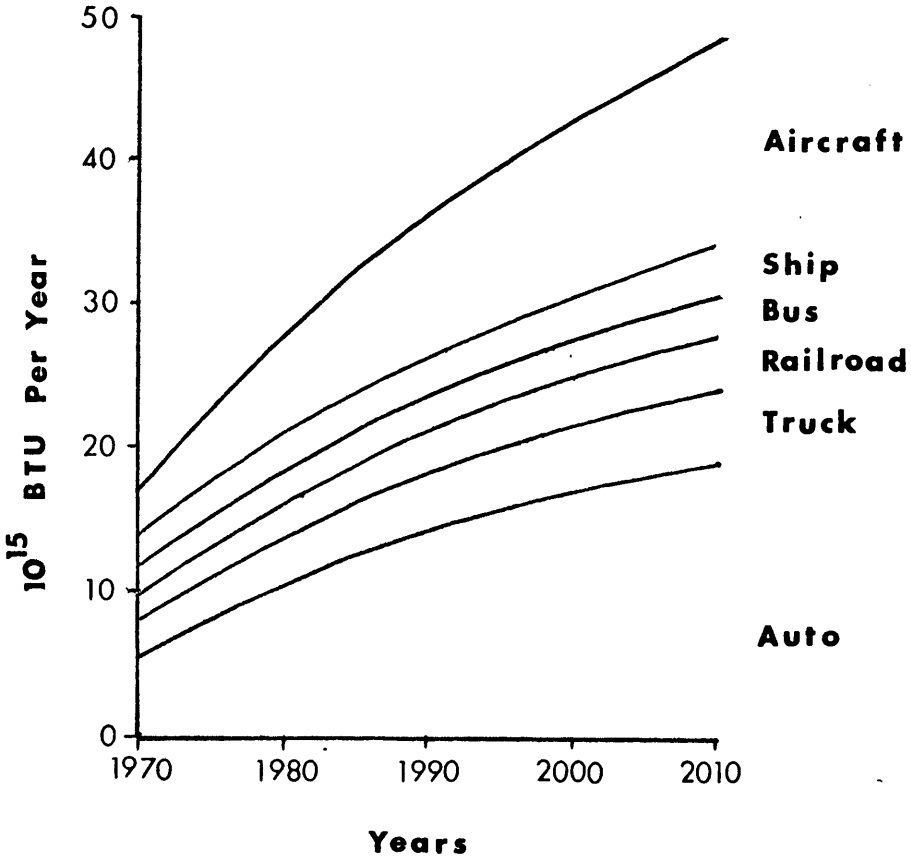


Figure 2

Transport Fuel Consumption

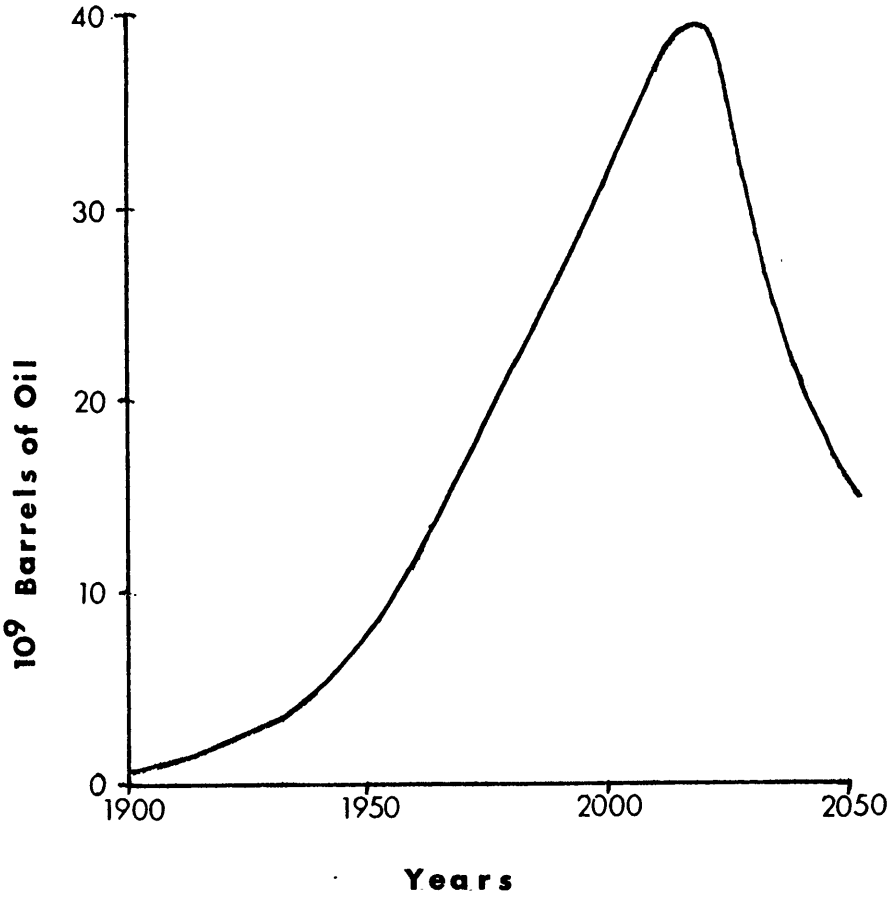


Figure 3

Projected World Oil Production

Delay

Many recent studies involving airline decision-making have been concerned with congestion and the resulting delay to air carriers which occurs at the major airports in the United States (see, for example, [30,36]). The importance of delay (which is commonly measured in minutes/aircraft flight) in air carrier decision-making can be seen in Table 8 [11]. This table, from an FAA study of the estimated total air carrier delay for 1973, shows that for the twenty-five highest delay airports in the United States, over 150 million dollars were lost because of delay. These costs (which are primarily direct operation costs and do not include costs resulting from diversions, missed connections, lost sales, etc.) represent a major source of lost revenue for the airlines.

In considering delay incurred by air carriers, it is important to evaluate the three major stages of the flight itself: (1) taxi out to takeoff, (2) takeoff, cruise and landing, and (3) the taxi in after landing. Each of these stages contain several causes of delay as can be observed in Table 9 [11].

Another study conducted by FAA [13] has shown that of these major reasons for delay, four of them usually constitute almost two-thirds of the delay incurred during the course of a flight. These are: (1) airport traffic in departures, (2) wind,

TABLE 8

ESTIMATED TOTAL AIR CARRIER DELAY (1973)

Rank by Delay Time	Airport[a]	Airport Cost (1000 dollars) Number	%	Cumulative Cost Number	%
1	ORD	26,912.0	13.8	26,912.0	13.8
2	ATL	29,597.8	15.2	56,509.8	29.0
3	JFK	16,346.9	8.4	72,856.7	37.3
4	LGA	8,903.3	4.6	81,760.0	41.9
5	SFO	5,833.7	3.0	87,593.7	44.9
6	LAX	6,207.9	3.1	93,801.6	48.1
7	DEN	4,943.4	2.5	98,745.0	50.6
8	PHL	5,168.6	2.7	103,913.6	53.2
9	EWR	5,167.0	2.6	109,080.6	55.9
10	MIA	4,694.6	2.4	113,775.2	58.3
11	DAL	4,722.4	2.4	118,497.6	60.7
12	DCA	3,757.4	1.9	122,255.0	62.6
13	DIT	3,676.0	1.9	125,931.0	64.5
14	BOS	3,440.0	1.8	129,371.7	66.3
15	CLE	2,741.6	1.4	132,113.3	67.7
16	DTW	2,675.3	1.4	134,788.6	69.0
17	MSY	1,919.0	1.0	136,707.6	70.0
18	LAS	2,153.2	1.1	138,842.8	71.1
19	HNL	3,311.1	1.7	142,153.9	72.8
20	STL	1,949.3	1.0	144,103.2	73.8
21	FLL	1,435.9	0.7	145,539.1	74.6
22	TPA	1,416.2	0.7	146,955.3	75.3
23	MSP	1,288.3	0.7	148,243.6	75.9
24	SEA	1,538.5	0.8	149,782.1	76.7
25	BAL	1,277.6	0.6	151,059.7	77.4[b]

[a]See Appendix C for identification

[b]The remaining airports in the country represent the remaining 22.6%.

TABLE 9

CAUSES OF DELAY

Taxi out to Takeoff

1. Gate procedures
2. Airport traffic
3. ATC (air traffic control) clearance
4. Taxi deviation (construction, etc.)
5. Miscellaneous (mechanical failure, extended run-up)

Takeoff to Landing

1. Terminal departure (climb restrictions)
2. Weather
3. ATC enroute
4. Wind
5. In trial (safety restrictions)
6. Terminal arrival (circling, awaiting landing)
7. Miscellaneous (deviation from flight plan)

Taxi In

1. Airport traffic
2. Taxi deviation
3. Awaiting gate
4. Gate procedures
5. Miscellaneous (snowy runways, etc.)

(3) terminal arrival, and (4) awaiting gates. In considering the effect of the aircraft itself on delay, the takeoff and landing requirement of the aircraft itself would have very little effect on the reduction of delay due to the separation of all aircraft in a particular aircraft class (see Appendix B for airplane classifications). However, studies by Lockheed [39], Charles Rivers Associates [6], and the Department of Transportation [40] have shown that the utilization of satellite airports for independent short-haul systems and as reliever airports would relieve congestion at the main airport. This reduction in congestion would reduce delay by affecting three of the four major causes of delay. These are: (1) reduction of airport traffic at major airports and a small traffic level for those aircraft using the satellite airports, (2) reduction of arrival time by the elimination of time spent in holding patterns at major airports, and (3) reduction of time waiting for gates caused by a reduction in the level of traffic at major airports and by the low level of activity at the satellite airports. The possible reduction in delay if satellite airports are used was demonstrated in Table 3.

Noise

In recent years, noise pollution has become a major concern to airline decision-makers because of restrictions put upon airports and aircraft by the Environmental Protection Agency [38]. In addition to these restrictions, the airlines have become more

responsive to the community's responses to aircraft noise on or near airports. The main sources of noise on and near airports are the following [38]: (a) aircraft taking off, landing, and operating in a certain traffic pattern; (b) aircraft undergoing engine maintenance run-ups; (c) engines being overhauled in a test stand; (d) various support equipment operating in the airport. Of these sources, (a) and (b) produce the most noise and affect a much wider area around an airport.

The intensity of noise in an area around an airport is dependent upon (a) the noise generated at the source, (b) the distance from the noise, (c) the dispersion of the noise (e.g., wind, buildings), and (d) the number of aircraft operations at the airport.

The measurement of airport noise is commonly performed using units of effective perceived noise in decibels (EPNDB). The contours of equal EPNDB can be drawn to show the noise produced for individual aircraft (and individual airports if sufficient data is known). An example of the noise contours for a current two engine aircraft such as a Boeing 737 is shown in Figure 4 [37]. To get some idea of the relative noise produced by an RTOL as compared to that of CTOL, the comparison of a typical current short-haul jet's 90 EPNDB footprint area (Trident 3) with an RTOL aircraft is shown in Figure 5 [42].

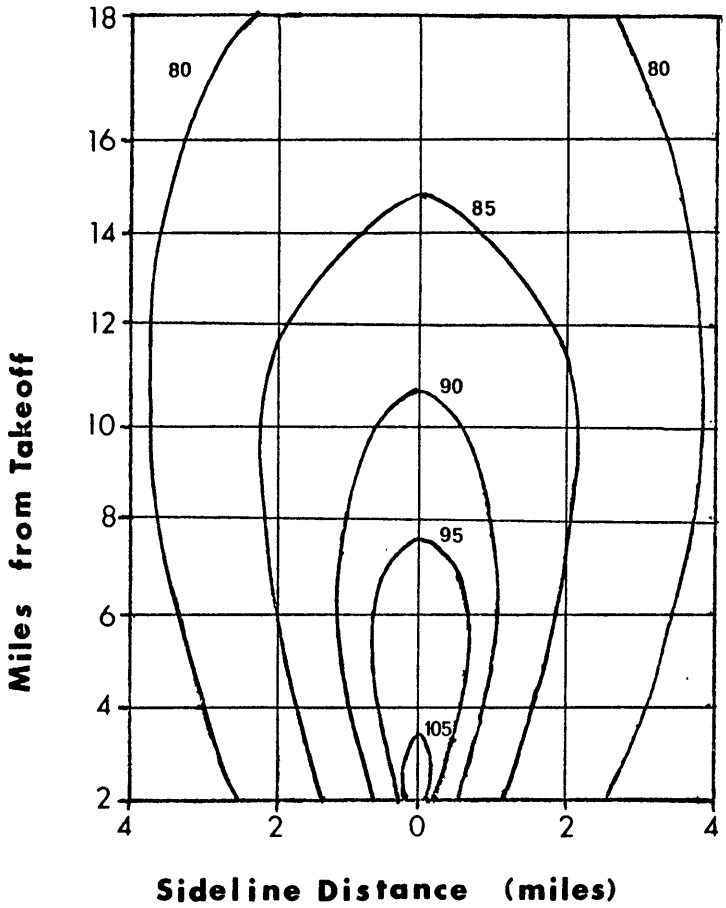


Figure 4

Noise Contours at Takeoff

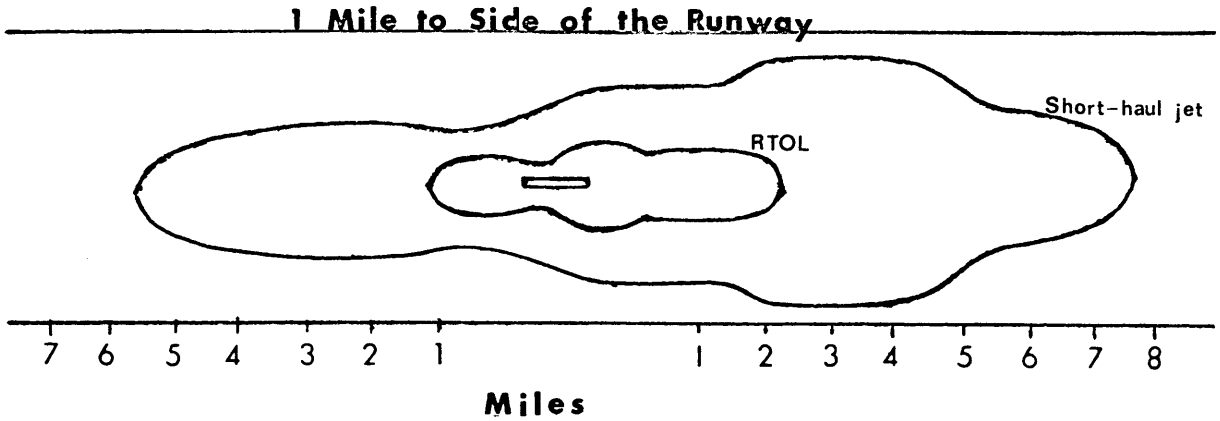


Figure 5

90 EPNDB Footprints

The cost of noise to the community near the airport comes from the fact that airport noise is considered to be a nuisance and possible health hazard and it destroys property by vibration [38]. For these reasons, several communities have developed noise abatement policies for their airports. Therefore, noise has become a major consideration for decision-makers associated with air transportation.

These three criteria of fuel usage, delay and noise levels are, therefore, very important criteria in determining the utilization of any type of aircraft in an air transportation system. These criteria also interact with each other in that as the delay level at an airport goes up, the fuel used and noise produced by aircraft awaiting takeoff or landing also increases.

CHAPTER 4

DECISION MODEL

The purpose of this chapter is to describe the development of the decision model. This discussion of the decision model includes: (a) the definition of the decision variables that are to be used; (b) the determination of the constraints that are placed on the air transportation system by the characteristics of the airports, aircraft and the system itself; (c) a concise statement of the decision problem; and (d) the mathematical model itself. The notation that is used in this chapter is also used in the discussion of the solution procedure in Chapter 5.

Decision Variable Description

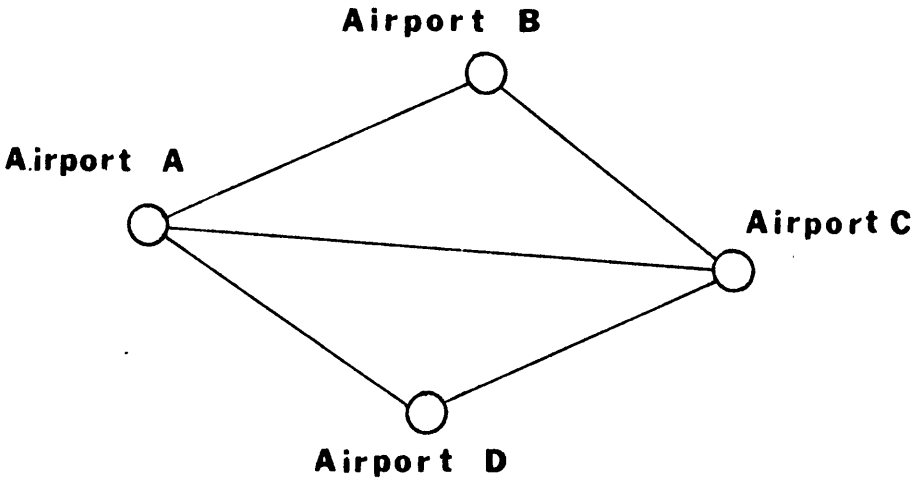
Before the decision variables in this problem can be defined, it is necessary to consider the situation under which they are developed. For each particular time period under consideration (usually one day), the aircraft fleet for the particular airline being studied must be scheduled over the airline's system to serve the passengers that demand service. The level of service that is provided must supply enough seats to meet the demand and yet not exceed the availability of aircraft or the capacity of individual aircraft. Since not all of the passengers will be flying nonstop between two locations, the service supplied by the airlines can be represented as multi-stop flights or

itineraries. It is these itineraries that commercial airlines advertise in their timetables. An example of a set of itineraries is given in Figure 6.

Scheduling of itineraries by the airlines is influenced by many different factors such as departure time, time of the year, quality of service (first class service versus tourist), weather conditions, etc. Therefore, no attempt will be made in this study to determine scheduling of the itineraries. The itineraries that will be considered in the example problems presented in Chapter 6 will be based on actual airline itineraries [32].

Therefore, the problem becomes one of determining the allocation of one of the several types of aircraft available to one or more flights over the predetermined set of itineraries. The allocation of these aircraft is made with respect to the previously mentioned criteria of fuel usage, delay and noise levels, and certain constraints that are dependent upon the air system being considered. The constraints used in this problem will be discussed in the next section.

With zero-one variables as the decision variables, the condition that one type of aircraft, say RTOL, is used to fly a particular itinerary, say itinerary number 1, can be represented by one and all other aircraft on that itinerary would be represented by zero. Therefore, if the value of the mth criteria that is associated with type i aircraft flown on itineray j as described by $a_{ij}^{(m)}$ (where $a_{ij}^{(m)}$ is implicitly defined as a function of the aircraft and itineraries used) is multiplied by the corresponding zero-one variable x_{ij}, then the



Example Itineraries:

A–B–C

B–C–D

C–D–A–B

D–A

Figure 6

Airline Itineraries

resulting function for the mth criteria can be represented as:

$$F = \sum_{j=1}^{I} \sum_{j=1}^{J} a_{ij}^{(m)} (x_{ij})$$

where I and J represent the total number of aircraft and itineraries, respectively. The purpose of this study can then be stated as trying to find values of the decision variables x_{ij} that will minimize F for the combined set of m criteria (in this study, m = 3). These criteria will be subject to constraints that will be discussed in the following section.

Model Constraints

In determining which aircraft to fly specified itineraries, several restrictions are placed upon the air transportation system encountered by the aircraft and the airports involved. In order to accurately represent the air traffic system under consideration, these restrictions must be considered. Several of these possible restrictions for air traffic systems were mentioned in Chapter 3. These constraints can be categorized as either, (a) aircraft constraints, (b) airport constraints, (c) budget constraints, or (d) system constraints.

Aircraft Constraints

These constraints are concerned with restrictions that occur as a consequence of the operating characteristics of the specific aircraft in question. The constraint that will be used in this model that falls into this category is that the total capacity of the aircraft used for

any particular itinerary must meet or exceed the expected demand for service on that itinerary.

Airport Constraints

Constraints in this category are those placed upon the system by either the physical characteristics or community statutes for a particular airport. The constraints included in this model are that, (a) the takeoff and landing capability of an aircraft cannot exceed the runway length of any airport at which it must land, and (b) the noise restrictions at individual airports should not be exceeded.

Budget Constraints

The decision-maker would be responsible for supplying these constraints. They would include restrictions placed upon the amount of capital available to operate the air transportation system. In this model, those constraints are, (a) limits on operating costs for a particular system, and (b) limits on investment funds for purchases of an aircraft fleet to operate the system.

System Constraints

These constraints are those assumptions imposed on the system in order to simplify it so that it is not too complex to be manageable. In this study, the constraint that will be placed on the system is that only one type of aircraft will be used on an individual itinerary.

Once these constraints have been formulated, they can be combined with the criteria discussed in Chapter 3 in a mathematical programming formulation to form a model of the decision problem under

consideration. The following sections will present a concise statement of the problem being considered and the mathematical model of the system.

Concise Problem Statement

The problem that will be considered in this research will be to determine which itineraries the aircraft under consideration (RTOL or CTOL) are to be assigned such that the amount of fuel used, delay and noise levels are to be minimized. These aircraft will be subject to the following constraints: (a) the minimum runway lengths at all airports in an itinerary must meet or exceed the necessary length for takeoff and landing requirements for a given aircraft, (b) total seating on the aircraft used must meet or exceed the maximum demand for air service between any city pair in an itinerary, (c) neither the indirect operating cost nor the total aircraft purchase price will exceed specified budgetary restrictions, and (d) the noise levels produced must not exceed restrictions set at any airport in an itinerary.

Mathematical Model

The following is a mathematical representation of the problem described in the previous section.

Consider the following notation:

i represents the ith type aircraft

j represents the jth itinerary

$x_{ij} = 1$ if type i aircraft is flown on itinerary j,
$\quad\quad\;\; 0$ otherwise

$\underline{x}$ represents a vector of x_{ij} variables for all i, j

I represents the maximum value of i

J represents the maximum value of j

$a_{ij}^{(m)}$ $(\underline{x})$ represents the value of the mth attribute associated with type aircraft flying itinerary j for a given $\underline{x}$

$a_{ij}^{(1)}$ $(\underline{x})$ represents the fuel usage in gallons

$a_{ij}^{(2)}$ $(\underline{x})$ represents the delay in minutes

$a_{ij}^{(3)}$ $(\underline{x})$ represents the noise level in decibels

R_i represents the minimum runway length for type i aircraft

r_k represents the runway length of the kth airport in set k_j

k_j represents the set of airports in itinerary j

c_i represents the capacity of type i aircraft

d_{jk} represents the demand for air service at airport k on itinerary j

b_{ij} represents the operating cost (excluding fuel) of aircraft i flying itinerary j

B represents the budgetary restrictions placed on daily operating cost, set by the decision-maker

P represents the budgetary restrictions placed on the purchase of a fleet of one type of aircraft

t represents a time period during the day in which an aircraft is being utilized

$\{j_i\}_t$ represents the set of itineraries that require an additional type aircraft beyond that required to fly itineraries $\{j_i\}_0, \{j_i\}_1, \ldots, \{j_i\}_{t-1}$

n_{it} represents the number of elements in $\{j_i\}_t$[1]

s_i represents the noise level produced by type i aircraft

S_k represents the maximum noise restrictions placed in sound levels at the kth airport

$G(\underline{x})$ represents the set of constraints used in the decision model

n represents the total number of criterion functions

C_ℓ represents the ℓth criterion function, $\ell = 1, \ldots n$,

$$C_\ell = \sum_{i=1}^{I} \sum_{j=1}^{J} a_{ij}^{(\ell)}(\underline{x})\, x_{ij}$$

A_ℓ represents the ℓth aspiration level, $\ell = 1, \ldots n$

D_ℓ represents the numberical values of the ℓth criterion evaluated at the solution vector values, $\ell = 1, \ldots n$.

The decision problem described previously can be expressed mathematically as follows:

Find x_{ij} $\forall$ i, j

$$\text{to min} \sum_{i=1}^{I} \sum_{j=1}^{J} a_{ij}^{(1)}(\underline{x})\, x_{ij},$$

$$\sum_{i=1}^{I} \sum_{j=1}^{J} a_{ij}^{(2)}(\underline{x})\, x_{ij} \text{ and} \qquad \text{(M1)}$$

$$\sum_{i=1}^{I} \sum_{j=1}^{J} a_{ij}^{(3)}(\underline{x})\, x_{ij}$$

Subject to:

---

[1]This set implies that one particular aircraft may be used to fly more than one itinerary during a stretch of time 0 to t. (For example, one aircraft may be used to fly one itinerary at some time t-3 and then fly the reverse itinerary later in the day at time t).

(A) The available runway at each airport should not be exceeded.

$$R_i x_{ij} \leq \min \{r_k, \forall\ k \varepsilon K_j\} \quad \forall\ i, j. \tag{M2}$$

(B) Demand must be satisfied.

$$\sum_{i=1}^{I} C_i x_{ij} \geq \max_{k\varepsilon\{K_j\}} \{d_{jk}\} \forall j \tag{M3}$$

(C) Operating cost restrictions must be satisfied.

$$\sum_{i=1}^{I} \sum_{j=1}^{J} b_{ij} x_{ij} \leq B \tag{M4}$$

(D) Restrictions on the purchase of aircraft must be satisfied.

$$\sum_{i=1}^{I} p_i q_i \leq P \tag{M5}$$

With the fleet size of each type aircraft defined as:

$$q_i = \sum_{t=1}^{T} n_{it}(\underline{x}) \quad \forall i$$

(E) Only one type of aircraft will be used on an itinerary.

$$\sum_{i=1}^{I} x_{ij} = 1 \quad \forall\ j \tag{M6}$$

(F) Restrictions on noise levels at individual airports should not be exceeded.

$$S_i\ x_{ij} \leq \min \{S_k, \forall k \varepsilon K_j\} \forall\ i, j \tag{M7}$$

CHAPTER 5

SOLUTION PROCEDURE

This chapter is concerned with the solution of the multicriteria decision problem that was discussed in Chapter 4. Many different procedures have been discussed in the literature since 1957 that have dealt with the solution of multicriteria models by mathematical programming methods. Several of these methods will be mentioned in the next section, and then the solution procedure developed for the problem in the current research will be presented.

Background

The categories of the mathematical programming methods of solution were shown in Chapter 3 in Table 7. These categories include: (a) linear programming, (b) goal programming, and (c) interactive, multicriterion programming. In the linear programming approach, each variable represents one criteria, the constraints are restrictions on combinations of the criteria and the solution of the linear programming problem is a global optimum for these criteria. The set of alternatives is an infinite set that is defined by the constraints. Several texts have been devoted to the discussion of the solution procedure for linear programming, (e.g., Gass [15] and Dantzig [10]). The second method, goal programming, deals more explicitly with multicriteria

programming through the use of multiple objective functions. The original work done in this field was that of Charnes and Cooper [7]. Other work associated with this procedure has been done by Ijiri [22], Boldur [4], Raiffa [33] and Lee [28].

The goal programming model is a linear mathematical model in which the optimum attainment of a set of goals is achieved. The objective function in goal programming is a linear combination of deviational variables from the various goals. The deviational variables may be weighted by a priority factor determined by the decision-maker. An example of a goal programming formulation with three goals and two decision variables would be:

$$\min Z = P_1 d_1^- + P_2 d_2^- + P_3 d_3^- + d_1^+$$

s.t.

$$\begin{aligned} &(1) \quad a_1 x_1 + a_2 x_2 + d_1^- + d_1^+ = b_1 \\ &(2) \quad x_1 \qquad\qquad + d_2^- = b_2 \\ &(3) \quad \qquad x_2 \qquad + d_3^- = b3 \\ &\qquad x_1,\ x_2,\ d_1^-,\ d_2^-,\ \bar{d}_3,\ d_1^+ \geq 0 \end{aligned}$$

where (1), (2), and (3) represent the three goals

P_i are the priority factors

d_i^+ are positive deviations from the goals

d_i^- are the negative deviations from the goals

x_i are the decision variables

a_i, b_i are constants

It should be noted that d_1^+ and d_1^- are complementary to each

other. That is, if one of them is nonzero, the other will be zero, (i.e., $(d_1^+)(d_1^-) = 0$).

The third category, that of interactive, multicriteria programming, is the class which contains the solution procedure developed in this study. The solution procedures in this study do not guarantee the achievement of a global optimum solution but use sequential trade-offs in the neighborhood of a feasible alternative. This trade-off procedure is used to formulate a better knowledge of the preference structure of the decision-maker. The trade-offs are used along with a mathematical programming algorithm to generate a satisfactory solution for the problem (this is a "satisficing" approach). The decision-maker then has an opportunity to provide new trade-offs which again serve as inputs to the algorithm. This process continues until the decision-maker no longer feels a need to revise his trade-offs and a satisfactory solution is found [9].

Early work in the area of interactive, multicriterion programming was done by Benayoun, De Montgolfier, Tergny and Laritchev [2]; Geoffrion [16]; and Geoffrion, Dyer and Feinberg [18]. Benayoun et al. use an interactive approach in which the decision-maker searches for an acceptable compromise (i.e., an acceptable compromise between criteria) solution rather than an optimum by means of an algorithm called the step method ("STEM") [2]. In using this procedure, the decision-maker is called upon to examine a table containing the value of each criteria function under alternate input conditions, then from this table, weights for objective functions are found and a linear

programming procedure is used to determine possible satisfactory solutions and elements for the next iteration's table. The procedure is continued until an acceptable solution is found.

In the procedure developed by Geoffrion in 1970 [16] and extended in 1971 [18], a question-answer format is used to ascertain the preference function of the decision-maker. This preference function is then implemented into an algorithm based on the Frank-Wolfe procedure [14] for optimizing nonlinear programming problems.

Other procedures have since been developed and discussed in the literature. These studies include work by Monarchi [31] (which represents the basis for this study and will be discussed in detail in the following section), Kapur [25], Roy [35], and Geoffrion and Hogan [19]. These procedures are based on different methods of determining the decision-maker's utility function.

The Monarchi Procedure

The procedure that will be used to solve the problem stated in Chapter 4 is based upon an interactive algorithm that was developed by Monarchi in 1972 for a study requiring multiobjective decision making in a water resource system [31]. One of the major reasons that this procedure was selected over those mentioned in the previous section is that this procedure appears to be easier for a decision-maker to use and understand. In addition to its ease of use, this procedure is concerned with the achievement of aspiration levels which may or may not be optimal, but which are satisfactory to the decision-maker. This

consideration generally allows a reduction in the numbers of iterations required by the decision-maker especially since an optimum solution may be very difficult to achieve because of the variability of a human decision-maker in choosing between preferred criteria. (For an extended discussion on the value of determining a satisfactum rather than an optimum in multicriteria decision making, see Monarchi [P. 6-28, 31] and Johnson, Chapters 3 and 9 [23].)

The basic steps in the Monarchi procedure are: (a) the selection of aspiration levels by the decision-maker, (b) the transformation of each criterion to a response surface defined on the interval [0, 1], (c) the development of surrogate functions, (d) optimization of these funcations, (e) a comparison of results obtained, and (f) the formulation of revised aspiration levels. The procedure ends when the decision-maker feels that he has reached a satisfactory solution. A detailed discussion of the various parts of this procedure is given in Appendix D. An example is also included to demonstrate the role of the decision-maker in this interactive procedure.

Monarchi summarizes the mechanism of his algorithm as follows [P. 56-57, 31] :

> . . . the algorithm will generate information under the guidance of the decision maker so he can make a decision, but the algorithm will not explicitly solve the decision problem itself. The mechanism whereby information is generated for the decision maker is to evaluate the cyclical optimization of a surrogate objective function S. Our problem is to find a satisfactum P^*. The function is not a substitute for P nor does optimization of S imply optimization of P in any sense. We have introduced

this function as a tool to help the decision maker explore his preferences.

In essence, the Monarchi procedure is designed to solve a secondary model rather than the model (M1) described in Chapter 4. It solves (M1) indirectly (finding a satisfactory solution rather than an optimum) by determining solution values such that

$$D_j - A_j \leq 0 \ \forall j$$

where A_j represents the jth aspiration level and D_j represents the value of the jth criterion function.

Modifications to the Monarchi Procedure

In order to use the basic procedure developed by Monarchi for the solution of the problem described in Chapter 4, several modifications were required. The Monarchi procedure was developed to solve nonlinear programming problems with continuous variables whereas the problem under consideration deals with 0-1 variables.

The major modification that was required was to change the solution process so that it utilizes a 0-1 algorithm in place of the Griffith-Stewart algorithm [21] that is used in the optimization phase of the Monarchi procedure (i.e., to solve problems (P1) and (P2) in Appendix D). Several algorithms for 0-1 programming were considered for use in this solution procedure (e.g. branch and bound techniques, cutting plane methods, etc.). However, an algorithm developed by Balas [1] was chosen because of its simplicity and its appropriate theoretical properties. The effect of this modification on the solution

procedure and the solution itself will be discussed in the next section.

The second modification of the Monarchi approach is the additional requirement that each criteria be optimized prior to the development of the surrogate objective function. This modification was made in order to provide the decision-maker with additional important information. Each of the criteria is optimized separately subject to the constraints, and then the surrogate function is formed if necessary. This procedure will provide the decision-maker with the optimum allocation for each of the criteria separately, and will allow the decision-maker to see what the lower limit (if minimization is done) for his aspiration levels is. Since each criterion is optimized without regard to the other criteria, the solution found is the minimum value for the given constraint set). In addition to providing this information, should the allocations achieved for each of the criteria be the same, the values of the criteria will all be at their minimum and the formation of the surrogate functions would be superfluous since a smaller value for each criteria could not be found.

The third modification in the Monarchi procedure concerns the construction of the surrogate objective function. In the surrogate developed by Monarchi for a minimization problem, the individual criterion functions are transformed into an altered response surface by substituting them into the equation

$$y_k = \frac{C_k(\underline{x}) - Z_{k(min)}}{Z_{k(max)} - Z_{k(min)}} \quad k = 1, \ldots, n \qquad \text{Eq. (1)}$$

where

y_k = the transformed k^{th} criterion function

$C_k(\underline{x})$ = the original k^{th} criterion function (which is a function of $\underline{x}$, the vector of decision variables

$Z_{k(max)}$ = the maximum value that $C_k(\underline{x})$ could possibly attain (as determined by the decision-maker, without regard to feasibility)

$Z_{k(min)}$ = the minimum value that $C_k(\underline{x})$ could attain

This transformation creates a response surface which is defined in the interval [0, 1]. The purpose of this transformation is to create a component of the surrogate function which will not unduly bias the final solution. By transforming each criteria to the interval [0, 1], the surrogate functions (Step 3 of Monarchi's procedure), which are the sums of the criteria functions, will not be biased towards some criteria having large units of measurement as opposed to criteria having small units of measurement. The y_k terms developed in Eq.(1) for the type of problem considered here are then divided by weighing factors which take under consideration the values of the aspiration levels desired by the decision-maker. These weighing factors are defined by

$$w_k = \frac{A_k - Z_{k(min)}}{Z_{k(max)} - Z_{k(min)}} \qquad k = 1, \ldots, n \qquad \text{Eq. (2)}$$

where

A_k = the aspiration level set by the decision-maker for the kth criterion function, and

$Z_{k(min)}$ and $Z_{k(max)}$ are the same values as previously defined

In modifying this procedure, the requirement of the decision-maker to define a range of $Z_{k(min)}$, $Z_{k(max)}$ for the criterion function was eliminated for this particular problem since the values of the decision variables would either be 0 or 1. This allows the use of a transform defined by the problem itself. For example, if the kth criterion were of the form

$$a_1^k x_1 + a_2^k x_2 + \ldots + a_m^k x_m = C_k(\underline{x})$$

(where a_i^k is the coefficient of the ith decision variable for the kth criteria):

then the transform,

$$y_k = \frac{C_k(\underline{x})}{\sum_{j=1}^{m} a_j^k} \qquad \text{Eq. (3)}$$

would correspond to Monarchi's y_k (see Eq. (1)). This corresponds to Monarchi's y_k because of the fact that the minimum value of the function is 0 (when all $x_k = 0$, $k = 1, \ldots, n$) which corresponds to Monarchi's $Z_{k(min)}$ and the maximum value of the function is $\sum_{j=1}^{m} a_j^k$ (when all $x_k = 1$, $\ldots, n$) which corresponds to Monarchi's $Z_{k(max)}$. Therefore,

$$\frac{C_k(\underline{x}) - Z_{k(min)}}{Z_{k(max)} - Z_{k(min)}} \Rightarrow \frac{C_k(\underline{x}) - 0}{\sum_{j=1}^{m} a_j^k - 0} = \frac{C_k(\underline{x})}{\sum_{j=1}^{m} a_j^k} \qquad \text{Eq. (4)}$$

To determine the weighing factor, the expression

$$w_k = \frac{A_k}{\sum_{j=1}^{m} a_j^k} \qquad \text{Eq. (5)}$$

where

$$A_k = \text{the decision-maker's } k^{th} \text{ aspiration level}$$

is used in place of Eq. (2). Therefore, each component of the surrogate objective function (Monarchi's d_i, see Appendix D) becomes:

$$d_k = \frac{C_k(\underline{x}) / \sum_{j=1}^{m} a_j^k}{A_k / \sum_{j=1}^{m} a_j^k} = \frac{C_k(\underline{x})}{A_k} \qquad \text{Ea. (6)}$$

With these modifications in mind, in the next section the solution procedure that has been developed for the problem being considered in this study will be presented.

Solution Procedure for RTOL Problem

Once the problem has been defined with regard to the geographical area to be served, the aircraft to be compared, and the criteria the decision-maker wishes to consider, the model can be formulated and solved. The basic steps involved in the solution procedure are as follows (a summary of these steps is given later in Figure 7):

Step 1. Obtain and input data concerning the characteristics of the air traffic system and the aircraft under consideration. These characteristics include:

> (A) the list of itineraries to be flown in this system (this would include the itinerary number and the airport in each itinerary), (B) the distances between airports in the system, (C) the number of operations per hour that each airport performs (taken as an average over the daylight hours)[1] (D) the longest

[1]This factor is used to determine the delay experienced at the airports.

runway of each airport (or the length of the runway that will be used for the air carrier under consideration), (E) the aircraft runway requirements, (F) the aircraft average airspeeds measured in miles per hour, (G) the aircraft passenger capacities in terms of number of seats, (H) the fuel penalty suffered by shorter takeoff and landing aircraft as a percentage of that used by the most fuel efficient aircraft, (I) the aircraft noise levels (as measured in EPNDB) of takeoff noise, (J) the population of the cities in the air system, (K) the aspiration levels desired by the decision-maker for each criteria being considered.

Step 2. Determine fuel usage, noise, delay and number of flights required for each aircraft on each itinerary. This information is determined by functional relationships with the various input parameters. These values of fuel, noise, and delay are represented by in the decision model (m = 1, fuel; m = 2, delay; and m = 3, noise), where it is understood that $a_{ij}^{(m)}$ is a function of the decision variables, $\underline{x}$.

Step 3. Route aircraft with allowable characteristics such as short runway potential, allowable noise levels, etc., to an available satellite airport if the number of operations per hour at the major airport exceeds a maximum allowable number as determined by the decision-maker.

Step 4. Develop objective functions and constraints to be used in an optimization procedure from values input in Step 1. (The objective functions and constraints used in this problem are described in Chapter 4 in Equations M1 through M7.)

Step 5. Using Balas' algorithm, determine the optimum scheduling of aircraft to itineraries for each individual criterion subject to all constraints. This procedure will generate a set of solution

vectors (one for each individual criterion) the elements of which are either zero or one (zero if a certain aircraft is not used on a particular itinerary, one otherwise). These solution vectors will then be used to evaluate each criteria and produce a vector of criteria values which represent a lower bound on each criterion.

Step 6. Determine if the aspiration levels supplied by the decision-maker are greater than or equal to these lower bounds. If they are not, relax the violated aspiration levels by setting them equal to the lower bounds and return to Step 4. For example, if the aspiration levels were to be:

$$\underline{A} = (600, 350, 350)$$

and the criteria were found to be:

$$\underline{D} = (750, 250, 350)$$

then the criteria level 750 would be higher than the aspiration level 600 (the aspiration level being the highest allowable value in the minimization problem) and therefore, this aspiration level would have to be raised to at least 750 before the procedure could be completed.

Step 7. Determine if the schedules are all the same. (In other words, determine if all of the solution vectors for the criteria functions are equal.) If they are, the procedure stops and the schedule found is satisfactory to the decision-maker. Since the Monarchi procedure is trying to find a solution such that $D_j - A_j \leq 0, \forall j$, this requirement is met if $A_j = D_j$. If they are not, continue.

Step 8. Develop the surrogate function and set up the corresponding surrogate problem with all criteria as follows:

$$\min \quad S_o = \sum_{k=1}^{n} \frac{C_k(\underline{x})}{A_k} \qquad \text{(SPO)}$$

$$\text{s.t.} \quad G(\underline{x}) \leq 0$$

where:

S_o is the surrogate function

$C_k(\underline{x})$ is the kth criterion objective function

A_k is the kth aspiration level

$G(\underline{x})$ is the original constraint set.

In addition to this problem, form one additional surrogate problem for each of the n criteria. These problems are formed by removing d_k (see Eq. 6) from the surrogate objective function and adding the corresponding criteria as a constraint having the following form

$$C_k(\underline{x}) \leq A_k$$

Therefore, each of the remaining surrogate problems becomes

$$\min \quad S_k = \sum_{\substack{\ell=1 \\ \ell \neq k}}^{n} d_\ell \qquad k = 1, \ldots, n$$

$$\text{s.t.} \quad G(\underline{x}) \leq 0$$

$$C_k(\underline{x}) \leq A_k$$

An example of this formation for the surrogate problem created for the first criteria is

$$\min S_1 = \sum_{\substack{\ell=1 \\ \ell \neq 1}}^{n} d_\ell \qquad \text{(SP1)}$$

$$\text{s.t.} \quad G(\underline{x}) \leq 0$$

$$C_1(x) \leq A_1$$

As mentioned earlier, the solution of these surrogate problems does not solve the original objective function (M1) but is used to provide information concerning the decision-maker's preferences.

Step 9. Determine the schedule for each of the surrogate problems using the Balas algorithm.

Step 10. Determine if the decision-maker's aspiration levels have been met for any of the schedules generated. If they have the procedure stops since a satisfactory schedule has been found. If not, continue.

Step 11. Manually plot the results of the solution of the surrogate problems and have the decision-maker alter his aspiration levels depending on the relationships of the surrogate criteria and his own utility. This plotting procedure plots the results of the first surrogate problem (SPO) versus each of the remaining surrogate problems (SP1 to SPn) (an example of this process is discussed in the example problem given after Step 12). This procedure supplies the decision-maker with information concerning the effect of using each of the criteria as a constraint in (SP1 to SPn) and allows him to consider the effect of altering his aspiration levels. (See Appendix D for a discussion of the motivation behind this graphical analysis).

Step 12. Once the decision-maker has altered his aspiration levels, the procedure returns to Step 8.

The solution procedure is summarized in Figure 7 in the form of a flow diagram.

In order to better understand the solution procedure for

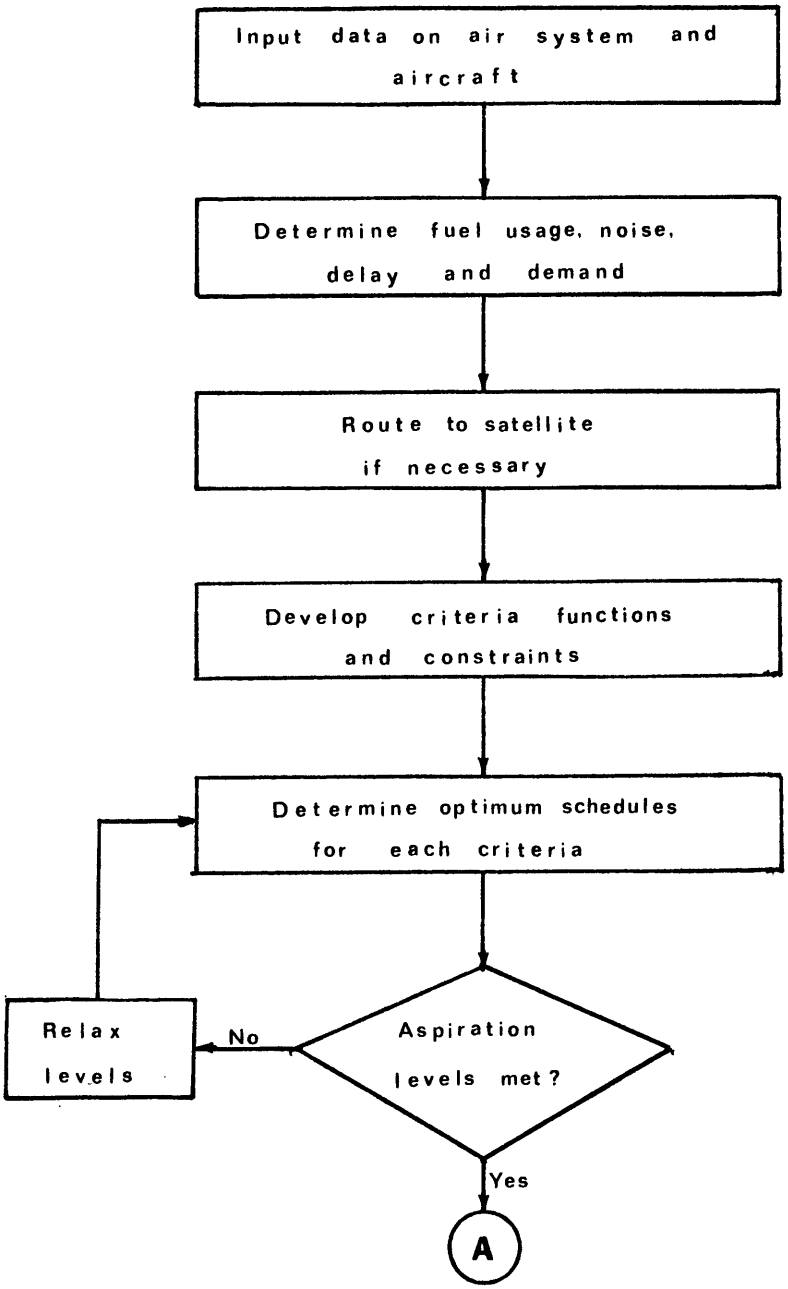


Figure 7

Solution Procedure

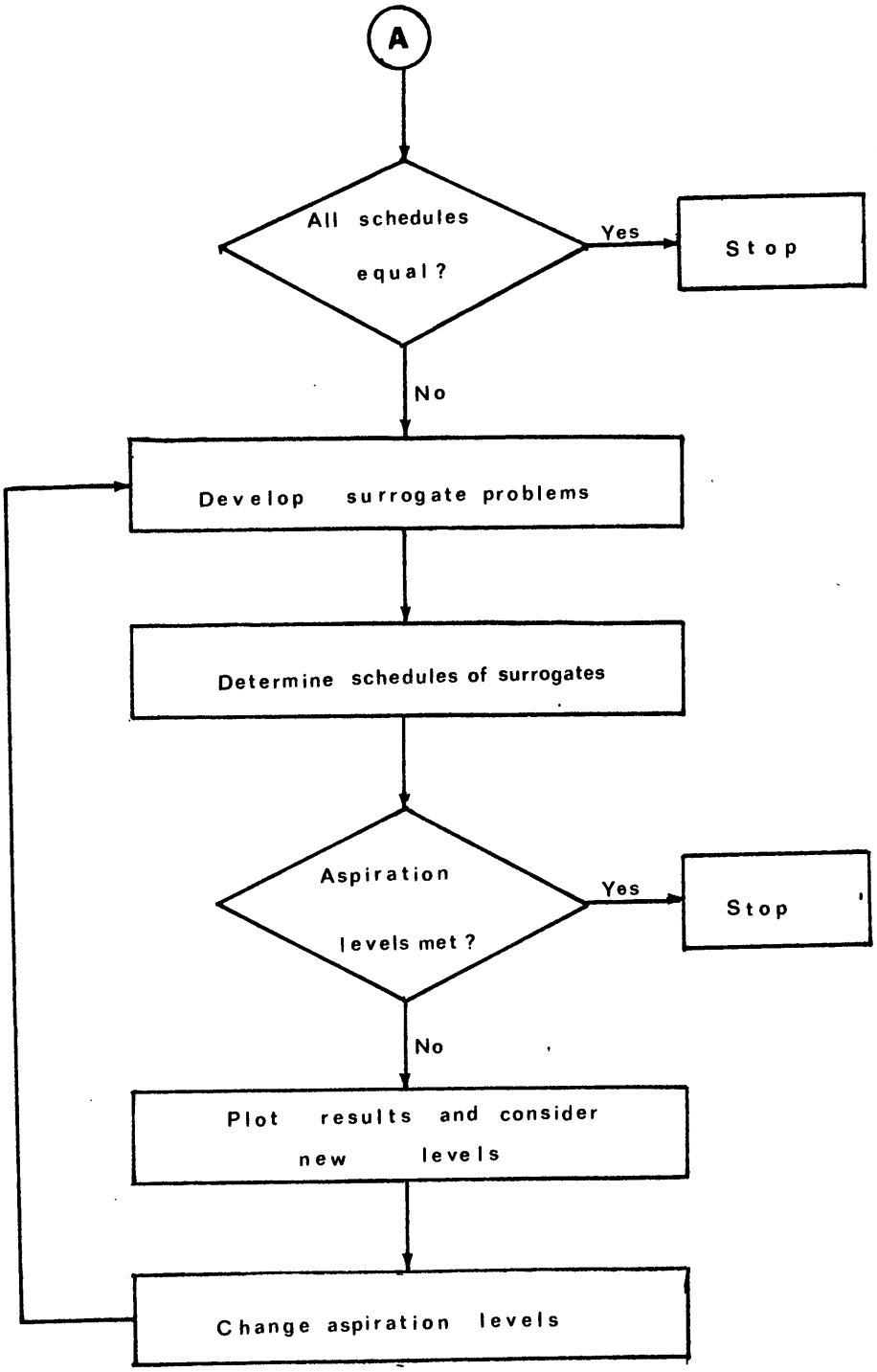


Figure 7 (cont.)

Steps 6 through 12, consider the following example: using the basic structure of the problem considered in Chapter 4 with three criteria $C_1(\underline{x})$, $C_2(\underline{x})$ and $C_3(\underline{x})$, and a constraint set $G(x) \leq 0$, the assignment of three different aircraft on four different itineraries is considered. In order to simplify the notation used to identify the solution vector in this example, let the assignment of aircraft i (with a maximum value of I) or (i = 1, . . . , I) on the itinerary j be represented as $(I)\cdot(j-1) + i$ (e.g., the assignment of aircraft 2 on itinerary 3 would be (3) (2) + 2 = 8, aircraft 3 on itinerary 4 would be (3) (3) + 3 = 12).

Assuming that Steps 1 through 5 have been completed with the aspiration levels of the decision-maker set equal to

$$\underline{A} = (40, 65, 85),$$

the solution vectors for each criteria are found to be:

$$\underline{x}_1 = (3, 4, 9, 12)$$

$$\underline{x}_2 = (2, 4, 8, 11)$$

$$\underline{x}_3 = (1, 4, 7, 10)$$

with the corresponding criteria values of

$$\underline{D} = (30, 60, 70).$$

Therefore, since $\underline{x}_1 \neq \underline{x}_2 \neq \underline{x}_3$, the surrogate functions must be formed. The surrogate problems would be formed as previously discussed, for example, SP1 would be

$$\min \quad S_1 = \sum_{\substack{\ell=1 \\ \ell\neq 1}}^{3} d_\ell \qquad \text{(SP1)}$$

$$\text{s.t.} \quad G(\underline{x}) \leq 0$$

$$C_1(\underline{x}) \leq 40$$

Each of the surrogate problems, SP0, SP1, SP2, and SP3 are then solved. Using the hypothetical results obtained in Table 10, the results are then manually plotted by the decision-maker in Figure 8A, 8B, and 8C. In plotting these results, the criteria that was included as a constraint is drawn in the middle of the plot and the other criteria are listed on either side. (For a discussion of the reason this graphical procedure is used to provide additional information to the decision-maker, see Appendix D.)

In Figure 8C, a solid line is drawn connecting each of the criteria values for SP3. Then, a dotted line is drawn connecting the criteria values of SP0. The purpose of this second set of lines is to allow the decision-maker to see the effect of putting the criteria under consideration into the constraint set.

If the decision-maker feels that he would be satisfied with any set of criteria values, D, that have determined for each of the surrogate problems, the process stops and the adopted schedule becomes the solution associated with the that was selected. If the decision-maker is not satisfied, he continues by considering the values plotted in Figures 8A, 8B, and 8C. By selecting the criteria he considers most important to him, say Criteria 3, he is able to see what effect the addition of this criteria as a constraint has had. For example, using Criteria 3, by drawing a straight line on Figure 9 (which is an enlargement of Figure 8C), through point M1 (which is the point at which

Table 10

Surrogate Solutions

Surrogate Problems	$\underline{D}$	$\underline{x}$
SP0	(35, 70, 85)	(3, 4, 8, 12)
SP1	(40, 65, 85)	(2, 4, 9, 12)
SP2	(45, 65, 85)	(2, 4, 8, 12)
SP3	(50, 75, 80)	(1, 4, 8, 10)

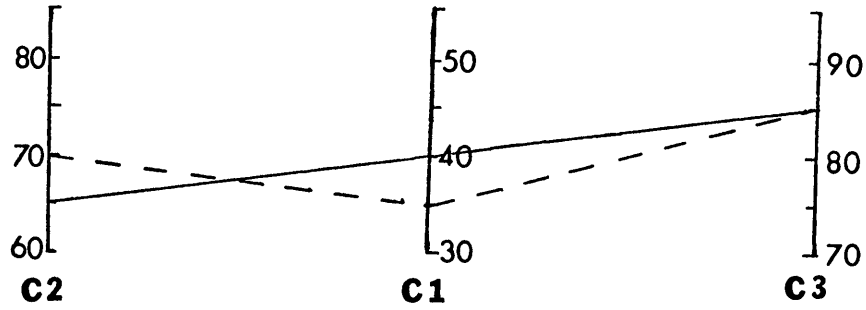


Figure 8a SP1 Plots

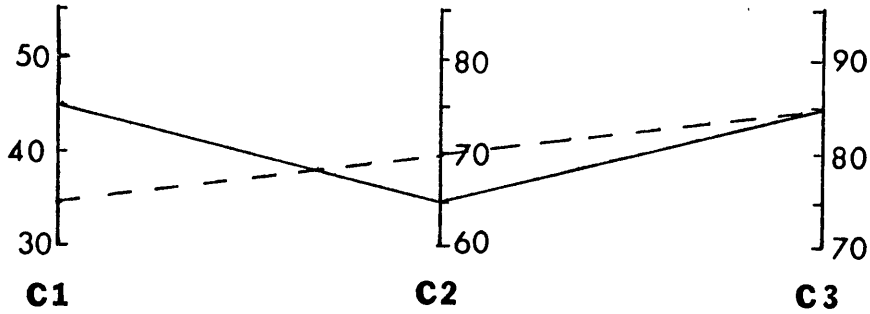


Figure 8b SP2 Plots

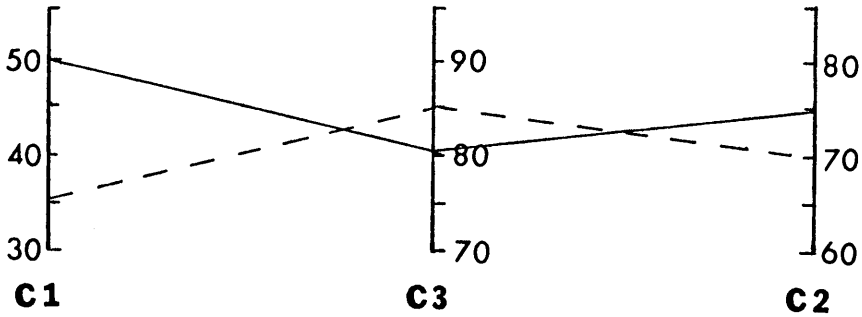


Figure 8c SP3 Plots

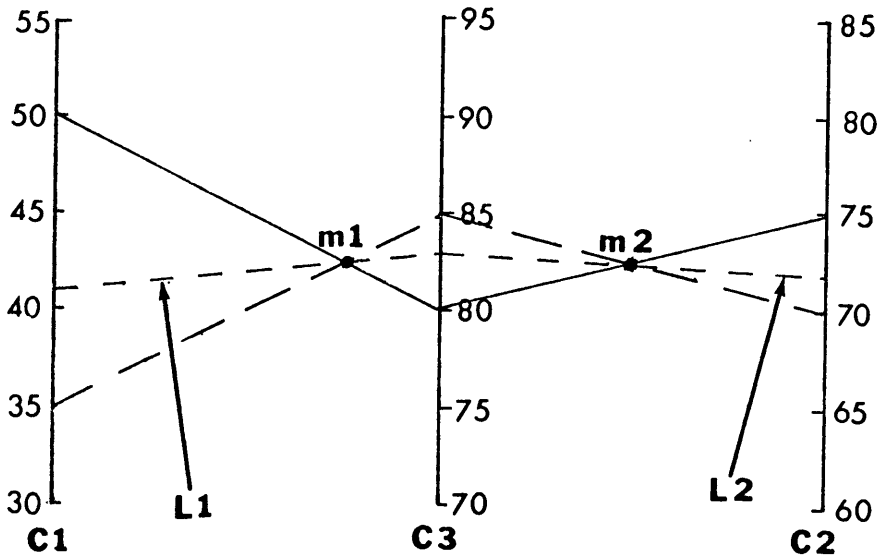


Figure 9

Criteria 3 Constrained

the change in transformed Criteria 3 is equal to the change in the transformed Criteria 1), the decision-maker can try out different aspiration levels to see how they would affect Criteria 1. A slight change in the aspiration level of Criteria 3 would have a rather large effect on Criteria 1. For example, as illustrated in Figure 9, suppose the decision-maker changes his aspiration level for Criteria 3 from 80 to 83. The result would change the value the decision-maker could expect for Criteria 1 from 50 to 41, as shown by dotted line L1.

In a similar manner, an aspiration level of 83 would change Criteria 2 to a value of approximately 72 as shown by L2 in Figure 9. This procedure of trying out new aspiration levels can then be done on the other figures (8B and 8C) until the decision-maker feels that he has an understanding of the effect that different changes in his aspiration levels would have on each of the criteria. He is then ready to change his aspiration levels. He may choose to change only one of the aspiration levels or he may change any number of them.

It should be noted, that due to the discrete nature of the decision variables in this problem, the criteria can only change by discrete amounts when the decision variables change. However, as the number of decision variables increases, these discrete changes will closely approximate changes in continuous variables. This is due to the fact that as the number of decision variables increases, a change in each separate decision variable contributes a smaller amount in the combined value of the criteria (since the criteria are transformed to be on the interval [0, 1]). The rate at which the solution

procedure converges to an acceptable answer is discussed in the next section.

Algorithm Convergence

Convergence, as it is used for this particular algorithm, implies that the algorithm will reach a finite solution that the decision-maker finds acceptable. This can be broken down into two different convergence considerations. The first consideration is the attainment of a finite solution. This concerns the algorithm used in the 0-1 optimization. The second consideration is the achievement of a satisfactory solution. This concerns the entire process with respect to the decision-maker and his desires.

The first consideration of convergence, that of the attainment of a finite solution is dependent upon the number of variables, the number of criteria and the number of constraints that are to be taken into consideration. The Balas algorithm was originally devised so that convergence to an optimal is guaranteed after all 2^m solutions were considered where m is the total number of variables [1]. However, this requirement has been eliminated with the concepts of fathoming and backtracking. These concepts were introduced and used to modify the Balas algorithm by Geoffrion [16]. This modified version of the Balas algorithm is used in the solution procedure presented here.

In the procedure used here, the 2^m possible solutions are only partially enumerated and convergence to an optimal solution is guaranteed for less than 2^m explicit solutions, through the use of fathoming

and backtracking. In order to consider a more complete discussion of the convergence of this procedure, Geoffrion's work should be consulted [16]. In the computer program that is used in the solution procedure (Appendix E), the number of possible solutions explicitly considered for each problem is listed in the output.

The second convergence consideration is that of convergence to an answer that is acceptable to the decision-maker. As Monarchi points out, the procedure will continue until either (a) the decision-maker finds a satisfactum or (b) he insists that he cannot find a satisfactory alternative and terminates the procedure from sheer frustration [31].

Johnsen [23], however, states that since the changes in the aspiration levels represent a learning process for the decision-maker, the existence of satisfactory solutions to decision problems is practically guaranteed. If a satisfactory solution is not found on the first iteration of the solution procedure (before the surrogate functions are formed), the rate of convergence will depend on how and when the decision-maker changes his aspiration levels. Therefore, the more the decision-maker relaxes his aspiration levels, the faster the procedure will converge to a satisfactory solution.

The next chapter will consider applications of the solution procedure with hypothetical but realistic air transportation systems.

Computer Program

The computer program that was developed to do the solution procedure described in the previous section is listed in Appendix E.

Comments are included in the program to describe its use. The program was written so that it could be used either with a corresponding data set in a batch mode or after slight modifications (described in Appendix E) in an interactive mode between the decision-maker and the computer.

The purpose for developing this program to operate both interactively and in the batch mode is that the user may not have access to a facility that allows computer-terminal interaction. If such a facility is available, however, the interactive approach is advantageous in that the decision-maker will be able to receive an immediate response to changes in his aspiration levels.

The size of problem that can be solved using this computer program is limited by the dimension size used in the program. The computer program as it is set up in Appendix E is set up to work problems with three aircraft and eight itineraries. The Balas optimization subroutines have the capability of handling 50 variables and 30 constraints. Storage for this program was done using computer core only since the size of the example problems worked presented no storage problems.

CHAPTER 6

APPLICATION OF SOLUTION PROCEDURE

This chapter illustrates the application of the solution procedure developed in the previous chapter. Before each example, a discussion is given concerning the air traffic system, the type of aircraft and the functional values used in the example.

Example I

Input Parameters

In developing a example problem to illustrate the use of the solution procedure, air transportation systems in several different geographic areas within a given sector were considered. The first area chosen was that of New York State with an air transportation system consisting of five major cities. The airports included in the system were: (a) Greater Buffalo International (Buffalo), (b) Albany County Airport (Albany), (c) Monroe County (Rochester), (d) Hancock International (Syracuse), and John F. Kennedy International (New York) with its satellite airport of Westchester County (White Plains). This area was chosen because of the diversity of airports within this region and because of the availability of information concerning the

system itself. This system allows for the inclusion of a major hub (New York City) with its satellite, its runway restrictions due to relatively short runways, (Albany) and its noise restrictions in takeoffs and landings (White Plains). The characteristics of this air system are shown in Table 11. The itineraries that will be flown in this system are also shown in Table 11.

In this problem, three different types of aircraft were considered for possible application to this system. The three different aircraft would be approximately equivalent to: (1) The Lockheed RTOL, (2) the DC-9 (i.e., CTOL1) and (3) the Boeing 727 (CTOL2). The characteristics of these aircraft are shown in Table 12.

The functions used in this study for fuel usage, delay, noise levels and demand were taken from Boeing [3], Lockheed [28] and Mitre [30] studies. It should be noted that the curve for fuel usage starts at the point where the cruise mode of the flight begins since it is assumed that all of the aircraft will require approximately the same amount of fuel for taxi-out, taxi-in, initial takeoff and landing. It should also be observed that these functions are for a specific problem and may not be applicable to all air traffic systems because of differing characteristics in geography, flight route, etc. The functions used in this particular example are:

TABLE 11

AIRPORT AND ITINERARY CHARACTERISTICS

Airport Number	Airport	Longest Available Runway	Average Number of Operations/Hour
1	New York	14,600	40
2	Buffalo	8,100	18
3	Syracuse	9,000	8
4	Rochester	8,000	9
5	Albany	6,000	10
6	White Plains	6,500	3

Itineraries[a] by airport number (distances between successive airports in parenthesis

Itinerary No.	Airports and distances
1	2-(183)-3(125)-5(131)-1
2	2-(289)-1
3	2-(60)-4(252)-1
4	4-(79)-3-(125)-5
5	3-(197)-1

[a]Based on actual commercial flights [32]

TABLE 12

CHARACTERISTICS OF AIRCRAFT

Aircraft	Type	Noise Level	Runway Required	Airspeed (miles/hr)	Capacity (Passengers)	Cruise Fuel Penalty
1	RTOL	98.0	4500	637	148	4.5%
2	CTOL1	100.0	6000	637	150	1.0%
3	CTOL2	164.8	8000	600	196	0%

Operating cost for all aircraft based on 1972 figures [40] = $700/hr

1. Fuel Usage [28]

$$f_a = 7.0\ t^3 + 26.0\ t^2 - 26.0\ t + 12.125$$

$$a_{ij}^{(1)} = f_a + f_a(P_i) \qquad i = 1,\ldots,I$$

where

f_a = base fuel usage in gallons

t = total air time in hours

P_i = fuel penalty of type i aircraft

2. Delay [3]

$$a_{ij}^{(2)} = 0.0206\ V_k^2 - 0.1181\ V_k - 0.1331$$

where

V_k = number of operations per hour at airport k

3. Noise Levels [3]

Aircraft 1 = 94.0 EPNDB

Aircraft 2 = 101.3 EPNDB

Aircraft 3 = 102.8 EPNDB

4. Demand

$$Y_{ij} = (K(Q_i)(Q_j))/(S_{ij})^2(365 \text{ days per year})$$

where

Y_{ij} = daily demand for air service between airport i and airport j,

K = a constant derived from the Mitre study [30]

Q_i = population in city i

Q_j = population in city j

S_{ij} = distance between city i and city j

Solution

These functions and the previously discussed airport and aircraft parameters were then input into a computer program that was developed to perform the optimization phase of the solution procedure. The computer program is discussed in Appendix E. The solution procedure was applied to the previously discussed problem under the supposition that the decision-maker (called DM) was concerned mainly with reducing delay in the air system and secondly with reducing fuel usage. The reduction of the noise levels was of only minor concern. Each of the steps in the solution procedure in Chapter 5 were applied, with the following results.

Step 1. The required values for the itineraries, airports and aircraft were read into the computer program. In addition to these system values, DM set his original aspiration levels at:

(1) Fuel usage A_1 = 590 gallons

(2) Delay A_2 = 780 minutes

(3) Noise levels A_3 = 2620 EPNDB

Step 2. The values of the criteria functions, operating cost, revenue, etc. were then determined by the functional relationships with the various input parameters. These values are given in Table 13. A value of 99999 is assigned to coefficient values if an aircraft is not able to meet the necessary constraints of an itinerary.

TABLE 13

DERIVED INFORMATION I

Decision Variable	Aircraft Number(i)	Itinerary Number(j)	Fuel ($a_{ij}^{(1)}$)	Delay ($a_{ij}^{(2)}$)	Noise ($a_{ij}^{(3)}$)	Operating Cost (bij)
1	1	1	232	235	686	5776
2	2	1	225	235	700	5776
3	3	1	99999	99999	99999	4221
4	1	2	134	196	588	4189
5	2	2	129	196	600	4189
6	3	2	99999	99999	99999	2849
7	1	3	197	264	784	5832
8	2	3	167	231	700	5103
9	3	3	99999	99999	99999	4469
10	1	4	15	3	196	483
11	2	4	15	3	200	483
12	3	4	99999	99999	99999	503
13	1	5	66	142	490	2753
14	2	5	64	142	500	2753
15	3	5	52	114	419	2226

Step 3. No aircraft were routed to satellite airports for this example.

Step 4. The objective functions and constraints in the decision problem were formulated using the values shown in Table 13.

Step 5. The solution vectors and objective function values for each criteria problem were obtained and are listed in Table 14.

Step 6. Comparison of the criteria values

$$D = (587.69,\ 779.33,\ 2588.80)$$

with the aspiration levels

$$\underline{A} = (590,\ 780,\ 2620)$$

shows that all aspiration levels have been met and it is not necessary to alter aspiration levels.

Step 7. Comparison of the schedules

$$\underline{X}_1 = (2,\ 5,\ 8,\ 11,\ 15)$$

$$\underline{X}_2 = (1,\ 4,\ 8,\ 10,\ 15)$$

$$\underline{X}_3 = (1,\ 4,\ 8,\ 10,\ 15)$$

shows that all of the schedules are not the same. Therefore, it is necessary to form the surrogate functions.

Step 8. The surrogate functions were then formed using the following transforms

TABLE 14

CRITERIA PROBLEMS SOLUTIONS

Fuel

$D_1 = 587.69$

where

$\underline{X} = (2, 5, 8, 11, 15)$

Aircraft 2 - Itineraries 1 2 3 4

Aircraft 3 - Itinerary 5

Delay

$D_2 = 779.33$

where

$\underline{X} = (1, 4, 8, 10, 15)$

Aircraft 1 - Itineraries 1 2 4

Aircraft 2 - Itinerary 3

Aircraft 3 - Itinerary 5

Noise

$D_3 = 2588.8$

where

$\underline{X} = (1, 4, 8, 10, 15)$

Aircraft 1 - Itineraries 1 2 4

Aircraft 2 - Itinerary 3

Aircraft 3 - Itinerary 5

$$d_1 = \frac{\Sigma_{i=1}^{3} \Sigma_{j=1}^{5} a_{ij}^{(1)} X_{ij}}{590},$$

$$d_2 = \frac{\Sigma_{i=1}^{3} \Sigma_{j=1}^{5} a_{ij}^{(2)} X_{ij}}{780},$$

$$d_3 = \frac{\Sigma_{i=1}^{3} \Sigma_{j=1}^{5} a_{ij}^{(3)} X_{ij}}{2620},$$

using these transformed values, the following surrogate problems were set up:

$$\text{Min} \quad S_0 = d_1 + d_2 + d_3 \qquad \text{(SPO)}$$

$$\text{s.t. } G(\underline{X}) \leq 0$$

$$\text{Min} \quad S_1 = d_2 + d_3 \qquad \text{(SP1)}$$

$$\text{s.t. } G(\underline{X}) \leq 0$$

$$\Sigma_{i=1}^{3} \Sigma_{j=1}^{5} a_{ij}^{(1)} X_{ij} \leq 590$$

(Similar formulations are developed for the remaining problems).

Step 9. These surrogate problems were solved and the restults from this procedure are given in Table 15.

Step 10. Since a single satisfactory solution has not been found, the results are plotted in Figure 10. (Since the criteria values are the same for SPO, SP2, and SP3, they are not plotted).

Step 11. Upon inspection of the plot in Figure 10, with the solid line representing the values of the criteria for SP1 and the dotted line representing the values of SPO, the differences

TABLE 15

SURROGATE PROBLEM SOLUTIONS

SP0

$\underline{X}$ = (2, 5, 8, 10, 15)

D_1 = 588.20

D_2 = 779.33

D_3 = 2614.80

SP1

$\underline{X}$ = (2, 5, 8, 10, 15)

D_1 = 588.20

D_2 = 779.33

D_3 = 2614,80

SP2

$\underline{X}$ = (2, 5, 8, 10, 15)

D_1 = 588.20

D_2 = 779.33

D_3 = 2614,80

SP3

$\underline{X}$ = (2, 5, 8, 11, 15)

D_1 = 587.69

D_2 = 779.33

D_3 = 2618,80

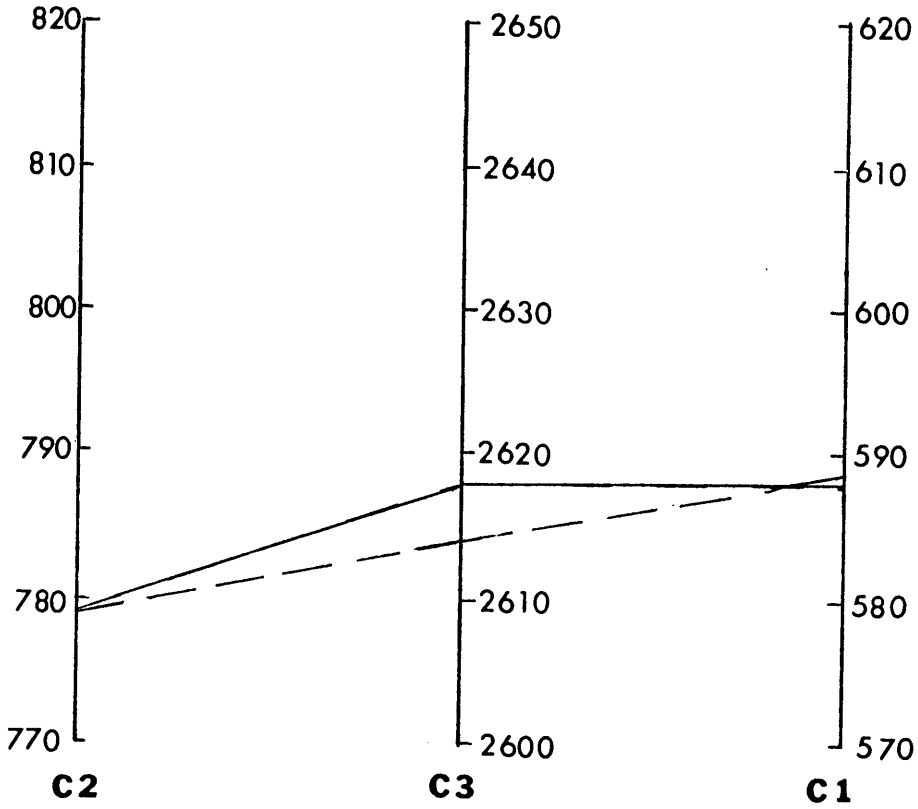


Figure 10

Example I Surrogate 3

between the criteria values are very small with a slight trade-off between fuel usage and noise levels. Therefore, since the decision-maker, DM, is more interested in conserving fuel than lowering noise levels, he is satisfied with the schedule formed by SPO (which is the same schedule formed by SP2 and SP3).

Since DM is satisfied with the schedule of

$$\underline{X} = (2, 5, 8, 10, 15)$$

with the corresponding criteria values of

$$\underline{D} = (588.2, 779.33, 2614,80)$$

the procedure stops.

Therefore, the system would use RTOL aircraft on itinerary 4, small CTOL on itineraries 1, 2, 3, and a large CTOL on Itinerary 5.

Example II

A second example problem was run using major hub areas in the northeastern section of the United States. Using the airports in New York City, Boston, Philadelphia, Washington, Pittsburgh and Cleveland, the allocation of different aircraft (RTOL and CTOL) was considered. This air system was chosen because it represented a well established short-haul air system with the possible use of satellite airports.

The CTOL used in this example is similar to the small CTOL used in the first example with the following exceptions:

(a) the noise level was increased to 101 EPNDB, and (b) the seating capacity was decreased to 148 seats. The functional values for the criteria of fuel usage, delay, and noise were the same as in Example I. The parameters used in this example for airports and itineraries is given in Table 16. However, all RTOL flights to New York City were routed to the White Plains Satellite. In this example, it was assumed that the decision-maker, again called DM, was concerned with fuel utilization as his primary concern while delay and noise levels were secondary.

The same procedure was used for this example as the previous example (the steps followed are not numbered to abbreviate the presentation) with the original aspiration levels set at

$$\underline{A} = (3150, 2400, 4450)$$

The resulting values of the criteria functions, operating cost, etc. are listed in Table 17. The solution vectors and objective function values for each criteria are listed in Table 18.

Since the aspiration levels had been met with the criteria function values, and since the allocations were dissimilar for each of the criteria, it was necessary to form surrogate functions.

The surrogate functions were formed using the following transforms

TABLE 16

AIRPORT AND ITINERARY CHARACTERISTICS EXAMPLE II

Airport Number	Airport	Runway	Operations/ Hour
1	New York	14600	40
2	Boston	10100	35
3	Philadelphia	10500	33
4	Washington, D.C.	6900	32
5	Pittsburgh	10500	35
6	Cleveland	9000	31
7	White Plains (New York Satellite)	6500	3

Itinerary Number	Airports and Distances
1	4-(133)-3-(84)-1-(191)-2
2	6-(104)-5-(194)-4
3	5-(274)-3-(84)-1
4	6-(279)-4
5	3-(274)-2
6	2-(274)-3-(274)-5-(107)-6

TABLE 17

COMPUTER DERIVED INFORMATION II

X_{ij}	i	j	$a_{ij}^{(1)}$	$a_{ij}^{(2)}$	$a_{ij}^{(3)}$	(bij)
1	1	1	1861	1188	1372	21999
2	2	1	1620	1104	1300	20214
3	1	2	353	380	686	7360
4	2	2	330	380	700	7276
5	1	3	1168	947	1372	18108
6	2	3	1015	880	1300	16627
7	1	4	50	67	200	1574
8	2	4	46	67	196	1551
9	1	5	29	39	98	836
10	2	5	27	39	100	825
11	1	6	1234	536	686	12405
12	2	6	1146	536	700	12221

TABLE 18

EXAMPLE II ORIGINAL SOLUTION

Fuel

$D_1 = 3129.5$

$\underline{X} = (1, 4, 5, 8, 10, 12)$

Delay

$D_2 = 2369.3$

$\underline{X} = (1, 4, 5, 7, 9, 12)$

Noise

$D_3 = 4410.0$

$\underline{X} = (1, 3, 5, 7, 9, 11)$

$$d_1 = \frac{\Sigma_{i=1}^{2} \Sigma_{j=1}^{6} a_{ij}^{(1)} X_{ij}}{3150}$$

(with d_2 and d_3 being formed in a similar manner)

The surrogate problems were set up in the same manner as in the previous example. The results of the solution of these problems is given in Table 19. Since a single satisfactory solution has not been found, the results are plotted in Figures 11A and 11B.

By considering Figure 11B, DM decides that it is possible to tighten his fuel aspiration level to 3135 if he loosens his noise aspiration level to 4460. The result of making this change, reformulating the surrogate problems and solving them is shown in Table 20. However, since the schedules in the second cycle (a cycle begins when the surrogate problems are formed) of surrogate formation are still not the same for all of the surrogate functions, the results are plotted in Figure 12.

Considering Figure 12, DM observes that it is possible to reduce his aspiration level for fuel to 3130 and still keep the noise level at 4460. If this change is made in the aspiration levels, the results of the third cycle are given in Table 21. In this cycle, the schedules are only different in SP3 and as it can be seen in Figure 13, the difference is very small. In fact, when DM increases his noise aspiration level by 1 to 4461, the procedure converges to a satisfactory solution of

$$\underline{X} = (1, 4, 5, 8, 10, 12)$$

TABLE 19

EXAMPLE II--SURROGATES CYCLE 1

SP0

$D_1 = 3129.5$

$D_2 = 2369.3$

$D_3 = 4661.0$

$\underline{X} = (1, 4, 5, 8, 10, 12)$

SP1

$D_1 = 3136.6$

$D_2 = 2369.3$

$D_3 = 4452.0$

$\underline{X} = (1, 4, 5, 7, 9, 12)$

SP2

$D_1 = 3129.5$

$D_2 = 2369.3$

$D_3 = 4461.0$

$\underline{X} = (1, 4, 5, 8, 10, 12)$

SP3

$D_1 = 3159.3$

$D_2 = 2369.3$

$D_3 = 4440.0$

$\underline{X} = (1, 3, 5, 8, 10, 12)$

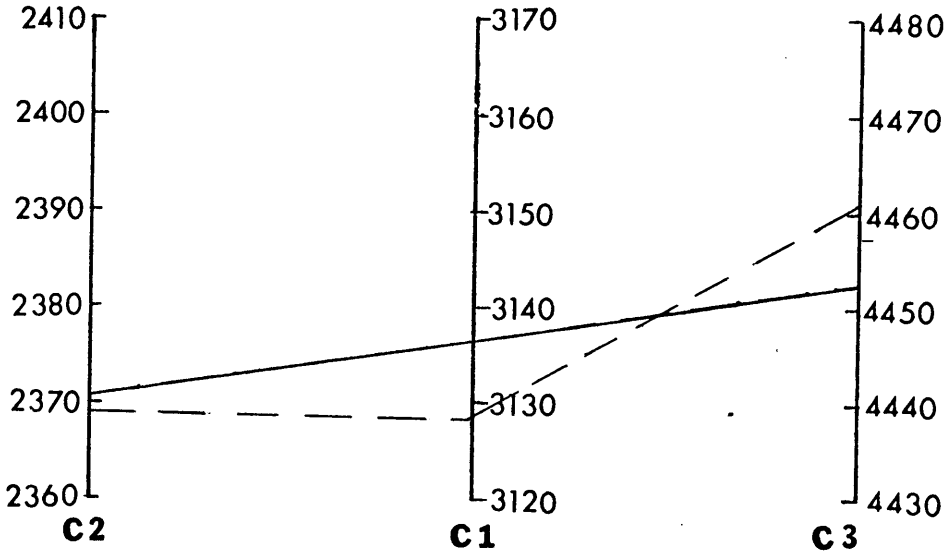


Figure 11a **SP1 - cycle 1**

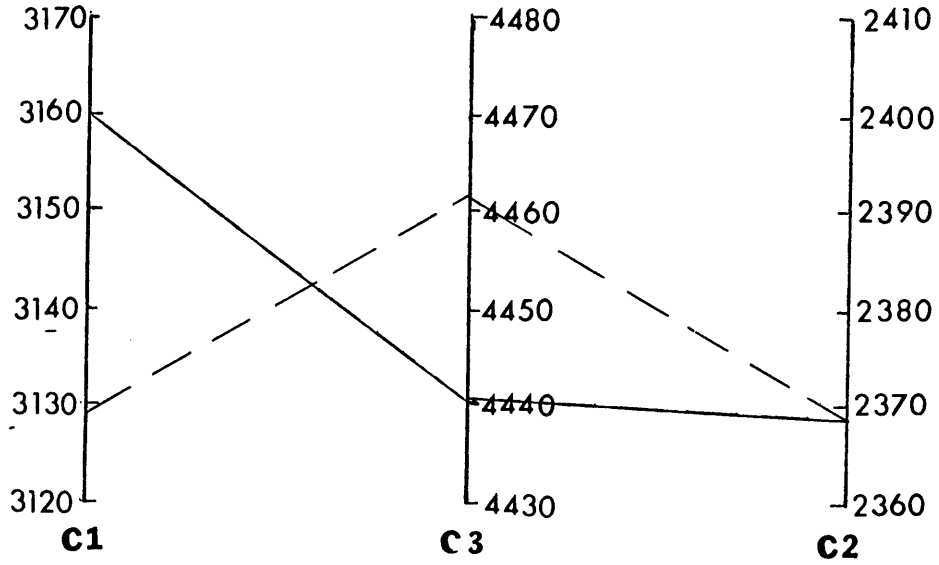


Figure 11b **SP3 – cycle 1**

TABLE 20

EXAMPLE II--SURROGATES CYCLE 2

SP0

$D_1 = 3129.5$

$D_2 = 2369.3$

$D_3 = 4461.0$

$\underline{X} = (1, 4, 5, 8, 10, 12)$

SP1

$D_1 = 3136.6$

$D_2 = 2369.3$

$D_3 = 4452.0$

$\underline{X} = (1, 4, 5, 7, 9, 12)$

SP2

$D_1 = 3129.5$

$D_2 = 2369.3$

$D_3 = 4461.0$

$\underline{X} = (1, 4, 5, 8, 10, 12)$

SP3

$D_1 = 3132.0$

$D_2 = 2369.3$

$D_3 = 4458.0$

$\underline{X} = (1, 4, 5, 8, 9, 12)$

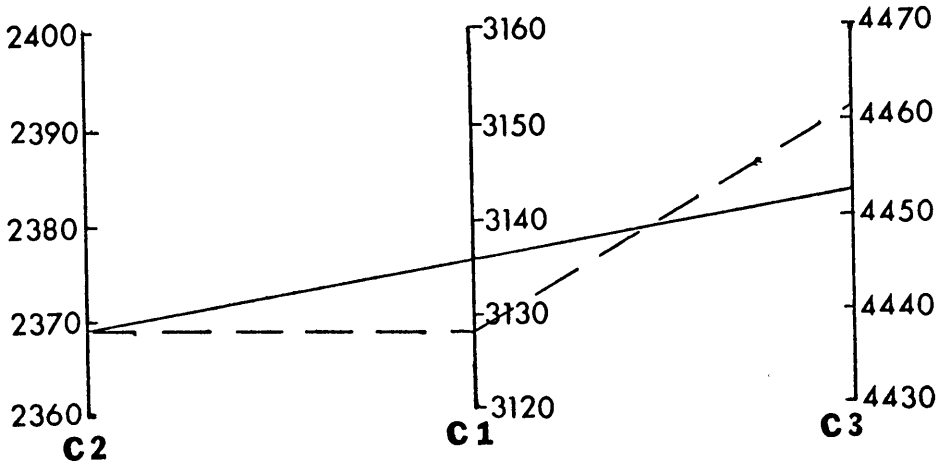


Figure 12a SP1–Cycle 2

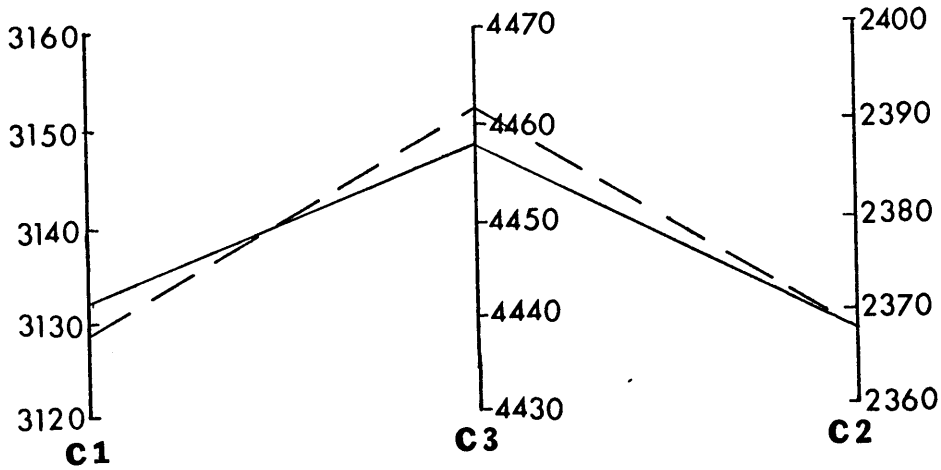


Figure 12b SP3–Cycle 2

TABLE 21

EXAMPLE II--SURROGATES CYCLE 3

SP0

D_1 = 3129.5

D_2 = 2369.3

D_3 = 4461.0

$\underline{X}$ = (1, 4, 5, 8, 10, 12)

SP1

D_1 = 3129.5

D_2 = 2369.3

D_3 = 4461.0

$\underline{X}$ = (1, 4, 5, 8, 10, 12)

SP2

D_1 = 3129.5

D_2 = 2369.3

D_3 = 4461.0

$\underline{X}$ = (1, 4, 5, 8, 10, 12)

SP3

D_1 = 3132.0

D_2 = 2369.3

D_3 = 4458.0

$\underline{X}$ = (1, 4, 5, 8, 9, 12)

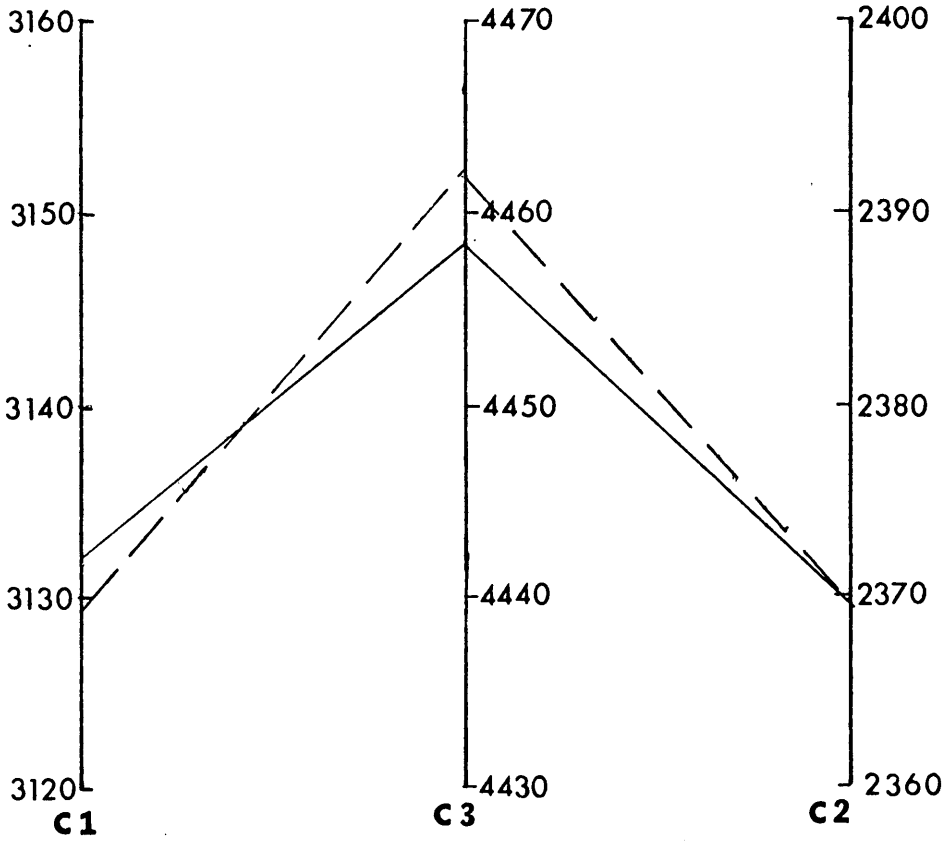


Figure 13

Example II Cycle 3

This schedule means that RTOL would be used on itineraries 1 and 3 while the CTOL would be used on itineraries 2, 4, 5 and 6. This indicates that the satisfactory solution is found when the RTOL is used, it is only used to fly to the satellite airport while the CTOL is used to fly to the other airports.

CHAPTER 7

RESULTS, SUMMARY AND RECOMMENDATIONS

There were three primary objectives of this study. The first was to determine the feasibility of introducing the RTOL aircraft into the national aviation system. The second was to formulate a decision problem model which accurately describes the RTOL utilization problem. The third purpose was to develop a decision-making procedure that could be used as an aid in resolving the question of determining the feasibility of the utilization of a certain configuration of aircraft (RTOL) in a specified aviation system.

The first purpose was only partially achieved. The study did show through the examples presented in Chapter 6 that RTOL has the potential to be utilized in situations which include: (2) the anticipated use of satellite airports, (b) the need to meet the requirements of reduced noise levels and reduced runway lengths, and (c) short-haul itineraries consisting of several short flights. However, it should be noted that a synthetic decision-maker was used in making the decisions involved in this process. The scope of this study was also limited to a single small area of the United States because of the complexity

involved with larger systems. Therefore, although the feasibility of establishing the RTOL aircraft as a successor to the CTOL aircraft in the commercial aviation system was not completely demonstrated, the possible use of RTOL in some situations was seen as being worthy of additional consideration in further studies.

The second purpose, that of formulating a decision problem to describe the problem of RTOL utilization, was completed as described in Chapter 4. Although only a small percentage of those potential decision-makers who were sent the questionnaire shown in Appendix A responded, the responses that were received were of great value in developing the decision model. Since the model was largely dependent upon these responses, a greater number of potential decision-makers may have caused the development of a somewhat different model.

The model itself could be expanded to include other criteria such as air pollution and level of service, and other constraints such as safety and aircraft maintainability. However, the expansion of the model in these cases would be dependent upon the situation in which it was used. The model itself was developed so that it would adequately model the situation and still be flexible enough for use by several different types of decision-makers. Therefore, further work on the model that was presented may be required to satisfy different types of decision-makers.

The third purpose, that of developing a decision-making procedure, was completed as described in Chapter 5. Although the procedure was only tried for a small number of synthetic examples with a synthetic decision-maker, it did work with reasonable efficiency for the examples that were attempted. In order to determine the true worth of the procedure, studies should be done using a real life situation with an actual decision-maker looking at a large (greater than 25 itineraries) system.

Recommended Research

Extensions of the work done in this thesis could be made in two areas, (1) the use of RTOL aircraft, and (2) the extension of multicriterion decision-making in aircraft assignment. The extensions in the use of RTOL would include:

1. Determining the desirability of RTOL aircraft with respect to passenger opinion.

2. Determining the potential market for the RTOL aircraft (for example, the development of an air system connecting cities presently not being served by commercial air service).

3. Determining the impact of RTOL use at satellite airports on the surrounding community.

The extensions in the use of multicriterion decision-making in aircraft assignment would be:

1. Extending the present decision model to include additional criteria and constraints, such as air pollution.

2. Determining the feasibility of aircraft such as STOL and VTOL in a short-haul system.

3. Combining the present procedure with a forecasting technique to determine the long range effects of RTOL utilization, by changing demand and cost levels over time.

4. Combining the present procedure with a computer simulation which would generate data to be used as input in the solution procedure.

The possible studies that were mentioned dealing with RTOL are dependent upon the continued possibility of the manufacture of RTOL aircraft. Since no RTOL have been used in commercial aviation systems to this date, future research should be geared toward the determination of the impact that RTOL usage would have on the national aviation system.

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APPENDICES

APPENDIX A

Decision-Maker's Questionnaire

This appendix includes a survey sent to the airlines listed below:

Alleghney	Northwest
American	Pam American
Braniff	Piedmont
Continental	Southern
Delta	Transworld
Eastern	United

This airlines responding to the survey included Eastern, American and Continental. A summary of the responses received is shown in Chapter 3.

The survey itself consists of a two page information form (Figure A1), a page describing the RTOL aircraft under consideration by Boeing (Figure A2) and an accompanying explanatory letter (Figure A3).

RTOL INFORMATION

Use of RTOL Factors to be considered:

1.
2.
3.
4.
5.
6.
7.
Suggestions and Recommendations:

Number of RTOL Factors to be considered:

a) Limited budget	b) Unlimited budget
1.	1.
2.	2.
3.	3.
4.	4.
5.	5.
6.	6.
7.	7.

Suggestions and Recommendations:

Routes to be flown by RTOL Factors to be considered:

1.
2.
3.
4.
5.
6.
7.
Suggestions and Recommendations:

Please include other problems and factors that you believe will present themselves in considering the use of RTOL for commercial air services:

Would you like to be informed of the results of this research concerning RTOL?

Date:_____ Signature_____

Figure A1 Information Form

RTOL CHARACTERISTICS*

The RTOL aircraft is presently under development by the Boeing Commercial Airplane Company. It is designed to provide a cruising speed of .90 mach, have a take-off gross weight of 330,000 pounds, an initial cruise altitude capability of over 40,000 feet, and approach speed of 120 knots, a range of 3,000 nautical miles. All of these factors are comparable to conventional take-off and landing aircraft.

The major differences between RTOL and conventional aircraft are: 1) RTOL can land on a 4,000 to 5,000 foot runway, while conventional aircraft generally require over 8,000 feet; 2) RTOL is capable of producing a noise level that is 10.3 EPNdB (effective perceived noise, in decibels) below Federal Air Regulation part 36; 3) RTOL will be capable of a 9.5% fuel saving over conventional aircraft on a 1,000 nautical mile trip; and 4) an anticipated reduction of CO, HC and NO_x emissions. The RTOL that is presently being considered will contain seats for 196 total passengers.

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*Taken from Advanced Subsonic Long-Haul Transport Terminal Area Compatibility Study, Vol. I, Boeing Commercial Airplane Company, under Contract NASI-12018.

Figure A2 RTOL Characteristic Discussion

Dear Sir:

We are presently involved in research concerning reduced take-off and landing (RTOL) aircraft, and the application of RTOL to commercial air service. We are working under a grant provided by the National Aeronautics and Space Administration (NASA Grant NGR-47-004-090) and have been informed by NASA that the introduction of RTOL into the National Aviation System will occur sometime in the near future. We are seeking information concerning the factors that must be considered before a decision to use RTOL can be made.

As examples of the kinds of problems for which we are seeking information, consider the following. Suppose you have been given the assignment of determining whether or not to use reduced take-off and landing aircraft in place of conventional take-off and landing aircraft in your commercial services. What variables must be considered in making your decision? If you decide to consider using RTOL, what factors must be considered in determining the number of aircraft to use, assuming (a) a very limited budget and (b) an almost unlimited budget? And finally, after the number of aircraft has been determined, what decision variables must be considered in determining the routes that will be served by RTOL?

In addition to the decision problems we have thus far mentioned, many more will have to be looked at. Would you please include other problems and decision factors that you believe will present themselves when considering the use of RTOL for commercial air service.

The following pages have been included for your convenience. They contain a form that can be filled out quite easily with information we are seeking and a sheet listing RTOL's proposed characteristics. We hope that you will take the time necessary to answer this letter as the results of our research may be of great value to the air transportation field.

Thank you very much for your cooperation.

Figure A3 Accompanying Letter

APPENDIX B

Aircraft Categories and Examples

The purpose of this appendix is to provide a description of the various aircraft classes, their characteristics and examples. Figure B1 is used to supply the characteristics and classes of RTOL and other aircraft described in the thesis.

Class	Description	Examples
A	All jet aircraft normally requiring runway lengths in excess of 6000 feet for takeoff and/or landing.	B707 and 720 series DC-8 series Convair 880 BAC VC 10
B	1) Piston and turbo prop aircraft having a normal loaded weight of greater than 36,000 lbs. 2) Jet aircraft not in class A but having a normal load weight of greater than 25,000 lbs.	RTOL B 727 Lockheed Jetstar BAC Vanguard Vickers Viscount DC-6 and DC-7 series Convair 240
C	1) Piston and turbo prop aircraft with a normal loaded weight of greater than 8000 lbs, but less than 36,000 lbs. 2) Jet aircraft having a normal loaded weight of greater than 8000 lbs but less than 25,000 lbs.	Fairchild F-27 Douglas B-26 DC-3 Beech 18
D	All light twin-engine piston/turbo prop aircraft with less than 8000 lbs normal loaded weight and some high performance single engine light a/c.	Beech 500 Twin Bonanza Beech Bonanza DeHavilland Dove Cessna 310
E	All single engine light aircraft other than those in class D.	Piper Cub Cessna 210 series DeHavilland Beaver

Figure B1 Aircraft Classes and Examples

APPENDIX C

Airport Codes

The purpose of this appendix is to provide the airport names for the codes used in this thesis and to identify the hub areas in the United States. Table C1 supplies this information.

TABLE C1

CODES FOR AIRPORTS AND AIR TRANSPORTATION HUBS

Large Hubs

ATL	Atlanta
BOS	Boston
CLE	Cleveland
CHI	Chicago Metro. Area
MDW	Midway Airport
ORD	O'Hare Airport
DAL/FTW	Dallas/Fort Worth Metro. Area
DEN	Denver
DTT	Detroit
HOU/IAH	Houston
MKC/MCI	Kansas City
LAS	Las Vegas
LAX Hub	Los Angeles Metro. Area
LAX	Los Angeles Int. Airport
BUR	Hollywood/Burbank
LGB	Long Beach Airport
MIA/FLL	Miami/Fort Lauderdale
MIA	Miami International
FLL	Fort Lauderdale Intl.
MSP	Minneapolis/St. Paul
MSY	New Orleans
NYC	New York Metro. Area
JFK	J.F. Kennedy Int. Airport
LGA	La Guardia Airport
EWR	Newark Airport
PHL	Philadelphia
PIT	Pittsburgh
STL	St. Louis
SFO HUB	San Francisco Met. Area
SFO	San Fran. Int. Airport
SJC	San Jose Airport
OAK	Oakland Int. Airport
SEA/BFI	Seattle/Tacoma Met. Area
SEA	Seattle/Tacoma Intl.
BFI	Boeing Field Airport
WAS/BAL	Washington/Baltimore Metropolitan Area
DCA	Wash. National Airport
IAD	Dulles Int. Airport
BAL	Baltimore Friendship

Medium Hubs

ALB	Albany
ABQ	Alburquerque
BMH	Birmingham
BUF	Buffalo/Niagara Falls
CLT	Charlotte
CVG	Cincinnati/Covington
CMH	Columbus
DAY	Dayton
DSM	Des Moines
ELP	El Paso
BDL	Hartford/Springfield Metropolitan Area
IND	Indianapolis
JAX	Jacksonville
SDF	Louisville
MEM	Memphis
MKE	Milwaukee
BNA	Nashville
ORF	Norfolk
OKC	Oklahoma City
OMA	Omaha
ORL/MCO	Orlando Metro. Area
PHX	Phoenix
PDX	Portland
PVD	Providence
RDU	Raleigh/Durham
RNO	Reno
ROC	Rochester
SAT	San Antonio
SMF	Sacramento
SLC	Salt Lake City
SAN	San Diego
GEG	Spokane
SYR	Syracuse
TPA	Tampa
TUL	Tulsa
TUS	Tuscon

Small Hubs

BOI	Boise
LBB	Lubbock
MAF	Midland/Odessa
SAV	Savannah
TLH	Tallahassee

APPENDIX D

The Monarchi Procedure

The purpose of this appendix is to present the weighing procedure used to develop surrogate functions in the solution method presented by Monarchi [31].

Before the Monarchi procedure is discussed, the definition of several variables should be made.

Let

T = the number of criteria functions

AL_i = the aspiration level of the ith criteria

AL = the set of aspiration levels, $(AL_1,\ldots,AL_t)$

C_i = the ith criterion function

C = the set of criteria functions, $(C_1,\ldots,C_t)$

Z_i = the value of the ith criterion evaluated at the solution vector,

$\underline{Z}$ = the set of values of the criteria functions, $(Z_1,\ldots,Z_t)$

h_i = the ith constraint

$\underline{h}$ = the set of all constraints

y_i = the transformed ith criterion function, (0,1)

$\underline{y}$ = the set of transformed criteria functions, $(y_i,\ldots,y_t)$

A_i = the transformed ith criterion function, $A_i \varepsilon (0,1)$

A = the set of transformed criteria functions, $(A,\ldots,A_t)$

$\underline{X}$ = the set of decision variables

The Monarchi procedure begins by defining a dimensionless indicator of achievement, d_i, which, for the minimization problem, is equal to

$$Y_i/A_i \ .$$

This indicator is used to form a surrogate objective function which is defined as

$$S = \Sigma_{t=1}^{T} d_i$$

The search for a satisfactum begins by solving T+1 optimization problems using the Griffith-Stewart approximation procedure. The first problem is

$$\text{Min } S_1 = \Sigma_{t=1}^{T} d_t \qquad \text{(P1)}$$

$$\text{S.t.} \quad \underline{h} \geq 0$$

T other problems are developed by removing d_k, $k=1,2,\ldots,T$, from the surrogate objective function and adding the corresponding criterion (criterion K) as a constraint. Specifically, the kth problem is

$$\underset{\underline{X}}{\text{Min}} \quad S_k = \Sigma_{\substack{t=1 \\ t\neq k}}^{T} d_t \qquad \text{(P2)}$$

$$\text{S.t.} \quad \underline{h} \geq 0$$

$$C_k \leq AL_k$$

This procedure develops T+1 feasible alternatives (sets of criteria function values) for the decision-maker to consider. However, if any of the original constraints or those criteria added as constraints is violated, the decision-maker will have less than T+1 alternatives.

In order to illustrate this procedure, consider a problem with three criteria. Let the aspiration levels

$$\underline{AL} = (75, 50, 65)$$

for three criterion functions. If the surrogate function s is minimized and the following results are obtained

$$\underline{Z}_1 = (50, 34, 39)$$

Then non of the decision-maker's aspiration levels have been attained. Therefore, the constrain $C \leq 75$ is added to the constraint set and the surrogate objective function is changed to

$$s_2 = d_2 + d_3$$

This surrogate function is optimized and the process is repeated using the other criterion functions. The solution of these surrogate problems provides the decision-maker would have three additional feasible alternatives to consider in addition to the alternative found with the first surrogate

$$\underline{Z}_2 = (75, 25, 30)$$

$$\underline{Z}_3 = (65, 50, 35)$$

$$\underline{Z}_4 = (60, 45, 65)$$

If any of these alternatives is satisfactory to the decision-maker,

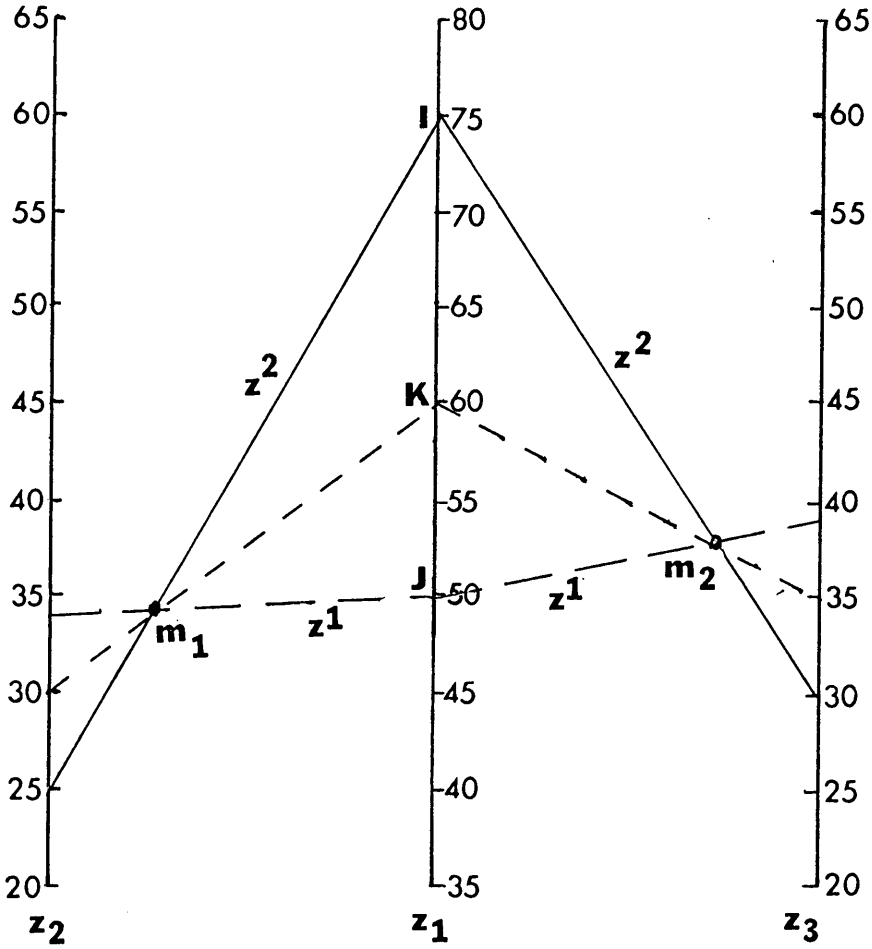

Figure D1

Criterion 1 Comparisons

then the process stops. If none of the solutions is satisfactory, the evaluation phase of the process begins.

Once the optimization of the surrogate problems has provided information to the decision-maker concerning the effects of having each of the criterion used as constraints, it is necessary for the decision-maker to compare these effects. For example, the comparisons with respect to criterion 1 between the different objective function values are made visually by the use of a graph in which the criteria levels of P1 and P2 are plotted. This graph is shown in Figure D1. Assuming the Z_i's to be linearly related, the change in Z_2 over the change in Z_1 and the change in Z_3 over the change in Z_1 are constants. To determine the effect of a new aspiration level $\hat{AL}_1$ on the other criteria, the decision-maker would have to solve the equations (the superscripts in the Z's represent the surrogate problem number, for example, Z_2^1 represents the Z values of the second criteria in the first surrogate problem).

$$\frac{\Delta\hat{Z}_2}{\hat{AL}_1 - Z_1^1} = \frac{Z_2^2 - Z_2^1}{Z_1^2 - Z_1^1} \qquad (1)$$

and

$$\frac{\Delta\hat{Z}_3}{\hat{AL}_1 - Z_1^1} = \frac{Z_3^2 - Z_3^1}{Z_1^2 - Z_1^1} \qquad (2)$$

for $\hat{AL}_1$. However, Monarchi shows that lines passing through the points M_1 and M_2 solve the equations (1) and (2) respectively, graphically. Therefore, by the use of a straight edge, the decision-maker can consider the effects of any AL between points i and j on the other criteria. This has been done for an aspiration level of 60 (point K) in Figure D1. As can be seen in this figure, the resulting values are these values are found by putting a straight line from 60 through M_1 and M_2 respectively.

$$Z_2 = 30$$

$$Z_3 = 35$$

Therefore, using this process and similar comparisons with criteria 2 and 3, by using the results of the remaining surrogate functions, the decision-maker is able to estimate the interactions among the the criteria as his aspiration levels change.

Once the decision-maker has considered the information provided by the first interation, he adjusts his aspiration levels. This information is used to reformulate the surrogate objective function by changing the d_i's, and the cycle of optimization and evaluation is repeated until a satisfactory solution is found.

APPENDIX E

Computer Program Listing

This appendix supplies the listing of the computer program used to solve the example problems in Chapter 6. The usage requirements of the program are listed in the program.

In order to change this program from a batch mode to an interactive mode, the following changes are required in the MAIN program:

```
        Replace
        READ (5,33) NIEX
        DO 3Ø NW=1, NIEX
        CGREEN = 1
        CALL BALAS
3Ø      CONTINUE
31      STOP

        With,
5Ø      READ (5,33) NIEX
        IF (NIEX.EQ.Ø) GO TO 31
        READ (5,34) (ALEVEL(I), I=1,NG)
        DO 3Ø NW=1, NIEX
        LGREEN=1
        CALL BALAS
3Ø      CONTINUE
        GO TO 5Ø
31      STOP
```

```
C     MAIN PROGRAM                                                      A   1
C     THIS PROGRAM IS DESIGNED TO EVALUATE A MULTICRITERIA OPTIMIZATION  A   2
C     PROBLEM DEALING WITH THE ALLOCATION OF VARIOUS TYPES OF AIRCRAFT T A   3
C     PRESPECIFIED ITINERARIES.  THE PROGRAM ITSELF CAN BE BROKEN DOWN  A   4
C     INTO FOUR MAJOR SECTIONS:                                         A   5
C     (1) MAIN PROGRAM - THE PURPOSE OF THIS SECTION IS TO READ DATA,   A   6
C     DETERMINE COEFFICIENTS FOR THE MATHEMATICAL PROGRAMMING PROBLEM,  A   7
C     CALL SUBROUTINES IN SECTIONS (2) AND (3), AND PRINT PERTINENT     A   8
C     INFORMATION.                                                      A   9
C     (2) CALCULATION SUBROUTINES - CONSISTING OF EQUATE AND HUB, THIS  A  10
C     SECTION CALCULATES VALUES FOR THE OBJECTIVE FUNCTIONS AND ROUTES  A  11
C     TRAFFIC TO SATELLITE AIRPORTS IF THE DELAY EXCEEDS PREDETERMINED  A  12
C     LEVELS.                                                           A  13
C     (3) SUBROUTINE BALAS - THE PURPOSE OF BALAS IS TO ORGANIZE THE ZER A  14
C     -ONE MATHEMATICAL PROGRAMMING PROBLEM INTO THE APPROPRIATE FORMAT. A  15
C     (4) ZERO-ONE ALGORITHM SUBROUTINES - CONSISTING OF SUBROUTINES    A  16
C     STEP0 TO STEP9,PRNT AND ORDER, THIS SECTION SOLVES THE PROBLEM    A  17
C     BASED ON THE BALAS ZERO-ONE ALGORITHM AND PRINTS APPROPRIATE      A  18
C     RESULTS.                                                          A  19
C     PERTINENT VARIABLES ARE IDENTIFIED BEFORE EACH SECTION AND COM-   A  20
C     MENTS DESCRIBING THE MECHANICS OF THE PROGRAM                     A  21
C     MENTS DESCRIBING THE MECHANICS OF THE PROGRAM ARE GIVEN IN        A  22
C     APPROPRIATE LOCATIONS.                                            A  23
C                                                                       A  24
      COMMON /UCOM3/ ASAVE(10,50),CSAVE(10),NNA,ALEVEL(10),AM,CA(50)    A  25
      COMMON /SCH/ IF,JF,KF,IIF,MZ,NC,ND                                A  26
      COMMON /ITER/ IAL,IZZ                                             A  27
      COMMON /UCOM2/ NG,LR,LGREEN,LEN,IAB,IDA                           A  28
      COMMON /RUN/ OPS(10,3),ITIN(10,3),DIST(10,8),RUNW(10,8),ACRU(3),AC A  29
     1SP(3),ACCAP(3),SUMDIS(10),SDEL(10,8),TIME(10,8),DELAY(10,8),FUEL(1 A  30
     2C,3),NOISE(10,3),DEMAND(10,8),DMAX(10),FLIT(10,5),OPCOST(10,8),II, A  31
     3J,K,I,OCOST,DEM1,DEM2                                             A  32
```

```
      COMMON /UCCM4/ ANGI(5),DCON,PUR(5),PMAX(10),PURCH(10,8)          A  33
      COMMON /UCCM5/ TPMI(5),REV1(10,3),REV2(10,3)                     A  34
      COMMON /FFF/ FREN(5),OCST(5)                                     A  35
      REAL ITIN,F,N,NOISE                                              A  36
      DIMENSION IFLY(10,5), SUM4(20), REST(10,5), IY(10,5)             A  37
C     NG = NUMBER OF CRITERIA                                          A  38
C     IF V TOTAL NUMBER OF AIRPORTS                                    A  39
C     JF = NUMBER OF AIRPORTS IN THE ITINERARY WITH MOST STOPS + 1     A  40
C     KF = TOTAL NUMBER OF AIRCRAFT TYPES                              A  41
C     IIF = TOTAL NUMBER OF ITINERARIES                                A  42
C     ND = NUMBER OF OPERATIONS PER HOUR AT AN AIRPORT AT WHICH THE    A  43
C     SHORTEST TAKEOFF AND LANDING AIRCRAFT IS DIVERTED TO A SATELLITE A  44
C     AIRPORT.                                                         A  45
C     NC = NUMBER OF CONSTRAINT TYPES (E.G. OPERATING COST)            A  46
      READ (5,39) NG,IF,JF,KF,IIF,ND,NC                                A  47
C     OCST(K) = OPERATING COST PER HOUR FOR TYPE K AIRCRAFT            A  48
      READ (5,40) (OCST(K),K=1,KF)                                     A  49
      CMAX=99999.                                                      A  50
      JAF=IF-1                                                         A  51
      JM=JF-1                                                          A  52
      JN=JF-2                                                          A  53
      DO 1 I=1,IIF                                                     A  54
C     ITIN(I,J) = ITINERARIES,                                         A  55
C             I=1,2 ... IIF                                            A  56
C             J=1 => ITINERARY NUMBER                                  A  57
C             J=2,3 ... => AIRPORTS IN ITINERARY                       A  58
      READ (5,33) (ITIN(I,J),J=1,JF)                                   A  59
C     DIST(I,J) = DISTANCES,                                           A  60
C             I=1,2 ... IIF                                            A  61
C             J=1 => ITINERARY NUMBER                                  A  62
C             J=2,3 ... JF-1 => DISTANCES                              A  63
      READ (5,36) (DIST(I,J),J=1,JM)                                   A  64
```

```
1     CONTINUE                                                          A  65
      DO 2 I=1,IF                                                       A  66
C     OPS(I,J) = OPERATIONS,                                            A  67
C              I=1,2 ... IF                                             A  68
C              J=1 => AIRPORT NUMBER                                    A  69
C               =2 => AVERAGE OPERATIONS PER HOUR                       A  70
C               =3 => ACCEPTABLE NOISE LEVEL IN EPNDB                   A  71
      READ (5,35) (OPS(I,J),J=1,3)                                      A  72
C     RUNWAY(I,J) = RUNWAY RESTRICTIONS,                                A  73
C             I=1,2 ... IIF                                             A  74
C             J=1 => AIRPORT NUMBER                                     A  75
C             J=2 => RUNWAY LENGTH                                      A  76
C             J=3 => RUNWAY NOISE RESTRICTIONS                          A  77
      READ (5,34) (RUNW(I,J),J=1,3)                                     A  78
2     CONTINUE                                                          A  79
C     ACRW(K) = RUNWAY RESTRICTION FOR TYPE K AIRCRAFT                  A  80
C     ACSP(K) = AIRCRAFT K AIRSPEED (MILES/HR)                          A  81
C     ACCAP(K) = AIRCRAFT K PASSENGER CAPACITY                          A  82
      READ (5,37) (ACRW(K),ACSP(K),ACCAP(K),K=1,KF)                     A  83
C     FPEN(K) = FUEL PENALTY EXPERIENCED BY TYPE K AIRCRAFT AS A        A  84
C     PERCENTAGE OF A BASE FIGURE  (USUALLY THE MOST FUEL EFFICIENT     A  85
C     AIRCRAFT)                                                         A  86
      READ (5,32) (FPEN(K),K=1,KF)                                      A  87
      IDA=0                                                             A  88
C     CALCULATE ITINERARY DISTANCES                                     A  89
      DO 11 II=1,IIF                                                    A  90
      SUMDIS(II)=0.0                                                    A  91
      DO 7 J=2,JM                                                       A  92
      SUMDIS(II)=SUMDIS(II)+DIST(II,J)                                  A  93
      M=ITIN(II,J)                                                      A  94
      N=ITIN(II,J+1)                                                    A  95
C     CALCULATE INTERAIRPORT DEMAND                                     A  96
```

```
      DO 5 L=1,IF                                                       A  97
      IF (M.NE.OPS(L,1)) GO TO 3                                        A  98
      DEM2=OPS(L,3)                                                     A  99
      GO TO 4                                                           A 100
3     CONTINUE                                                          A 101
4     DO 5 L=1,IF                                                       A 102
      IF (N.NE.OPS(L,1)) GO TO 5                                        A 103
      DEM1=OPS(L,3)                                                     A 104
      GO TO 6                                                           A 105
5     CONTINUE                                                          A 106
6     CALL EQUAT (4)                                                    A 107
7     CONTINUE                                                          A 108
      TEMP=0.0                                                          A 109
      JN=JAF-1                                                          A 110
C     DETERMINE MAXIMUM INTERAIRPORT DEMAND IN EACH ITINERARY FOR       A 111
C     USE IN DETERMINING FLEET SIZE                                     A 112
      DO 9 JA=2,JN                                                      A 113
      DMAX(II)=AMAX1(DEMAND(II,JA),DEMAND(II,JA+1))                     A 114
      IF (DMAX(II).LE.TEMP) GO TO 8                                     A 115
      TEMP=DMAX(II)                                                     A 116
8     IF ((JA+1).EQ.JN) GO TO 10                                        A 117
9     CONTINUE                                                          A 118
10    DMAX(II)=TEMP                                                     A 119
11    CONTINUE                                                          A 120
C     CHECK NOISE AND RUNWAY CONSTRAINTS, RECORD VIOLATIONS WITH        A 121
C     ICCA AND ICCB                                                     A 122
      DO 14 K=1,KF                                                      A 123
      ICCA=0                                                            A 124
      ICCB=0                                                            A 125
      DO 13 I=1,IF                                                      A 126
      REST(I,K)=0.0                                                     A 127
      IF (RUNW(I,2).LT.ACRW(K)) REST(I,K)=1.0                           A 128
```

```
      IF (RUNW(I,2).LT.ACRW(K)) ICCA=1                                  A 129
      IF (RUNW(I,3).LT.ANDI(K)) REST(I,K)=1.0                           A 130
      IF (RUNW(I,3).LT.ANDI(K)) ICCB=1                                  A 131
      IF (OPS(I,2).GT.NO) GO TO 12                                      A 132
      CALL EQUAT (1)                                                    A 133
      GO TO 13                                                          A 134
12    OPSAV=OPS(I,2)                                                    A 135
      CALL HUB                                                          A 136
      OPS(I,2)=OPSAV                                                    A 137
13    CONTINUE                                                          A 138
      IF (ICCA.EQ.1) WRITE (6,44) K                                     A 139
      IF (ICCB.EQ.1) WRITE (6,45) K                                     A 140
14    CONTINUE                                                          A 141
      DO 17 II=1,IIF                                                    A 142
      DO 16 K=1,KF                                                      A 143
      IY(II,K)=0                                                        A 144
C     CALCULATE AIRPORT DELAY                                           A 145
      SDEL(II,K)=0.0                                                    A 146
      DO 15 J=2,JF                                                      A 147
      IT=ITIN(II,J)                                                     A 148
      IF (IT.EQ.0) GO TO 15                                             A 149
      IF (REST(IT,K).EQ.1.0) IY(II,K)=1                                 A 150
      SDEL(II,K)=SDEL(II,K)+DELAY(IT,K)                                 A 151
15    CONTINUE                                                          A 152
16    CONTINUE                                                          A 153
17    CONTINUE                                                          A 154
      DO 20 II=1,IIF                                                    A 155
      DO 19 K=1,KF                                                      A 156
      REV1(K,1)=0.0                                                     A 157
C     CALCULATE REVENUES FOR EACH ITINERARY BASED ON TICKET PRICE       A 158
C     PER MILE                                                          A 159
      DO 18 J=2,JN                                                      A 160
```

```
      REV1(K,J)=DEMAND(II,J)*TPRI(K)*DIST(II,J)/100.+REV1(K,J-1)
      IF (J.EQ.JM) REV2(II,K)=REV1(K,J)
18    CONTINUE
19    CONTINUE
20    CONTINUE
      DO 22 K=1,KF
C     CALCULATE AIRTIME FOR EACH AIRCRAFT AND EACH ITINERARY
      DO 21 II=1,IIF
      TIME(II,K)=SUMDIS(II)/ACSP(K)+SDEL(II,K)/60.
      CALL EQUAT (2)
      CALL EQUAT (3)
21    CONTINUE
22    CONTINUE
      DO 25 II=1,IIF
C     CALCULATE THE NUMBER OF FLIGHTS REQUIRED FOR EACH AIRCRAFT ON
C     EACH ITINERARY
      DO 24 K=1,KF
      FLIT(II,K)=DMAX(II)/ACCAP(K)
      IFLY(II,K)=INT(FLIT(II,K))+1
      OPCOST(II,K)=OPCOST(II,K)*IFLY(II,K)
      IF (IY(II,K).EQ.1) GO TO 25
C     CHECK PURCHASE CONSTRAINTS.  IF ANY CONSTRAINTS ARE VIOLATED
C     SET CRITERIA EQUAL TO A LARGE VALUE, CMAX, HERE CMAX=99999
      PURCH(II,K)=PUR(K)*IFLY(II,K)
      IF (PURCH(II,K).GT.PMAX(II)) GO TO 23
      FUEL(II,K)=IFLY(II,K)*FUEL(II,K)
      SDEL(II,K)=IFLY(II,K)*SDEL(II,K)
      NOISE(II,K)=IFLY(II,K)*NOISE(II,K)
      DELAY(II,K)=SDEL(II,K)
      GO TO 24
23    FUEL(II,K)=CMAX
      DELAY(II,K)=CMAX
```

```
      NOISE(II,K)=CMAX                                                  A 193
24    CONTINUE                                                          A 194
25    CONTINUE                                                          A 195
      IF (IAL.GT.0) GO TO 28                                            A 196
C     WRITE CRITERIA COEFFICIENTS, OPERATING COSTS AND REVENUES.        A 197
C     THIS CAN BE DELETED BY SETTING IAL EQUAL TO 1 IN THE BLOCK DATA   A 198
C     SUBPROGRAM                                                        A 199
C     IF IAB IS SET EQUAL TO ANY VALUE BUT ZERO, SURROGATE FUNCTIONS    A 200
C     WILL NOT BE FORMULATE                                             A 201
      DO 27 II=1,IIF                                                    A 202
      DO 26 K=1,KF                                                      A 203
      WRITE (6,41) II,K                                                 A 204
      WRITE (6,42) IFLY(II,K),FUEL(II,K),DELAY(II,K),NOISE(II,K)        A 205
      WRITE (6,43) OPCOST(II,K),REV2(II,K)                              A 206
26    CONTINUE                                                          A 207
27    CONTINUE                                                          A 208
28    IAB=0                                                             A 209
      LM=0                                                              A 210
      LEM=0                                                             A 211
      MZ=0                                                              A 212
C     ALEVEL(I) = ASPIRATION LEVELS FOR EACH CRITERIA                   A 213
C             I=1,2 ... NG                                              A 214
      READ (5,34) (ALEVEL(I),I=1,NG)                                    A 215
      DO 29 IG=1,NG                                                     A 216
      LGREEN=0                                                          A 217
      MZ=MZ+1                                                           A 218
      CALL BALAS                                                        A 219
29    CONTINUE                                                          A 220
      IF (IAB.EQ.0) GO TO 31                                            A 221
C     NIEX = TOTAL NUMBER OF SURROGATE FUNCTIONS TO BE FORMED           A 222
      READ (5,35) NIEX                                                  A 223
      DO 30 NW=1,NIEX                                                   A 224
```

```
      LGREEN=1                                                          A 225
      CALL BALAS                                                        A 226
30    CONTINUE                                                          A 227
31    STOP                                                              A 228
C                                                                       A 229
C                                                                       A 230
C                                                                       A 231
32    FORMAT (5F5.4)                                                    A 232
33    FORMAT (I3)                                                       A 233
34    FORMAT (3F6.0)                                                    A 234
35    FORMAT (3F4.0)                                                    A 235
36    FORMAT (3F4.0)                                                    A 236
37    FORMAT (3F5.0)                                                    A 237
38    FORMAT (8F3.0)                                                    A 238
39    FORMAT (7I3)                                                      A 239
40    FORMAT (5F7.3)                                                    A 240
41    FORMAT (1X,10HITINERARY ,I3,5X,9HAIRCRAFT ,I3)                    A 241
42    FORMAT (1X,18HFLIGHTS REQUIRED  ,I5,5X,13HFUEL USAGE = ,F15.5,5X,6 A 242
     1HDELAY = ,F15.5,5X,3HNOISE = ,F15.5)                              A 243
43    FORMAT (1X,17HOPERATING COST = ,F15.2,5X,10HREVENUE = ,F15.2,/)   A 244
44    FORMAT (1X,9HAIRCRAFT ,I3,37H DOES NOT MEET ALL RUNWAY CONSTRAINTS A 245
     1)                                                                 A 246
45    FORMAT (1X,9HAIRCRAFT ,I3,35H DOES NOT MEET ALL NOISE CONSTRAINTS) A 247
      END                                                               A 248
C     ******************************************************************B   1
C     BLOCK DATA                                                        B   2
      BLOCK DATA                                                        B   3
      COMMON /HUB0/ IA(10),HOPS(10),KND(10),RUNWAY(10)                  B   4
      COMMON /ITER/ IAL,IZZ                                             B   5
      COMMON /UCCM4/ ANOI(5),DCON,PUR(5),PMAX(10),PURCH(10,8)           B   6
      COMMON /UCCM5/ TPNI(5),REV1(10,8),REV2(10,8)                      B   7
      COMMON /UCCM6/ BSAVE(10,50),ZSAVE(10),MNC,ALEVEL(10),MA,BA(50)    B   8
```

```
C       VARIABLES TO BE SUPPLIED                                          B   9
C       ANOI(KE = NOISE LEVEL PRODUCED BY TYPE K AIRCRAFT  (IN EPNDB)     B  10
C       IW(A) = SATELLITE AIRPORT NUMBER FOR HUB AIRPORT A                B  11
C       HOPS(A) = SATELLITE OPERATIONS PER HOUR                           B  12
C       RUNWAY(A) = SATELLITE RUNWAY LENGTH                               B  13
C       RNO(A) = SATELLITE NOISE RESTRICTION                              B  14
C       DCON = CONSTANT FOR GRAVITY DEMAND MODEL                          B  15
C       TPMI(K) = TICKET PRICE PER PASSENGER MILE FOR AIRCRAFT K          B  16
C       MA = NUMBER OF CONSTRAINTS                                        B  17
C       BA( ) = CONSTRAINT RHS                                            B  18
C       PUR( ) = PURCHASE PRICE FOR EACH K TYPE AIRPORT                   B  19
C       PMAX(B) = TOTAL ALLOWABLE BUDGET FOR AIRCRAFT FLEET FLYING        B  20
C       ITINERARY B                                                       B  21
C                                                                         B  22
        DATA IAL/0/                                                       B  23
        DATA IW(1),HOPS(1),RUNWAY(1),RNO(1)/11,3.,6500.,100./             B  24
        DATA PUR(1),PUR(2),PUR(3)/17.31,16.00,16.53/                      B  25
        DATA DCON/.0100/                                                  B  26
        DATA MA/5/,BA(1),BA(2),BA(3),BA(4),BA(5)/6000.,7000.,8000.,6500.,6 B  27
      1000./                                                              B  28
        DATA PMAX(1),PMAX(2),PMAX(3),PMAX(4),PMAX(5),PMAX(6),PMAX(7)/400., B  29
      1400.,400.,400.,400.,400.,400./                                     B  30
        DATA TPMI(1),TPMI(2),TPMI(3)/7.0,7.0,7.0/                         B  31
        DATA ANOI(1),ANOI(2),ANOI(3)/98.0,100.,104.7/                     B  32
        END                                                               B  33
C       ******************************************************************C   1
C       SUBROUTINE EQUAT                                                  C   2
C       THE FOLLOWING FUNCTIONS MUST BE SUPPLIED (THESE MAY BE CHANGED    C   3
C       TO MODEL DIFFERENT CRITERIA)                                      C   4
C       DELAY(I,K) = DELAY FOR AIRCRAFT K AT AIRPORT I AS A FUC           C   5
C       DELAY(I,K) = DELAY FOR AIRCRAFT K AT AIRPORT I AS A FUNCTION OF   C   6
C       OPERATIONS                                                        C   7
```

```
C       FUEL(II,K) = FUEL FOR AIRCRAFT K ON ITINERARY II AS A FUNCTION OF
C       AIRTIME
C       NOISE(II,K) = NOISE OF AIRCRAFT K ON ITINERARY II = ANOI(K)
C       DEMAND(II,J) = DEMAND FOR SERVICE AT AIRPORT J ON ITINERARY II,
C       BASED ON THE GRAVITY MODEL
C
        SUBROUTINE EQUAT (NUM)
        COMMON /UCOM4/ ANOI(5),DCON,PUR(5),PMAX(10),PURCH(10,8)
        COMMON /UCOM2/ NG,LN,LGREEN,LE4,IAE,IDA
        COMMON /RUN/ OPS(10,3),ITIN(10,3),DIST(10,3),RUNW(10,3),ACRW(3),AC
       1SP(3),ACCAP(3),SUMDIS(10),SDEL(10,3),TIME(10,3),DELAY(10,3),FUEL(1
       20,3),NOISE(10,3),DEMAND(10,3),DMAX(10),FLIT(10,5),OPCOST(10,3),II,
       3J,K,I,OCOST,DEM1,DEM2
        COMMON /FFF/ FPEN(5),CCST(3)
        REAL NOISE
        GO TO (1,2,3,4), NUM
C       DELAY FUNCTION
1       DELAY(I,K)=(.02066*OPS(I,2)**2)-(.11306*OPS(I,2))-.13276
        IF (DELAY(I,K).LT.0.0) DELAY(I,K)=0.0
        RETURN
C       FUEL FUNCTION
2       FUEL(II,K)=(43.13579*TIME(II,K)**2)-(36.42293*TIME(II,K))+14.75194
        FUEL(II,K)=FPEN(K)*FUEL(II,K)+FUEL(II,K)
C       OPERATING COST FUNCTION
        OPCOST(II,K)=TIME(II,K)*CCST(K)
        RETURN
C       NOISE FUNCTION
3       NOISE(II,K)=ANOI(K)
        RETURN
4       IF (DIST(II,J).NE.0.) GO TO 5
C       DEMAND FUNCTION
        DEMAND(II,J)=0.0
```

```
      RETURN                                                            C  40
5     DEMAND(II,J)=DCOST*(DEM1*DEM2*1.E6)/((DIST(II,J)**2)*365.)        C  41
      RETURN                                                            C  42
      END                                                               C  43
C     ***********************************************************       D   1
C     SUBROUTINE HUB                                                    D   2
C     ROUTES ALLOWABLE AIRCRAFT TO HUB AIRPORTS IF DELAY AT HUB IS      D   3
C     EXCESSIVE                                                         D   4
C                                                                       D   5
      SUBROUTINE HUB                                                    D   6
      COMMON /UCOM4/ ANOI(5),DCOST,PUR(5),PMAX(10),PURCH(10,8)          D   7
      COMMON /HUB/ IW(10),HCPS(10),RNO(10),RUNWAY(10)                   D   8
      COMMON /SCH/ IF,JF,KF,IIF,MZ,MC,MD                                D   9
      COMMON /UCOM2/ MG,LM,LGREEN,LEN,IAC,IDA                           D  10
      COMMON /RUN/ OPS(10,3),ITIN(10,8),DIST(10,8),PUTIN(10,3),ACRW(3),AC  D  11
     1SP(3),ACCAP(3),SJMDIS(10),SDEL(10,8),TIME(10,3),DELAY(10,8),FUEL(1  D  12
     20,3),NOISE(10,3),DEMAND(10,8),DMAX(10),FLIT(10,5),OPCOST(10,8),II,  D  13
     3J,K,I,DCOST,DEM1,DEM2                                             D  14
      IF (RUNW(I,2).LT.ACRW(K)) GO TO 1                                 D  15
      IF (RUNW(I,3).LT.ANOI(K)) GO TO 1                                 D  16
      CPS(I,2)=HCPS(I)                                                  D  17
      RUNW(I,2)=RUNWAY(I)                                               D  18
      RUNW(I,3)=RNO(I)                                                  D  19
      IDA=K+((II-1)*IIF)                                                D  20
      WRITE (6,2) I,IW(I)                                               D  21
1     CALL EQUAT (1)                                                    D  22
      RETURN                                                            D  23
C                                                                       D  24
C                                                                       D  25
C                                                                       D  26
2     FORMAT (1X,25H     AIRCRAFT TO AIRPORT ,I3,29HWAS SENT TO SATELLIT  D  27
     1E AIRPORT,I3)                                                     D  28
```

```
      END                                                               D  29
C     ******************************************************************  E   1
C     SUBROUTINE BALAS                                                  E   2
C     PUTS PROBLEM INTO STANDARD FORM AND THEN CALLS SUBROUTINES FOR THE E   3
C     ZERO-ONE PROCEDURE                                                E   4
C     VARIABLES TO BE READ IN                                           E   5
C     IEX(I) = CRITERIA IN SURROGATE FUNCTION                           E   6
C            = 1 => IN SURROGATE FUNCTION                               E   7
C            = 0 => NOT IN SURROGATE FUNCTION                           E   8
C              I=1,2 ... NG                                             E   9
C                                                                       E  10
      SUBROUTINE BALAS                                                  E  11
C     BALAS ZERO-ONE PROGRAMMING ALGORITHM                              E  12
      COMMON /UCOM3/ PSAVE(10,30),ZSAVE(10),NNC,ALEVEL(10),MA,BA(30)    E  13
      COMMON /UCOM2/ NG,LM,LGREEN,LEM,IAB,IDA                           E  14
      COMMON /SCH/ IF,JF,KF,IIF,MZ,NC,ND                                E  15
      COMMON /RUN/ OPS(10,3),ITIN(10,8),DIST(10,8),PUNW(10,3),ACRW(3),AC E  16
     1SP(3),ACCAP(3),SUMDIS(10),SDEL(10,8),TIME(10,8),DELAY(10,8),FUEL(1 E  17
     20,3),NOISE(10,3),DEMAND(10,3),DMAX(10),FLIT(10,3),OPCOST(10,8),II, E  18
     3JZ,KZ,IZ,OCCST,DEM1,DEM2                                          E  19
      COMMON /UCOM1/ N,M,C(50),A(30,50),B(30),XL(30),SIGMA(50),ZSTAR,LST E  20
     1AR,LEVEL,Z,V(30),F(50),Y(30),IIA(30),E(30),JSTAR,S(200),SSTAR(50), E  21
     2BB(50),NNV,NNF,NNII,NNE,NAB,NDI                                   E  22
      COMMON /DEF/ SA(10,50)                                            E  23
      DIMENSION JQ(30), SUR(30), IEX(10), JQA(30)                       E  24
      REAL NOISE                                                        E  25
      M=MA                                                              E  26
      DO 1 I=1,M                                                        E  27
      B(I)=BA(I)                                                        E  28
1     CONTINUE                                                          E  29
      N=IIF*KF                                                          E  30
      IQ=0                                                              E  31
```

```
C     LGREEN EQUAL TO A NONZERO VALUE SETS UP THE SUBROGATE PROBLEMS
      IF (LGREEN.NE.0) GO TO 8
      DO 7 II=1,IIF
      DO 6 K=1,KF
      IQ=IQ+1
C     MZ IS USED TO DETERMINE EACH OF THE CRITERIA SEPARATELY
      GO TO (2,3,4), MZ
2     XY=FUEL(II,K)
      GO TO 5
3     XY=DELAY(II,K)
      GO TO 5
4     XY=NOISE(II,K)
5     C(IQ)=XY
      SA(MZ,IQ)=C(IQ)
6     CONTINUE
7     CONTINUE
      GO TO 14
8     READ (5,32) (IEX(I),I=1,NG)
      NN=0
      NNA=0
C     THIS DO LOOP IS USED TO DETERMINE WHICH CRITERIA ARE USED AS
C     CONSTRAINTS, IEX(I)=0 FOR CRITERIA TO BE USED AS CONSTRAINTS
C     THE STATEMENTS FROM HERE TO M=LE ARE USED TO SET UP CONSTRAINTS
C     FOR THE PROBLEM BEING CONSIDERED. THEY MAY BE CHANGED TO FIT THE
C     USER'S PARTICULAR PROBLEM
      DO 10 I=1,NG
      IF (IEX(I).NE.1) GO TO 9
      NN=NN+1
      JQ(NN)=I
      GO TO 10
9     NNA=NNA+1
      JQA(NNA)=I
```

```
10    CONTINUE                                                          E  64
      DO 12 II=1,N                                                      E  65
      SUR(II)=0.0                                                       E  66
      DO 11 III=1,NN                                                    E  67
      JJ=JO(III)                                                        E  68
      SUR(II)=SA(JJ,II)/ALEVEL(JJ)+SUR(II)                              E  69
11    CONTINUE                                                          E  70
12    CONTINUE                                                          E  71
      DO 13 IV=1,N                                                      E  72
      C(IV)=SUR(IV)                                                     E  73
13    CONTINUE                                                          E  74
14    N=(IIF*2)+M                                                       E  75
      DO 16 I=1,M                                                       E  76
      DO 15 J=1,N                                                       E  77
      A(I,J)=0.0                                                        E  78
15    CONTINUE                                                          E  79
16    CONTINUE                                                          E  80
      LC=0                                                              E  81
      DO 22 LD=1,NC                                                     E  82
      LE=LC+1                                                           E  83
      LC=LC+IIF                                                         E  84
      NA=0                                                              E  85
      NB=1                                                              E  86
      DO 21 I=LE,LC                                                     E  87
      L=NA+1                                                            E  88
      NA=NA+KF                                                          E  89
      LA=NB*KF                                                          E  90
      NB=NB+1                                                           E  91
      DO 20 J=L,LA                                                      E  92
      GO TO (17,18,19), LD                                              E  93
17    NE=(J+KF)-LA                                                      E  94
      A(I,J)=OPCOST(I,NE)                                               E  95
```

```
      GO TO 20
18    A(I,J)=1
      B(I)=1
      GO TO 20
19    A(I,J)=-1
      B(I)=-1
20    CONTINUE
21    CONTINUE
22    CONTINUE
      IF (LGREEN.EQ.0) GO TO 25
      IF (NMA.EQ.0) GO TO 25
      DO 24 IAA=1,NMA
      JJA=JJA(NMA)
      LE=LC+IAA
      DO 23 J=1,N
      A(LE,J)=SA(JJA,J)
      B(LE)=ALEVEL(JJA)
23    CONTINUE
24    CONTINUE
      M=LE
C     THESE STATEMENTS CONTROL THE BALAS ZERO-ONE PROGRAMMING PROCEDURE.
C     BY CALLING SUBROUTINES STEP0 THROUGH STEP9 IN A SEQUENCE DETER-
C     MINED BY THE PROBLEM ITSELF, THE SOLUTION IS FOUND
C     INITIALIZE VARIABLES
25    CALL STEP0
C     START ALGORITHM
C     DETERMINE VIOLATED CONSTRAINTS
26    CALL STEP1
C     IF NNV = 0; THERE ARE NO VIOLATED CONSTRAINT, RECORD SOLUTION
      IF (NNV.EQ.0) GO TO 29
C     OTHERWISE DETERMINE WHICH VARIABLES ARE 'FREE' VIA STEP 2.
      CALL STEP2
```

```
C       IF NO VARIABLES ARE FREE - BACKTRACK AT STEP 8.
        IF (NNF.EQ.0) GO TO 30
C       CALCULATE UPPER BOUND ESTIMATES ON CONSTRAINTS
        CALL STEP5
C       IF WE CANNOT IMPROVE ZSTAR - BACKTRACK VIA STEP 3.
        IF (NNII.GT.0) GO TO 30
C       IF WE CAN IMPROVE ZSTAR BY TURNING UP MORE THAN ONE
C       VARIABLE - THEN DO SO.
        IF (NNE.GT.0) GO TO 27
C       DETERMINE BEST MOVE AVAILABLE AT THIS POINT AND BRANCH FORWARD
        CALL STEP4
        GO TO 28
27      CALL STEP5 (SUM)
C       IF NEW SOLUTION IS > CURRENT SOLUTION - BACKTRACK
        IF (SUM.GE.ZSTAR) GO TO 30
C       IF NOT - GO TO FORWARD BRANCH
28      CALL STEP6
C       GO BACK TO STEP 1.
        GO TO 26
C       RECORD BEST SOLUTION SO FAR
29      CALL STEP7
C       IF LEVEL=0, CANNOT BACKTRACK => FINISHED.
30      IF (LEVEL.EQ.0) GO TO 31
C       BACKTRACK
        CALL STEP8
        GO TO 26
C       CALCULATE FINAL ANSWER
31      CALL STEP9
        RETURN
C
C
C
```

```
52    FORMAT (10I3)                                                    E 160
      END                                                              E 161
C     STEP SUBROUTINES                                                 F   1
C     THESE SUBROUTINES PERFORM THE ZERO-ONE PROCEDURE.  THE ORDER IN  F   2
C     WHICH THEY ARE CALLED IS DEPENDENT UPON THE PROBLEM BEING SOLVED F   3
C     SUBROUTINE PRNT                                                  F   4
C     THIS SUBROUTINE PRINTS THE RESULT OF THE ZERO-ONE PROCEDURE      F   5
C     SUBROUTINE ORDER                                                 F   6
C     THIS SUBROUTINE PLACES THE SOLUTION VECTOR IN ASCENDING ORDER    F   7
C                                                                      F   8
C     ****************************************************************F   9
C                                                                      F  10
C     SUBROUTINE STEP0                                                 F  11
C                                                                      F  12
      SUBROUTINE STEP0                                                 F  13
      COMMON /UCOM1/ N,M,C(50),A(30,50),B(30),XL(30),SIGMA(50),ZSTAR,LST F  14
     1AR,LEVEL,Z,V(30),R(50),Y(50),IIA(30),E(30),JSTAR,S(200),SSTAR(50), F  15
     2BB(50),NNV,NNF,NNII,NNE,NN2,NOI                                  F  16
      ZSTAR=1.0                                                        F  17
      NOI=1                                                            F  18
      DO 1 I=1,N                                                       F  19
1     ZSTAR=ZSTAR+C(I)                                                 F  20
      LSTAR=N+1                                                        F  21
      LEVEL=0                                                          F  22
      Z=0.                                                             F  23
      DO 2 I=1,N                                                       F  24
2     SIGMA(I)=1.0                                                     F  25
      DO 3 J=1,M                                                       F  26
3     XL(J)=0(J)                                                       F  27
      CALL PRNT (1)                                                    F  28
      RETURN                                                           F  29
      END                                                              F  30
```

```
C     ***********************************************************************
C     SUBROUTINE STEP1
C
      SUBROUTINE STEP1
      COMMON /UCOM1/ N,M,C(50),A(30,50),B(30),XL(50),SIGMA(50),ZSTAR,LST
     1AR,LEVEL,Z,V(30),F(50),Y(30),IIA(30),E(30),JSTAR,S(200),SSTAR(50),
     2BB(50),NNV,NNF,NNII,NNE,NNB,NOI
      NNV=0
      DO 2 J=1,N
      V(J)=0.
      IF (XL(J).LT.0.) GO TO 1
      GO TO 2
1     NNV=NNV+1
      V(NNV)=J
2     CONTINUE
      RETURN
      END
C     ***********************************************************************
C     SUBROUTINE STEP2
C
      SUBROUTINE STEP2
      COMMON /UCOM1/ N,M,C(50),A(30,50),B(30),XL(50),SIGMA(50),ZSTAR,LST
     1AR,LEVEL,Z,V(30),F(50),Y(30),IIA(30),E(30),JSTAR,S(200),SSTAR(50),
     2BB(50),NNV,NNF,NNII,NNE,NNB,NOI
      NNF=0
      DO 3 J=1,N
      F(J)=0.
      IF (SIGMA(J).NE.1.) GO TO 3
      X=C(J)+Z
      IF (X.GE.ZSTAR) GO TO 3
      DO 1 III=1,NNV
      I=V(III)
```

```
      IF (A(I,J).GE...) GO TO 1                                         H  16
      GO TO 2                                                           H  17
1     CONTINUE                                                          H  18
      GO TO 3                                                           H  19
2     NNF=NNF+1                                                         H  20
      F(NNF)=J                                                          H  21
3     CONTINUE                                                          H  22
      RETURN                                                            H  23
      END                                                               H  24
C     ******************************************************************I   1
C     SUBROUTINE STEP3                                                  I   2
C                                                                       I   3
      SUBROUTINE STEP3                                                  I   4
      COMMON /UCOM1/ N,M,C(50),A(30,50),B(30),XL(30),SIGMA(50),ZSTAR,LST I   5
     1AR,LEVEL,Z,V(30),F(50),Y(30),IIA(30),E(30),JSTAR,S(200),SSTAR(50), I   6
     2BB(50),NNV,NNF,NNII,NNE,NNB,NDI                                   I   7
      DO 2 III=1,NNV                                                    I   8
      SUM=0.                                                            I   9
      I=V(III)                                                          I  10
      DO 1 JJ=1,NNF                                                     I  11
      J=F(JJ)                                                           I  12
      X=AMIN1(0.0,A(I,J))                                               I  13
      SUM=SUM+X                                                         I  14
1     CONTINUE                                                          I  15
      Y(I)=XL(I)-SUM                                                    I  16
2     CONTINUE                                                          I  17
      NNII=0                                                            I  18
      NNE=0                                                             I  19
      DO 4 III=1,NNV                                                    I  20
      I=V(III)                                                          I  21
      E(I)=0.                                                           I  22
      IIA(I)=0                                                          I  23
```

```
      IF (Y(I).LT.0) GO TO 3                                            I   24
      IF (Y(I).NE.0) GO TO 4                                            I   25
      NNE=NNE+1                                                         I   26
      E(NNE)=I                                                          I   27
      GO TO 4                                                           I   28
3     NNII=NNII+1                                                       I   29
      IIA(NNII)=I                                                       I   30
4     CONTINUE                                                          I   31
      RETURN                                                            I   32
      END                                                               I   33
C     ******************************************************************J    1
C     SUBROUTINE STEP4                                                  J    2
C                                                                       J    3
      SUBROUTINE STEP4                                                  J    4
      COMMON /UCOM1/ N,M,C(50),A(30,50),F(50),XL(50),SIGMA(50),ZSTAR,LST J    5
     1AR,LEVEL,Z,V(50),P(50),Y(50),IIA(50),E(50),JSTAR,S(200),SSTAR(50), J    6
     2BB(50),NNV,NNF,NNII,NNE,NNP,NCI                                   J    7
      OLDSUM=-99999.0                                                   J    8
      DO 3 JJ=1,NNF                                                     J    9
      J=F(JJ)                                                           J   10
      SB(J)=0.                                                          J   11
      SUM=0.                                                            J   12
      DO 1 I=1,M                                                        J   13
      XZ=XL(I)-A(I,J)                                                   J   14
      X=AMIN1(0.0,XZ)                                                   J   15
1     SUM=SUM+X                                                         J   16
      IF (SUM.LT.OLDSUM) GO TO 3                                        J   17
      IF (SUM.GT.OLDSUM) GO TO 2                                        J   18
      IF (C(J).GT.C(JSTAR)) GO TO 3                                     J   19
2     OLDSUM=SUM                                                        J   20
      JSTAR=J                                                           J   21
3     CONTINUE                                                          J   22
```

```
      BB(1)=JSTAR                                                       J  23
      NNB=1                                                             J  24
      RETURN                                                            J  25
      END                                                               J  26
C     ******************************************************************K   1
C     SUBROUTINE STEP5                                                  K   2
C                                                                       K   3
      SUBROUTINE STEP5 (SUM)                                            K   4
      COMMON /UCBM1/ N,M,C(50),A(50,50),B(50),XL(30),SIGMA(50),ZSTAR,LST K   5
     1AR,LEVEL,Z,V(30),F(50),Y(30),IIA(30),E(30),JSTAR,S(200),SSTAR(50), K   6
     2BB(50),NNV,NNF,MMII,NNE,NNB,NBI                                   K   7
      NNB=0                                                             K   8
      DO 2 JJ=1,NNF                                                     K   9
      J=F(JJ)                                                           K  10
      DO 1 III=1,NNE                                                    K  11
      I=E(III)                                                          K  12
      IF (A(I,J).GE.0) GO TO 1                                          K  13
      NNB=NNB+1                                                         K  14
      BB(NNB)=J                                                         K  15
1     CONTINUE                                                          K  16
2     CONTINUE                                                          K  17
      SUM=0.                                                            K  18
      DO 3 J=1,NNB                                                      K  19
      I=BB(J)                                                           K  20
      SUM=SUM+C(I)                                                      K  21
3     CONTINUE                                                          K  22
      SUM=SUM+Z                                                         K  23
      RETURN                                                            K  24
      END                                                               K  25
C     ******************************************************************L   1
C     SUBROUTINE STEP6                                                  L   2
C                                                                       L   3
```

```
      SUBROUTINE STEP6                                                  L    4
      COMMON /UCOM1/ N,M,C(50),A(30,50),Z(30),XL(30),SIGMA(50),ZSTAR,LST L    5
     1AR,LEVEL,Z,V(30),F(50),Y(30),IIM(30),E(30),JSTAR,S(200),SSTAR(50), L    6
     2BB(50),NNV,NNF,NNII,NNE,NNB,NCI                                   L    7
      NCI=NCI+1                                                         L    8
      DO 1 J=1,NNB                                                      L    9
      I=BB(J)                                                           L   10
      SIGMA(I)=0.                                                       L   11
1     CONTINUE                                                          L   12
      DO 2 J=1,N                                                        L   13
      IF (SIGMA(J).LT.1.) SIGMA(J)=SIGMA(J)-1.                          L   14
2     CONTINUE                                                          L   15
      DO 4 J=1,NNB                                                      L   16
      IF (J.GT.1) GO TO 3                                               L   17
      S(LEVEL+1)=-1*BB(1)                                               L   18
      GO TO 4                                                           L   19
3     S(LEVEL+J)=BB(J)                                                  L   20
4     CONTINUE                                                          L   21
      DO 5 J=1,NNB                                                      L   22
      I=BB(J)                                                           L   23
      Z=Z+C(I)                                                          L   24
5     CONTINUE                                                          L   25
      DO 7 I=1,M                                                        L   26
      DO 6 J=1,NNB                                                      L   27
      JJ=BB(J)                                                          L   28
      XL(I)=XL(I)-A(I,JJ)                                               L   29
6     CONTINUE                                                          L   30
7     CONTINUE                                                          L   31
      LEVEL=LEVEL+NNB                                                   L   32
      RETURN                                                            L   33
      END                                                               L   34
C     ***************************************************************** M    1
```

```
C     SUBROUTINE STEP7                                                  M   2
C                                                                       M   3
      SUBROUTINE STEP7                                                  M   4
      COMMON /UCOM1/ N,M,C(50),A(30,50),B(30),XL(30),SIGMA(50),ZSTAR,LST M   5
     1AR,LEVEL,Z,V(30),F(30),Y(30),IIA(30),E(30),JSTAR,S(200),SSTAR(50), M   6
     2BB(50),NNV,NNF,NNII,NNE,NNB,NCI                                   M   7
      LSTAR=LEVEL                                                       M   8
      IF (LEVEL.EQ.0) LSTAR=1                                           M   9
      IF (LEVEL.EQ.0) S(1)=0.0                                          M  10
      ZSTAR=Z                                                           M  11
      DO 1 I=1,LSTAR                                                    M  12
1     SSTAR(I)=S(I)                                                     M  13
      RETURN                                                            M  14
      END                                                               M  15
C     ****************************************************************  N   1
C     SUBROUTINE STEP8                                                  N   2
C                                                                       N   3
      SUBROUTINE STEP8                                                  N   4
      COMMON /UCOM1/ N,M,C(50),A(30,50),B(30),XL(30),SIGMA(50),ZSTAR,LST N   5
     1AR,LEVEL,Z,V(30),F(30),Y(30),IIA(30),E(30),JSTAR,S(200),SSTAR(50), N   6
     2BB(50),NNV,NNF,NNII,NNE,NNB,NCI                                   N   7
      NCI=NCI+1                                                         N   8
      MM=LEVEL+1                                                        N   9
      DO 1 I=1,LEVEL                                                    N  10
      IF (S(MM-I).LT.0) GO TO 2                                         N  11
1     CONTINUE                                                          N  12
2     IDELTL=I                                                          N  13
      DO 3 I=1,N                                                        N  14
3     BB(I)=0.                                                          N  15
      NNB=1                                                             N  16
      BB(1)=-1*S(MM-IDELTL)                                             N  17
      NB=IDELTL-1                                                       N  18
```

```
      IF (NB.EQ.0) GO TO 3                                              N  19
      DO 4 I=1,NB                                                       N  20
      NB3=NB3+1                                                         N  21
      BB(I+1)=S(NB-IDELTL+1)                                            N  22
4     CONTINUE                                                          N  23
5     DO 6 J=1,N                                                        N  24
      IF (SIGMA(J).LT.1.) SIGMA(J)=SIGMA(J)+1                           N  25
6     CONTINUE                                                          N  26
      DO 7 JJ=1,NB3                                                     N  27
      J=BB(JJ)                                                          N  28
      IF (J.LT.0) J=(-1)*J                                              N  29
      Z=Z-C(J)                                                          N  30
7     CONTINUE                                                          N  31
      DO 9 I=1,M                                                        N  32
      DO 8 JJ=1,NB3                                                     N  33
      J=BB(JJ)                                                          N  34
      IF (J.LT.0) J=(-1)*J                                              N  35
      XL(I)=XL(I)+A(I,J)                                                N  36
8     CONTINUE                                                          N  37
9     CONTINUE                                                          N  38
      LEVEL=LEVEL-IDELTL                                                N  39
      RETURN                                                            N  40
      END                                                               N  41
C     ******************************************************************  0   1
C     SUBROUTINE STEP9                                                  0   2
C                                                                       0   3
      SUBROUTINE STEP9                                                  0   4
      COMMON /RUN/ OPS(10,3),ITIN(10,8),DIST(10,8),RUNW(10,3),ACRW(3),AC  0   5
     1SP(3),ACCAP(3),SUMDIS(10),SDEL(10,9),TIME(10,3),DELAY(10,8),FUEL(1  0   6
     2C,3),NOISE(10,3),DEMAND(10,3),DMAX(10),FLIT(10,5),OPCOST(10,3),II,  0   7
     3J,K,I,DCOST,DEM1,DEM2                                             0   8
      COMMON /UCOM1/ N,M,C(50),A(30,50),B(30),XL(30),SIGMA(50),ZSTAR,LST  0   9
```

```
      LAP,LEVEL,Z,V(50),F(50),Y(50),IIA(50),E(50),JSTAR,S(200),SSTAR(50),
     2SS(50),NNV,NAF,NNII,NNE,NND,NCI
      COMMON /UCC-2/ NC,LM,LGREEN,LEM,IBB,IBA
      COMMON /SCH/ IF,JF,KF,IIF,NZ,NC,ND
      COMMON /UCCAB/ BSAVE(10,50),ZSAVE(10),NNC,ALEVEL(10),NA,BA(50)
      DIMENSION IM(10)
      IF (LSTAR.EQ.(N+1)) GO TO 13
      ZSTAR=0.
      KNB=LSTAR
      IN=0
      IF (IM.EQ.0) GO TO 3
      DO 2 IO=1,IN
      DO 1 JJ=1,KNB
      SSTAR(JJ)=ABS(SSTAR(JJ))
      LII=(SSTAR(JJ)-IM(IO))
      IF (LII.GT.0.AND.LII.LT.IIF) SSTAR(JJ)=IM(IO)
1     CONTINUE
2     CONTINUE
3     DO 5 JJ=1,LSTAR
      J=SSTAR(JJ)
      IF (J.NE.0) GO TO 4
      J=1
      C(1)=0.0
4     IF (J.LT.0) J=(-1)*J
      SS(JJ)=J
      ZSTAR=ZSTAR+C(J)
5     CONTINUE
      NNC=KNB
      CALL ORDER
      CALL PRNT (2)
      LM=LM+1
      DO 6 J=1,NND
```

```
      BSAVE(LM,J)=BB(J)                                                 0  42
6     CONTINUE                                                          0  43
      ZSAVE(LM)=ZSTA                                                    0  44
      IF (LMREEN.EQ.0) GO TO 14                                         0  45
      IF (ZLEVEL(LM)-ZSAVE(LM)) 13,7,7                                  0  46
7     WRITE (6,16) LM                                                   0  47
      IF (LEM.GT.0) GO TO 11                                            0  48
      IF (MZ.NE.NG) GO TO 12                                            0  49
      LX=LM-1                                                           0  50
      DO 9 I=1,LX                                                       0  51
      DO 8 J=1,NN3                                                      0  52
      IF (BSAVE(I,J).EQ.BSAVE(I+1,J)) GO TO 8                           0  53
      IAB=1                                                             0  54
8     CONTINUE                                                          0  55
9     CONTINUE                                                          0  56
      GO TO 12                                                          0  57
10    WRITE (6,17) LM                                                   0  58
      LEM=1                                                             0  59
11    IF (MZ.NE.NG) GO TO 14                                            0  60
12    RETURN                                                            0  61
13    WRITE (6,15)                                                      0  62
14    RETURN                                                            0  63
C                                                                       0  64
C                                                                       0  65
C                                                                       0  66
15    FORMAT (2X,27H*** NO SOLUTION IS POSSIBLE)                        0  67
16    FORMAT (1X,17HASPIRATION LEVEL ,I3,26H IS MET WITH THIS SCHEDULE) 0  68
17    FORMAT (1X,17HASPIRATION LEVEL ,I3,26HNOT MET WITH THIS SCHEDULE,/ 0  69
     1,40HA SOLUTION AT THIS LEVEL IS NOT POSSIBLE)                     0  70
      END                                                               0  71
C     ******************************************************************P   1
C     SUBROUTINE PRNT                                                   P   2
```

```
C     THIS SUBROUTINE PRINTS THE RESULTS OF THE  BALAS PROCEDURE
C
      SUBROUTINE PRNT (ICODE)
      COMMON /COM1/ N,M,C(50),A(30,50),L(30),XL(30),SIGMA(50),ZSTAR,LST
     1AR,LEVEL,Z,V(30),F(50),Y(30),IIN(30),E(30),JSTAR,S(230),SSTAR(50),
     2SB(50),NNV,NNF,NNII,NNE,NNS,NCI
      COMMON /LCOM2/ NG,LR,LGREEN,LER,IAL,IDA
      COMMON /DEF/ SA(1 ,50)
      DIMENSION HOLD(50)
      IX=ICODE-1
      GO TO (1,2), ICODE
1     WRITE (6,6) ZSTAR,LSTAR,LEVEL,Z
      RETURN
2     WRITE (6,8) (SB(I),I=1,NNC)
      IF (LGREEN.EQ.0) GO TO 5
      DO 4 J=1,NG
      HOLD(J)=0.0
      DO 3 I=1,NNB
      IQ=INT(SB(J))
      HOLD(J)=SA(IQ,J)+HOLD(J)
3     CONTINUE
      WRITE (6,10) J,HOLD(J)
4     CONTINUE
5     WRITE (6,7) ZSTAR
      WRITE (6,9) NCI
      RETURN
C
C
C
6     FORMAT (15X,8HZSTAR = ,F20.4,/,15X,9HLSTAR = ,I2,/,15X,8HLEVEL = ,
     1I2,/,15X,4HZ = ,F24.4)
7     FORMAT (15X,8HZSTAR = ,F20.4)
```

```
8     FORMAT (13X,4HW = ,20(2X,F4.0))                                    P  35
9     FORMAT (13X,32H*** NUMBER OF POINTS EXAMINED = ,I10)               P  36
10    FORMAT (13X,15HCRITERA NUMBER,,I3,6H    =   ,F5.2)                 P  37
      END                                                                P  38
C     ******************************************************************Q   1
C     SUBROUTINE ORDER                                                   Q   2
C     THIS SUBROUTINE PUTS THE ELEMENTS OF AA IN INCREASING ORDER        Q   3
C                                                                        Q   4
      SUBROUTINE ORDER                                                   Q   5
      COMMON /UCOM1/ N,M,C(30),A(30,30),B(30),AL(30),SIGMA(50),ZSTAR,LST  Q   6
     1AR,LEVEL,Z,V(30),F(30),Y(30),IIA(30),E(30),JSTAR,S(200),SSTAR(30),  Q   7
     2BB(30),NNV,NNF,NNII,NNE,NNB,NCI                                    Q   8
      DO 3 I=1,NNB                                                       Q   9
      DO 2 J=I,NNB                                                       Q  10
      IF (BB(J).LT.BB(I)) GO TO 1                                        Q  11
      GO TO 2                                                            Q  12
1     TEMP=BB(J)                                                         Q  13
      BB(J)=BB(I)                                                        Q  14
      BB(I)=TEMP                                                         Q  15
2     CONTINUE                                                           Q  16
3     CONTINUE                                                           Q  17
      RETURN                                                             Q  18
      END                                                                Q  19
```

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A DECISION PROBLEM INVOLVING THE INTRODUCTION OF RTOL AIRCRAFT INTO COMMERCIAL AIR TRANSPORTATION SYSTEMS

by

Gary A. Schmitt

(ABSTRACT)

This study is concerned with determining the feasibility of introducing a reduced takeoff and landing (RTOL) aircraft into the national aviation system. In considering this problem, a multiple criteria decision model based on the responses of airline executives was developed to describe the RTOL utilization problem.

The exact problem that is considered in this thesis is, for a given set of itineraries, determine the itineraries for which aircraft (RTOL or CTOL, conventional takeoff and landing) are to be assigned such that the amount of fuel used, delay and noise levels are to be minimized. These assignments are subject to aircraft, airport, system and budgetary constraints.

A decision-making procedure was formulated to solve the decision problem utilizing an interactive, multicriteria programming procedure. This procedure was developed to consider the use of 0-1 decision variables.

Two example problems are presented. The air transportation systems considered in the examples include (a) six airports in New York State and (b) five major airport hub areas in the northeastern section of the United States.

The results obtained in this study demonstrated that RTOL has the potential to be utilized in situations that include: (a) the anticipated use of satellite airports, (b) the need to meet the requirements of reduced noise levels and reduced runway lengths and (c) short haul itineraries consisting of several short hops.