A DYNAMIC PROGRAMMING APPROACH TO THE DAILY ROUTING OF AEROMEDICAL EVACUATION SYSTEM MISSIONS

THESIS

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THESIS

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Preface

I would like to take this opportunity to express my appreciation to all of those who have helped and supported me through this effort. The comments provided by my advisor, Dr. James Chrissis, were invaluable in the research effort and in preparing the written document. I would also like to thank my reader, Dr. Yupo Chan, for his comments on the document and also the information he provided on various routing algorithms.

I would also like to express my appreciation to the people at the Patient Airlift Center for the information they provided. Maj. Bruce Bossart was especially helpful in filling in information about the way the AES currently operates and in allowing me access to the data used in this study. Capt. Kelley Kash was also very helpful. During my visit to gather data, he took the time to show me how their current system works; I greatly appreciate his efforts.

Most of all, I would like to thank my wife, Sandy, for putting up with all the late hours and the continual encouragement she provided throughout the past several months. Without her support, I wouldn't have been able to finish this project.

David C. Mullen

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Abstract

This thesis examines vehicle routing algorithms to determine if they would be applicable to routing Aeromedical Evacuation System (AES) daily missions.

The objective of the study was to develop an algorithm that could find the optimum routing to visit airfields selected by the Patient Airlift Center (PAC) schedulers. If such an algorithm could be developed, a subobjective was to see if such an application would result in a savings in total flying distances for these missions. Such savings could be used to shorten the mission time to allow another airfield to be serviced by a mission, reduce the operating costs of the AES, or allow more training time for the crews manning the system.

A forward dynamic programming algorithm developed by Desrosiers, Dumas, and Soumis was modified to model the AES. This algorithm was then applied to several actual AES missions to determine if a distance savings could be realized. Of the 53 missions examined, 14 resulted in routings with shorter distances. The savings varied from 4 to 179 miles. The other 39 resulted in the same routing as that determined by the schedulers.

Overall, the savings realized were insignificant showing that the schedulers are routing the missions in an efficient manner. The algorithm does however, have the potential to save time in the scheduling process.

Keywords: Theses (GC)

A DYNAMIC PROGRAMMING APPROACH TO THE DAILY ROUTING OF AEROMEDICAL EVACUATION SYSTEM MISSIONS

I. Introduction

Introduction

Vehicle routing is an important aspect of any system involved in the delivery of goods or services. Examples of such systems include school bus routing, garbage collection routing, and on a larger scale, airline or aircargo routing. These vehicle routing problems (VRP) usually have as their objective either to minimize costs for a given service level, or to maximize service for a set cost level (10:113). The method used to solve these types of problems can differ based on constraints placed on the problem. These constraints can include:

(i) Vehicles must pass through certain nodes;

(ii) vehicles must pass through certain arcs;

(iii) all vehicles located at one node;

(iv) vehicles are located at different nodes.

(v) The route lengths are limited by time and/or vehicle capacity;

(vi) the route lengths are unrestricted;

(vii) only one vehicle is available;

(viii) more than one vehicle is available.

(14:112)

This research focuses on vehicle routing algorithms that can be used to assist in the daily routing of the Aeromedical Evacuation System (AES) missions. Like many other systems, the AES must pick up and deliver its goods (in this case patients) at many locations and under certain constraints.

AES Background

The idea of using aircraft to transport patients was conceptualized by Capt. George Gosman in 1910, but his idea did not gain widespread acceptance until World War II (13:8). Even then, only a small percentage of wounded were returned to the United States by air. In fact, of the more than 86,000 casualties returned to the U.S. in 1945, only 22.5% came by air transportation (13:8).

The movement of patients by air became the policy of the U.S. armed forces in 1949 when the Secretary of Defense issued this directive:

> In both peace and war, the transport of patients of the Armed Forces shall be accomplished by aircraft when air transportation is available and conditions are suitable for air evacuation unless medically contraindicated (13:9).

Medical personnel in both the Korean and Viet Nam conflicts have expressed their belief that air transportation of casualties greatly increased the probability of survival for those casualties. The Viet Nam-era Navy surgeon general said "the rapid evacuation to specialized medical facilities ... is giving Vietnam casualties the best chance of survival in the history of warfare" and, then-Air Force Surgeon General, Lt Gen Kenneth Pletcher stated "thousands of US fighting men are alive today because speed, new techniques, and trained personnel of aeromedical evacuation teams are giving the wounded in Vietnam better than twice the chance of survival than ever before" (13:10-11).

Many hospitals in large metropolitan areas today use helicopters to transport critically injured and ill patients to treatment centers. Most of these systems service only a single metropolitan area; a few provide more far-reaching service. One of the larger civilian systems, Flight for Life, operated by St. Anthony's Hospital in Denver, links remote areas of Colorado and several surrounding states with the large hospitals in the Denver area (15:15). But none of these systems is on a scale with the DOD AES. In 1981, 42 US hospital-based systems handled a total of 30,000 patients; the AES served more than twice that number (15:16).

DOD Hospital System. The DOD operates 650 hospitals throughout the United States (13:51). Budget constraints and the supply of trained specialists do not allow each of these facilities to be fully staffed with each type of specialist. Even if it were possible to fully staff all medical facilities, it would be an inefficient use of these specialists by having them at a facility where their services may be demanded only two or three times a year. Many of these facilities are small clinics which provide only primary care and refer patients to larger facilities when specialized treatment is required. The DOD has regionalized its hospital system (13:12). Small local clinics are grouped together based on geographical region and rely on a regional hospital to provide such specialized treatments. Since all medical facilities do not have the capability to provide all services, the need exists to transport patients to where they can receive required treatments.

Aeromedical Evacuation System. The obvious need for the AES is the wartime evacuation of casualties to rear areas where proper care can be administered. However, to ensure that AES personnel are properly trained and prepared to perform this wartime function, the DOD operates the AES during peacetime. A 1975 General Accounting Office audit questioned the need for peacetime operation of the Aeromedical Evacuation System. Then-Assistant Secretary of the Air Force David Taylor responded by saying that the system was needed to assure the AES's capability to support wartime requirements and that in particular, the system must have the potential to support:

- total force structure in times of contingencies;
- medical crew exposure and experience with real patients to maintain qualification and proficiency;

- patients arriving from overseas who require further movement within CONUS;

- CHAMPUS cost reduction program;

- over 650 federal medical facilities with frequent service; and

- urgent and priority patients requiring life, limb, or sight saving care when the required care is not available locally.

(13:15)

The primary peacetime mission of the AES is to transport active-duty patients to ensure the combat readiness of U.S. forces. However, dependents and retired patients can use the system if their movement does not detract from the primary mission (13:11). In 1975 the Military Airlift Command (MAC) was designated the manager for DOD aeromedical evacuation. MAC has 18 C-9A aircraft (12 to support CONUS operations) to meet the demands placed on the system (1:1). Each aircraft can accommodate 40 patients: 34 ambulatory and six (waiverable to eight) on litters (4). In addition C-130 and C-141 aircraft can be used to transport patients in emergency situations.

Patients are assigned a priority based on their condition to ensure that the most critical patients are moved first. The three patient priorities and desired movement times are:

Routine - pickup within 72 hours

Priority - pickup within 24 hours and least possible delay in delivery

Urgent - immediate pickup is required to "save life or limb, or to prevent complication of a serious illness."

(1:1)

Also, a routine or priority patient may be categorized as "special." Such patients may not require immediate pickup, but they may require special handling. Examples would be a patient that requires no enroute stops between pickup and delivery or that special equipment be onboard the aircraft.

Figure 1 shows the six AES regions in the United States. Patients are moved within these regions to provide the required care. If a hospital within the region cannot provide the needed care, then a patient may be moved to a hospital in another region that can provide the service.

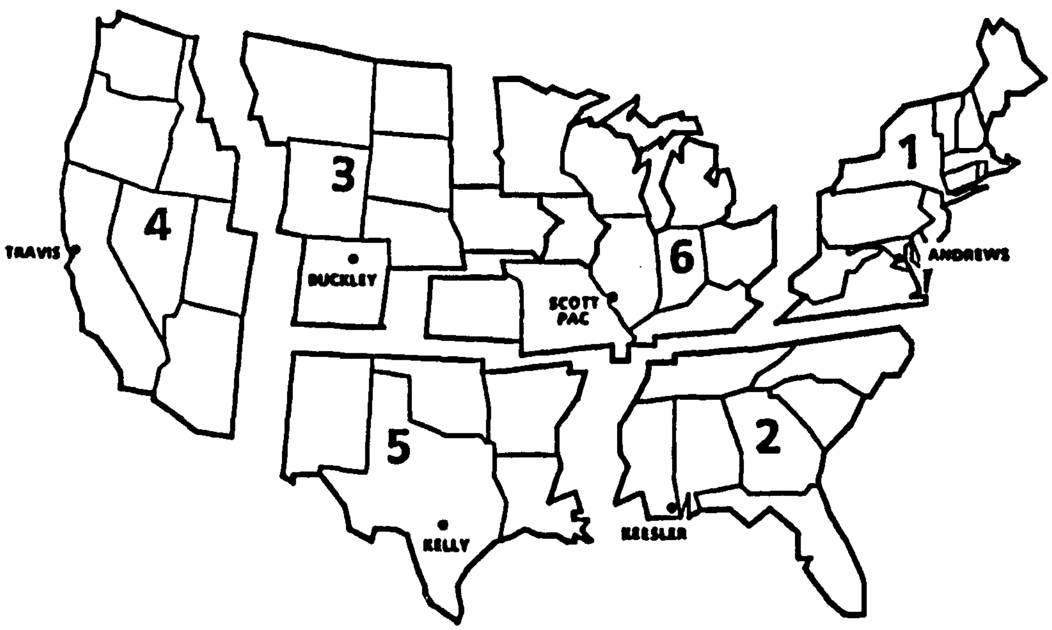


Figure 1. AES Regions (1:3)

AES Scheduling. When a patient is identified as requiring treatment not available at the local facility, the Armed Services Medical Regulating Office (ASMRO) has the responsibility of selecting the facility where treatment will be provided. Until 1980, the Army directed this regulating function at the Pentagon. In 1980, in order to streamline the process, ASMRO was collocated with the Patient Airlift Center (PAC) and in 1984 the Air Force assumed responsibility for this function (13:13). Once the patient and the facility are identified, and it is determined that air transportation is required, the information is passed to the PAC for scheduling.

ASMRO and PAC are located at Scott Air Force Base, Illinois in region 6. Scott is the home of the 375th Aeromedical Airlift Wing which has overall responsibility for the AES and all AES aircraft and crews are based there.

The AES operates using a fixed weekly schedule of six missions per day. Each mission has the starting and ending nodes set, and intermediate stops determined by the region being served and the patient demand for that particular day. Of the twelve aircraft assigned to CONUS operations, on any given day six are used for scheduled missions, one is available for local training or "urgent" requests, one is designated as a spare for the scheduled missions and the other three are undergoing periodic maintenance inspections (15:102). Table 1 shows the current weekly schedule.

Table 1

AES Weekly Schedule (1:3)

MON	TUES	WED	THUR	FRI	SAT	SUN
0126		0634	0444	0456		0621
		0666	1614	0436	0666	
0654	0456	0654	1416		0634	1416
0663	0336		0636	0663	0336	
06X6	0656		0655	0526	0655	0526
0622	0222	0256		0622	0256	06X6
	0636	0621	0126		1614	0456
06X1	0111	0116		0611	0116	

The four-digit mission numbers are interpreted as follows. A "1" as the first digit indicates a cross-country mission while the second, third, and fourth digits indicate the origin, service, and destination regions respectively. An "x" as the third digit indicates that the mission will be routed as necessary to meet demands. As the table shows, several missions continue over two or three days. As an example, the 0634 mission starts at Scott AFB in region 6 on Wednesday, services region 3 and ends at Travis AFB in region 4. On Thursday, it continues starting at Travis AFB, provides service to region 4 and terminates again that night at Travis AFB. On Friday, it starts at Travis AFB, services region 5 and then terminates back at home station, Scott AFB.

In late 1988, the PAC completed installation of a computerized scheduling system called the Automated Patient Evacuation System (APES). The APES has several objectives including:

Provide more accurate and timely transfer of data/messages between AE units.

Provide flight clinical coordinator with more complete accurate patient data.

Generate proposed mission plan. Optimize mission plan for medical need and airlift resources.

Automate preparation of patient movement documents and reports

Notify origin/destination medical facilities through DMRIS interface.

Enhance mission control for patient add-ons/cancellations.

Automate procedures and quality control for urgent/priority patient movement.

(13:144)

The system handles the data functions well, but falls short when it comes to routing missions. It does not optimize the routing at all and only schedules about 50% of the patients. Each day, the PAC schedulers input mission templates into the system for the missions scheduled for that day. These templates are typical itineraries that these missions have flown in the past. APES then does a patient-by-patient search to match patients against these templates, inserting those that fit, leaving the rest for the schedulers to input manually (4).

Summary. It is obvious that the primary purpose of the AES is the wartime movement of casualties to where their injuries can be treated. It is through the peacetime operation of this system that the crews receive the training and experience necessary to enable them to perform their wartime mission.

Problem Statement

Currently, some medical facilities must transport patients by ambulance to distant airfields in order to meet AES flights (1:2). Doing this results in an ambulance and two or more attendants being unavailable for emergency calls for most of the day. The problem then, is to find a method to route the AES missions more efficiently thus shortening the duration of the missions and possibly allowing time to serve more airfields while still meeting the time constraints placed on these missions. Also, by more efficiently routing the missions, a flying hour reduction could be realized which could either result in cost reductions or in allowing more training time to be made available to the flying unit within the AES thereby increasing readiness.

Scope

The scope of this thesis is limited to the daily routing of the AES missions serving the six regions within the continental United States. The primary focus is developing a vehicle routing algorithm that can aid the Patient Airlift Center (PAC) schedulers in routing these missions.

In a previous thesis pertaining to the AES, Whetstone discussed four types of VRP (19:1). In particular, he dealt with the assignment routing problem and developed a heuristic for improving the weekly schedule. The work herein deals with the daily routing problem and the models examined in this effort will deal with the daily routing. Since heuristics play such an important role in scheduling these missions, the scheduler must be able to revise the routes determined by the algorithm to account for medical considerations that perhaps cannot be modeled explicitly. It must interface with the APES system to access the data APES maintains on patients and airfields. This will allow the user to apply the heuristics he has developed to schedule missions, or make changes to missions more quickly than the current manual method of scheduling.

By focusing on the daily routing, an algorithm can be developed that provides the maximum service level possible in conjunction with the limit of eight stops set by current policy (13:14). These eight stops can then be "optimally" routed using the selected algorithm resulting in a decrease in flying time and cost savings.

Assumptions

The main assumption in this research is that the AES will continue to use a fixed weekly schedule (as described previously) with fixed start and end nodes for each of the daily missions.

The PAC has started using the APES. It tracks the patients and has a limited capability to route missions. This research assumes that the approach discussed herein can be implemented so as to interface with APES, allowing access to the patient and airfield data within APES.

Outline of Following Chapters

Chapter II provides a review of relevant literature. It includes a section covering previous studies of the AES and another discussing vehicle routing algorithms that could be used. The third chapter addresses the selected algorithm in detail. An example problem and the results obtained by applying the algorithm to several missions are discussed in chapter IV. Chapter V discusses recommendations for further study in this area and the conclusions of this research.

II. Literature Review

This chapter reviews the literature related to the AES and vehicle routing. The first section looks at three recent studies of the AES. The second section discusses various vehicle routing algorithms.

AES Literature

In his 1984 dissertation, McLain looks at the planning aspects of the AES. He states his purpose as the design/ redesign the aeromedical planning system. To accomplish this he says there are two major design tasks; create 1) an information system and 2) a decision making system (15:34-35). In his research he notes several conflicts which create problems in planning for this system. One of the more important conflicts arises when selecting measures of performance for the system. He says that the system serves many different client groups and that the goals of these groups create a conflict. As an example, one group of clients is the patients served and another is the taxpayers who provide the funds to operate the AES. The taxpayers' goal would be to minimize the costs of operations which is in conflict with the patient's goal of minimizing delays (15:76). As an example, a Government Accounting Office (GAO) and Air Force Audit Agency report questioned some flights which served small numbers of patients. In response, the system planners imposed restrictions on the minimum number of patients required to fly a mission (15:69). While this may have improved efficiency in terms of number of patients served per mission, it resulted in a decreased level of service.

Another problem he noted was that certain biases impacted on the choice of treatment facilities. In general, patients are transported to hospitals of their own service (i.e. Army patients to Army hospitals), even if a facility of another service were closer and could provide the same care (15:6). ASMRO only has approval authority for routine, inpatient transfers; the local facility and physician coordinate for higher priority patients and outpatient transfers (15:28). These policies can put unnecessary demands on the system which result in inefficient operations.

A third problem McLain encountered was that the system was having to cope with problems of increasing demand while at the same time the available resources were decreasing (15:139). Finally, he encountered a problem in determining whether the patients were driving the system or the system was driving the patients. What this means is that it is likely that physicians are timing movement requests to coincide with the known AES schedules (15:146).

In modeling the system McLain looked for dominant flow patterns and found several. He noted that facilities served by two airfields, Kelly and Andrews AFBs, were the destinations for one-third of all patient transfers (15:154). He proposed linear programming (LP) as a possible modeling and solution technique for the routing problems. In chapters 4 and 5 he examines increasingly more complex models; starting with the Single Vehicle, Many-to-Many Routing Problem (SVMRP) and progressing to the Multiple Vehicle, Multiple Depot, Many-to-Many Routing Problem (MVMDMRP). The study presented herein treats each mission as independent, and only looks at the SVMRP class.

In a 1986 report, Lee looked at policy decisions which have affected the AES and some proposals to improve service.

Several policy changes have been instituted in the AES which have caused the system to reach a saturation point (13:3). Lee specifically noted four decisions which have contributed to system saturation; these are:

> 1) the 1975 transfer of two C-9A aircraft to Europe to provide operational support for theater commanders.
>
> 2) a 1979 decision to reduce the maximum number of enroute stops for a given mission from ten to seven (which including the final stop allows eight total stops on a mission).
>
> 3) a 1978 policy change allowing outpatients to use the AES
>
> 4) a decision in 1982 to cut increasing CHAMPUS costs by using the AES to transport patients to military facilities who would normally use CHAMPUS benefits at civilian hospitals.
>
> (13:13-14)

The first two decisions reduced the level of service of the system and the others increased the demands placed on the system which, when combined, have caused the current overload condition. This problem, increasing demand and decreasing resources, was also noted by McLain (15:139). In particular, Lee says that the decision to reduce the number of stops reduced the capability of the system by 30% and created a requirement for 40 hospitals previously served by the system to transport patients by ambulance to facilities over one hour away (13:42). In addition, between 1975 and 1984 the demands on the system increased by nearly 50% (35,473 patients in 1975 to 52,039 in 1984), causing the percentage of patients required to remain in the system overnight (RON) from 28% to 40% (13:43).

To counter this saturation, Lee discussed several proposed changes to improve the level of service. The most drastic recommendation came from the GAO in 1975. They recommended that patients who were eligible for CHAMPUS benefits not be authorized to use the AES. These patients accounted for 30% of the transfers in 1973. The Air Force responded by citing concern in Congress over rising CHAMPUS costs (13:28). Lee contends that cutting stops that serviced outpatients only would be a better approach. He noted that during the week of 1-7 May 1985, 40 of 248 total stops serviced outpatients only and estimated that service for inpatients could have been increased by 19% if those 40 stops were eliminated (13:29). Another policy change that Lee says would increase the level of service would be the return of the two European C-9As to domestic use (13:76). Lee said that even this would not be enough to relieve the current saturation, and he recommends implementing a Hub-Spoke concept studied in 1983 (13:77). Under this plan four C-9As would fly out of Scott AFB daily to service four quadrants of the U.S.. The C-9s would service major nodes in the system and then smaller, more efficient aircraft would fly spoke routes from these nodes to service the areas around each hub. Lee describes a number of benefits from implementing this plan; they include:

- more timely service to patients in remote areas
- lower flying hour costs for the smaller aircraft
- increase the number of stops available each day
- estimated increase in same-day delivery of patients 85-90% versus the current 63%

(13:77-78)

A more detailed account of this proposal is available in the Lee report (13:Appendix E).

Lee himself notes that policies are difficult to change and that the return of the two C-9s from Europe is doubtful (13:15). With the current federal budget problems, it is also doubtful that funds will be made available to purchase the new aircraft that would be required to implement the hub-spoke concept. It appears that for the near future the AES will continue to operate as described earlier.

Whetstone's thesis in 1988 developed a heuristic algorithm to improve the weekly schedule. He found that four constraining factors needed to be considered in modeling the problem. Two of these were vehicle constraints (# of vehicles available each day, and capacity of each vehicle) and two constraints were subjective and set by the user (the # of patients required to assign a vehicle to a region and the # of patients required to end a mission at a location other than Scott AFB, α and β) (19:27-28). In chapter III of his study, Whetstone identifies the six variables used by the algorithm and presents the algorithm itself (19:32-34). The fifth step of his algorithm allows for an additional vehicle to be assigned to a region if the number of patients requesting service exceeds vehicle capacity. One note of caution needs to be added to this step. While the total patient demand in a region may exceed the vehicle capacity on a given day, the capacity on any of the legs may not be exceeded because patients both enplane and deplane at each stop. Increasing the number of planes in a region because the overall demand exceeds capacity could result in two vehicles operating in a region when only one is really required.

Whetstone applied this algorithm to data obtained from the PAC and arrived at an improved weekly schedule based on the frequency of customer demands (19:38). He then performed sensitivity analysis by varying the range of α and β and varying patient demand to account for seasonal changes and found that the initial improved schedule was still valid over the range of α and β and for seasonal variations (19:45).

Lee, McLain, and Whetstone all recommended that further work be done on the daily routing problem which is the objective of this study. The next section looks at various routing algorithms to determine if they are suitable for this purpose.

Routing Literature

The vehicle routing problem (VRP) is a variant of the traveling salesman problem (TSP). The objective of the TSP is to find the minimum distance tour that visits each of the n nodes in a problem once, and only once, and then returns to the origin (11:377). A generalized formulation of this problem is given in Chan and Rowell (5:11) and is shown below.

$$\text{Min.} \quad \sum_{i \in I} \sum_{j \in I} d_{ij} x_{ij}$$

(d_{ij} is the distance between nodes i and j)

$$\text{s.t.:} \quad \sum_{j \in M_m} x_{mj} = 1 \quad \text{(m is origin)}$$

$$\sum_{i \in \bar{M}_n} x_{in} = 1 \quad \text{(n is destination)}$$

$$\sum_{i \in M_j} x_{ij} - \sum_{i \in M_j} x_{ji} = 0 \quad \forall j \in I,\ j \neq m,n$$

(provides a continuous path through all remaining nodes)

$$\sum_{i \in J} \sum_{j \notin J} x_{ij} \geq 1$$

(subtour breaking constraint)

It is well documented throughout the literature that this type problem is NP-hard. As the number of nodes increases, so do the number of constraints and the solution time increases in nonpolynomial time. As an example, Merrill formulated a seven node TSP and solved it using a microcomputer. The solution took more than six hours (16:31). When the additional constraints for the precedence (pick up a patient before you can deliver him) relationships are included, the solution time would increase even more. With the added fact that many AES missions involve eight nodes, and the system flies six missions per day, such a formulation would take more than 24 hours to obtain a solution, thus being of no use to the AES schedulers.

Merrill proposed the use of Bartholdi and Platzman's heuristic algorithm based on space-filling curves to solve a TSP involving the routing of MAC's flight inspection aircraft (16). Like the AES, the flight inspection aircraft are based at Scott AFB and must travel to various bases throughout the CONUS to perform their mission (16:1). The essence of this method is that the points to be visited are mapped onto a unit square. The square is then collapsed iteratively and geometrically into smaller and smaller squares until all points are touched by the "curve" created (3:123). While this methodology does not find the optimal tour, it is estimated in several sources to be within 25% of the optimum, even with very large N (3:124, 8:806). Merrill found that for small N, the algorithm produced results within 10% of the optimum (16:75). Bartholdi and Platzman include source code in BASIC for this algorithm in their article (3:124-125). The output of this method is a numbered list of all the points within the area of interest which can be stored in something as simple as an index card file. Golden and Assad mention that this method was used by a "meals on wheels" service and reduced travel times by an average of 13% (8:806). One disadvantage of this method for use in the present study is that it does not account for pickup/delivery precedences. Also, not all AES missions start and end at the same node. Therefore, this method could not be used as the primary method of routing AES missions. However, it could be used to insert stops in a mission that did not use all eight stops and that was under the 16 hour crew-day limitation.

Standard TSP algorithms do not account for pickup/ delivery precedence constraints and therefore would not be useful in this problem. Recent work has been done in the area of problems which have customers with pickup and delivery relationships. Kalantari, et. al. propose a branch-and-bound technique for the solution of the TSP with pickup and delivery customers (11:377). Included in his paper are algorithms to solve both single and multiple vehicle cases and also considers vehicles with both finite and infinite capacity. A problem with this method is, as the authors noted, that while such an approach may be practical on small problems, large scale problems would need to resort to heuristics to reduce the problem.

Another recent development in vehicle routing area are studies concerning routing with time windows. A time window at a node is a "pre-specified time interval within which the customer must, or desires to, be visited" (9:253). While AES missions do not have any explicit time windows for visiting demand locations, there is an implied not-later-than time at each node which, is the latest time the aircraft can depart a node and reach its final destination within the 16 hour crew-day. Kolen, et. al. describe a branch-and-bound method for solving the time-constrained vehicle routing problem (TCVRP) 12:266). Included in their discussion are computational results. Solomon describes several heuristic algorithms for solving the TCVRP (18). Particularly promising were insertion heuristics which found solutions very close to the optimum (18:264). These methods however, do not solve the pickup/delivery problems noted earlier.

An entire issue of the American Journal of Mathematical and Management Sciences (vol. 6, nos. 3&4) was devoted to time-constrained vehicle routing problems. Two of the papers presented dealt with the so-called dial-a-ride problem (6,17). The dial a ride problem deals with scheduling vehicles to serve customers with specified origins and destinations (17:328).

Psaraftis discusses two algorithms for this type of problem; the "Group/Clustering/Routing" (GCR) algorithm, and the "Advanced Dial-A-Ride algorithm with Time Windows" (ADARTW). The GCR approach allows customers to be served by picking them up and/or delivering them "reasonably close" to their desired times, while the ADARTW approach is stricter in adhering to time windows (17:330). He also presents computational results applying both algorithms to a data set and comparing how the two algorithms fared against each other (17:350).

The most promising method, and the one which most closely models the AES, is a dynamic programming approach to the dial-a-ride problem presented by Desrosiers, et. al. (6). The algorithm presented minimizes distance traveled, uses a single vehicle, models vehicle capacity constraints, and considers pickup/delivery precedence requirements (6:302). Another advantage of this algorithm, is that while the other algorithms previously mentioned assume the same starting and ending location for the vehicle, this algorithm allows for the start and end nodes to be different; something very common in the AES missions. A more detailed discussion of this method appears in the next chapter.

III. Daily Routing

Introduction

This study proposes a two step method of routing the daily AES missions. The first step is selecting the stops and the second is routing the missions through those stops.

The AES schedulers must choose at most, seven intermediate stops from as many as 20 requesting service on any particular mission. Currently the stops are selected manually (see page 9 of this report.) The recommendations section of the next chapter discusses some alternatives to this method.

This research assumes the stops will continue to be selected in the manner previously described. Once the stops have been selected, the routing algorithm presented in the next section can be employed to find the optimum routing based on minimizing total flight distance.

The routing algorithm proposed by this study is based on the dynamic programming algorithm developed by Desrosiers, Dumas, and Soumis. Their formulation of the single vehicle routing problem with time constraints is as follows:

$$\text{Min} \quad Z = \sum_{i=0}^{2n} \sum_{j=1}^{2n+1} D_{ij} \, x_{ij} \qquad (1)$$

$$\text{s.t.} \quad \sum_{j=1}^{n} x_{0j} = 1 \qquad (2)$$

$$\sum_{i=n+1}^{2n} x_{i,2n+1} = 1 \qquad (3)$$

$$\sum_{i=0}^{2n} x_{i\ell} = \sum_{j=1}^{2n+1} x_{\ell j} = 1 \qquad (4)$$

$$x_{ij} \text{ binary} \qquad (5)$$

$$A_i \le t_i \le B_i \qquad (6)$$

$$t_i + M_i + T_{i,n+i} \le t_{n+i} \qquad (7)$$

$$x_{ij} = 1 \Rightarrow t_i + M_i + T_{ij} \le t_j \qquad (8)$$

$$0 \le y_i \le C \qquad (9)$$

$$x_{ij} = 1 \Rightarrow y_i + C_j = y_j \qquad (10)$$

(6:304-5)

The equations are explained as follows:

(1) is the objective function with D_{ij} being the distance along an arc.

(2) & (3) a single vehicle operating

(4) each node only visited once

(6) time window constraints

(7) origin/destination precedence requirement

(8) flow/time relationships

(9) vehicle capacity constraint

(10) flow/capacity relationships

(6:305)

As the number of nodes increases, the number of possible states generated at each iteration grows dramatically. The authors have developed nine state elimination criteria to limit the number of states (6:310-313). The first criteria states that a node may not have already been visited. The second criteria eliminates destinations whose origins have not been previously visited. Criteria three eliminates origins that would violate vehicle capacity constraints. The remaining six criteria eliminate various states based on the time windows imposed at each node.

Some modifications need to be made to more realistically model the AES. In some instances, a patient requires special handling. While their priority may be routine, a medical condition may exist which requires that the aircraft fly directly to that patient's destination, without intermediate stops. This can be implemented in the algorithm by setting the distances from that origin to all nodes except the destination to very large values. This would drive the algorithm to making a direct flight between the two nodes.

The second problem is that the algorithm only allows one visit to each node. In many instances, there can be a pair of hospitals that both have patients going to and from the other hospital. This would require one of the bases serving these hospitals to be visited twice. A situation like this can be modeled by generating artificial nodes at both locations; one for patient pickup and one for patient delivery. Since the distance between the two nodes representing each base is zero, there will be no increase in flying distance for the mission.

The authors coded their algorithm in FORTRAN and ran 98 test cases against it, each having from 5 to 40 nodes. Using a Cyber computer, 76 of 82 cases having 25 or fewer nodes were solved in under two seconds (6:319).

The algorithm developed by the current research is presented in the next section.

Dynamic Programming Method

AES missions can be routed using the forward dynamic programming (DP) method presented by Desrosiers, et. al. (6), with some modifications.

Algorithm Variables. Several variables are used in this dynamic programming method; they are:

C = aircraft capacity in number of patients.

C_i = number of patients onboard leaving node i.

FT_i = flight time from previous node.

GT_i = ground time at node i.

T_i = Cumulative mission time to node i.

D_i = Cumulative mission distance.

n = the number of intermediate stops planned for the mission, not including the destination node.

k = the current stage.

Vehicle capacity, C, is 40 for AES C-9A aircraft and ground time is twenty minutes for a normal enroute stop, and fifty minutes for a refueling stop. Ground time at busy airports such as Los Angeles International are planned for one hour (4). FT_i is computed by dividing the distance between two nodes by 450 (the normal cruise speed for the C-9A (4)) and then adding twenty minutes to account for the slower speeds flown during departure and climb out, and approach and landing. T_i is computed by summing T_i from the previous node, FT_i from the previous node to node i, and GT_i for the current node i.

This study used great circle distances for the flying distances between bases. A program was written in BASIC to calculate a matrix of distances between bases served by a mission. For the interested reader, the source code has been included in appendix A along with the distance matrix for the example mission presented in the next chapter.

Routing Procedure. At each stage (k) of the procedure, states are generated. For each mission, k=n+2 stages will be created. Each state identifies the following:

({S},i): {S} = the set of nodes visited and i is the terminal node.

$L=(T_i, D_i, C_i)$: the state label.

At k=0, set {S} contains only the origin node for the mission, O. The label associated with this state is (2:00,0,x). The 2:00 represents the two hours of crew-duty-day used in preflight activities and x is the number of patients leaving the origin node on the mission. For all subsequent stages, create states by adding to the previous set {S}, an unvisited origin, or a destination node whose origin has been previously visited and create the state label.

The potential for growth in the number of states generated is enormous. For an AES mission with seven intermediate nodes and no precedence relationships other than visiting all intermediate nodes before the final destination, 448 states would be generated. At each stage, the number of states generated would be the mathematical combination of n nodes taken k at a time, multiplied by k or,

$$N = k * n!/[k!*(n-k)!]$$

where

N = the number of states
n = the number of nodes in the network
k = the stage number

Pickup/delivery constraints reduce many of these possible states. As discussed earlier, the authors presented several elimination criteria based on the time windows at each node. These do not apply to AES missions, but states are eliminated that would result in total mission time exceeding the 16 hour crew-duty-day restriction. There is also the possibility of eliminating states based on vehicle capacity limitations.

The dynamic programming algorithm as it applies to the AES is outlined below.

1) At k=0, ({S},i)=({O},O) L=(2:00,0,x)

2) Set k=k+1

3) Create new states ({S},i) by adding a single node i from the set of unvisited nodes (either an origin, or a destination whose origin has been previously visited and define their associated labels.

4) Eliminate states whose terminal node i is a destination node whose origin has not been visited.

5) Eliminate states whose T_i > 16:00 or C_i > 40.

6) If k=n+1, terminate. The optimal route is found by tracing back through the label numbers.

7) If k < n+1, return to step 2.

The next chapter presents the results of the study conducted by comparing the routing of actual AES missions against the routings obtained from applying this algorithm to those same missions. An example of the algorithm applied to an actual AES mission is also included.

IV. Results

This research examined historical data obtained from the PAC. The data covered a four week period from 6 March - 2 April 1989. The following section presents an example of the results obtained by applying the algorithm to an actual AES mission and the results obtained by applying the algorithm to the missions during the four week period.

Dynamic Programming Results

Example Mission. This example uses the 456 mission flown on Tuesday, 7 March 1989. Table 2 presents a list of the bases serviced on this mission, the destinations of patients at each node and the number of patients going to each destination.

The International Civil Aviation Organization (ICAO) has assigned four letter identifiers for each airfield. The first letter represents the country or region of the world. For example, all continental United States airfields have a "K" as the first letter of their identifier. The "ID" in table 2 is the remaining three letters of the airfield's ICAO identifier. A listing of ICAO identifiers for the missions examined in this study and their corresponding airfield names are presented in appendix B.

The actual mission visited the airfields in the order listed in Table 2 and the total enroute distance was 2307

Table 2

Base Information for 456 Mission

Node #	ID	Dest. ID	Number of Patients	Total Onboard
0	SUU	BLV	1	2
		SKF	1	
1	LUF	BIF	3	9
		SKF	1	
		BLV	3	
2	DMA	SKF	2	16
		BIF	5	
3	BIF	SKF	2	10
4	ABQ	SKF	3	13
5	SKF	BLV	12	16
D	BLV	Termination		0

miles. The dynamic programming solution for this mission is shown in Figure 2. The optimum solution is found by tracing back through the labels to be 0-1-2-4-3-5-D and represents a savings of 56 miles off the routing determined by the PAC scheduler.

In addition to the state elimination criteria listed in chapter III (pg. 30), any state that would have node 4 visited prior to both nodes 1 and 2 was eliminated. This was done after looking at a map of the western U.S.. Since ABQ (node 3) is so far east of both LUF and DMA nodes (1 and 2), it is obvious that the shortest distance to SKF (node 5) would be found by visiting both nodes 1 and 2 prior to node 4.

k	States			Label Number	Prior Label
	Set	End Node	Labels		
0	{O}	O	(2:00,0,2)		
1	{O,1}	1	(3:52,543,9)	1	0
	{O,2}	2	(4:07,653,9)	2	0
2	{O,1,2}	1	(5:02,765,16)	3	2
		2	(4:47,655,16)	4	1
3	{O,1,2,3}	3	(5:58,883,10)	5	4
	{O,1,2,4}	4	(6:04,930,19)	6	4
4	{O,1,2,3,4}	3	(7:40,1122,13)	7	6
		4	(7:34,1075,13)	8	5
5	{O,1,2,3,4,5}	5	(9:17,1551,16)	9	7
6	{O,1,2,3,4,5,D}	D	(11:10,2251,0)	10	9

Figure 2. DP Results for the Tues 456 Mission

Study Results. Initially, the dynamic programming algorithm was applied to all of the missions flown during the first week of the time period covered. Of the 42 missions flown the first week, 33 resulted in the same routing as that determined by the PAC schedulers. Nine missions resulted in shorter flying distances. The range in distance saved was from 14 to 179 miles with a mean of 66.4 miles. The average total flying distance for these missions was approximately 2000 miles.

Three missions showed savings of more than 100 miles, or approximately five percent; they were the Monday 611, Tuesday 656, and Thursday 444 missions. The results from the dynamic programming algorithm for these missions are presented in appendix C. The 611 mission is also a scheduled mission on Fridays. The algorithm was then applied to these four missions for all four weeks of data obtained from the PAC. These missions were selected because these missions showed potential for significant savings. The results from these missions are shown in Table 3.

Table 3

Mission Distance Savings

	611	656	444
Wk 1	103 32	113	179
Wk 2	0 0	11	0
Wk 3	5 0	0	4
Wk 4	14 52	N/A	0
MEAN	25.75	41.33	45.75

The high distances saved in the first week were not realized in subsequent weeks. One possible explanation for the savings in the first week is that one or more patients may have required direct delivery on those missions, and that these special routings were not indicated in the data.

On the whole, the distances saved by applying the dynamic programming algorithm were insignificant. This indicates that the current manual method of routing provides reasonably efficient routing for these missions. Merrill also found that attempts to optimize the routing of Flight

Inspection Aircraft from Scott AFB also resulted in insignificant savings (16:75).

One possible explanation for this could be that the heuristics developed by schedulers over time lead to "optimum" routings if the area covered is large and the nodes in the network are widely dispersed. In all cases where the dynamic programming algorithm produced savings in mission distance, there were two or more bases clustered in a small area in comparison with the entire area covered by the mission.

System Flexibility

In McLain's dissertation, he mentioned the possibility that physicians were requesting transportation in response to the known schedule rather than the AES responding to patient demand. This research checked the frequency of visits to different bases on each mission in an attempt to determine how flexible the AES daily schedule actually is. Appendix D displays tables showing the frequency of visits to each base during each mission. Fifteen of the missions make the same stops each of the four weeks indicating that these missions have no flexibility in the bases they provide service to. Another nine missions made half or more of their maximum of eight stops at the same bases. These missions showed very little flexibility in the service they provide. One of the missions was flown only once during the study period. The other 17 weekly missions show somewhat more flexibility in the service they provided during the four weeks studied since only 2 or three nodes were visited every week. These results provides some evidence to support McLain's conclusion that the system is driving demand rather than demand driving the system.

Summary

This chapter presented the results obtained by applying the dynamic programming algorithm to actual AES missions. Overall, very little savings was realized by applying this methodology. The next chapter presents the conclusions of this research and recommendations for further study in this area.

V. Recommendations and Conclusions

Recommendations

The AES flies six missions per day, 365 days per year. Due to the volume of data and the time required to examine it, this study only examined the missions flown during a four week period from 6 March - 2 April 1989. While this is a small sample size, it is recent data and Whetstone, using aggregated data, noted that the variations in demand through a one year period were not significant (19:46).

The following sections discuss possible research extensions.

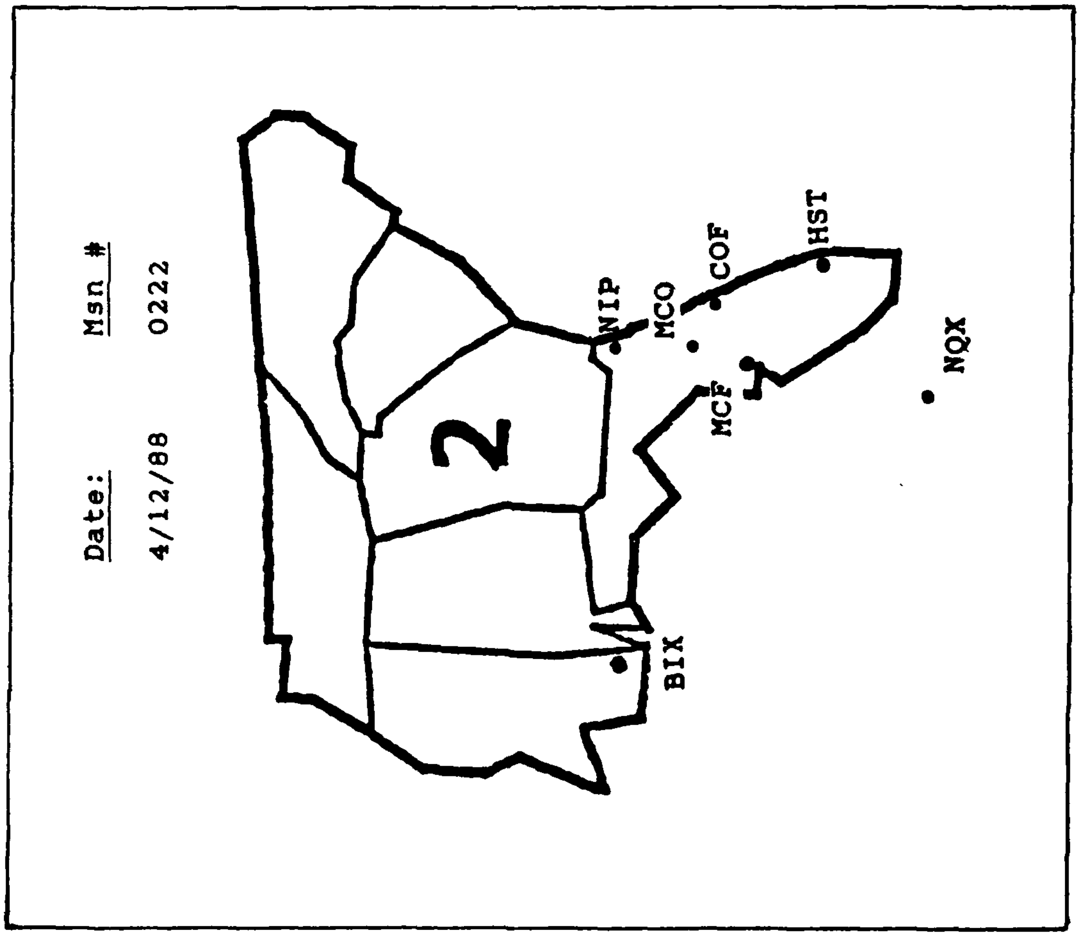
Larger Data Sample. One area for further study would be to encode the algorithm discussed herein and apply it to AES missions for a longer time period. This would provide statistically significant evidence as to whether or not any savings could be realized by implementing this algorithm.

System Responsiveness. McLain's dissertation indicates that the system may be driving the demand as opposed to the demand driving the system. The inflexibility of most of the missions indicated in the previous chapter supports his conclusion. A study to determine if this is the case would be extremely useful. Interviews conducted with physicians could be used to determine whether or not McLain's hypothesis is true. If such a study shows that McLain is correct, then new scheduling procedures would need to be implemented that would allow the demand to drive the system. After all, the peacetime mission of the AES is to prepare for its wartime task, the movement of casualties. It is doubtful that a fixed schedule would be able to accommodate the demands generated during wartime and the schedulers would need extensive computer support to quickly and efficiently route missions.

If the system proves to be more flexible than the data studied indicates, there are still some improvements that could be made to the APES to aid the schedulers in routing missions. These suggestions are discussed in the following sections.

Selecting Stops. The AES schedulers must choose at most, seven intermediate stops from as many as 20 requesting service on any particular mission. There are several ways of accomplishing this task. First, they could continue to select them manually as described earlier in this report (pg. 9). One enhancement to the APES would be a graphical display of the region being served and a listing of airfields requesting service. A possible configuration for this display is shown in figure 3. Such a display would provide a visual image of the region and the spatial relationships among the bases, thus aiding the scheduler in this difficult task.

Another possibility would be to build an expert system using the knowledge of the experienced schedulers at the



Origin	Dest.	#	Sp
BIX	MCF	2	
	HST	4	
	COF	4	
	NIP	2	
	MCO	1	
	NQX	1	
NIP	BIX	2	
MCO	BIX	6	
	NQX	1	
COF	BIX	7	
HST	BIX	2	
NQX	BIX	1	
	NIP	3	
	MCO	3	
MCF	BIX	4	

Fig. 3 Example Scheduling Aid

PAC. A copy of PACOI 164-2 was included in some background information sent by the CINCMAC Analysis Group regarding this problem (1:Attachment 1). This operating instruction provides some detailed heuristic rules concerning which patients to move on particular missions and which to hold for another mission so as to provide more direct service for the patient. This OI provides a good background for building an expert system. This information could be augmented by interviews with senior PAC schedulers.

A final possibility for determining the stops to visit would be a simple LP with the following formulation.

$$\text{Max} \quad \Sigma \quad U_i \, x_i$$

$$\text{s.t.} \quad \Sigma \quad x_i \leq N$$

$$x_i \quad \text{Binary } \forall \; i$$

U_i is the value of visiting a node determined by multiplying a weighting factor representing the patient priority by the number of patients in each priority category at each base. N is the maximum number of stops allowed on a particular mission. This could be determined by averaging the number of stops a mission made over a period of time.

Table 4 represents the average number of stops made by missions servicing the six regions over the period from 6 Mar to 2 Apr 1989. Cross-country missions are listed separately and identified as CC. If a mission had sufficient crew-day remaining and had not made eight stops, an insertion technique based on Bartholdi and Platzman's

Table 4

Average # of Stops per Region

Region	1	2	3	4	5	6	CC
N	7	7	7	7	7	8	5

space filling curve algorithm (3) could be applied to allow the mission to provide service to another base. This would reduce the requirement for some hospitals to dispatch ambulances and attendants to distant airfields to meet AES flights. As mentioned earlier, the use of ambulances for this purpose reduces the emergency response capability of those hospitals.

Any of these methods would work, but the expert system has the advantage of allowing the PAC to retain the expert knowledge developed over the years by its senior schedulers.

Mission Routing. While the approach taken in this study did not produce significant savings in terms of total mission distance, it has potential to be a time saving measure for the AES schedulers. This algorithm could be encoded and combined with the graphical display discussed in the preceding section to give the schedulers an interactive method of mission routing. Golden and Assad have noted several successes in using graphic and interactive routing methods in other VRP applications (8:804).

Multi-Vehicle Routing. This thesis treated each mission as an independent single-vehicle routing problem.

If all missions for a day were combined in a multi-vehicle formulation, it is possible that more significant savings could be realized.

As the literature suggests, even the basic TSP is an NP-hard problem which requires extensive computing power to solve. When pickup/delivery precedences and multiple vehicles are included, the computational requirements grow rapidly with the number of nodes in the network. American Telephone and Telegraph (AT&T) has developed KORBX to solve such large-scale problems. KORBX is an AT&T computer system that employs Karmarkar's algorithm to solve large-scale LPs.

MAC recently purchased KORBX for use in the CINCMAC Analysis Group and has already used the system to analyze mission routings in the Pacific and European theaters. These analyses resulted in more efficient operations in those two regions (7:3). Using KORBX, an analysis of the entire AES could be accomplished treating each day as a MVRP.

Conclusions

Routing AES missions is a complicated process. The schedulers must consider numerous variables including patient needs, airfield availability, and aircraft capabilities. The dynamic programming algorithm developed in this research can be used to route AES missions. In all cases examined, it did at least as well as the schedulers, and in some cases it improved upon their routing.

In the current peacetime environment the schedulers do an efficient job routing AES missions with the fixed weekly schedule. However, as the demands on the system increase and budget allocations decrease, as seems to be the trend, the task will become even more difficult. Furthermore, should the U.S. become involved in a conflict employing large numbers of troops, it is doubtful that the current fixed schedule would be able to handle the influx of casualties. These two possibilities would result in the need for increased computer support in the routing process.

Appendix A

BASIC Source Code for Computing Distance Matrices

```
10 DIM DIST(25,25),BSID$(25),BL(25.2)
20 LPRINT CHR$(27)":";
30 :
40 REM  ***  Lines 60-110 allow the user to input mission
information and then print out the header.   ***
50 :
60 INPUT "Enter # of bases:    ",NB
70 INPUT "Enter day of week:   ",DAY$
80 INPUT "Enter mission id:    ",ID
90 CLS
100 A$="          DISTANCE MATRIX FOR THE ":C$="MISSION"
110 LPRINT A$;DAY$;ID;C$
120 LPRINT
130 LPRINT SPC(5);
140 :
150 REM   ***  Lines 170-200 read the base id from the data
statements and then prints them out as the column headings
for the distance matrix.
160 :
170 FOR I = 1 TO NB
180    READ BSID$(I)
190    LPRINT USING "\  \";BSID$(I);
200 NEXT I
210 LPRINT
220 PI = 3.141593
230 :
240 REM   ***  Lines 260-310 read in the base latitude and
longitude from the data statements and then converts them to
radians.  ***
250 :
260 FOR I = 1 TO NB
270    FOR N = 1 TO 2
280       READ BL(I,N)
290       BL(I,N)=BL(I,N)*PI/180
300    NEXT N
310 NEXT I
320 :
330 REM   ***  Lines 350-430 compute and print the distance
matrix.  ***
340 :
350 FOR I = 1 TO NB
360    LPRINT USING "\  \";BSID$(I);
370    FOR N = 1 TO NB
380       IF I = N THEN DIST (I,N) = 0: GOTO 410
390       X=SIN(BL(I,1))*SIN(BL(N,1))+COS(BL(I,1))*
            COS(BL(N,1))*COS(BL(N,2)-BL(I,2))
```

```
400         DIST(I,N)=CINT(60*(180/PI)*(PI/2-ATN(X/SQR(1-
              X*X))))
410         LPRINT USING "#####";DIST(I,N);
420      NEXT N
430      LPRINT
440 NEXT I
450 LPRINT
460 LPRINT
470 LPRINT
480 DATA " SUU"," LUF"," DMA"," BIF"," ABQ"," SKF"," BLV"
490 DATA 38.2633,121.9267,33.535,112.3817,32.165,110.8817,
         31.85,106.38,35.0417,106.6067,29.38,98.5833,38.5367
         ,89.8517
500 END
```

The formula for computing great circle distances is:

$$D=60*\arccos[\sin(Ls)*\sin(Ld)+\cos(Ls)*(\cos(Ld)*\cos(ld - ls)] \quad (2:49)$$

Where

Ls = latitude of origin (degrees)
Ld = latitude of destination (degrees)
ls = longitude of origin (degrees)
ld = longitude of destination (degrees)

The distance matrix for the example mission presented in chapter IV is shown in table 5.

Table 5

Example Distance Matrix

DISTANCE MATRIX FOR THE TUESDAY 456 MISSION

	SUU	LUF	DMA	BIF	ABQ	SKF	BLV
SUU	0	543	653	853	761	1275	1501
LUF	543	0	112	319	300	748	1130
DMA	653	112	0	230	275	655	1095
BIF	853	319	230	0	192	429	902
ABQ	761	300	275	192	0	530	831
SKF	1275	748	655	429	530	0	700
BLV	1501	1130	1095	902	831	700	0

Appendix B

Airfield Listings

Table 6

Airfield Listing for Region 1

ID	Airfield	Location	Lat	Long
ADW	Andrews AFB	Washington, D.C.	38.8117	76.8667
ALB	Albany County	Albany, NY	42.7500	73.8050
BDL	Bradley Intl	Windsor Locks, CT	41.9383	72.6833
BOS	General Edward Lawrence Logan Intl	Boston, MA	42.3633	71.0067
BRG	Bangor Intl	Bangor, ME	44.8083	68.8283
ERI	Erie Intl	Erie, PA	42.0817	80.1767
EWR	Newark Intl	Newark, NJ	40.6900	74.1683
HPN	Westchester CO	White Plains, NY	41.0650	72.6833
LIZ	Loring AFB	Limestone, ME	46.9500	67.8867
NGU	Norfolk NAS	Norfolk, VA	36.9367	76.2900
NHZ	Brunswick NAS	Brunswick, ME	43.8933	69.9400
PBG	Plattsburgh AFB	Plattsburgh, NY	44.6517	73.4683
PHL	Philadelphia Intl	Philadelphia, PA	39.8700	75.245
PIT	Greater Pittsburgh Intl	Pittsburgh, PA	40.4917	80.2317
PSM	Pease AFB	Portsmouth, NH	43.0750	70.8233
PVD	Theodore Francis Green State	Providence, RI	41.7250	71.4283
RIC	Richmond Intl	Richmond, VA	37.5050	77.3200
RME	Griffis AFB	Rome, NY	43.2335	75.4067
ROA	Roanoke Regional	Roanoke, VA	37.3250	79.9767
SWF	Stewart Intl	Newburgh, NY	41.5067	74.0983
WRI	McGuire AFB	Wrightstown, NJ	40.0150	74.5933

Table 7

Airfield Listing for Region 2

ID	Airfield	Location	Lat	Long
ABY	Albany-Dougherty County	Albany, GA	31.5350	84.1950
AGS	Bush Fld	Augusta, GA	33.3700	81.9650
BHM	Birmingham Muni	Birmingham, AL	33.5633	86.7550
BIX	Keesler AFB	Biloxi, MS	30.4117	88.9233
BNA	Nashville Metro	Nashville, TN	36.1267	86.6817
CAE	Columbia Metro	Columbia, SC	33.9400	81.1200
CBM	Columbus AFB	Columbus, MS	33.6433	88.4433
CHS	Charleston AFB	Charleston, SC	32.8993	80.0400
COF	Patrick AFB	Cocoa Beach, FL	28.2400	80.6083
DHN	Dothan	Dothan, AL	31.3217	85.4500
FLL	Ft Lauderdale Intl	Ft Lauderdale, FL	26.0717	80.1550
GNV	Gainsville Regional	Gainsville, FL	29.6900	82.2717
HST	Homestead AFB	Homestead, FL	25.4883	80.3833
HSV	Huntsville, Intl	Huntsville, AL	34.6417	86.7733
LSF	Lawson AAF	Columbus, GA	32.3383	84.9917
MCF	Mac Dill AFB	Tampa, FL	27.8500	82.5217
MCO	Orlando Intl	Orlando, FL	28.4317	81.3250
MEI	Key Field	Meridian, MS	32.3333	88.7517
MGE	Dobbins, AFB	Marietta, GA	33.9150	84.5167
MXF	Maxwell AFB	Montgomery, AL	32.3800	86.3633
NIP	Jacksonville, NAS	Jacksonville, FL	30.2350	81.6750
NKT	Cherry Point MCAS	Cherry Point, NC	34.9033	76.8817
NMM	Meridian NAS	Meridian, MS	32.5550	88.5600
NQA	Memphis NAS	Millington, TN	35.3550	89.8700
NQX	Key West NAS	Key West, FL	24.5750	81.6900
NRB	Mayport NAF	Jacksonville, FL	30.3917	81.4233
PAM	Tyndall AFB	Panama City, FL	30.0700	85.5767
POB	Pope AFB	Fayetteville, NC	35.1700	79.0150
SSC	Shaw AFB	Sumter, SC	33.9733	80.4733
TYS	McGhee-Tyson	Nashville, TN	35.8117	83.9933
VAD	Moody AFB	Valdosta, GA	30.9683	83.1933
VPS	Eglin AFB	Valparaiso, FL	30.4867	86.5283
WRB	Robins AFB	Warner Robins, GA	32.6400	83.5917

Table 8

Airfield Listing for Region 3

ID	Airfield	Location	Lat	Long
BKF	Buckley ANGB	Aurora, CO	39.7100	104.7583
DSM	Des Moines Intl	Des Moines, IA	41.5350	93.6650
MIB	Minot AFB	Minot, ND	48.4150	101.3567
GFA	Malmstrom AFB	Great Falls, MT	47.5050	111.1833
OFF	Offutt AFB	Omaha, NE	41.1183	95.9117
RCA	Ellsworth AFB	Ellsworth, SD	44.1467	103.1017
RDR	Grand Forks AFB	Grand Forks, ND	47.9617	97.4000

Table 9

Airfield Listing for Region 4

ID	Airfield	Location	Lat	Long
CHD	Williams AFB	Chandler, AZ	33.3100	111.6567
DMA	Davis-Monthan AFB	Tucson, AZ	32.1650	110.8817
EDW	Edwards AFB	Mojave, CA	34.9050	117.8833
FHU	Libby AAF	Sierra Vista, AZ	31.5883	110.3433
HIF	Hill AFB	Ogden, UT	41.1283	111.9717
LAS	McCarran Intl	Las Vegas, NV	36.0800	115.1544
LAX	Los Angeles Intl	Los Angeles, CA	33.9417	118.4067
LSV	Nellis AFB	Las Vegas, NV	36.2367	115.0333
LUF	Luke AFB	Glendale, AZ	33.5350	112.3817
MRY	Monterey Peninsula	Monterey, CA	36.5900	121.8483
MUO	Mountain Home AFB	Mountain Home, ID	43.0433	115.8700
NKX	Miramar NAS	San Diego, CA	32.8700	117.1467
RIV	March AFB	Riverside, CA	33.8800	117.2583
SBD	Norton AFB	San Bernardino, CA	34.0950	115.2367
SKA	Fairchild AFB	Spokane, WA	47.6150	117.6567
SLI	Los Alamitos AAf	Los Alamitos, CA	33.7900	118.0500
SUU	Travis AFB	Fairfield, CA	38.2633	121.9267
TCM	McChord AFB	Tacoma, WA	47.1400	122.4750
VBG	Vandenberg AFB	Lompoc, CA	34.7300	120.5767
VCV	George AFB	Victorville, CA	34.5883	117.3833

Table 10

Airfield Listing for Region 5

ID	Airfield	Location	Lat	Long
ABQ	Kirtland AFB	Albuquerque, NM	35.0417	106.6067
AEX	England AFB	Alexandria, LA	31.3267	92.5483
BAD	Barksdale AFB	Bossier City, LA	32.5017	93.6633
BIF	Biggs AAF	El Paso, TX	31.8500	106.3800
BYH	Eaker AFB	Blytheville, AR	35.9650	89.9467
BPT	Jefferson CO	Beaumont, TX	29.9500	94.0200
CVS	Cannon AFB	Clovis, NM	34.3850	103.3233
DYS	Dyess AFB	Abilene, TX	32.4200	99.8533
EFD	Ellington Field	Houston, TX	29.6067	95.1583
ELP	El Paso Intl	El Paso, TX	31.9067	106.3733
ESF	Esler Regional	Alexandria, LA	31.3950	92.2967
FWH	Carswell AFB	Fort Worth, TX	32.7683	97.4417
GRK	Robert Gray AAF	Killeen, TX	31.0650	97.8283
LAW	Lawton Muni	Lawton, OK	34.5667	98.4167
LBB	Lubbock Intl	Lubbock, TX	33.6633	101.8217
LRF	Little Rock AFB	Jacksonville, AR	34.9167	92.1467
MAF	Midland Intl	Midland, TX	31.9417	102.2017
REE	Reese AFB	Lubbock, TX	33.5967	102.0417
SKF	Kelly AFB	San Antonio, TX	29.3800	98.5833
SPS	Sheppard AFB	Wichita Falls, TX	33.9883	98.4917
TIK	Tinker AFB	Oklahoma City, OK	35.4183	97.3883
TUL	Tulsa Intl	Tulsa, OK	36.1983	95.8883

Table 11

Airfield Listing for Region 6

ID	Airfield	Location	Lat	Long
BLV	Scott AFB	Belleville, IL	38.5367	89.9517
BTL	W.K. Kellogg	Battle Creek, MI	42.3100	85.2483
CLE	Cleveland Intl	Cleveland, OH	41.4067	81.8483
CMI	Univ of Illinois	Champaign, IL	40.0383	88.2783
CVG	Grtr Cincinnati	Covington, KY	39.0483	84.6667
DTW	Detroit Metro	Detroit, MI	42.2150	83.3483
FFO	Wright-Patt AFB	Dayton, OH	39.8267	84.0483
FOE	Forbes Field	Topeka, KS	38.9517	95.6633
FTK	Godman AAF	Ft Knox, KY	37.9067	85.9733
GUS	Grissom AFB	Peru, IN	40.6483	86.1517
HOP	Campbell AAF	Hopkinsville, KY	36.6717	87.4933
IAB	McConnell AFB	Wichita, KS	37.6233	97.2667
IND	Indianapolis Intl	Indianapolis, IN	39.7250	86.2833
LAN	Capital City	Lansing, MI	42.7783	84.5867
MCI	Kansas City Intl	Kansas City, KS	39.2983	94.7250
MFD	Mansfield Muni	Mansfield, OH	40.8217	82.5167
MKE	Gen Mitchell Intl	Milwaukee, WI	42.9467	87.8967
MLI	Quad-City	Moline, IL	41.4483	90.5100
MSN	Dane CO	Madison, WI	43.1400	89.3367
MSP	Minneapolis Intl	Minneapolis, MN	44.8833	93.2150
NBU	Glenview NAS	Chicago, IL	42.0900	87.8200
OSC	Wurtsmith AFB	Oscoda, MI	44.4517	83.3950
RST	Rochester Muni	Rochester, MN	43.9083	92.4983
SAW	K.I. Sawyer AFB	Gwinn, MI	46.3533	87.3950
SDF	Standiford Field	Louisville, KY	38.1750	85.7389
SZL	Whiteman AFB	Knob Noster, MO	38.7300	93.5467
TBN	Forney AAF	St Robert, MO	37.7417	92.1400
YNG	Youngstown Muni	Youngstown, OH	41.2583	80.6750

Appendix C

Dynamic Programming Results

This appendix contains the outputs of the dynamic programming algorithm applied to the 6 Mar 0611, 7 Mar 0656, and 9 Mar 0444 missions. Since the objective of this research was to minimize flight distances, the only portion of the labels created at each state is the distance. The scheduled missions visited the bases in the order indicated in the respective tables.

Table 12

Base Information for 611 Mission

Node #	ID	Dest. ID	Number of Patients	Total Onboard
0	BLV	WRI	2	16
		PIT	1	
		ADW	7	
		NKT	6	
1	PIT	ADW	1	16
2	ADW	NKT	1	9
3	ALB	ADW	1	10
4	WRI	ADW	3	11
5	NKT			4
D	ADW	Termination		0

k	States Set	 End Node	 Labels	Label Number	Prior Label
0	{0}	0	(0)	0	-
1	{0,1}	1	(460)	1	0
	{0,2}	2	(608)	2	0
	{0,3}	3	(772)	3	0
	{0,4}	4	(713)	4	0
2	{0,1,2}	1	(793)	5	2
		2	(645)	6	1
	{0,1,3}	1	(1090)	7	3
		3	(778)	8	1
	{0,1,4}	1	(973)	9	4
		4	(720)	10	1
	{0,2,3}	2	(1046)	11	3
		3	(882)	12	2
	{0,2,4}	2	(841)	13	4
		4	(736)	14	2
	{0,2,5}	5	(843)	15	2
	{0,3,4}	3	(881)	16	4
		4	(940)	17	3
3	{0,1,2,3}	1	(1200)	18	12
		2	(1052)	19	8
		3	(919)	20	6
	{0,1,2,4}	1	(996)	21	14
		2	(848)	22	10
		4	(773)	23	6
	{0,1,2,5}	1	(1214)	24	15
		5	(880)	25	6
	{0,1,3,4}	1	(1199)	26	16
		3	(888)	27	10
		4	(946)	28	8
	{0,2,3,4}	2	(1068)	29	17
		3	(904)	30	14
		4	(1050)	31	12
	{0,2,3,5}	3	(1335)	32	15
		5	(1281)	33	11
	{0,2,4,5}	4	(1168)	34	15
		5	(1061)	35	14

Figure 4. DP Results for the 611 Mission, Mon 6 Mar 89

k	States			Label Number	Prior Label
	Set	End Node	Labels		
4	{0,1,2,3,4}	1	(1222)	36	30
		2	(1074)	37	28
		3	(941)	38	23
		4	(1087)	39	20
	{0,1,2,3,5}	3	(1372)	40	25
		5	(1287)	41	19
	{0,1,2,4,5}	1	(1428)	42	34
		4	(1205)	43	25
		5	(1083)	44	22
	{0,2,3,4,5}	3	(1336)	45	34
		4	(1503)	46	32
		5	(1303)	47	29
5	{0,1,2,3,4,5}	3	(1373)	48	43
		4	(1540)	49	40
		5	(1309)	50	37
6	{0,1,2,3,4,5,D}	D	(1544)	51	50

Figure 4. cont.

The optimum routing is 0-1-3-4-2-5-D with a total distance of 1544 miles versus 1647 miles on the scheduled mission, or a savings of 103 miles (6.3%).

Table 13

Base Information for 656 Mission

Node #	ID	Dest. ID	Number of Patients	Total Onboard
0	BLV	SKF	3	6
		LAW	1	
		LRF	2	
1	FWH	SKF	2	8
2	SKF	LAW	5	15
		BLV	2	
		BAD	1	
		LRF	2	
		TIK	2	
3	BAD	BLV	3	17
4	LAW	BLV	9	20
5	TIK	BLV	2	20
6	LRF	BLV	6	22

k	States			Label Number	Prior Label
	Set	End Node	Labels		
0	{0}	0	(0)	0	-
1	{0,1}	1	(506)	1	0
2	{0,1,2}	2	(718)	2	1
3	{0,1,2,3}	3	(1033)	3	2
	{0,1,2,4}	4	(1029)	4	2
	{0,1,2,5}	5	(1085)	5	2
	{0,1,2,6}	6	(1184)	6	2

Figure 5. DP Results for the 656 Mission, Tues 7 Mar 89

k	States			Label Number	Prior Label
	Set	End Node	Labels		
4	{0,1,2,3,4}	3	(1297)	7	4
		4	(1301)	8	3
	{0,1,2,3,5}	3	(1340)	9	5
		5	(1288)	10	3
	{0,1,2,3,6}	3	(1347)	11	6
		6	(1196)	12	3
	{0,1,2,4,5}	4	(1157)	13	5
		5	(1101)	14	4
	{0,1,2,4,6}	4	(1494)	15	6
		6	(1339)	16	4
	{0,1,2,5,6)	5	(1443)	17	6
		6	(1344)	18	5
5	{0,1,2,3,4,5}	3	(1356)	19	14
		4	(1360)	20	10
		5	(1373)	21	8
	{0,1,2,3,4,6}	3	(1502)	22	16
		4	(1506)	23	12
		6	(1460)	24	7
	{0,1,2,3,5,6}	3	(1507)	25	18
		5	(1455)	26	12
		6	(1503)	27	9
	{0,1,2,4,5,6}	4	(1515)	28	17
		5	(1566)	29	15
		6	(1360)	30	14
6	{0,1,2,3,4,5,6}	3	(1523)	31	30
		4	(1527)	32	26
		5	(1578)	33	23
		6	(1519)	34	19
7	{0,1,2,3,4,5,6,D}	D	(1544)	35	34

Figure 5. cont.

The optimum routing is 0-1-2-4-5-3-6-D with a total distance of 1763 miles versus 1876 miles on the scheduled mission, or a savings of 113 miles (6.0%).

Table 14

Base Information for 444 Mission

Node #	ID	Dest. ID	Number of Patients	Total Onboard
0	SUU	MRY	3	20
		TCM	8	
		VCV	2	
		NKX	6	
		SLI	1	
1	TCM			12
2	MRY	VCV	1	10
3	VCV	SUU	5	12
4	SLI	SUU	2	13
5	NKX	SUU	1	8
6	LSV	SUU	1	9
D	SUU	Termination		0

k	States			Label Number	Prior Label
	Set	End Node	Labels		
0	{0}	0	(0)	0	-
1	{0,1}	1	(533)	1	0
	{0,2}	2	(100	2	0
2	{0,1,2}	1	(734)	3	2
		2	(1167)	4	1
	{0,2,3}	3	(349)	5	2
	{0,2,4}	4	(351)	6	2
	{0,2,5}	5	(422)	7	2
	{0,2,6}	6	(430)	8	2
3	{0,1,2,3}	3	(1416)	9	4
	{0,1,2,4}	4	(1418)	10	4
	{0,1,2,5}	5	(1489)	11	4
	{0,1,2,6}	6	(1467)	12	3

Figure 6. DP Results for the 444 Mission, Thurs 9 Mar 89

k	Set	End Node	Labels	Label Number	..ior Label
	States				
3	{0,2,3,4}	3	(409)	13	6
		4	(407)	14	5
	{0,2,3,5}	3	(526)	15	7
		5	(453)	16	5
	{0,2,3,6}	3	(582)	17	8
		6	(501)	18	5
	{0,2,4,5}	4	(493)	19	7
		5	(422)	20	6
	{0,2,4,6}	4	(639)	21	8
		6	(560)	22	6
	{0,2,5,6}	5	(657)	23	8
		6	(649)	24	7
4	{0,1,2,3,4}	3	(1476)	25	10
		4	(1474)	26	9
	{0,1,2,3,5}	3	(1593)	27	11
		5	(1520)	28	9
	{0,1,2,3,6}	3	(1619)	29	12
		6	(1568)	30	9
	{0,1,2,4,5}	4	(1560)	31	11
		5	(1489)	32	10
	{0,1,2,4,6}	4	(1676)	33	12
		6	(1627)	34	10
	{0,1,2,5,6}	5	(1694)	35	12
		6	(1716)	36	11
	{0,2,3,4,5}	3	(526)	37	20
		4	(524)	38	16
		5	(478)	39	14
	{0,2,3,4,6}	3	(697)	40	21
		4	(640)	41	17
		6	(561)	42	13
	{0,2,3,5,6}	3	(761)	43	23
		5	(686)	44	17
		6	(678)	45	15
	{0,2,4,5,6}	4	(728)	46	23
		5	(710)	47	21
		6	(649)	48	24
5	{0,1,2,3,4,5}	3	(1593)	49	32
		4	(1591)	50	28
		5	(1545)	51	26
	{0,1,2,3,4,6}	3	(1734)	52	33
		4	(1677)	53	29
		6	(1628)	54	25

Figure 6. cont.

k	States			Label Number	Prior Label
	Set	End Node	Labels		
5	{0,1,2,3,5,6}	3	(1798)	55	35
		5	(1723)	56	29
		6	(1745)	57	27
	{0,1,2,4,5,6}	4	(1765)	58	35
		5	(1747)	59	33
		6	(1716)	60	32
	{0,2,3,4,5,6}	3	(786)	61	46
		4	(757)	62	44
		5	(711)	63	41
		6	(678)	64	37
6	{0,1,2,3,4,5,6}	1	(1411)	65	64
		3	(1823)	66	58
		4	(1856)	67	55
		5	(1748)	68	53
		6	(1745)	69	49
7	{0,1,2,3,4,5,6,D}	D	(1944)	70	65

Figure 6. cont.

The optimum routing is 0-2-4-5-3-6-1-D with a total distance of 1944 miles versus 2123 miles on the scheduled mission, or a savings of 179 miles (8.4%).

Appendix D

Frequency of Visits Tables

Note: the number below the mission number is the number of times that mission was flown during the four week period. The number beside each base identifier is the number of times that base was visited. Pairs of bases marked by an asterisk (*), are bases that are within 30 miles of each other that are visited by a particular mission on different days. These bases represent the same location.

Table 15

Frequency Table for Monday Missions

0126	0654	0663	06X6	0622	06x1
4	4	4	1	3	4
POB 4	BLV 4	BLV 4	BLV 1	BLV 3	BLV 4
NGU 4	SKF 4	NBU 4	HOP 1	SDF 2	PIT 1
ADW 4	BIF 3	SAW 4	CBM 1	BNA 1	ADW 4
CHS 4	ABQ 2	CLE 1	GNV 1	NQA 1	ALB 1
AGS 4	LUF 4	FFO 4	NBU 1	MGE 2	WRI 4
BIX 4	NKX 4	IND 1	ADW 1	BHM 1	NKT 4
CAE 2	RIV 1	DSM 1		BIX 3	HOP 1
LSF 2	SUU 4	BKF 4		SKF 1	CVG 1
	FWH 1	LAN 1		CMI 1	ROA 1
	DMA 2	SDF 1		HOP 2	GUS 1
	SZL 1	BYH 1		BYH 1	EWR 1
	CVS 1	MLI 1		VPS 1	NHZ 2
		BTL 1		WRB 1	BGR 1
		MSP 1		NMM 1	ERI 1
		OSC 1			PVD 1

Table 16

Frequency Table for Tuesday Missions

0456	0336	0656	0222	0636	0111
4	4	3	4	4	4
SUU 4	BKF 4	BLV 3	BIX 4	BLV 4	NKT 1
LUF 4	RCA 4	FWH 3	NIP 4	MCI 4	BLV 1
DMA 4	RDR 4	SKF 3	MCF 4	FOE 4	ADW 4
BIF 4	MIB 4	BAD 3	NQX 4	BKF 4	RME 3
ABQ 2	HIF 4	LAW 3	HST 4	IAB 4	PBG 4
SKF 4	OFF 3	TIK 2	COF 3	TBN 4	NHZ 3
BLV 4	BLV 4	LRF 3	MCO 3		WRI 3
VCV 1		*AEX 1	FLL 1		ROA 1
LAX 1		*ESF 1			BGR 1
NKX 1		SPS 1			PSM 3
CVS 1					PVD 3
					HPN 1

Table 17

Frequency Table for Wednesday Missions

0634	0666	0654	0256	0621	0116
4	4	4	4	4	4
BLV 4	BLV 4	BLV 4	BIX 4	BLV 4	ADW 4
BKF 4	HOP 4	SKF 4	VPS 3	BIX 4	PVD 1
MUO 4	SDF 3	BIF 4	VAD 4	LSF 4	PSM 1
GFA 4	IND 2	DMA 4	MGE 3	AGS 4	BGR 1
SKA 4	GUS 1	LUF 4	CBM 1	CHS 4	LIZ 4
TCM 4	FFO 4	*RIV 1	NMM 1	*SSC 3	PIT 1
SUU 4	OSC 2	SUU 4	SKF 4	POB 4	BLV 4
	NBU 2	CVS 2	WRB 2	NGU 4	RME 1
	OFF 1	AEX 1	HSV 1	ADW 4	NKT 2
	BYH 1	NKX 1	MXF 3	*CAE 1	ROA 1
	SZL 1	*SBD 1	BLV 4		BOS 1
	CMI 2		AGS 1		WRI 1
	SAW 2		BHM 1		NHZ 1
	BTL 1				YNG 1
	RST 1				
	NQA 1				

Table 18

Frequency Table for Thursday Missions

0444	1614	1416	0636	0655	0126
4	3	4	4	4	4
SUU 4	BLV 3	SUU 4	BLV 4	BLV 4	ADW 4
TCM 3	ADW 3	SKF 4	TBN 4	SKF 4	NGU 4
MRY 3	EFD 1	BIX 4	MCI 4	*ESF 2	POB 4
VCV 1	SKF 3	AGS 1	FOE 4	BAD 4	SSC 2
SLI 1	SUU 3	ADW 4	IAB 4	LFR 4	CHS 4
NKX 4	BDL 1	BLV 4	BKF 4	TIK 3	AGS 4
LSV 4	BIF 1	SWF 1		SPS 4	LSF 4
VBG 3		GNV 1		DYS 3	BIX 4
LAX 2		NIP 1		*AEX 2	BLV 4
RIV 3				FWH 1	
EDW 1					

Table 19

Frequency Table for Friday Missions

0456	0436	0663	0526	0622	0611
4	4	4	3	4	4
SUU 4	SUU 4	BLV 4	SKF 3	BLV 4	BLV 4
*LUF 3	TCM 4	MSN 1	BIX 3	BIX 4	ADW 4
DMA 4	SKA 4	MKE 2	BPS 3	MCF 4	ROA 2
BIF 4	GFA 4	CLE 1	NIP 1	NQX 4	NKT 4
CVS 2	MUO 4	FFO 4	WRB 1	HST 4	NGU 1
SKF 4	HIF 3	SDF 3	MXF 2	COF 4	ALB 1
BLV 4	BKF 4	HOP 4	BHM 2	MCO 4	PSM 3
LAX 1	BLV 4	BKF 4	HSV 3	NIP 3	PVD 4
*CHD 1		NQA 2	BLV 3		SWF 1
ABQ 2		GUS 1	DHN 1		RME 2
NKX 2		OSC 2	*MEI 1		EWR 3
		SAW 2	CBM 1		WRI 2
		BYH 1	*NMM 1		PBG 1
		NBU 1	BAD 1		
			SZL 1		

Table 20

Frequency Table for Saturday Missions

0666	0634	0336	0655	0256	1614	0116
4	4	4	3	4	4	4
BLV 4	BLV 4	BKF 4	BLV 3	BIX 4	BLV 4	ADW 4
NQA 2	BKF 4	RCA 4	SKF 3	VPS 4	PIT 1	RME 2
FFO 4	MUO 4	RDR 4	MAF 1	MXF 3	ADW 4	PBG 4
MFD 1	SKA 4	MIB 4	DYS 3	SKF 4	SKF 4	LIZ 4
OSC 1	GFA 3	HIF 4	LAW 3	LBB 1	SUU 4	PSM 3
SAW 1	TCM 4	OFF 4	TIK 2	ELP 1	NGU 1	SWF 1
MSP 2	SUU 4	BLV 4	LRF 3	BLV 4	SBD 1	WRI 2
NBU 3			*ESF 1	PAM 1	GRK 1	BLV 4
MSN 1			*AEX 2	BAD 1	BIF 2	NHZ 3
MKE 1			FWH 2	MGE 2	NKX 1	BGR 2
DTW 1				WRB 2		EWR 1
CMI 2				HSV 1		HPN 1
HOP 1				BHM 1		RIC 1
SZL 1				EFD 1		
GUS 2				TUL 1		
SDF 1						
BYH 1						

Table 21

Frequency Table for Sunday Missions

0621	1416	0526	06X6	0456
4	4	3	3	3
BLV 4	SUU 4	SKF 3	BLV 3	SUU 3
BIX 4	LAX 1	BLV 3	SZL 1	NKX 2
LSF 4	SKF 4	BPT 1	BKF 1	LUF 2
AGS 4	BIX 4	BIX 3	OFF 1	DMA 1
CHS 4	PAM 1	MEI 1	RST 1	BIF 1
*SSC 3	ADW 4	BHM 1	MSN 1	CVS 2
POB 4	BLV 4	TIK 1	CMI 1	SKF 3
NGU 4	LAS 1	REE 1	VPS 1	BLV 3
ADW 4	FFO 2	PAM 1	SUU 1	MRY 1
*CAE 1	NKX 1	MXF 2	GUS 1	LAX 1
	BIF 1	BAD 1	NBU 1	SBD 1
	PHL 1	VAD 1	OSC 1	FHU 1
		VPS 1	DTW 1	ABQ 1
		HSV 1	FFO 1	
		TYS 1	SDF 1	

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This thesis applies a dynamic programming approach to routing the daily missions of the aeromedical evacuation system (AES).
The objective of the research was to develop a model that could be used in routing daily missions. An example of the algorithm as applied to an actual mission is included.

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