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Location and Routing of the Defense Courier Service Aerial Network

THESIS

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This study extends work done by the Military Airlift Command's Analysis Group on reducing the operating costs of the Defense Courier Service aerial network. The study's primary focus is to minimize those costs by varying the number and location of servicing depots, and the routes flown from those depots. The theoretical algorithm used in the methodology is an expansion of Laporte's (1986) formulation of the multiple depot multiple travelling salesmen facility-location problem. Multiple servicing frequency is addressed by clustering co-located demands with Kulkarni's (1985) subtour breaking constraint. Vehicle range is considered by redressing a shortfall of the subtour breaking constraint, which was noted by Brodie (1988). The formulation is used as a validation of a system wide solution heuristic, since exact solution is beyond the range of current computing. The solution heuristic is a combination of the minimum spanning forest (Prim and Dijkstra) and the Clark-Wright method. The spanning forest is used for depot location and partitioning, while the Clarke-Wright computes the routes flown from the depots to their assigned service points. The heuristic averaged 3.3% worse than optimal in six validation runs, with no run greater than 15.25% worse than optimal. The results indicate several depots may be closed without large increase of system mileage.

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Location and Routing of the Defense Courier Service Aerial Network

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
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In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Operations Research

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March 1991

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Preface

Depot location and routing of delivery vehicles is a longstanding application of Operations Research techniques. Although the field is replete with optimizing algorithms which theoretically solve such problems, a more practical approach is dictated by the limitations of computing power. Consequently, alternate methodologies are developed which are feasible by modern computer standards, but which sacrifice solution accuracy by various amounts. This study applies several of the theoretical and practical algorithms with the goal of improving the Defense Courier Service aerial network.

During the course of the research I discovered that there were many experts in the field who were more than willing to offer their assistance. Major Mike Ackley and Capt Keith Ware of the MAC Command Analysis Group (HQ MAC XPY) were two such individuals. Their knowledge and insights of the DCS problem were key to the success of my effort.

In addition to the fine support I received from HQ MAC, as well as DCS itself, I am indebted to my advisor, Dr Yupo Chan. His ability to listen, counsel, and direct (when necessary) makes him an outstanding educator and researcher.

Throughout the research, my sanity was maintained with the loving support of my wife, Donna, and daughters, Kelly and Stacy. I hope that I may again provide them with the time that was formerly consumed by this study.

The current war in the Persian Gulf puts all defense oriented research in perspective. It is for the American soldier that all our efforts must be directed, and I hope this research ultimately makes contribution to that end. I salute all those currently defending our freedom.

Steven F. Baker

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Abstract

This study extends work done by the Military Airlift Command's Analysis Group on reducing the operating costs of the Defense Courier Service aerial network. The study's primary focus is to minimize those costs by varying the number and location of servicing depots, and the routes flown from those depots.

The theoretical algorithm used in the methodology is an expansion of Laporte's (1986) formulation of the multiple depot multiple travelling salesmen facility-location problem. Multiple servicing frequency is addressed by clustering co-located demands with Kulkarni's (1985) subtour breaking constraint. Vehicle range is considered by redressing a shortfall of the subtour breaking constraint, which was noted by Brodie (1988). The formulation is used as a validation of a system wide solution heuristic, since exact solution is beyond the range of current computing.

The solution heuristic is a combination of the minimum spanning forest (Prim and Dijkstra) and the Clark-Wright method. The spanning forest is used for depot location and partitioning, while the Clarke-Wright computes the routes flown from the depots to their assigned service points. The heuristic is suboptimal by 3.3% on average in six validation runs, with no run greater than 15.25% worse than optimal. The results indicate several depots may be closed without large increase of system mileage.

LOCATION AND ROUTING OF
THE DEFENSE COURIER SERVICE
AERIAL NETWORK

Chapter I. Introduction and Background

The Defense Courier Service (DCS) is responsible for the transportation of classified material between Department of Defense installations. Some of this material has a low level of classification and may be carried by the US Postal Service. Some material is quite large and must be hauled by either cargo aircraft or truck. Much of the material, however, is small package size. Frequently, it is also too sensitive for ordinary postal procedure. The DCS has organized a secure network for the transportation of this material.

According to LTC Hughes of the HQ MAC command analysis group, the current DCS distribution network includes over 200 CONUS locations, most of which are serviced by aircraft. LTC Hughes further stated that the network is similar to a multiple "hub and spoke" system used by the nation's commercial airlines. The system also extends to overseas locations. Because classified material is generated at all the sites, the system is two-way. Most of the individual sites are served by contracted small aircraft, which transport the material to a regional hub. The hubs serve as a secure transshipment center to United Parcel Service (UPS) aircraft, which move the accumulated cargo to another regional hub near the material's destination. The link is completed when another contracted general aviation contract aircraft delivers the material to its final destination. The major exceptions to this system are two east coast regional centers which are served by truck from the Washington DC area, a regional center (14).

Specific Problem

Over the years, the aerial portion of the DCS route structure has grown incrementally to 12 regional hubs serving 169 additional sites (1). Such a piecemeal growth pattern has resulted in a less than optimal route structure, though many of the current policies are sound. The DCS is satisfied with the current system of the UPS trunk carrier serving secure transshipment hubs which, in turn, supply the sites through general aviation aircraft. The current security, frequency of service, and capacity of the system components are adequate and need not be changed. Given these constraints, analysis of the current routes flown and hub locations will certainly indicate potential for overall cost reduction. This research explores the possibility of system cost reduction by reducing the number of depots, altering depot locations, and changing the routes flown.

The costs associated with the aerial DCS network can be broken into 3 categories: 1) trunk cost fees paid to UPS; 2) payroll and other overhead associated with maintaining the regional hubs; and 3) contract costs to the general aviation carriers. Each of these three cost categories plays a major role in the route structure.

UPS charges the government a flat rate of 45 cents per pound of freight carried within its route system (18). This cost implies that there is no incentive in locating hubs close to each other, as they are separated by identical cost, regardless of the intervening distance. It also forces all hubs to be situated at locations served by UPS. Regarding the latter point, the DCS has stipulated that only military installations should be considered as potential hubs for security reasons (19). This constraint considerably reduces the number of candidate depots when combined with the UPS servicing requirement. The special government flat rate also reduces the study's scope, since trunking costs will not vary much regardless of number and location of depots.

Total hub operating costs vary with the number of hubs in the system, and the traffic through each hub. Clearly, adding more hubs will reduce the mileage flown by the small aircraft, but may adversely affect the economies of scale associated with fewer but larger hub operations. Currently, there are 12 hubs, with yearly operating budgets (excluding contract costs) averaging $718,000 (24). Though current depot operating costs are explored in Chapter III, varied regional and relocation expenses make the estimation of hub costs associated with a future network beyond the scope of this research.

The general aviation contractors are paid by the mile flown. The mileage rate is a function of many variables, including number of stops, total mileage, and number of bids received, as well as many other factors. A seperate contract is negotiated each year for each depot, and the current agreements average between 1 and 2 dollars per mile (22). According to Capt Smith of DCS, security requirements generally necessitate that aircraft make only day-long missions. Furthermore, trip lengths are also limited by the FAA's 14 hour cap on the crew's duty day, and a ten flying hour maximum per crew, per day. Since the cargo is small package size, aircraft capacity is not a problem. Sites are serviced with established frequencies, generally either once or twice a week. These frequencies, though not beyond alteration, are currently satisfactory and are not to be varied in this study (19).

Since the UPS trunking cost is not largely affected by depot location and routing, and the depot costs involve significant regional factors which are best studied by DCS itself, the primary focus of this research is the minimization of milage flown for a given number of depots. The methodology focuses on optimizing depot location and routing for a parametrically varied number of depots.

Though the primary effort of the research is focused on the scope described above, there are several additional considerations which will be addressed as warranted. According to Maj Perry of DCS, three of the hubs also serve as debarkation points for overseas cargo, effectively disqualifying them for potential relocation. Additionally, there are three priority routes which are flown from the Baltimore-Washington hub despite the higher costs associated with not providing service from the nearest depot. Finally, Maj Perry explained that there is no firm policy on the required servicing frequency of current depots, should they be relocated. He states that it is reasonable to use the frequency associated with the most served site within a given depot's route system (18).

Approach to the Problem

The research involves several phases. In order to determine an improved route structure, the current system must be examined in detail. Once familiarity with the structure is gained, mathematical formulation of the problem is used to gain further insight into practical solution methodologies, as well as validate the chosen technique.

Since DCS routing is a large problem, exact solution via mathematical programming is not possible using current algorithms and computers. Consequently, the problem must then be reformulated using heuristics, which will approximate an optimal system wide solution. Development of the the mathematical formulation as well as the appropriate heuristics is addressed in Chapters II and III.

System familiarity and data gathering are the central components to an understanding of the current DCS route structure. The HQ MAC analysis group has provided a large "head start" on data gathering, since they have already done considerable research on the problem. In addition to compiling the 181 locations and service frequencies, the analysis shop has completed a two stage series of recommendations to DCS (14). According to HQ MAC's report, the first stage involved reducing the current yearly system mileage of 1,550,395 without changing depots, depot assignments, or frequency of service. Their recommendation rearranged routes so as to fly only 1,454,609 miles per year, a 6.2% savings (13). The second stage recommended altering the depot assignments of some of the service sites. These changes resulted in a yearly mileage total of 1,400,070, cr an additional 3.7% savings (13). Therefore, this research represents a third stage of MAC's analysis, in which the number of depots and their locations are varied in addition to the routing.

Summary

Although the DCS routing problem can basically be summarized as a multiple depot, multiple tour facility location and routing problem, it represents several challenges from a theoretical as well as a practical standpoint. Foremost among these is the problem size, which precludes exact solution by existing algorithms. This research focuses on tayloring existing mathmatical algorithms to the specific problem, as well as developing a heuristic methodology for full scale solution.

Chapter II. Literature Review

Scope

The DCS aerial routing structure is a large network which schedules depot based aircraft to numerous demand locations, with subsequent return to base. This description squarely places the DCS network into the travelling salesman problem (TSP) category of Operations Research methodologies. Consequently, TSP literature is at the heart of the research background required for this study. While methodologies for solving TSP's are widespread, several specific formulations are applicable to the DCS aerial network. Those addressed in this review include: 1) the Vehicle Routing Problem (VRP); 2) modifications to the VRP; 3) the multiple depot multiple TSP; 4) TSP coefficient determination; and 5) heuristic solution techniques. These methodologies show great promise for adaptation to the DCS network.

The Vehicle Routing Problem

The Travelling Salesman Problem seeks the shortest route which connects a group of points (nodes) that begins and ends at the same point. One of the most comprehensive formulations of the TSP is the Vehicle Routing Problem as described by Chan and Rowell (6:13-14). The following list includes the notation used in this and subsequent formulations:

I= set of nodes
i= departing node
j= arriving node
H= vehicle fleet
h= individual vehicle
d= arc distance
x= 0,1 arc use indicator
M= set of incident nodes
N= set of eminent nodes
f= amount of demand at a node
V= vehicle capacity
t= dwell time at a node
U= tour time limit
J= any node subset $\leq$ I .

The formal VRP problem statement is:

$$\min \sum_{i \in I} \sum_{j \in I} \sum_{h \in H} d_{ij} x^h_{ij} \qquad (1)$$

The first two constraints insure each point (except the depot) is served by only one vehicle:

$$\text{s.t.} \sum_{i \in I} \sum_{h \in H} x^h_{ij} = \begin{cases} |H| & \text{if } j=1 \\ 1 & \text{if } j=2,3..,|I| \end{cases} \qquad (2)$$

$$\sum_{j \in I} \sum_{h \in H} x^h_{ij} = \begin{cases} |H| & \text{if } i=1 \\ 1 & \text{if } i=2,3..,|I| \end{cases} \qquad (3)$$

The third constraint insures flow conservation:

$$\sum_{i \in M_p} x^h_{ip} - \sum_{j \in N_p} x^h_{pj} = 0 \quad \forall\, h,\ \forall\, p \in I \qquad (4)$$

The fourth and fifth constraints restrict vehicle payload and range, respectively:

$$\sum_{i \in I} f_i \sum_{j \in I} x^h_{ij} \leq V_h \quad \forall\, h \qquad (5)$$

$$\sum_{i \in I} t^h_i \sum_{j \in I} x^h_{ij} + \sum_{i \in I} \sum_{j \in I} d^h_{ij}\, x^h_{ij} \leq U_h \quad \forall h \qquad (6)$$

Constraints six and seven insure the fleet size is not exceeded:

$$\sum_{j \in M_1} x^h_{1j} \leq 1 \quad \forall\, h \qquad (7)$$

$$\sum_{i \in N_1} x^h_{i1} \leq 1 \quad \forall\, h \qquad (8)$$

Finally, tours which do not originate at the depot (subtours) are prohibited:

$$\sum_{h\in H}\sum_{j\notin J}\sum_{i\in J} x^{h}_{ij} \geq 1 \quad \forall\ J \leq I \qquad (9)$$

Though this formulation is very comprehensive, it is also somewhat cumbersome, and may be "streamlined" in many applications.

Vehicle Routing Problem Modifications

Merrill offers a considerably simplified multiple vehicle TSP (which eliminates the superscripts that delineate individual vehicles). The formulation combines the fleet size equations (7) and (8) into equations (2) and (3) above, and eliminates the payload and range considerations (16:2-3). Merrill also offers a much simpler subtour breaking method, which works for up to seven nodes. Merrill's primary effort, however, was focused on probabilistic demands within the network, a complication which the DCS network does not exhibit.

In an expanded discussion of the TSP, Chan and Rowell offer numerous ways of subtour breaking for problems with many nodes (6:12-15). Perhaps the most promising involves the use of "nodal potential" variables δ. These real variables force all connected nodes to be also connected with the depot in order to reduce their "potential" difference to 1:

$$\delta_i - \delta_j + |I| x_{ij} \leq |I|-1 \quad \forall\ 1 \leq i \neq j \leq |I| \qquad (10)$$

Chan and Rowell note work done by Kulkarni and Bhave which expand this constraint to restrict vehicle capacity and range:

$$\pi_i - \pi_j + Vx_{ij} \leq V - f_i \quad \forall\ K+1 \leq i \neq j \leq |I| \qquad (11)$$

$$\sigma_i - \sigma_j + Ux_{ij} \leq U - d_{ij} \quad \forall\ K+1 \leq i \neq j \leq |I| \qquad (12)$$

Here, the problem has been expanded to include K depots (discussed further below), and π and σ are capacity and range potentials respectively (6:15). Though the range restriction has been partially refuted by Brodie and Waters, both show promise after some modification (5:403-404).

One aspect of the multiple travelling salesmen problem which offers potential cost reduction is split delivery as described by Dror and Trudeau (11:139-145). Consider a vehicle which is close to a demand point, yet has insufficient capacity remaining to fully service the node. By partially serving the demand, other nearby vehicles may be enabled to use their remaining capacity to fully satisfy the node. Dror's algorithm is based on one and two node swaps among routes of a feasible solution. This has potential application to the DCS problem because the same node may require service from more than one vehicle. Such a split load in the DCS network is not capacity driven, but is required by the varying service frequencies of the demand sites.

Multiple Depot Problems

The complete DCS network involves the use of a trunk carrier (UPS) in order to supply the 12 regional depots. Though this research focuses on delivery from regional centers, the full nature of the network is best described by a hierarchical depot model. Such a model is formulated by Perl and Daskin, and described by Chan and Rowell (6:26-27). The hierarchical model consists of a single source which supplies regional depots by way of a trunk mode. From the regional centers, a second mode delivers the product to a final destination. The model is very comprehensive; consideration is given to trunking costs, regional operating costs, transshipment costs, and delivery costs. Because of its detail in describing a complex operation, the model formulation becomes quite large when even a small problem is considered.

Many delivery problems simply involve regional factories or distribution centers serving proximate demand locations. As described earlier, the DCS network is effectively such a problem, since the delivery costs to the centers (trunking costs) are independent of depot location. Laporte et al describe such a "multi-depot, multi-tour model" (15:293-302). In addition to those listed above, the following variables are used in Laporte's formulation:

c= fixed cost of a depot
b= fixed cost of a vehicle
m= number of vehicles at a depot

J= subset of I including only depots
B= arbitrarily large constant
pi,Pi= lower and upper limits on total depots
t,T= lower and upper limits on fleet size at a depot

The arcs are two-way and not capacitated by a binary variable, therefore the problem is symmetric. The model formulation is:

$$\min \sum_{i,j\in I} d_{ij}\, x_{ij} + \sum_{r\in J} (c_r\, y_r + b_r\, m_r) \tag{13}$$

$$\text{s.t.} \sum_{i<k} x_{ik} + \sum_{k<j} x_{kj} = 2 \qquad k\in I-J \tag{14}$$

$$\sum_{i<r} x_{ir} + \sum_{r<j} x_{rj} = 2m_r \qquad r\in J \tag{15}$$

$$\sum_{i\in L}\sum_{j\in L} x_{ij} \le |L| - \frac{\Sigma f_i}{V} \qquad L\le I-J \tag{16}$$

$$x_{i1i2} + 3x_{i2i3} + x_{i3i4} \le 4 \qquad i1,i4\in J \quad i2,i3\in I-J \tag{17}$$

$$x_{i1i2} + x_{i(h-1)ih} + 2 \sum_{i,j\in\{i2..i(h-1)\}} x_{ij} \le 2h-5 \qquad \begin{array}{l} h>5 \\ i1,ih\in J \\ i2..i(h-1)\in I-J \end{array} \tag{18}$$

$$y_r \le m_r \le B\, y_r \qquad r\in J \tag{19}$$

$$t \le m_r \le T \qquad r\in J \tag{20}$$

$$p \le y_r \le P \qquad r\in J \tag{21}$$

The objective function seeks to minimize the sum of the leg costs, the depot overhead costs, and the aircraft overhead costs. Therefore, for routes of equal length, a single base with one aircraft is cheaper than multiple bases with multiple aircraft. Constraint (14) specifies that all nodes not used as a depot must be serviced exactly once. The second constraint (15) insures that m vehicles travel from their depot. Constraint (16) is a combined subtour breaking constraint and vehicle capacity constraint. Constraints (17) and (18) are chain barring constraints. They preclude a vehicle from originating at one depot and terminating at another. Constraint (19) requires that at least one vehicle is based only where depots are used. Equation (20) limits the number of vehicles at any depot, and (21) limits the total number of depots used.

One drawback of mathematical TSP formulations is that subtour breaking and chain barring constraints expand geometrically with problem size. Many such constraints are not binding on problem optimization however, and can be selectively eliminated. Chan offers such a constraint relaxation of the Laporte formulation described above (7:8-13). The process is iterative; it begins by comparing a known feasible (but not optimal) solution to a sub-problem solution which does not consider chain barring or subtour breaking. When such a sub-problem offers solution improvement, integer, subtour, and chain barring restrictions are added as necessary to induce sub-problem feasibility. If that sub-problem still offers improvement, it is stored as the best known and a new sub-problem is considered. The process continues until all sub-problems are considered.

Coefficient Determination

All of the vehicle routing problems described above require usable data regarding inter-network distances. Most of the formulations also simultaneously require fixed and variable costs for both depots and aircraft. Some research is warranted on transforming location data into distance information, as well as the factors which affect depot operating costs.

Transforming the latitudes and longitudes of two locations into inter-nodal distance is accomplished by the great circle distance formula provided in the Air Force Manual of Air Navigation (10:23-4):

$$D = 60\cos^{-1}[\sin(lat_1)\sin(lat_2) + \cos(lat_1)\cos(lat_2)\cos(long_2 - long_1)] \qquad (22)$$

Here, lat and long denote latitude and longitude respectively, and distance (D) is given in nautical miles. Since a statute mile (used exclusively in this research) equals 5280 feet, and a nautical mile equals 6076 feet, the conversion is trivial.

Although cost evaluation of individual depots is beyond the scope of this research, relevant background is given by Corbett (9:25-39). Central to that research is the analysis of payroll and O&M costs of the southwestern depots of the DCS. While the research notes that the depots operate with some inefficiency, it finds that the basic DCS structure is sound.

Heuristic Solution Techniques

For large problems, the methodologies previously described become unusable. The constraints quickly become so numerous that the processing time becomes prohibitive. Consequently, heuristics have been developed to yield approximate solutions to large TSP's. The space filling curve, sweep, spanning tree, and Clarke-Wright are all heuristic methodologies which relate to travelling salesmen problems and their variants.

Space Filling Curves. Bartholdi and Platzman describe the space filling curve (SFC) as a curve of unit length which connects a given set of sub-squares within a region (2:121-125). The central operation of the curve is to join a point with its immediate neighbors before proceeding to the next subregion. Each "neighborhood" is defined by repeated division of the entire region into 4 smaller and equally sized regions. The division continues until all points of interest (in this case, network nodes) occupy a square of their own. Figure 1 illustrates this. Once the

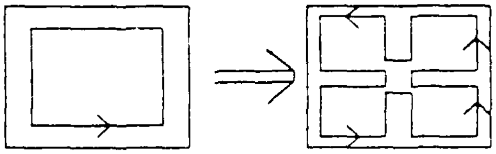


Figure 1. Space Filling Curves. Reprinted from (2:123)

space filling is complete, the points are assigned a value between 0 and 1, as specified by their position on the unit curve. The order of points determines the vehicle's route. Bartholdi and Platzman claim solution accuracy to be no worse than 25 percent from optimal, and Merrill produced results averaging 4.5 percent (16:10).

The space filling curve may be used to solve problems other than the single TSP. In several works, Bartholdi and Platzman offer numerous such applications. Vehicle assignment to particular demand nodes can be formulated with the SFC (3:298), which applies space filling to a multiple TSP. In the same reference, multiple depot location is addressed. By segmenting the elongated curve into equally spaced portions, demand points are assigned to the potential depot location which is nearest the center of the segment. Alternately, segmenting and depot location may be done by placing a depot at intervals defined by equal number of demand points (3:298). Both of these methods are very simple, though they completely ignore natural clusters of demands which may occur along the curve. Even so, the multiple depot extension of the SFC make it potentially useful in solving the DCS problem.

Sweep Heuristic. Vehicle range limitation for a single depot is addressed by Teodorovic's description of the sweep heuristic (21:138-141). This heuristic plots the network on polar coordinates, with the depot located at the origin. An arbitrary starting demand point is chosen, which is point 1 in Figure 2. In this case, the heuristic sweeps

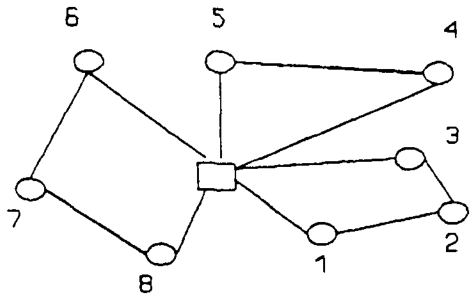


Figure 2. The Sweep Heuristic

counterclockwise through points 2 and 3, checking for range limitation prior to moving on. At point 3, the heuristic forces a return to the depot because proceeding to point 4 would exceed vehicle range. A new tour includes points 4 and 5, but proceeds back to the depot in lieu of exceeding vehicle range. The remaining points are added similarly until the sweep returns to point 1. The heuristic is simple, yet could be used to address aircraft range in the DCS aerial network.

<u>Spanning Trees.</u> A minimum spanning tree (MST) connects every point of a network to every other point with a minimum arc length. The name of the method springs from the resemblance of this collection of nodes and arcs to the branches of a tree. Prim and Dijkstra devised similar methods for MST construction; the latter is described by Syslo (20:259-265). Prim's algorithm begins at a seed (or depot) node and selects the least cost arc which includes an additional node into the "tree." At first this is simply the nearest neighbor to the seed. Thereafter, the nearest

unconnected neighbor to any node within the current tree is selected. At each iteration, the total arc length from the seed to the most current inclusion is added to the total network cost. Syslo also offers a PASCAL coding of Prim's algorithm which demonstrates the simplicity of MST construction (20:263-264).

A heuristic which transforms an MST into a travelling salesman problem is described by Nemhauser & Wolsey (17:475-482). The heuristic operates by doubling each of the arcs of an MST, then selectively eliminating those which cause node repetition along a continuous path. This formulation implies a relationship between the minimal spanning tree of a network and a suitable travelling salesman counterpart.

The connection between a network's MST and an efficient TSP tour is exploited by Ware in numerous applications within the Military Airlift Command's analysis group (23). One such application is the extension of the MST to include a forest, or many independent spanning trees within a system of nodes. In the minimal spanning forest, connecting arcs are grown from many seed nodes until every node is included in exactly one tree (23). This formulation has dual advantages: 1) demand points are assigned to depots; and 2) the MST algorithm which Nemhauser describes may be applied.

Clarke-Wright Method. Once demand nodes are assigned to depots, the DCS problem becomes an extension of the single depot multiple travelling salesmen problem. Several heuristic algorithms exist which solve such a formulation. One such formulation which shows promise for dealing with the DCS considerations of range and multiple frequency servicing is the Clarke-Wright algorithm. Originally described in 1964 (8:568-581), the Clarke-Wright algorithm initializes by assigning a separate "out-and-back" tour from the depot to each demand point. It iterates by combining the tours which offer the greatest savings as computed by the equation:

$$S_{ij} = D_{i1} + D_{j1} - D_{ij} \tag{23}$$

In this equation, the savings S equals the combined cost of travel to the depot from both nodes i and j, minus the cost of travel between nodes. This makes sense intuitively, as returning to the depot between proximate tasks can waste nearly an entire round trip from the depot. The algorithm terminates when no additional savings may be made, either through demand point exhaustion or vehicle capacity. Though the DCS problem is not restricted by vehicle capacity, range considerations could potentially be incorporated into the algorithm.

Beltrami and Bodin discuss the use of the Clarke-Wright algorithm for a network involving multiple servicing frequencies (4:406-427). In their discussion, New York City garbage trucks are routed to locations with varying service frequencies using a modified Clarke-Wright algorithm. Though the detailed formulation is not given, the general procedure is discussed, which indicates usefulness to the DCS methodology.

Modifications to the Clarke-Wright algorithm are also discussed at length by Golden (12:113-148). Of particular note is his discussion of a multiple depot formulation. Unfortunately, the formulation includes only fixed depots, and does not iterate potential depot sites. Such a formulation could still be useful to the DCS solution, but only when a small number of iterations are required.

Summary

There is much literature which is both current and applicable to the DCS aerial network. Mathematical programming algorithms are available which solve problems which are virtually identical to courier routing, size being the only major difference. Heuristic algorithms are available which solve larger problems with reduced, but acceptable accuracy for many applications. These two areas of Operations Research provide the foundation for the research reported in this thesis. The remainder of the study is based on this foundation.

Chapter III. Methodology

Overview

The methodology outlined in this chapter is divided into two portions. First, a mathematical programming algorithm is developed which considers the DCS aerial network peculiarities. As stated earlier, such an approach is not applicable for solution of the full problem, though is useful from the standpoint of validation and analytical rigor. Second, a dual heuristic strategy is developed which: 1) approximates the optimal depot locations; 2) assigns demand locations to one of the depots; and 3) develops routing of aircraft between demand nodes and their depots. Together, the formulations provide for either redesign or modification of the DCS routing structure, as well as a reduced scale validation of results.

Mathematical Programming

The DCS aerial network most closely resembles the formulation given by Laporte, which is described in the previous chapter (equations 13-21). The formulation provides for multiple depots and multiple tours, though does not include provisions for range limitation or multiple servicing frequency. Additionally, some estimate of both fixed and variable depot cost is required for this model. Consequently, major foci of the DCS formulation involve computation of suitable depot costs, and modifying Laporte's formulation for range and multiple servicing.

Depot Costs. Unlike many travelling salesman variants, Laporte's objective function seeks to minimize values which are not often thought of as being equivalent units. Furthermore, the DCS system involves numerous contracts spread throughout the CONUS, which implies that node and arc costs are dependent on numerous regional factors. Data is available on the current depot and per mile costs, but none exist for potential relocations. One way to approach the subordination of regional costs into the full network might be to assume that potential hubs would have equivalent costs to nearby existing hubs. Unfortunately, this method becomes rather uncertain when two existing hubs are proximate to a potential relocation site. The chosen method for regional smoothing of data is to predict potential depot and arc costs by using national data. Specifically, coefficients must be established for arc cost (d), depot fixed cost (c), and aircraft fixed cost (b). Since the demand servicing frequency is most often weekly, the model is formulated on a per week basis.

Contracts are awarded to small aircraft operators based on a negotiated per mile fee. As stated in Chapter I, this fee is a function of many variables including number of bidders, total miles flown, stops made, and operational complexity. Many of these factors are highly variable, but are reasonably independent of the exact routing and depot location within the region. Using a national average might result in a slightly lower than optimal depot density where arc costs are relatively high (and vice versa), but the alternative of modelling so many variables makes the problem much less tractable. Therefore, a national average per mile arc cost of $2.2287 (22) is used. This cost is not used directly in the formulation; rather it is used as a conversion factor between dollars and miles when incorporating depot costs. Note that the fee paid to the contractor includes all aircraft costs. This is very attractive as it assimilates the $b_r m_r$ terms of the objective function into the d_{ij} per mile coefficients. The d_{ij} terms are computed in statue miles, and the c_r terms are computed as described below and converted into a milage equivalent.

The depot overhead (including payroll and O&M costs) coefficients c_r, are a function of many disparate regional factors as well as more identifiable national ones. Appendix A shows the available data on the current number of total visits to demand points per two week period (labeled STA), number of yearly miles traveled by the contractor (MILES), number of sorties flown by the contractor (MSNS), and yearly depot overhead costs (COST). The three depots which are debarkation points for international traffic have disproportionally high operating costs, and are inappropriate for use in the O&M cost data set. The remaining nine data points are analyzed using linear regression for coefficient determination.

Appendix A gives the results of the regressions done by SAS. Simple correlation indicates STA has the most promise for a good regression. That suspicion is borne out by scattergrams of the three candidate predictors. Though the most error is "captured" by the full model (as expected), the two predictor model including STA and MILES has a nearly identical R^2 of 0.2027. Unfortunately, both of these models have an unacceptably high p value associated with the F test. In each case, the null hypothesis of statistical model significance is rejected with greater than 50% confidence. The model with the most promise includes only the predictor STA. Its R^2 is 0.1525 and has a relatively low p value of 0.2988. A residual plot and Wilk-Shapiro test confirm normality of the error terms. While these results are hardly convincing of a strong regression relationship, they are a better measure than a raw average of depot cost, which completely ignores variable costs. It is also important to note that this calculation will ultimately be used only when a decision must be made between the cost of one additional depot versus the potential mileage saved. Since this decision is not included in the heuristic solution methodology, statistical skepticism of the depot cost model does not impact the validating power of the mathematical formulation, which is its primary goal.

Because the chosen model includes only the first order term STA, the size of a depot as measured by demand points served (per week) does not benefit from an economy of scale. Consequently, for a system with n nodes and I depots, the total per year depot cost (in thousands) is $I*b_0 + b_1*(n-I)$, where b_0 and b_1 are the regression lines's slope and intercept, respectively. Because of the linear relationship (which the scatterplot verifies), $b_1*(n-I)$ is constant regardless of how the demand is split among the depots, and may be added to the total cost after the optimal solution is reached. Appendix A shows that the intercept b_0 is $392 thousand per year (or $7538 per week), which corresponds to the fixed depot cost without the "stations serviced" constant. When converted to a statute mile cost equivalent, the weekly fixed cost is 3382 sm. Effectively, $b_0/(52*2.23) = c_r \;\forall\; r \in (I-J)$, provided a constant 45.0 statute miles (5220/[52*2.23]) per demand serviced is added to the minimum weekly cost.

Since the regression attempt has severe statistical limitations, little value can be placed on the exact relative cost of depot overhead versus contracted operating costs. The regression does indicate that depots are relatively "expensive," since approximately 176,000 miles (392,000/2.23) must be saved in order for an additional depot's overhead to be justified. Additionally, depot construction costs are not considered, whose amortization only increases the premium paid for potential depot sites. Although exact computation of relative depot costs is clearly beyond the scope of this research, system cost may be expressed by parametric weighting of operating versus depot costs. Stated in mathmatical terms, Total cost = L_1(number of depots) + L_2(yearly mileage), where the L's are weighting variables that equate the two disparate expenditures. Using this approach, the best solution is offered for each of a given number of depots, whereupon the DCS may asses depot costs on a case by case basis.

Range Limitation. Both the Vehicle Routing Problem and Kulkarni formulations addressed in the previous chapter offer range limiting constraints which may be used in a travelling salesman problem formulation. Neither is exactly suited to Laporte's formulation, but Kulkarni's constraint has fewer disadvantages. The VRP range constraint forces the use of a vehicle superscript, which adds dimensionality and fixes number of vehicles. Consequently, Kulkarni's constraint is chosen and restated here for easy reference:

$$Ux_{ij} + \sigma_i - \sigma_j \leq U - d_{ij} \quad \forall \ |J+1| \leq i \neq j \leq |I| \qquad (12)$$

The set $\{|J+1|, |J+2|, \ldots |I|\}$ represents the set of non-depot nodes; σ is an unrestricted variable associated with each node which indicates how much range capability remains in the associated tour (6:15). Note that the notation used here is the same as that used in the Laporte formulation (equations 13-21).

Careful inspection of the above equation reveals how σ serves as a tour "odometer." If an arc x_{ij} is used, its value is one, and the equation becomes:

$$U + \sigma_i - \sigma_j \leq U - d_{ij} \tag{23}$$

which can be simplified to:

$$\sigma_i + d_{ij} \leq \sigma_j \tag{24}$$

This states that the "odometer" variable associated with a demand node must be incremented by at least the distance separating it with the prior node on the tour. If the arc between two nodes is not used, the equation's right hand side becomes large relative to the left hand side, and the constraint is non binding.

Kulkarni's range equation requires x_{ij} to be distinct from x_{ji}. Otherwise, the incrementing from i to j is nondirectional, and a running total of milage is not forced. This complicates Laporte's heretofore symmetrical formulation by nearly doubling the number of variables, as well as forcing more rigorous conservation of flow equations. Specifically, equations (14) and (15) of the Laporte formulation become:

$$\sum_{i \in I} x_{ij} = \begin{cases} m_j \text{ for } j<J \\ 1 \text{ for } j<I-J \end{cases} \tag{25}$$

$$\sum_{i \in J} x_{ij} = \begin{cases} m_i \text{ for } i<J \\ 1 \text{ for } i<I-J \end{cases} \tag{26}$$

Additionally, the chain barring constraints must be altered to reflect the asymmetric formulation. The alternative to this approach is to ignore range considerations, or revert to the vehicle routing problem formulation. Resorting to an asymmetric formulation remains preferable to either of these options.

The other major problem with incorporating Kulkarni's equation into the DCS problem formulation is that it ignores distance to and from the depot, which makes it incomplete. From the discussion above, it is clear that the σ associated with the first demand point on a tour should equal the distance from the depot. Additionally, the distance from the last node prior to returning to the depot cannot exceed the remaining range of the vehicle. Consequently, two constraints are added to redress Kulkarni's omission:

$$d_{ij}\, x_{ij} \leq \sigma_j \quad \forall 1 \leq i \leq |J| \quad \forall |J+1| \leq j \leq |I| \qquad (27)$$

$$d_{ji}\, x_{ji} + \sigma_j \leq U \quad \forall 1 \leq i \leq |J| \quad \forall |J+1| \leq j \leq |I| \qquad (28)$$

These equations, when used in conjunction with Kulkarni's, sufficiently restrict range.

By strictest definition, the DCS problem is not restricted by range, but by either the crew's duty day limitation of 14 hours, or by the less restrictive ten hour flying time limitation. According to Capt. Smith of DCS, 45 minutes is allocated at each stop for preflight and package delivery. Additionally, when circuitous routing and terminal procedures are considered, the aircraft travel at 200 statute miles per hour (19). Thus, the effective range of the aircraft is 2800 sm (14 hrs * 200 sm/hr), and the "range cost" per stop is effectively 150 miles (200 sm/hr * .75 hr/stop). Prudence dictates that an error margin be added to these calculations, so Capt. Smith feels that no trip should be scheduled to last more than 13 hours, which corresponds to 2600 statute miles (19). Of course, the computed mileage between nodes must include 150 miles of "dwell time" in order to properly account for range considerations. This 150 mile cost per arc should be subtracted from the optimized cost after the program is completed.

Servicing Frequency. The most obvious way to allow for different servicing frequencies is to relax the binary mixed integer program into a simple mixed integer program. This would allow an arc flow greater than one, which permits a node to be served more than once. Because of the subtour breaking constraint (12), such a repeat servicing would have to occur on separate tours, lest a cycle occur which does not include the depot. This reformulation of equations (25) and (26) (conservation of flow) sets the right hand side equal to s_i or s_j for $i \in I-J$ and $j \in I-J$, respectively. S in this case equals the number of required servicings in a given period. Unfortunately, this prescription has one significant drawback; the "odometer" variables σ in equation (12) would no longer be multiplied by a binary variable, and would thus not record accurate "mileage."

Another method of forcing multiple servicing of a demand node is to redefine that node as a group of co-located nodes, between which no arcs exist. Such a scheme allows the formulation to remain a binary one (except for the σ's), since each node of the group requires one and only one servicing. One problem remains with this formulation. Theoretically, a path can visit one node of a collocated group, subsequently visit an adjacent node outside the group, and return to another node within the group. Since these visits all occur on the same tour, such a scenario does not conform with the intent of forcing multiple visits by different tours (conceivably at different times). To force all visits within a node group to occur via different tours, all nodes of a group are assigned only one "odometer" variable (σ). As before, this prohibits a tour from servicing any grouping of nodes more than once, effectively forcing as many tours as there are nodes into a given group. Thus, Kulkarni's constraint serves the DCS model by forcing multiple servicing, as well as subtour breaking and range limitation.

Full Mathematical Model. The complete DCS aerial network mathematical model is stated below in its entirety. Note that most of the equations have already been stated, and all bear close resemblance to previous equations:

I= set of all nodes
d= statute mile distance + 150
x= 0,1 arc use indicator
U= vehicle range
σ= unrestricted "odometer" variable
c= fixed cost of a depot
m= number of vehicles at a depot

J= subset of I including only <u>depots</u>
B= arbitrarily large constant
pi,Pi= lower and upper limits on total depots
t,T= lower and upper limits on fleet size at a depot

$$\min \sum_{i,j\in I} d_{ij} x_{ij} + \sum_{r\in J} c_r y_r \qquad (29)$$

s.t.

$$\sum_{i\in I} x_{ij} = \begin{cases} m_j & \text{for } j\in J \\ 1 & \text{for } j\in I-J \end{cases} \qquad (25)$$

$$\sum_{i\in J} x_{ij} = \begin{cases} m_i & \text{for } i\in J \\ 1 & \text{for } i\in I-J \end{cases} \qquad (26)$$

$$Ux_{ij} + \sigma_i - \sigma_j \le U - d_{ij} \quad \forall\ |J+1| \le i \ne j \le |I| \qquad (12)$$

$$d_{ij}\ x_{ij} \le \sigma_j \quad \forall 1 \le i \le |J| \quad \forall |J+1| \le j \le |I| \qquad (27)$$

$$d_{ji}\ x_{ij} + \sigma_j \le U \quad \forall 1 \le i \le |J| \quad \forall |J+1| \le j \le |I| \qquad (28)$$

$$x_{i1i2} + x_{i2i1} + 3(x_{i2i3} + x_{i3i2}) + x_{i3i4} + x_{i4i3} \le 4 \quad i1,i4\in J \quad i2,i3\in I-J \qquad (30)$$

$$x_{i1i2} + x_{i2i1} + x_{i(h-1)ih} + x_{ihi(h-1)} + 2 \sum_{i,j\in\{i2..i(h-1)\}} x_{ij} \le 2h-5 \quad h>5 \quad i1,ih\in J \quad i2..i(h-1)\in I-J \qquad (31)$$

$$y_r \le m_r \le B\ y_r \quad r\in J \qquad (19)$$

$$t \le m_r \le T \quad r\in J \qquad (20)$$

$$p \le y_r \le P \quad r\in J \qquad (21)$$

The above model may be input into any mixed integer algorithm and serves as a reduced scale validation of the heuristics described in the next section.

<u>Heuristic Methodology Selection</u>

The literature review suggests three possible methodologies for solving the full-scale DCS network problem. Space filling curve (SFC) heuristics offer simplicity and a combined ability to accomplish both the depot location and routing aspects of the problem. The minimum spanning tree (MST) formulation (and the minimum spanning forest (MSF) extension) is a bit more complex, but potentially offers improved depot location. The Clarke-Wright algorithm, though somewhat more complex than either the SFC or MSF approach, is very adaptable to the DCS range and multiple frequency extensions of the TSP. Unfortunately, none of these methods are without significant drawback. Space filling curves do not have a sophisticated approach to multiple tours, which is a critical factor in multiple servicing route design. The transformation of a spanning tree into a TSP is also poorly suited to multiple tours. The Clarke-Wright algorithm can only handle pre-defined depot locations, and requires too much time to iterate between all the potential DCS depot locations. Consequently, a hybrid approach to depot location and routing is appropriate.

Regarding depot location, speed is the chief advantage of space filling curves. The minimum spanning forest must iterate through all possible depot combinations before selecting the best single solution. However, the MSF is very well suited to grouping proximate demand points and depot sites, which is a shortcoming of the SFC. Additionally, a demand node may be weighted so as to reflect its required servicing frequency. In this way, depot selection will tend to favor proximity to multiple frequency demand points. Finally, The MSF algorithm can be forced to preclude branches from becoming so long as to violate the range requirement. Because of these advantages, the MSF is selected as the depot location algorithm for the DCS solution heuristic.

Once the optimal forest is chosen, the individual trees indicate depot-demand assignments. Although Nemhauser's MST-TSP transformation heuristic seems appropriate for use here, its application to a multiple TSP is not provided in any of the reviewed literature. Moreover, the transformation from a MST to a TSP does not appear to readily lend itself to multiple tours. Since multiple tours are central to both the range and service frequency aspects of the DCS network, the MST-TSP transformation is not considered further. On the other hand, the Clarke-Wright heuristic does provide a workable incorporation of range and service frequency. For that reason, a combination minimum spanning forest and Clarke-Wright algorithm is chosen for solution of the DCS location-routing problem. Examples of the codes used are included in Appendix B, as well as the diskette included with this document. They should be referenced while reading the next two sections.

Minimum Spanning Forest Coding

As mentioned in Chapter II, Prim's spanning tree algorithm successively finds the shortest arc which adds another node into the current collection of nodes and arcs. The spanning forest expands this idea to several unconnected node-arc collections. The algorithm is a modified nearest neighbor heuristic, and the procedure for forest selection is as follows:

1. Select a combination of depots for branching. Define this set as the nodes currently included in the forest.
2. Admit the nearest node to the current forest unless the new branch connects that node to a depot which is greater than 1000 miles away.
3. Repeat step 2 until all nodes are included in the forest. Save as the best solution if the weighted distance is the smallest yet found.
4. Repeat step 1 until all combinations of depots have been explored.

The FORTRAN coding of this algorithm is straightforward. Initialization occurs by creating an inter-arc distance matrix, which is measured in statute miles and includes 150 miles per arc dwell time. Depot assignments are done first by declaring the fixed depots at Baltimore (KBWI), Kelly AFB (KSKF), and Travis AFB (KSUU). Thereafter, a succession of DO loops (FORTRAN syntax) define the current iteration of depot candidates. Initialization is completed by resetting the counters used during each iteration of depot combinations.

The main body of the code begins by pairing each demand node with its closest neighbor that is currently included in a collection (tree). Initially, this is simply the closest depot. Once each demand node is assigned a NEAR (variable name) tree branch, the current depot locations are defined as "collections of one," since no node-arc pairs have yet been formed. The program then searches the for the smallest NEAR value, whose index corresponds to the next node to be included into a tree. Nodes whose inclusion would cause a potential tour to exceed 2000 miles (round trip distance to the depot) are disqualified. This is the upper bound on the distance to a service location, since the round trip flight time at this distance is approximately ten hours. Once a suitable candidate for inclusion into a tree is found, its distance to the tree's depot, times its service frequency rate is added to the total cost. Finally, the NEAR array is updated to determine if the proximity of each unattached node to the enlarged forest is changed.

The branch selection process continues until all nodes are included in exactly one tree. If the total cost is the best so far, it is stored along with the associated node-arc forest. A new initialization of depots occurs until all possible depot combinations are explored. The best solution is then written to an output file.

The main drawback of the spanning forest approach is the large number of iterations required to explore all possible depot combinations. In addition to the current 12 depots, there are 18 CONUS locations where UPS provides service to a city near an active military airfield. Since only three of the depots are fixed, 27 choices remain from which to choose. In a problem which seeks 11 depots, the number of iterations required is over 2.2 million. The selection process requires considerable computer time.

Despite the daunting size of the depot selection process, the MSF coding is highly effective as it incorporates range and multiple frequency weighting. These advantages make it a critical part of the DCS solution heuristic.

Modified Clarke-Wright Coding

The original Clarke-Wright (CW) algorithm was designed as a multiple tour, vehicle capacity constrained heuristic for solving single depot TSPs (8:569). The DCS problem relaxes the vehicle capacity portion, but includes range and multiple frequency servicing. As with the mathematical programming approach, range is constrained by disallowing links on a tour which would cause the overall length to exceed 2600 sm. Also borrowed from the mathematical programming formulation is the concept of node clustering to simulate multiple demands. Both of these methods require keeping track of which tour each node is on, which is the major extension of the CW algorithm used in this research. The procedure follows these steps:

1. Construct the savings matrix using equation (23).

2. Select the arc offering the greatest savings unless the new tour length would exceed range, or the new tour involves revisiting a cluster already served along the route.

3. Proceed until no further savings can be achieved due to the restrictions in step 2.

FORTRAN implementation of this algorithm initializes by assigning a unique tour number to each node, except for clustered nodes, which are assigned one number per cluster. Each node is then assigned the number two, representing the number of connections with the depot it currently has. During the course of the run, this number is reduced to as low as zero, indicating that no further route consolidation can be considered using this node. Finally, the distance and savings matrices are computed, using equations (22) and (23), respectively.

The code's main body scans the savings matrix for the maximum value, which is chosen unless: 1) either of the nodes cannot further consolidate an arc; 2) consolidation would exceed range; or 3) the consolidation would revisit a cluster already included in the tour. The range and tour number arrays are then updated to include the most recent consolidation. This is a rather arcane piece of code, replete with buffer arrays and arrays used as indices for matrices. The foundation lies in accurate updating of the tour number array (NC) of every node of a newly consolidated tour. This is accomplished by combining and then scanning the NCV matrix row for each of the newly combined nodes, which keeps track of the other nodes in the indexed node's tour. In turn, this information is copied into those nodes' NC and NCV arrays, which completes the update. Finally, the new arc is written and tallied into the total network cost. When no further consolidations are feasible, the total cost and remaining depot connections are written, and the run terminates.

Heuristic Summary

As noted earlier, depot location and routing for the DCS problem is a two part process, first involving an exhaustive search of location possibilities, then designing routes from those depots which conform to the DCS network constraints. As expected for any large network, the combined process involves considerable computer time, but promises to be quite flexible. Though the principal focus of this research is a long term relocation strategy, a more useful short term application is selection of a depot for closure as a cost cutting measure. It is this flexibility which will allow the combined heuristic to serve the DCS for the foreseeable future.

Chapter Summary

The mathematical program offered at the beginning of the chapter is a rigorous formulation of the problem which confronts the DCS location and routing analyst. The heuristic solution approach offered in the chapter's second half provides a medium by which those problems can be solved at a system sized level. The combination of the two methodologies offer not only a solution scheme, but a means by which to validate the results. The next chapter describes the outcome of that process.

Chapter IV. Results

Overview

This chapter focuses on validation of the heuristic methodology via mathematical programming, and solution of the DCS network by the verified heuristic. The validation portion consists of three separate problems of sharply reduced size. They are each solved to optimality using the modified Laporte formulation developed in Chapter III; those solutions in turn are used as performance measures of the approximated solution using the combined minimum spanning forest/Clarke-Wright (MSF/CW) heuristic. The chapter then describes the use of the heuristic to offer best known routings for a given number of depots (using the criteria for depot location given in chapter III). Finally, a near term restructuring of the network is presented which offers savings through depot closures without drastic system change.

Validation

The three "mini-networks" used for validation purposes consist of locations served by the DCS network. Since even regional DCS modelling is beyond the capability of current computers, the maximum number of locations considered is six. This allows for co-location of demand and potential depot sites, as well as multiple servicing demands (recall that a demand frequency of 2 effectively requires 2 nodes within the formulation). Although the locations correspond to actual DCS service points, the servicing frequencies and depot suitability do not mimic reality, since those parameters are chosen to test various aspects of the code.

Since number of depots must be varied manually in the MSF/CW heuristic, two separate problems must be considered for each test case (each of the three regions offers two potential depot locations). Each region is first solved for optimality, which results in a single depot selection since depots are relatively expensive. A two depot case is forced after the results of the single case are known, and both cases are compared with the heuristic solution.

The Laporte algorithm is coded into MIP83, a PC-based mixed integer solver. Run times on an AT class microcomputer at 8 MHz (with math coprocessor) varied between 15 minutes and 6 hours, which is testament to the limitation of the algorithm to small problems. Samples of the input code as well as all of the output files are given in Appendix C and the accompanying diskette. Also included in Appendix C are the output files for all of the (test region) heuristic code runs.

Once the exact solution has been determined by the Laporte algorithm, the test region data are loaded into the

MSF code in order to select depots and assign demand locations to depots. The optimal forest is then broken into its component trees for input into the CW code. Thus, the validation process for each case consists of three steps: 1) exact solution by Laporte algorithm; 2) selection of heuristic forest by the MSF code; and 3) tour selection by the CW code, using the MSF results as input. Total system mileage is the measure of effectiveness used to evaluate the heuristic methodology.

<u>Region 1.</u> This test consists of several Northwest bases, including potential depots at McChord (TCM) and Travis (SUU), single demands at TCM, SUU, Klamath Falls

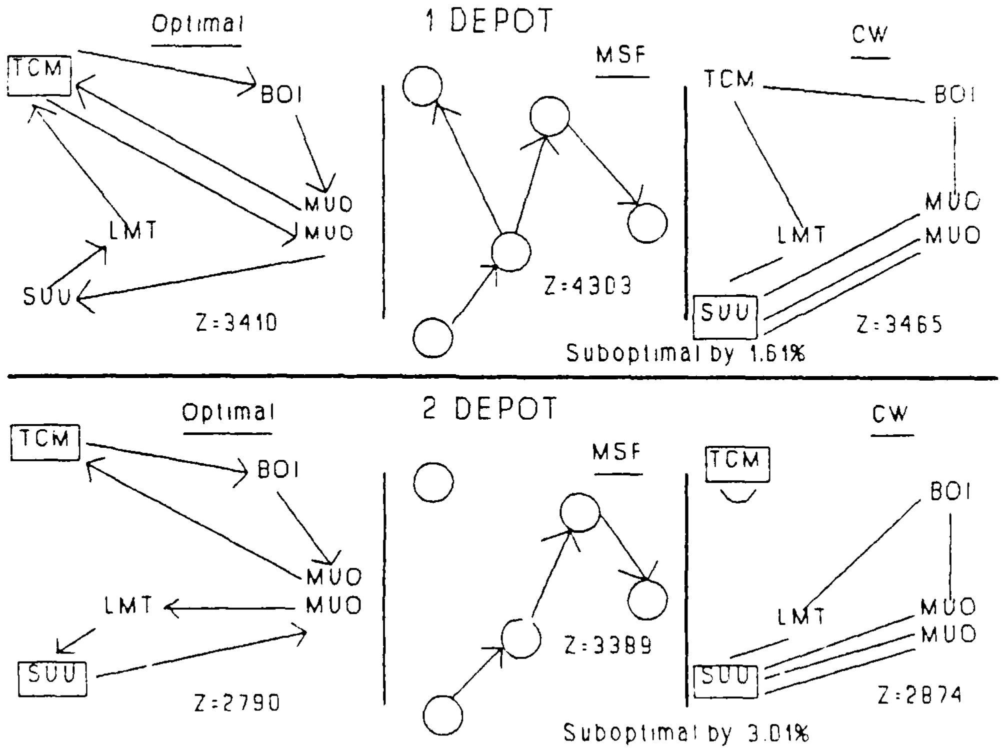


Figure 3. Validation Region 1

(LMT) and Boise (BOI), and a double frequency demand at Mountain Home (MUO). Figure 3 summarizes the various computer outputs. It is chosen because the geometry offers two nearly equal depot candidates from a visual inspection. It also forces at least two sorties since MUO must be visited twice. The graphics conventions for this and the ensuing routing figures depict the chosen depot within a box, and multiple servicing requirements by repeated station name (i.e. MUO written twice). The leftmost portion of the figure illustrates the optimal solution as delineated by Laporte's algorithm run using MIP83; the center portion depicts the Minimum Spanning Forest solution as computed by the code in Appendix B. The far right portion depicts the approximate solution as computed by the Clarke-Wright code and the depot-demand pairings given by the MSF. The objective function values are also given as a reference.

The results of this first validation run show the heuristic to be suboptimal by only 1.61% for the single depot case, and just 3.01% when two depots are forced. However, the MST heuristic chose SUU instead of the optimal TCM in the one depot case, and did not fully utilize TCM in the two depot instance. Fortunately, these deviations did not result in significant loss of overall performance.

Region 2. This validation includes six Midwest bases which all require only one servicing. The depot candidates are Offutt (OFF) and Wright-Patterson (FFO). The

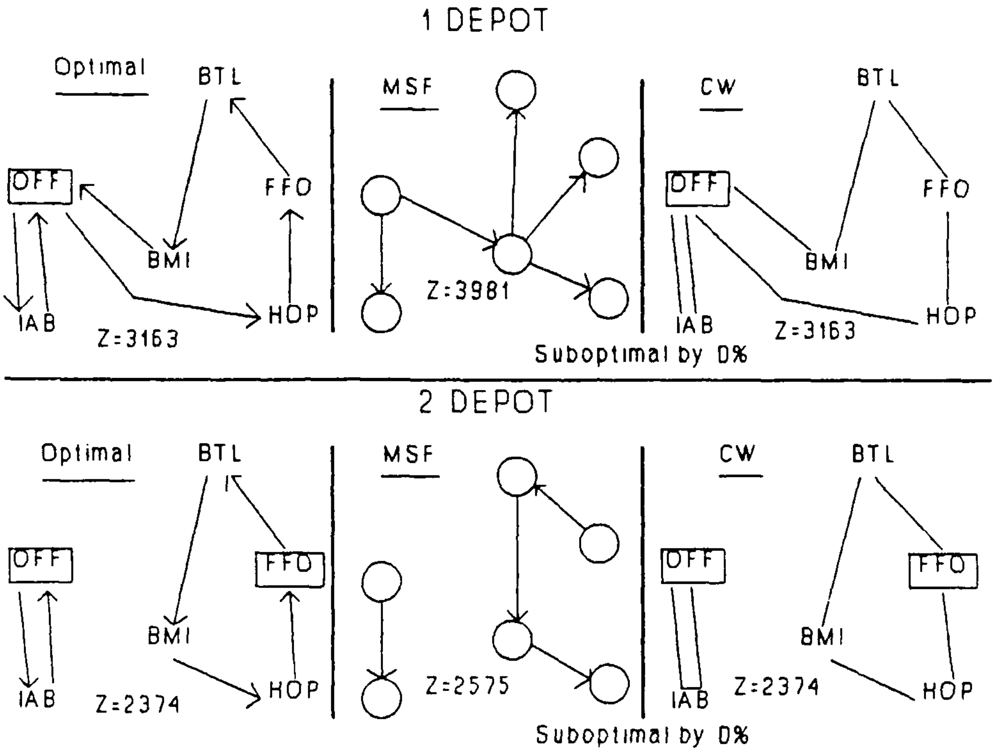


Figure 4. Validation Region 2

other bases requiring service are McConnell (IAB), Battle Creek (BTL), Bloomington IL (BMI), and Ft. Campbell (HOP). The demands are geographically distanced so as to exceed the maximum sortie range, thereby forcing at least two separate missions. Despite the proximity of more of the servicing locations to FFO, OFF is chosen for the single depot because of the remoteness of IAB. The MSF/CW heuristic is not fooled by this; it chooses the optimal solution in both the one and two depot cases. Additionally, none of the solutions include missions of excessive length, indicating that the code properly constrains range.

Region 3. This region consists of bases located in the Southeast with potential depots at Charleston (CHS) and

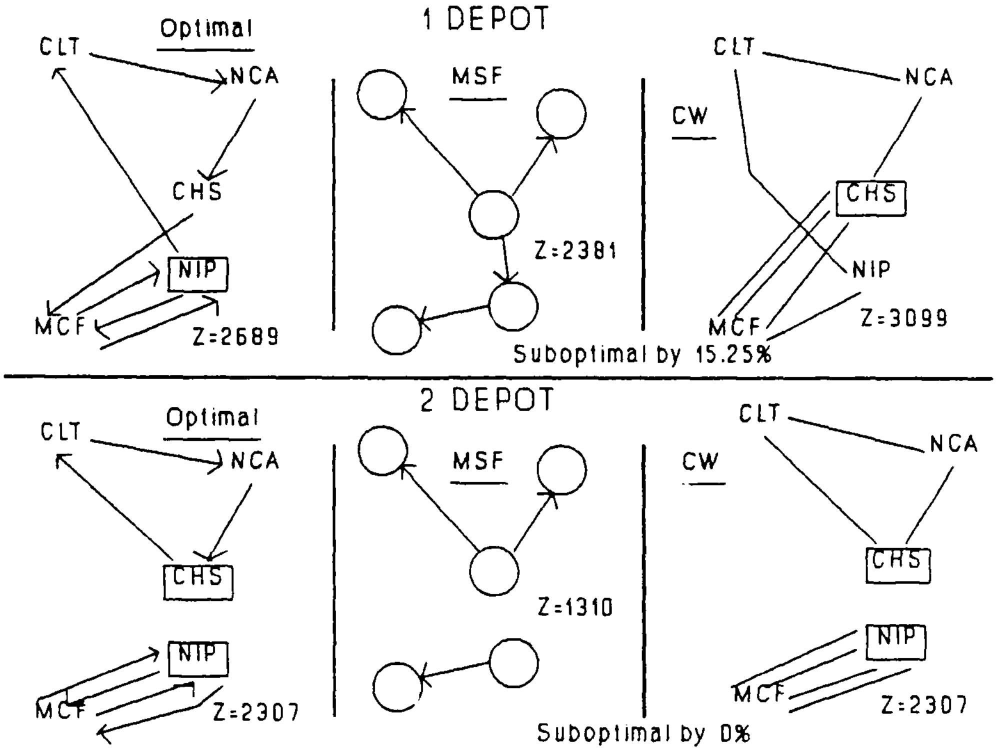


Figure 5. Validation Region 3

Jacksonville FL (NIP). Service must include the depot candidates as well as Charlotte (CLT), Jacksonville NC (NCA), and MacDill (MCF). The locations are chosen in order to force a choice between a depot with a proximate multiple servicing requirement (NIP serving MCF), and a depot nearby two single-service locations (CHS serving NCA and CLT). Although the optimal single depot solution selects CHS, the MSF forces a solution using NIP, which restricts the solution to 15.25% from optimal. This does not occur when a two-depot solution is forced; the heuristic replicates the optimal solution.

Validation Summary. The heuristic solution averages 3.32% from optimal for the six problems considered. The range of error spans between 0% (three occurrences) and 15.25% (1 occurrence). Although an upper bound is not established by this method, one may be reasonably assured that other results would not be markedly worse than those produced by the runs, since the region geometry was purposely chosen to make location-routing selection difficult. Depot selection appears to be the weakest ability of the MSF/CW heuristic; both division of service among depots and routing within a depot system mimic the optimal with reasonable accuracy. Consequently, MSF/CW results produced on the full DCS network should be reasonable (within 15%), though some depot misplacement may occur. This characteristic may be ameliorated by serendipity; one of the strengths of parametrically varying the number of depots may well be the continued reselection of many of the same depots. Indeed, Ware of the MAC analysis group has found a robustness of depot selection in similar networks (23). If indeed this is true for the DCS network, greater confidence of these robust depots may be assumed. The next section addresses this aspect, as well as the entire MSF/CW heuristic solution of the DCS network.

MSF/CW Heuristic Solution

Since the MAC analysis group has already offered a restructuring of the DCS network using the 12 current depots, and since depots appear to be relatively expensive entities, solutions offered in this research only consider fewer than the 12 current depots. To that end, the number of depots is varied between 11 and four; the latter figure proves to be infeasible due to inadequate aircraft range. At the outset of each iteration, the data set listed in Appendix D is input into the MSF code described in Chapter III. That set first lists the three unmovable depots, followed by the remaining 27 depot candidates and the 151 service-only locations. The data are arranged with the current depots first in order to award ties to those locations.

As stated earlier, the MSF code is computationally intense; in the case of the 11 depot run the code must find the best of "27 choose eight" forests, which is in excess of 2.2 million iterations. Fortunately, the number of possible combinations drops quickly as the required number of depots is reduced. The ten depot problem involves less than 900 thousand combinations, and the seven depot problem requires scarcely 17.5 thousand forests. All runs were made on a VAX 8550. The 11 depot problem required just over 2.7-CPU days. Each remaining problem was run in decreasing order of complexity and, predictably, took less than half the CPU time of its antecedent. Each CW run took nominal CPU time and most were accomplished on a microcomputer. The output of each MST and appropriate CW runs are given in Appendix E.

Once the best forest is chosen it is split into its component "trees," which are (in turn) input to the CW code. Since the frequency of service varies from every other month to six times per week, many of the "trees" have a different least occurring frequency, which corresponds to the smallest usable increment of time when computing the route structure. In other words, a depot which serves an every-other-month location must have its routes computed for two months before repetition, which cannot be directly compared with a depot whose least occurring service frequency is weekly. Another standardization measure is the subtraction of the 150 statute miles per leg which was added in order to restrict range. Each of these two computations is done manually and accompanies the CW output. Since many of the CW output files apply to several of the MSF runs, the output is only given the first time it is needed. The following is a summary of those runs.

11 Depot Model. The MSF computation finds that nine of the 11 depots chosen are current depots. Only Griffiss AFB (which is served by UPS at Syracuse), and Little Rock AFB (served by UPS at the adjacent city) are new to the system. The McChord AFB, Norfolk, and Denver depots have been deleted from the system. A graphic presentation of the MSF structure is given in Figure 6. The forest cost, though not physically representative of any network cost, is 279,481 statute miles. The inter-depot boundaries appear

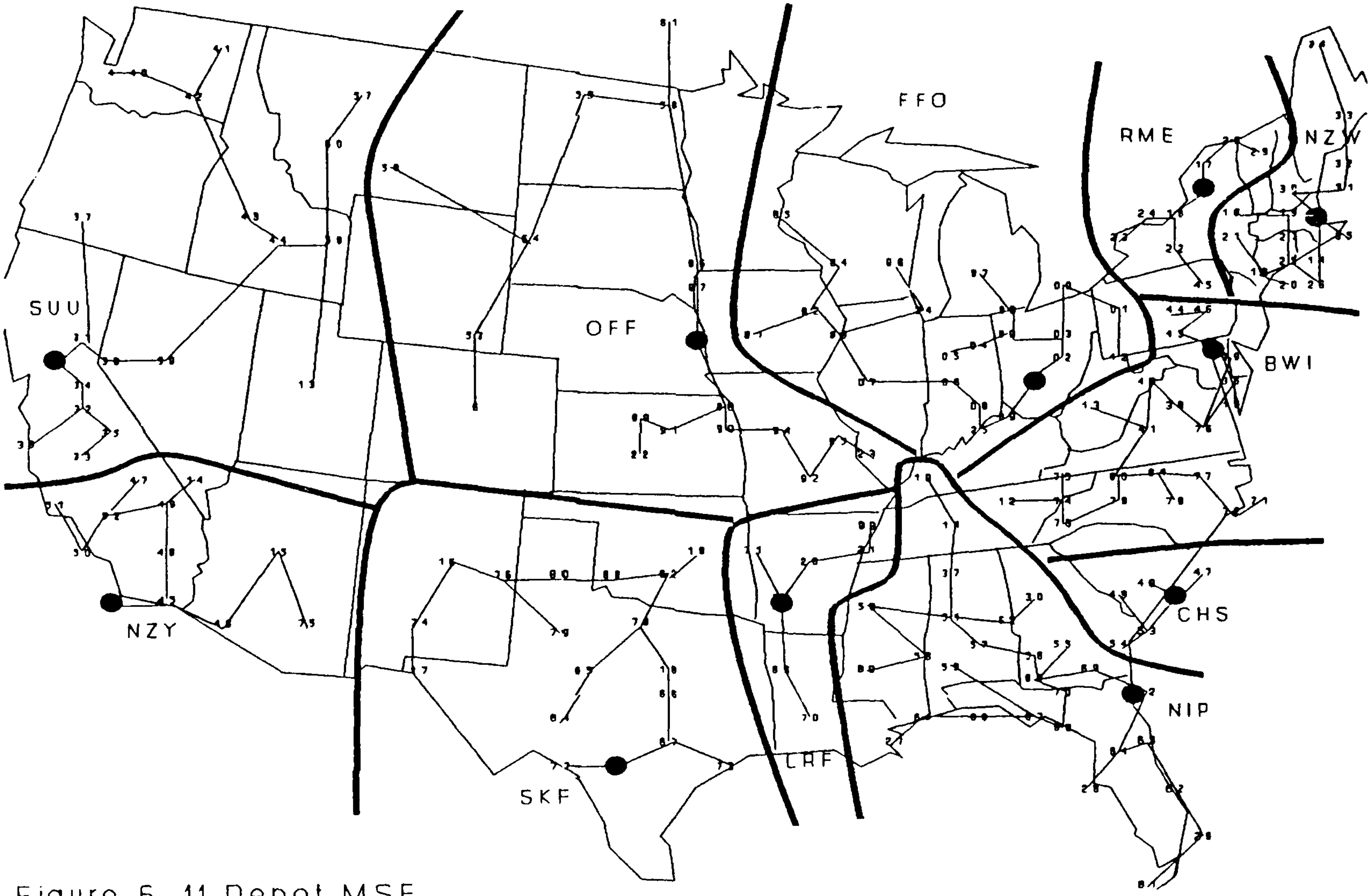


Figure 6. 11 Depot MSF

logical in nearly all locations, and even appear similar to many current boundaries. An unnatural association with one Montana location and the depot at Offutt exists, and is due to the range limitation of aircraft stationed at the Travis depot.

The combined total mileage flown is computed by the CW code to be 24,070 sm per week, or 1,251,640 sm per year. This compares very favorably with the current yearly mileage of 1,550,395 (13). It also compares well with MAC's stage two suggestion of 1,400,070 sm per year (13). Although many factors (addressed in the next chapter) must be considered before directly comparing these models with the current system, the results are, nonetheless, encouraging.

10-4 Depot Models. Each of the reduced depot models is similar to its predecessor model with regard to forest appearance. In all cases, the service stops of one depot are assimilated into a nearby depot, and the widowed depot is closed. This characteristic makes the new route mileage very simple, since only one depot's routes are changed (due to the inclusion of its former neighbor's service locations).

Table 1 lists the number of depots in each of the reduced models ("Depots"), the name of the eliminated depot ("Loss"), the assimilating depot ("Expand"), the yearly mileage cost, and the difference in mileage from the next larger system model.

Table 1.
Iterated Depot Closures

Depots	Loss	Expand	Yearly Mileage	Mileage added
10	NZY	SUU	1,275,924	24,284
9	LRF	NIP	1,332,344	56,420
8	CHS	BWI	1,360,424	28,080
7	RME	NZW	1,374,152	13,728
6	NZW	BWI	1,428,284	54,132
5	FFO	BWI	1,635,764	207,480

The only exception to the iterated depot closure routine is between the six and five depot models. Two of the service locations (DSM and MSP) of FFO are not within range of BWI, so the MSF attached those locations to the OFF tree. Limited range also precludes a system with less than 5 depots. Since three of the depots are fixed, a four depot model only allows one variable depot location. Significant voids exist in both the North-Central and Southeast CONUS, and a single depot cannot serve both regions. The MSF code notes this by assigning a very large penalty cost for infeasibility.

Depot Closure Sequence. Since depot closures appear to be events which affect only one other depot in the system, it is clear that the depots ought to be closed in an order where the mileage increase is always the least. In other words, there is little merit in merging North Island's routes into Travis' (at a yearly cost of 24,284 miles), when Griffiss' routes may be merged into Boston's for a lower yearly mileage addition (13,728). The fact that the MSF code does not shut down depots in this order shows some limitation of its effectiveness.

The inherent difference between a spanning forest and a travelling salesman route system is to blame for the less than optimal ordering of depot closures. When Appendix E is examined, the MSF objective function differentials are continuously increasing. Unfortunately, Table 1 testifies that this does not translate into a continuously increasing cost differential for the CW route structure. This discrepancy may be rectified by examination, however. Table 2, supported by the calculations at the end of Appendix E, accomplishes this reordering. As with Table 1, it uses the 11 Depot model (shown in Figure 6) as a starting point.

Table 2.
Improved Depot Closure Sequence

Depots	Loss	Expand	Yearly Mileage	Mileage added
10	RME	NZW	1,265,368	13,728
9	NZY	SUU	1,289,652	24,284
8	CHS	BWI	1,317,732	28,080
7	NZW	BWI	1,371,864	54,132
6	LRF	NIP	1,428,284	56,420
5	FFO	BWI	1,635,764	207,480

The order of depot closure stated in this table presents a more cost effective closure sequence, since the minimal incremental cost is added at each level.

The data in Table 2 are central to finding the optimal number of depots for the DCS network. The curved line in Figure 7 is a plot of these data, and it portrays the cost line formed by trading depot and operating (mileage) costs. The straight lines in Figure 7 are the budget lines (estimated, 90% upper, and 90% lower bounds)

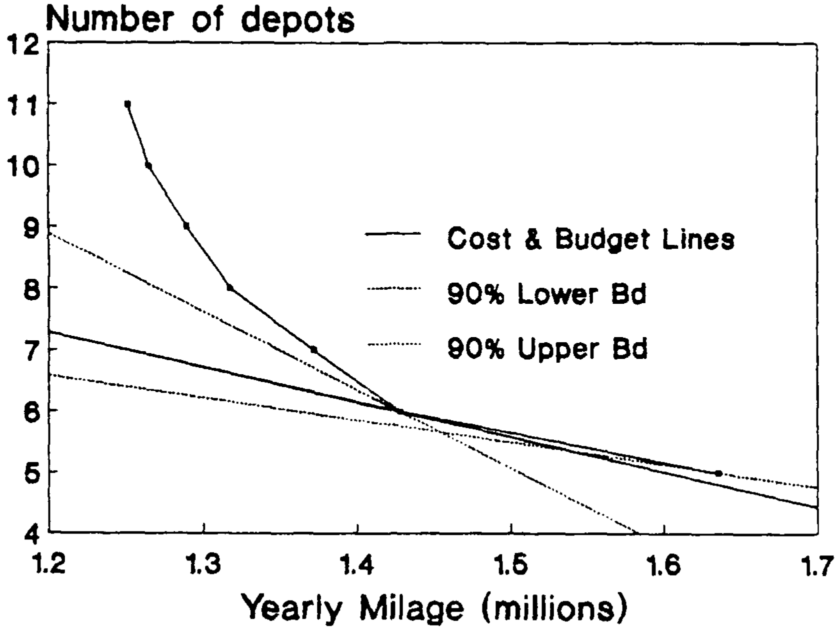


Figure 7. Depot Versus Operating Costs

computed in the regression done in Chapter III. The regressed slope of the estimated budget line is -5.681, or 2.229 dollars per mile divided by .392 million dollars per depot (the negative sign accounts for the inverse relationship of depots and mileage). Budget estimation based on these coefficients must also include a constant term for the number of stations served, since the regression model incorporates that parameter. As caveated in Chapter III, these computations are more of an example than a statistically sound estimate, since: 1) the hypothesis test associated with the depot cost model is not convincing; and 2) the dollars per mile estimate is a nationwide average. However, based on these cost figures, a six depot system is optimal. Stated another way, the yearly mileage cost of a depot in this model is (3382*52) = 175,864 miles. Since the transition from six to five depots is the first reduction which exceeds that cost, the six depot network is the cheapest alternative.

Formal restatement of the depot versus mileage ($5 \leq$ depots ≤ 11) optimization for the DCS network is best done mathematically. :

$$\min \quad L_1\, DEP + L_2\, SM \tag{32}$$

$$\text{s.t.} \quad -\,72.99\, MSM + 102.33 \leq DEP \tag{33}$$

$$-\,41.19\, MSM + 62.13 \leq DEP \tag{34}$$

$$-\,35.61\, MSM + 54.90 \leq DEP \tag{35}$$

$$-\,18.47\, MSM + 32.34 \leq DEP \tag{36}$$

$$-\,17.72\, MSM + 31.31 \leq DEP \tag{37}$$

$$-\,4.82\, MSM + 12.86 \leq DEP \tag{38}$$

Here, DEP, SM, and MSM denote the number of depots, statute miles, and million statute miles per year, respectively; L_1 and L_2 equal their associated costs. Regional estimations of these coefficients by DCS will dictate the system optimal. finally, a constant term is included in the objective function in order to convert to a budget estimate.

Near-Term Recommendation

Since the methodology discussed so far calls for radical restructuring of the DCS aerial network, a near term solution is proposed which looks much more like the current structure. Notably, this proposal does not include any new depots, and preserves the three "priority routes" between Baltimore and FFO, LFI, and HUA. This proposal is much more problem specific; it is consequently less theoretically rigorous.

Because the priority routes to Wright-Patt, Langley, and Huntsville are high-frequency events (six, six, and two times per week, respectively), there is considerable ability for aircraft flying these missions to also serve other locations along the route. Since these aircraft are, by definition, Baltimore based, all locations between BWI and the priority destinations are good candidates to be included in the BWI depot structure. Although the term "between" is somewhat ill-defined, use of the system map aids in approximating good potential enroute stops. Figure 8 shows the approximation used in this research; it is a combination of prior depot divisions and "eyeball estimation." Analytical selection is a clear topic for further research.

The number of depots is another variable which could be altered prior to final system selection. In this case, however, the MAC analysis group has already made recommendations regarding a 12 depot structure. Additionally, the proximity of the depot at Norfolk to the enlarged BWI depot (proposed here) makes NGU a good candidate for elimination. Finally, one other depot shall be eliminated in order to not replicate MAC's results in areas

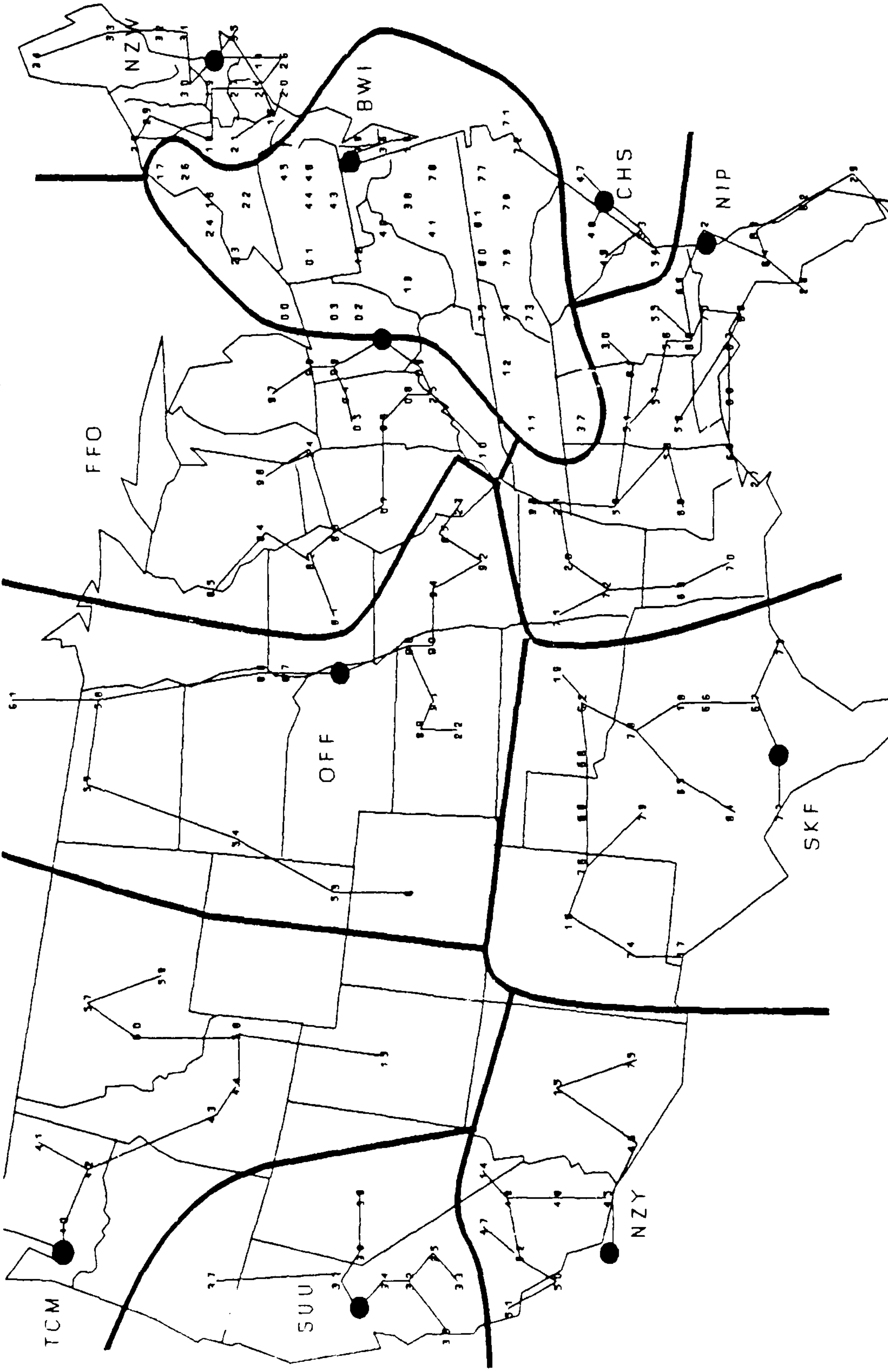


Figure 8. Near term MSF

outside the BWI region. Thus, a ten depot MSF/CW model is considered using the a priori BWI service locations.

In addition to the BWI exclusions, Figure 8 depicts the output MSF. The computer output for this and the associated CW runs are included in Appendix F. Accompanying the output is a full output interpretation of the routes.

The combined heuristic determines that Denver is the most eligible base for closure, based on route efficiency. The solution directs 1,448,148 miles per year without radical restructuring. This figure, while 48,000 miles per year above the 12 depot network offered by MAC, accomplishes the same level of service without the Denver or Norfolk depots. For that reason, the ten base option appears competitive, and should be considered if depot reduction is a priority.

Heuristic Summary

The combined MSF/CW heuristic can be used to construct a DCS routing system that offers depot reduction without large mileage penalties. The combined solutions range from 11 depots with 1.2 million yearly miles flown, to five depots with missions totaling 1.6 million yearly miles. The method is also flexible; the inputs are easily varied to accommodate short term network improvements. It appears to be well suited to DCS network analysis.

Chapter Summary

The formulation given by Laporte and modified in Chapter III is verified by integer programming using several test problems. Those problems are used in turn to validate the combined minimum spanning forest/Clarke-Wright heuristic developed in Chapter III. The validation uncovers heuristic errors ranging from zero to 15.25%. The weakest single aspect of the heuristic is its ability to distinguish between depots which offer similar degrees of network improvement. This is borne out in the analysis of DCS data. Fortunately, some of the error can be easily seen and subsequently reprioritized by hand calculation.

Usefulness of the validated heuristic is shown by the results which direct less yearly distance than is currently flown. The heuristic is flexible and can be used on the DCS network regardless of the degree of restructuring which is practical or desired. It leaves the decision maker with many attractive options.

Chapter V. Contributions and Conclusion

The purpose of this study as stated in Chapter I is to explore the possibility of system cost reduction by decreasing the number of depots, altering depot locations, and changing the routes flown. A methodology for the reduction of DCS network costs by these means has been developed and demonstrated in this research. Central to the study is the development of extensions to the multiple-depot, multiple travelling salesmen problem. These extensions encompass the theoretical problem as well as heuristic alterations that accommodate a specific set of range and servicing constraints. During the course of the research, several areas for future study have been uncovered, and provide for ample follow on research topics. Finally, the techniques used are shown to be an effective and flexible tool to DCS aerial network improvement analysis. This chapter summarizes these aspects of the research.

Mathematical Programming Extensions

Tailoring the well known Laporte formulation of the multiple-depot, multiple travelling salesmen problem is essential to rigorous mathematical statement of the DCS network. To that end, one key contribution of this research is the clustering of nodes to allow for multiple servicing by different tours. The other primary contribution is the "shoring up" of the Kulkarni method of combined subtour breaking and range limitation. These two additions to the formulation are, however, performed at the cost of restating the formulation asymmetrically. Despite this added complexity, the extended formulation has applications well beyond the specific DCS problem, since range and servicing constraints are frequent characteristics of real world TSPs.

Heuristic Extensions

Spanning forests have been used in the past for the partitioning and depot location portion of multiple depot TSPs (23). This research shows that the technique is useful when a large number of potential depot combinations exist. The research also shows that MSFs are somewhat limited in their ability to accurately prioritize the inclusion (or exclusion) of depots when there are many candidates from which to choose. Fortunately for this specific application (the DCS network), the limitation is, in some measure, ameliorated by manually altering the depot closure sequence. From a practical standpoint, this computationally "un-pure" aspect must be balanced with the fact that a truly exceptional depot location heuristic still evades the state-of-the-art in this field. The research shows that the MSF, though not without disadvantage, is a useful tool for this application.

The Clarke-Wright extensions developed in Chapter III are a key part of the heuristic used for the DCS network, and no significant drawbacks are noticeable in their implementation. The code used in this research incorporates the multiple-servicing extension proposed by Beltrami and Bodin (4:417). More importantly, this study develops a range constrained version of the Clarke-Wright algorithm. This inclusion of range limitation is critical to the DCS formulation. When run with the MSF output, the CW heuristic may be used in multiple depot applications, which broadens its scope from the single-depot TSP application for which it was originally developed.

Follow-on Research

Follow-on research topics fall into two broad categories: 1) recommended study by DCS prior to effecting any solution proposed in this document; and 2) supplementary analysis which would augment the body of knowledge surrounding the extended multiple-depot, multiple TSP. There are numerous opportunities for inquiry in each category.

As became apparent in the course of the research, depot costs are not readily modelled. Prior to any alteration of depot locations, closure or construction costs must be thoroughly examined on a case by case basis. Inclusion of a penalty factor for depot construction is one modelling alternative which should be explored in further research. Another important additional cost factor which was not previously addressed is the overland aspect of the DCS network. Clearly, a depot which is a significant trucking hub is not as good a candidate for closure as a depot whose sole mission is aerial transshipment, since the trucking support would also be displaced. Additionally, growth of a hub beyond a certain point may force negative economies of scale, since limitations on physical space or contractor fleet size may exist. Rethinking service requirements is also warranted whenever a major structural change is made to the network. What was formerly a convenient stop to make weekly may require a special trip after restructuring. Finally, the proposed routes all limit the crew day to 13 hours without overnight requirements (which even the current structure violates occasionally). However, the routes tend to average close to 13 hours, which is longer than the current average. Convincing a contractor to fly a few extended missions may prove easier than providing him a ceaseless string of long sorties. These are all issues which mathematical algorithms alone cannot resolve.

The larger issue of extended multiple-depot, multiple-tour TSP solution methodology is also replete with unanswered questions. This research provides empirical evidence of the upper error bound of the MSF/CW algorithm, but offers no theoretical one. Since both the spanning forest (as it relates to the TSP) and the Clarke-Wright algorithm have been around for some time, their respective accuracies have no doubt been largely fathomed. However, the error incurred by a synthesis of the two methods remains unexplored. Since much of the error appears to be in the MSF portion of the duo, further exploration of methods which provide depot location and partitioning are warranted. One possible area for study is the use of statistical cluster analysis of demand locations to provide a location/ partitioning heuristic. The multiple depot methods proposed by Golden also show some promise for application, though modifications for problem size would have to be addressed (12:113-148). Many other possibilities no doubt exist.

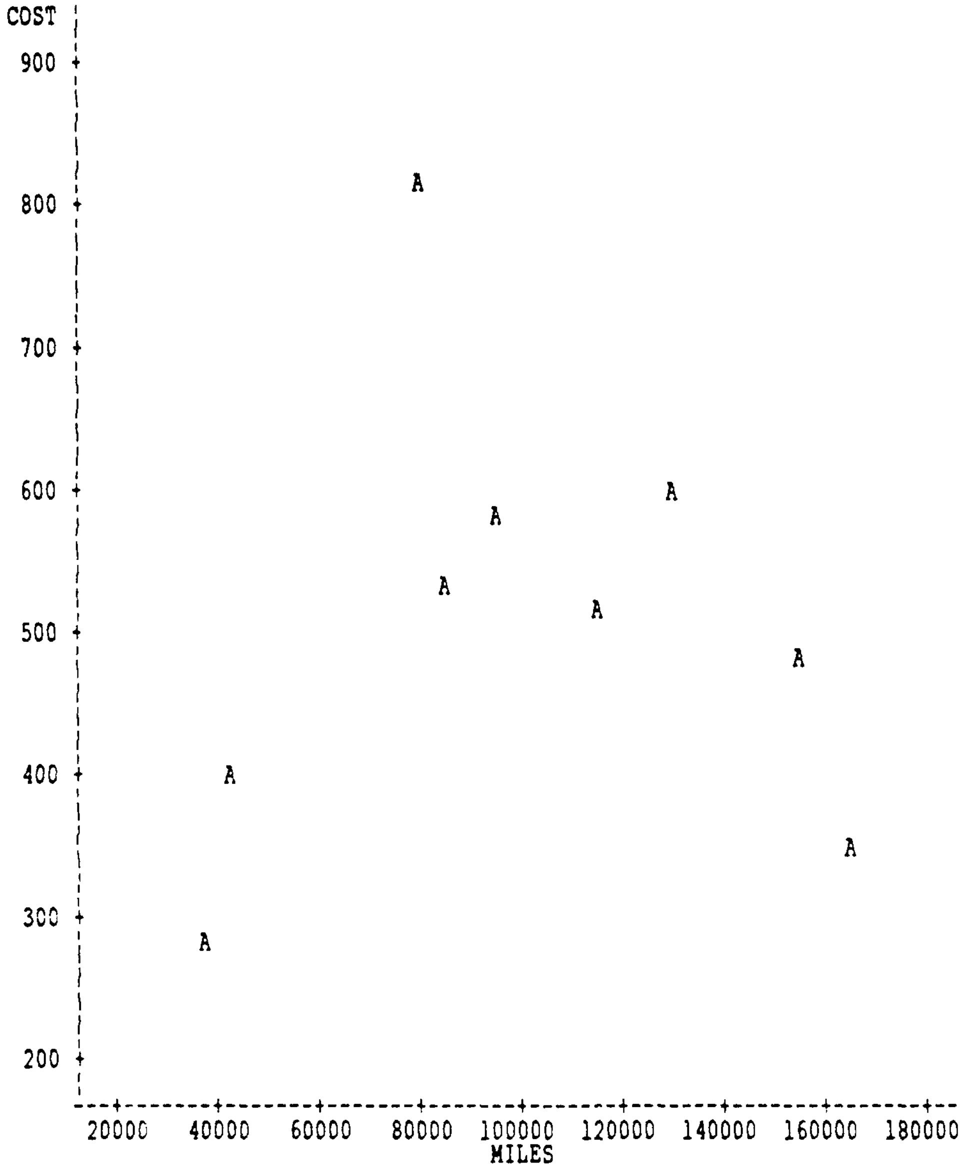
Summary

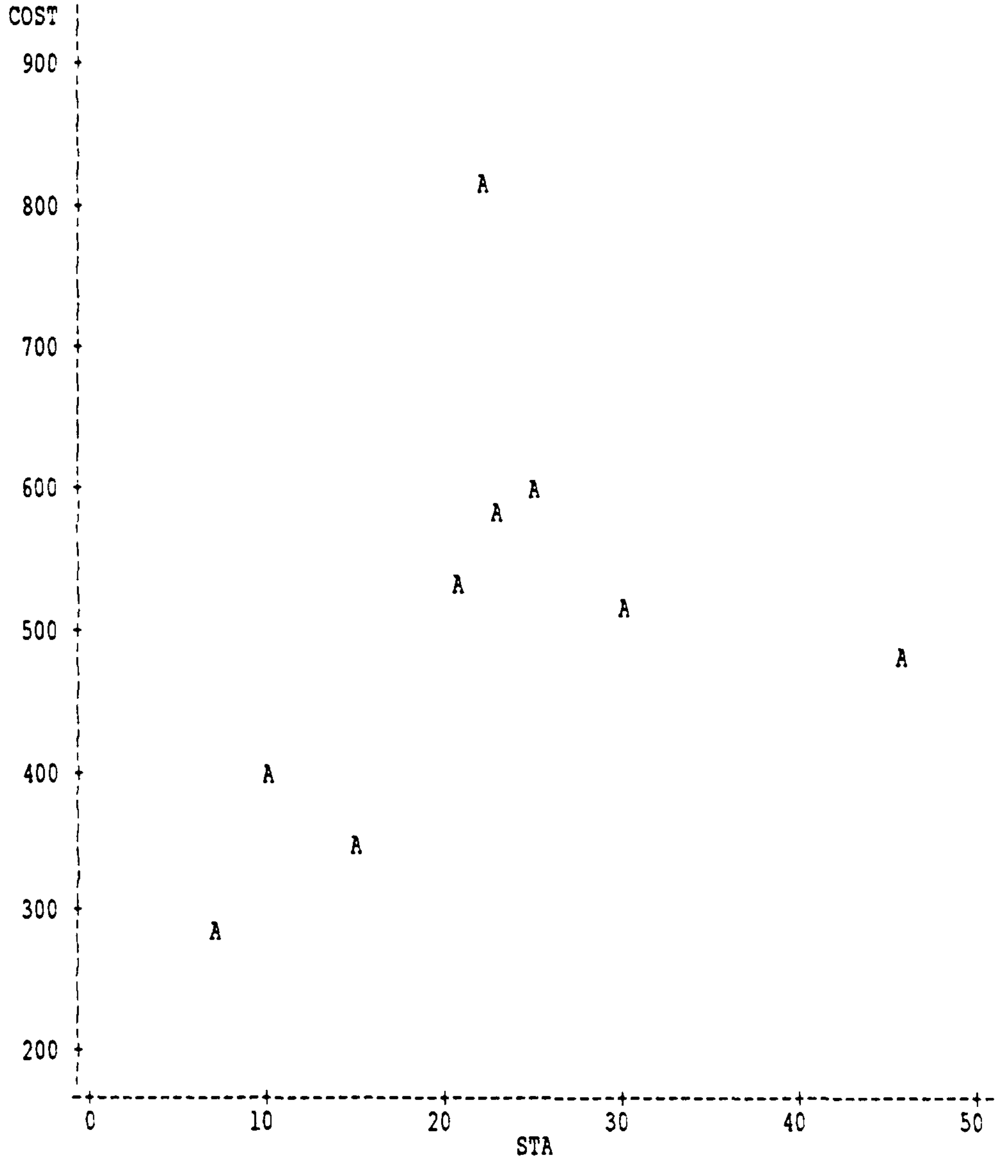
Reduction of overall network costs are achievable by altering the location of depots, depot assignments, and routes flown by the DCS contractors. This report shows that tailoring existing mathematical models to assist in this process is extremely beneficial. The tools offered in the research are adaptable to both near-term and long-term network strategies, and can be altered to resolve countless "what if" inquiries. Hopefully, their use will prove beneficial to both the Defense Courier Service and the Military Airlift Command.

Appendix A: Regression of Depot Costs

```
                         OBS    MSNS    STA     MILES    COST
                          1      8.0     46    155397     486
                          2      4.0     30    114920     523
                          3      4.0     23     96104     577
                          4      4.0     22     80132     811
                          5      4.0     21     85406     529
                          6      5.0     25    130798     602
                          7      4.2     15    165210     350
                          8      2.0      7     37924     287
                          9      1.8     10     41742     405

                                Correlation Analysis
                  4 'VAR' Variables:  MSNS     STA      MILES    COST
                                 Simple Statistics
     Variable           N        Mean     Std Dev         Sum    Minimum     Maximum

     MSNS               9      4.1111      1.7947     37.0000     1.8000      8.0000
     STA                9     22.1111     11.5590    199.0000     7.0000     46.0000
     MILES              9      100848       45216      907633      37924      165210
     COST               9    507.7778    154.5031        4570   287.0000    811.0000

      Pearson Correlation Coefficients / Prob > |R| under Ho: Rho=0 / N = 9

                       MSNS              STA              MILES              COST
    MSNS            1.00000          0.92724            0.79619           0.28996
                     0.0              0.0003             0.0102            0.4491

    STA             0.92724          1.00000            0.65169           0.39050
                     0.0003           0.0                0.0572            0.2988

    MILES           0.79619          0.65169            1.00000           0.08450
                     0.0102           0.0572             0.0                0.8289

    COST            0.28996          0.39050            0.08450           1.00000
                     0.4491           0.2988             0.8289            0.0
```

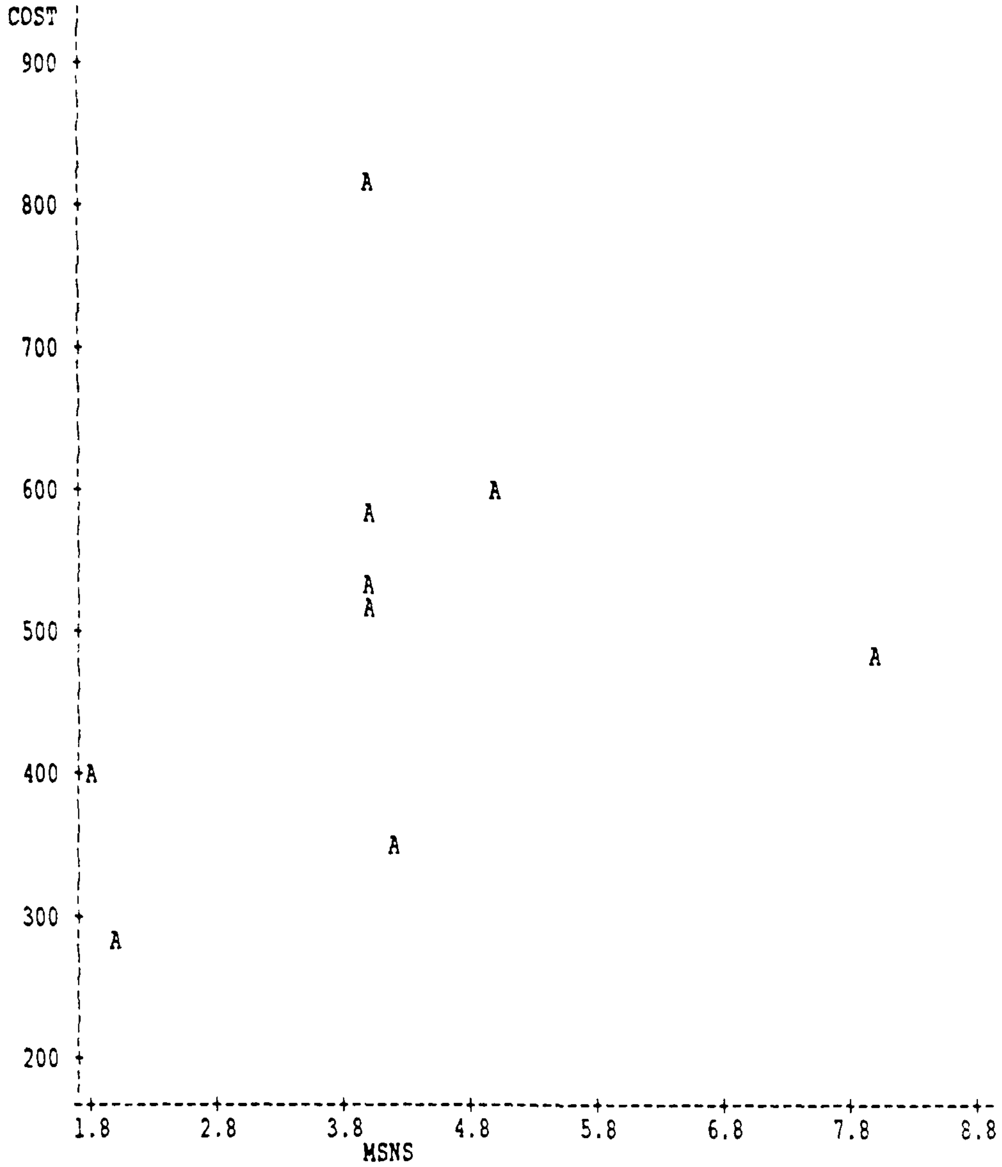
Plot of COST*MILES. Legend: A = 1 obs, B = 2 obs, etc.





Plot of COST*STA. Legend: A = 1 obs, B = 2 obs, etc.

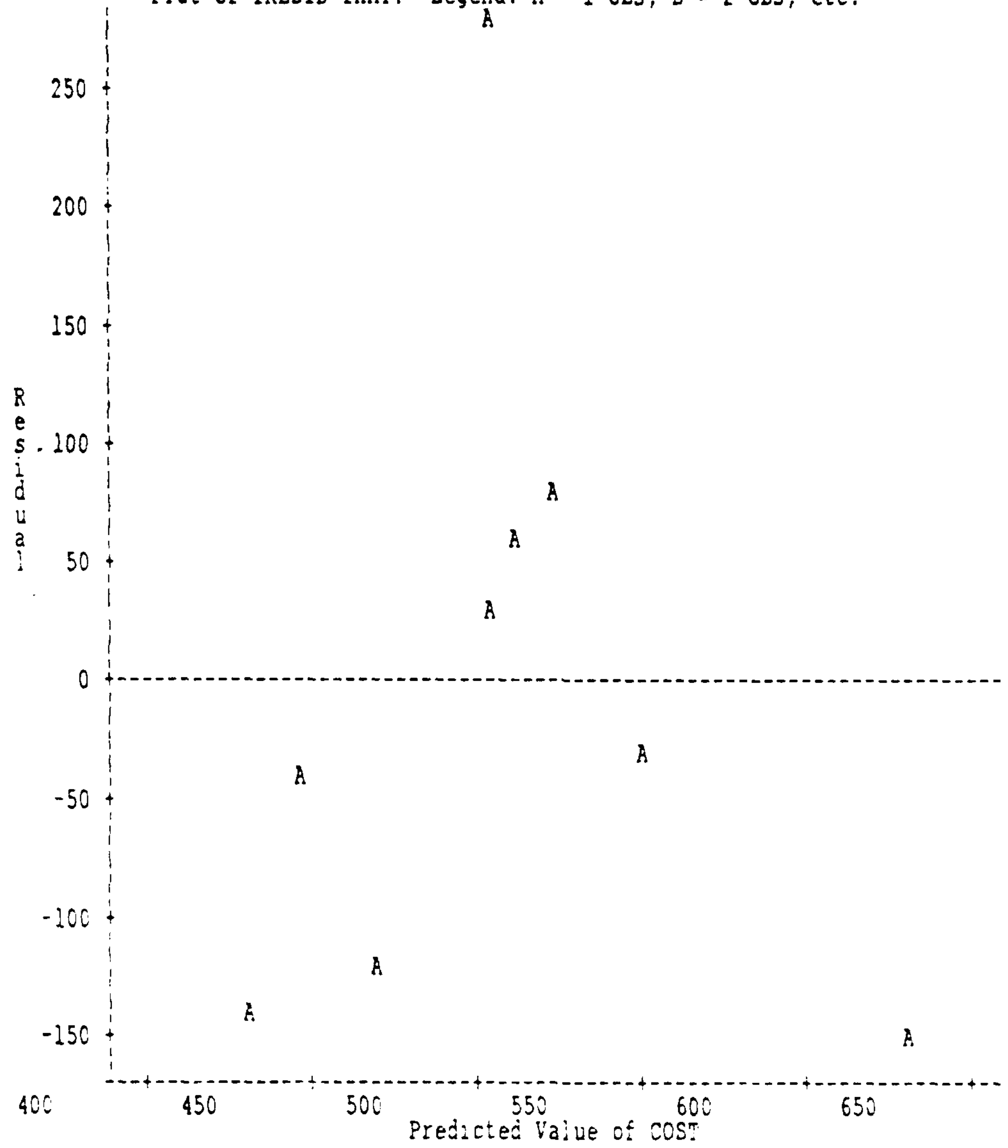
Plot of COST*MSNS. Legend: A = 1 obs, B = 2 obs, etc.



```
Model: MODEL1
Dependent Variable: COST
                             Analysis of Variance
                                Sum of         Mean
       Source          DF      Squares        Square         F Value       Prob>F
       Model            1   1363.61815   1363.61815           0.050        0.8289
       Error            7 189605.93741  27086.56249
       C Total          8 190969.55556
           Root MSE     164.57996     R-square       0.0071
           Dep Mean     507.77778     Adj R-sq      -0.1347
           C.V.          32.41181
                             Parameter Estimates
                      Parameter      Standard    T for H0:
     Variable  DF      Estimate         Error   Parameter=0    Prob > |T|
     INTERCEP   1    478.658966  140.89780276         3.397        0.0115
     MILES      1      0.000289    0.00128688         0.224        0.8289

Model: MODEL2
Dependent Variable: COST
                             Analysis of Variance
                                Sum of         Mean
       Source          DF      Squares        Square         F Value       Prob>F
       Model            1  16055.59436  16055.59436           0.643        0.4491
       Error            7 174913.96119  24987.70874
       C Total          8 190969.55556
           Root MSE     158.07501     R-square       0.0841
           Dep Mean     507.77778     Adj R-sq      -0.0468
           C.V.          31.13075
                            Parameter Estimates
                      Parameter      Standard    T for H0:
     Variable  DF      Estimate         Error   Parameter=0    Prob > |T|
      INTERCEP   1   405.159538  138.43875239         2.927        0.0221
      MSNS       1    24.961194   31.13976789         0.802        0.4491

Model: MODEL 3
Dependent Variable:COST
                             Analysis of Variance
                                 Sum of         Mean
       Source          DF      Squares        Square         F Value       Prob>F
       Model            1  29121.56813  29121.56813           1.260        0.2988
       Error            7 161847.98742  23121.14106
       C Total          8 190969.55556
           Root MSE     152.05637     R-square       0.1525
           Dep Mean     507.77778     Adj R-sq       0.0314
           C.V.          29.94546
                             Parameter Estimates
                      Parameter      Standard    T for H0:
     Variable  DF      Estimate         Error   Parameter=0    Prob > |T|

     INTERCEP   1    392.365593  114.64920757         3.422        0.0111
     STA        1      5.219647    4.65091444         1.122        0.2988

Model: MODEL4
Dependent Variable: COST
                             Analysis of Variance
                                Sum of         Mean
       Source          DF      Squares        Square         F Value       Prob>F
       Model            2  27230.05559  13615.02779           0.499        0.6303
       Error            6 163739.49997  27289.91666
       C Total          8 190969.55556
           Root MSE     165.19660     R-square       0.1426
           Dep Mean     507.77778     Adj R-sq      -0.1432
           C.V.          32.53325
                             Parameter Estimates
                      Parameter      Standard    T for H0:
     Variable  DF      Estimate         Error   Parameter=0    Prob > |T|
     INTERCEP   1    430.272902  149.90425236         2.870        0.0284
     MSNS       1     52.364068   53.78561961         0.974        0.3679
     MILES      1     -0.001366    0.00213488        -0.640        0.5459
```

```
Model: MODEL 5
Dependent Variable: COST
                                Analysis of Variance
                                   Sum of          Mean
       Source            DF       Squares        Square          F Value       Prob>F
       Model              2   38713.50936   19356.75468            0.763       0.5068
       Error              6  152256.04620   25376.00770
       C Total            8  190969.55556
           Root MSE       159.29849      R-square        0.2027
           Dep Mean       507.77778      Adj R-sq       -0.0630
           C.V.            31.37169
                                Parameter Estimates
                         Parameter       Standard     T for H0:
     Variable  DF         Estimate          Error    Parameter=0      Prob > |T|
     INTERCEP   1       437.275143   140.57764382          3.111          0.0208
     MILES      1        -0.001010     0.00164220         -0.615          0.5613
     STA        1         7.793507     6.42391661          1.213          0.2706
Model: MODEL6
                               Analysis of Variance
                                   Sum of          Mean
       Source            DF       Squares        Square          F Value       Prob>F
       Model              2   36208.44250   18104.22125            0.702       0.5322
       Error              6  154761.11305   25793.51884
       C Total            8  190969.55556
           Root MSE       160.60361      R-square        0.1896
           Dep Mean       507.77778      Adj R-sq       -0.0805
           C.V.            31.62872
                                Parameter Estimates
                         Parameter       Standard     T for H0:
     Variable  DF         Estimate          Error    Parameter=0      Prob > |T|
     INTERCEP   1       433.452592   144.24939131          3.005          0.0239
     MSNS       1       -44.286491    84.48881151         -0.524          0.6190
     STA        1        11.595612    13.11839689          0.884          0.4108
Model: FULL MODEL
Dependent Variable: COST
                                Analysis of Variance
                                   Sum of          Mean
       Source            DF       Squares        Square          F Value       Prob>F
       Model              3   39310.16210   13103.38737            0.432       0.7394
       Error              5  151659.39346   30331.87869
       C Total            8  190969.55556
           Root MSE       174.16050      R-square        0.2058
           Dep Mean       507.77778      Adj R-sq       -0.2706
           C.V.            34.29857
                                Parameter Estimates
                         Parameter       Standard     T for H0:
     Variable  DF         Estimate          Error    Parameter=0      Prob > |T|
     INTERCEP   1       443.180599   159.35638901          2.781          0.0389
     MSNS       1       -17.431414   124.28578418         -0.140          0.8939
     STA        1         9.714722    15.39375717          0.631          0.5557
     MILES      1        -0.000779     0.00243552         -0.320          0.7621
```

Plot of YRESID*YHAT. Legend: A = 1 obs, B = 2 obs, etc.



```
              WILK-SHAPIRO
OBS    SAMSIZE    NORMTSPV
 1        9       0.93381
```

Appendix B: Spanning Forest and Clarke-Wright Code

MSF:

```
C CAPT. S.F. BAKER
C MINIMAL SPANNING FOREST PROGRAM
C FOR DCS PROBLEM SET
C
C VARIABLE EXPLANATION:
C N: # OF NODES
C NDEP: # OF DEPOTS TO BE SELECTED
C       (NOT INCLUDING FIXED DEPOTS)
C NFXDEP: # OF FIXED DEPOTS
C NDPCAN: # OF DEPOT CANDIDATES
C         (NOT INCLUDING FIXED)
C NMND: N-NTDEP, OR NODES
C       MINUS TOTAL DEPOTS
C NTDEP: TOTAL DEPOTS (NDEP+NFXDEP)
C LAT,LONG: COORDINATES OF NODE
C LATR,LONGR: COORDINATES IN RADIANS
C W: DISTANCE MATRIX
C FREQ: FREQUENCY OF DEMAND
C D1-D9: LOOP INDEX OF SELECTED DEPOTS
C NEAR: SELECTED NODE WHICH IS CLOSEST
C       TO INDEXED NODE
C DIST: DISTANCE BETWEEN NEAR AND ITS INDEX
C TCOUNT: COUNTER OF SELECTED EDGES
C V: DUMMY VAR TO HOLD A CANDIDATE NODE
C DEPOT: DEPOT ASSOCIATED WITH A BRANCH
C TEDGE1: EMINENT NODE OF AN EDGE
C TEDGE2: INCIDENT NODE OF AN EDGE
C TWGT: SUMMED WEIGHTS OF A FOREST
C TW: DISTANCE FROM DEPOT TO NODE *
C     SERVICING FREQUENCY
C BESTW: BEST TWGT OF DEPOT ITERATIONS
C EBST1,EBST2: BEST OF TEDGE1,TEDGE2
C ID,INF: DUMMY VARS TO HOLD MIN EDGES
C
* WHEN ALTERING PROBLEMS, THE FOLLOWING
* MUST BE CHANGED TO ACCOMODATE:
* SUCH CHANGES ARE FLAGGED BY AN ASTERIK
* IN A NEARBY COMMENT LINE
C 1) PARAMETER LINE AT TOP OF PROGRAM
C    INSURE: NMND=N-NTDEP, NTDEP=NFXDEP+NDPCAN
C 2) LOOP 30, WHICH MUST REFLECT ALL POSSIBLE
C    COMBINATIONS OF POTENTIAL DEPOTS. THERE
C    WILL BE NDEP DO STATEMENTS.
C 3) THE DATA FILE MUST INCLUDE THE FIXED DEPOTS
C    FIRST, FOLLOWED BY THE CANDIDATE DEPOTS,
C    FOLLOWED BY THE REMAINING DEMANDS
C 4) THE OPEN STATEMENTS IN DECLARATION SEGMENT
C    MUST REFLECT DESIRED INPUT AND OUTPUT FILENAMES
```

```
C
C DECLARATIONS
*
      PARAMETER(N=181,NDEP=8,NFXDEP=3,
     1 NDPCAN=27,NMND=170,NTDEP=11)
      REAL LAT(N),LONG(N)
      DOUBLE PRECISION LATR(N),LONGR(N)
      INTEGER W(N,N),FREQ(N),D(NTDEP),D1,D2,
     1 NEAR(N),DIST(N),TCOUNT,V,
     2 TEDGE1(NMND),TEDGE2(NMND),TWGT,TW(N),
     3 BESTW,EBST1(NMND),EBST2(NMND),ID,
     4 D3,D4,D5,D6,D7,D8,D9,IDEP(NTDEP),DEPOT(N)
*
      OPEN(4,FILE='CON22.DAT',STATUS='OLD')
      OPEN(6,FILE='CON8A.OUT',STATUS='NEW')
      INF=3000
      BESTW=5000000
C
C INPUT LOCATIONS
C
      DO 5 I=1,N
       READ(4,100) LAT(I),LONG(I),FREQ(I)
*
* INPUT ECHO IF DESIRED
*       WRITE(6,100) LAT(I),LONG(I),FREQ(I)
C
C CONVERT TO RADIANS
C
      LATR(I)=((LAT(I)-AINT(LAT(I)))/.6
     1           +AINT(LAT(I)))*3.141592653/180
      LONGR(I)=((LONG(I)-AINT(LONG(I)))/.6
     1           +AINT(LONG(I)))*3.141592653/180
5     CONTINUE
C
C COMPUTE DISTANCE MATRIX
C
      DO 10 I=1,N
       DO 10 J=1,I
        IF (I.EQ.J) THEN
         W(I,J)=0
        ELSE
        W(I,J)=INT(3956.013*ACOS(SIN(LATR(I))
     1        *SIN(LATR(J))+COS(LATR(I))*COS(LATR(J))
     2        *COS(ABS(LONGR(J)-LONGR(I)))))+150
        W(J,I)=W(I,J)
        ENDIF
10    CONTINUE
C      DO 20 I=1,N
C       WRITE(6,200) (W(I,J),J=1,N)
20    CONTINUE
C
C DEFINE FIXED DEPOTS
C
```

```
      DO 21 I=1,NFXDEP
       D(I)=I
21    CONTINUE
C
C LOOP FOR DEPOT CHOICE ITERATIONS
C
*
      DO 30 D1=NFXDEP+1,NFXDEP+NDPCAN-NDEP+1
       D(NFXDEP+1)=D1
       DO 30 D2=D1+1,NFXDEP+NDPCAN-NDEP+2
        D(NFXDEP+2)=D2
        DO 30 D3=D2+1,NFXDEP+NDPCAN-NDEP+3
         D(NFXDEP+3)=D3
         DO 30 D4=D3+1,NFXDEP+NDPCAN-NDEP+4
          D(NFXDEP+4)=D4
          DO 30 D5=D4+1,NFXDEP+NDPCAN-NDEP+5
           D(NFXDEP+5)=D5
           DO 30 D6=D5+1,NFXDEP+NDPCAN-NDEP+6
            D(NFXDEP+6)=D6
            DO 30 D7=D6+1,NFXDEP+NDPCAN-NDEP+7
             D(NFXDEP+7)=D7
             DO 30 D8=D7+1,NFXDEP+NDPCAN-NDEP+8
              D(NFXDEP+8)=D8
C
C RESET COUNTERS BETWEEN ITERATIONS
C INDENTS RESTARTED IN CODE
C
      ID=3000
      V=0
      TCOUNT=0
      TWGT=0
      DO 35 J=1,N
       TW(J)=0
35    CONTINUE
C
C SET NEAR EQUAL TO NEAREST DEPOT
C
      DO 40 J=1,N
       ID=3000
       DO 40 I=1,NFXDEP+NDEP
        IF (W(D(I),J).LT.ID) THEN
         NEAR(J)=D(I)
         DEPOT(J)=NEAR(J)
         DIST(J)=W(D(I),J)
         ID=W(D(I),J)
        ENDIF
      CONTINUE
40    CONTINUE
C
C SET DEPOTS NEAR NOTHING IMPLYING
C CURRENT INCLUSION INTO FOREST
C
      DO 45 I=1,NFXDEP+NDEP
```

```
         NEAR(D(I))=0
         DEPOT(D(I))=D(I)
45    CONTINUE
C
C SELECT MINIMUM EDGE
C
50    IF (TCOUNT.LT.NMND) THEN
       MIN=INF
       DO 60 J=1,N
C CHECK FOR QUALIFIED EDGE
        IF ((NEAR(J).GT.0).AND.
     1     (DIST(J).LT.MIN).AND.
     2     (W(DEPOT(NEAR(J)),J).LT.1000)) THEN
C IF BEST AND QUALIFIED, SELECT
         V=J
         MIN=DIST(J)
        ENDIF
60     CONTINUE
C
C PENALTY FOR INFEASIBILITY
C
       IF (MIN.EQ.INF) DIST(V)=1000000
C
C UPDATE FOREST WITH NEW BRANCH
C
       TCOUNT=TCOUNT+1
       TEDGE1(TCOUNT)=NEAR(V)
       TEDGE2(TCOUNT)=V
       TW(V)=TW(NEAR(V))+DIST(V)
       TWGT=TWGT+TW(V)*FREQ(V)
       DEPOT(V)=DEPOT(NEAR(V))
       NEAR(V)=0
C
C UPDATE NEAR
C
       DO 70 J=1,N
        IF (NEAR(J).NE.0) THEN
         IF (W(J,NEAR(J)).GT.W(J,V)
     1   .AND.(W(DEPOT(V),J).LT.1000)) THEN
          DIST(J)=W(J,V)
          NEAR(J)=V
         ENDIF
        ENDIF
70     CONTINUE
       GO TO 50
      ENDIF
C
C STORE FOREST AS BEST IF APPLICABLE
C
      IF (TWGT.LT.BESTW) THEN
       BESTW=TWGT
       DO 80 J=1,NMND
        EBST1(J)=TEDGE1(J)
```

```
           EBST2(J)=TEDGE2(J)
80        CONTINUE
          DO 81 J=1,NTDEP
           IDEP(J)=D(J)
81        CONTINUE
         ENDIF
30       CONTINUE
C
C WRITE RESULTS
C
         WRITE(6,*)'BEST WEIGHT=',BESTW
         WRITE(6,*)'DEPOTS='
         WRITE(6,200) (IDEP(I), I=1,NTDEP)
         WRITE(6,*)'EMINATING NODES ON TOP'
         WRITE(6,*) 'INCIDENT NODES BELOW'
         JU=NMND
         JL=1
90       IF (JU.LE.10) THEN
          WRITE(6,300) (EBST1(J), J=JL,NMND)
          WRITE(6,300) (EBST2(J), J=JL,NMND)
          WRITE(6,*)
          STOP
         ELSE
          WRITE(6,300) (EBST1(J), J=JL,JL+9)
          WRITE(6,300) (EBST2(J), J=JL,JL+9)
          WRITE(6,*)
         ENDIF
         JU=JU-10
         JL=JL+10
         GO TO 90
100      FORMAT(1X,F5.2,3X,F6.2,2X,I2)
200      FORMAT(1X,11I5)
300      FORMAT(1X,10I5)
         END
```

CLARKE-WRIGHT CODE:

```
C CAFT S.F. BAKER
C MODIFIED CLARKE-WRIGHT ALGORITHM
C WRIGHT-PATT NEAR TERM DEPOT MODEL
C
C VARIABLE EXPLANATION:
C N: NUMBER OF DEMAND POINTS (NODES OTHER
C    THAN DEPOT WITH
C    FREQUENCY 2 COUNTS AS 2)
C LAT,LONG: LATITUDE AND LONGITUDE OF NODE
C LATR,LONGR: LAT AND LONG IN RADIANS
C DEP: NUMBER OF EDGES A NODE SHARES WITH DEPOT
C C: DEMAND FREQUENCY OF A NODE
C W: DISTANCE BETWEEN 2 NODES
C S: POTENTIAL SAVINGS FROM ROUTE CONSOLIDATION
C NCV: NODES INCLUDED (J) IN SAME TOUR AS I
C R: DISTANCE FROM ORIGIN OF A NODE IF 1
C    ORIGIN EDGE IS SEVERED
C NC: TOUR ASSOCIATED WITH NODE I
C U,V: DUMMY VARS HOLDING CURRENT
C      CONSOLIDATION OPTION
C CI,IRIJ,ICV: DUMMY VARS HOLDING CURRENT
C     C,R,NC
C MIN: BEST KNOWN SAVINGS IN ITERATION
C TOT: MILAGE TOTAL
C
* REQUIREMENTS FOR ALTERING DATA SET
C 1) CHANGE PARAMETER TO REFLECT
C    TOTAL DEMANDS (DEPOT COUNTS AS
C    1 ALWAYS!!!, OTHER NODES COUNT AS THEIR
C    DEMAND FREQUENCY
C 2) INSURE DEPOT IS FIRST IN DATA SET
C    AND HAS FREQUENCY 1 REGARDLESS OF
C    ACTUAL FREQUENCY
C 3) INSURE OPEN STATEMENTS REFLECT DESIRED
C    INPUT AND OUTPUT FILES
C
C DECLARATIONS
C
*
      PARAMETER(N=20)
      REAL LAT(N),LONG(N)
      DOUBLE PRECISION LATR(N),LONGR(N)
      INTEGER DEP(N),C(N),W(N,N),S(N,N),
     1 NCV(N,N),R(N),U,V,CI,NC(N),TOT
*
      OPEN(4,FILE='PFF.DAT',STATUS='OLD')
      OPEN(6,FILE='PFF.OUT',STATUS='NEW')
C
C OUTPUT SETUP
C AND INPUT LOCATIONS
C
```

```
      I=1
2     IF (I.LE.N) THEN
       READ(4,100) LAT(I),LONG(I),C(I)
       CI=C(I)
C DUPLICATE NODES IF NECESSARY TO REFLECT DEMAND
        IF (I.GT.1) THEN
         DO 5 J=0,CI-1
          LAT(I+J)=LAT(I)
          LONG(I+J)=LONG(I)
          C(I+J)=C(I)
*
* INPUT ECHO IF DESIRED
*
*         WRITE(6,100) LAT(I+J),LONG(I+J),C(I+J)
*
C LOAD INITIAL TOUR NUMBERS, TOUR LOADS
          DO 5 K=0,CI-1
           NC(I+J)=I+J
           NCV(NC(I+J),I+K)=1
5        CONTINUE
        ELSE
         CONTINUE
        ENDIF
C INCREMENT I TO NEXT NODE
        I=I+CI
        GOTO 2
       ELSE
        CONTINUE
       ENDIF
C CONVERT TO RADIANS
      DO 8 I=1,N
      LATR(I)=((LAT(I)-AINT(LAT(I)))/.6
     1       +AINT(LAT(I)))*3.141592653/180
      LONGR(I)=((LONG(I)-AINT(LONG(I)))/.6
     1       +AINT(LONG(I)))*3.141592653/180
8     CONTINUE
C
C INITIALIZE ARRAYS AND
C COMPUTE DISTANCE MATRIX
C
      DO 10 I=1,N
       DEP(I)=2
C SET DISTANCE TO 0 IF IDENTICAL LOCATION
       DO 10 J=1,I
        DIFLAT=ABS(LAT(I)-LAT(J))
        DIFLON=ABS(LONG(I)-LONG(J))
        IF ((DIFLAT.LT..01).OR.(DIFLON.LT..01)) THEN
         W(I,J)=0
        ELSE
        W(I,J)=INT(3956.013*ACOS(SIN(LATR(I))
     1        *SIN(LATR(J))+COS(LATR(I))*COS(LATR(J))
     2        *COS(ABS(LONGR(J)-LONGR(I)))))+150
C INITIAL R AND SAVINGS CALCULATION
```

```
        R(I)=W(I,1)
        S(I,J)=W(I,1)+W(J,1)-W(I,J)
        ENDIF
10    CONTINUE
*
* OUTPUT DISTANCE HALF MATRIX
* IF IT IS SMALL ENOUGH FOR
* DESIRED OUTPUT
*
*      DO 20 I= 1,N
* COMMENT OUT IF N IS LARGE
*       WRITE(6,200) (W(I,J),J=1,I)
*20     CONTINUE
*
      WRITE(6,*)'ARCS IN THE SOLUTION'
C
C FIND GREATEST SAVINGS
C DISQUALIFY IF
C 1) NODE IS INTERNAL TO A ROUTE
C 2) SAVINGS NOT THE BEST
C 3) RANGE EXCEEDED
C 4) TOUR INCLUDES > 1 VISITS/CLUSTER
C
40    DO 50 I=2,N
       DO 50 J=1,I-1
        IF ((DEP(I).LE.0).OR.(DEP(J).LE.0)) GOTO 70
        IF (S(I,J).LE.MIN) GOTO 70
        IRIJ=R(I)+R(J)+W(I,J)
        IF (IRIJ.GT.2600) GOTO 70
        DO 60 K=1,N
         NCVI=NCV(NC(I),K)+NCV(NC(J),K)
         IF (NCVI.GT.1) GOTO 70
60       CONTINUE
C
C HOLD BEST SAVINGS IN PASS
C
        MIN =S(I,J)
        U=I
        V=J
70     CONTINUE
C
C UPDATE ARRAYS AND WRITE NEW ARC
C
50    CONTINUE
C QUIT IF NO QUALIFIED CONSOLIDATION
      IF(MIN.EQ.0) GOTO 80
C UPDATE CONSOLIDATED NODE ARRAYS
      DEP(U)=DEP(U)-1
      DEP(V)=DEP(V)-1
C UPDATE RANGE VARS
      IRU=R(U)
      IRV=R(V)
      DO 55 J=1,N
```

```
       IF (NC(J).EQ.NC(U))
     1   R(J)=R(J)+W(U,V)+IRV-W(U,1)
       IF (NC(J).EQ.NC(V))
     1   R(J)=R(J)+W(U,V)+IRU-W(V,1)
55    CONTINUE
      S(U,V)=0
      ICV=NC(V)
      DO 65 J=1,N
       NCV(NC(U),J)=NCV(NC(U),J)+NCV(NC(V),J)
65    CONTINUE
C CONSOLIDATE TOUR LOADING ARRAYS INTO ONE TOUR
      DO 68 J=1,N
       IF (NC(J).EQ.ICV) NC(J)=NC(U)
68    CONTINUE
C ADD NEW LEG TO TOTAL
      TOT=TOT+W(U,V)
C WRITE NEW LINK AND RETURN
      WRITE(6,300) U,V
      MIN=0
      GOTO 40
80    CONTINUE
C
C WRITE REMAINING DEPOT CONNECTIONS
C
      DO 90 I=2,N
       IF(DEP(I).EQ.1) THEN
        TOT=TOT+W(I,1)
        WRITE(6,500) I
       ELSEIF (DEP(I).EQ.2) THEN
        TOT=TOT+2*W(I,1)
        WRITE(6,600) I
       ELSE
       CONTINUE
       ENDIF
90    CONTINUE
C WRITE TOTAL COST
      WRITE(6,*) 'THE TOTAL COST='
      WRITE(6,400) TOT
100   FORMAT(1X,F5.2,3X,F6.2,2X,I2)
200   FORMAT(1X,15I4)
300   FORMAT(1X,2I3)
400   FORMAT(1X,I6)
500   FORMAT(1X,I3,'  1')
600   FORMAT(1X,I3,'  1 TWICE')
      END
```

Appendix C: Validation Code and Output

The code below is used to solve the region 1 validation with optimal depots. It is typical of the code used for the other regions.

```
* CAPT S.F. BAKER
* DCS MULTIPLE DEPOT OPTIMIZATION REGION 1
*
* POTENTIAL DEPOTS AT MCCHORD, TRAVIS AFB
* DEMANDS AT MCCHORD,TRAVIS,BOISE,KLAMATH FALLS,
* AND 2 DEMANDS AT MT HOME
* ALL VARS 0,1 EXCEPT #ACFT (M1,M2), WHICH ARE INT,
* AND D3 - D7, WHICH ARE UNRESTRICTED
* OBJECTIVE COEFFICIENTS ARE GREAT CIRCLE STATUTE
* MILES PLUS 150 (GROUND TIME), EXCEPT FOR DEPOT
* COEFFICIENTS, WHICH ARE COSTS CONVERTED TO MILES
* X VARS ARE EDGES, YVARS ARE DEPOT LOCATION BINARY,
* M VARS ARE # ACFT AT A STATION
* SUBSCRIPTS: 1,5=KTCM; 2,6=KSUU; 3=KLMT; 4=KBOI;
* 7,8=KMUO
..TITLE
REG11
*
..OBJECTIVE MINIMIZE
*
[[ 764 X12 + 496 X13 + 541 X14 + 0 X15 + 764 X16
+ 578 X17 + 578 X18
+ 419 X23 + 621 X24 + 764 X25 + 0 X26
+ 608 X27 + 608 X28
+ 445 X34 + 496 X35 + 419 X36 + 454 X37 + 454 X38
+ 541 X45 + 621 X46 + 190 X47 + 190 X48
+ 764 X56 + 578 X57 + 578 X58
+ 608 X67 + 608 X68
+ 764 X21 + 496 X31 + 541 X41 + 0 X51 + 764 X61
+ 578 X71 + 578 X81
+ 419 X32 + 621 X42 + 764 X52 + 0 X62
+ 608 X72 + 608 X82
+ 445 X43 + 496 X53 + 419 X63 + 454 X73 + 454 X83
+ 541 X54 + 621 X64 + 190 X74 + 190 X84
+ 764 X65 + 578 X75 + 578 X85
+ 608 X76 + 608 X86
+ 3382 Y1 + 3382 Y2 ] + 0 M1 + 0 M2 ]
+ 0 D3 + 0 D4 + 0 D5 + 0 D6 + 0 D7
*
..CONSTRAINTS
*
* 1 VISIT PER DEMAND POINT
*
C1: X13 + X14 + X15 + X16 + X17 + X18 - M1 = 0
C2: X23 + X24 + X25 + X26 + X27 + X28 - M2 = 0
C3: X31 + X32 + X34 + X35 + X36 + X37 + X38 = 1
C4: X41 + X42 + X43 + X45 + X46 + X47 + X48 = 1
```

```
C5: X51 + X52 + X53 + X54 + X56 + X57 + X58 = 1
C6: X61 + X62 + X63 + X64 + X65 + X67 + X68 = 1
C6A: X71 + X72 + X73 + X74 + X75 + X76 = 1
C6B: X81 + X82 + X83 + X84 + X85 + X86 = 1
*
C7: X31 + X41 + X51 + X61 + X71 + X81 - M1 = 0
C8: X32 + X42 + X52 + X62 + X72 + X82 - M2 = 0
C9: X13 + X23 + X43 + X53 + X63 + X73 + X83 = 1
C10: X14 + X24 + X34 + X54 + X64 + X74 + X84 = 1
C11: X15 + X25 + X35 + X45 + X65 + X75 + X85 = 1
C12: X16 + X26 + X36 + X46 + X56 + X76 + X86 = 1
C12A: X17 + X27 + X37 + X47 + X57 + X67 = 1
C12B: X18 + X28 + X38 + X48 + X58 + X68 = 1
*
* SUBTOUR BREAKING WITH RANGE LIMITATION
*
C48: 2600 X43 + D4 - D3 <= 2155
C49: 2600 X34 + D3 - D4 <= 2155
C50: 2600 X53 + D5 - D3 <= 2104
C51: 2600 X35 + D3 - D5 <= 2104
C52: 2600 X63 + D6 - D3 <= 2181
C53: 2600 X36 + D3 - D6 <= 2181
CE3: 2600 X73 + D7 - D3 <= 2146
CE4: 2600 X37 + D3 - D7 <= 2146
CE5: 2600 X83 + D7 - D3 <= 2146
CE6: 2600 X38 + D3 - D7 <= 2146
C54: 2600 X54 + D5 - D4 <= 2059
C55: 2600 X45 + D4 - D5 <= 2059
C56: 2600 X64 + D6 - D4 <= 1979
C57: 2600 X46 + D4 - D6 <= 1979
CE8: 2600 X74 + D7 - D4 <= 2410
CE9: 2600 X47 + D4 - D7 <= 2410
CE1: 2600 X84 + D7 - D4 <= 2410
CE2: 2600 X48 + D4 - D7 <= 2410
C58: 2600 X65 + D6 - D5 <= 1836
C59: 2600 X56 + D5 - D6 <= 1836
C60: 2600 X75 + D7 - D5 <= 2022
C61: 2600 X57 + D5 - D7 <= 2022
C62: 2600 X85 + D7 - D5 <= 2022
C63: 2600 X58 + D5 - D7 <= 2022
C64: 2600 X76 + D7 - D6 <= 2022
C65: 2600 X67 + D6 - D7 <= 2022
C66: 2600 X86 + D7 - D6 <= 2022
C67: 2600 X68 + D6 - D7 <= 2022
*
* RANGE COMPUTATION FROM DEPOT
*
C82: 496 X13 - D3 <= 0
C83: 541 X14 - D4 <= 0
C84: 764 X16 - D6 <= 0
CG4: 578 X17 - D7 <= 0
CG5: 578 X18 - D7 <= 0
C86: 419 X23 - D3 <= 0
```

```
C87: 621 X24 - D4 <= 0
C88: 764 X25 - D5 <= 0
CG8: 608 X27 - D7 <= 0
CG9: 608 X28 - D7 <= 0
*
* RANGE COMPUTATION TO DEPOT
*
C89: 496 X31 + D3 <= 2600
C90: 541 X41 + D4 <= 2600
C91: 764 X61 + D6 <= 2600
CH1: 578 X71 + D7 <= 2600
CH2: 578 X81 + D7 <= 2600
C92: 419 X32 + D3 <= 2600
C93: 621 X42 + D4 <= 2600
C94: 764 X52 + D5 <= 2600
CH4: 608 X72 + D7 <= 2600
CH5: 608 X82 + D7 <= 2600
*
* CHAIN BARRING
*.
C76: X13 + 3 X34 + X24 + X31 + 3 X43 + X42 <= 4
C78: X13 + 3 X36 + X26 + X31 + 3 X63 + X62 <= 4
C77: X13 + 3 X37 + X27 + X31 + 3 X73 + X72 <= 4
CG7: X13 + 3 X38 + X28 + X31 + 3 X83 + X82 <= 4
C79: X14 + 3 X34 + X23 + X41 + 3 X43 + X32 <= 4
C13: X14 + 3 X46 + X26 + X41 + 3 X64 + X62 <= 4
C80: X14 + 3 X47 + X27 + X41 + 3 X74 + X72 <= 4
CH0: X14 + 3 X48 + X28 + X41 + 3 X84 + X82 <= 4
C14: X15 + 3 X35 + X23 + X51 + 3 X53 + X32 <= 4
C15: X15 + 3 X56 + X26 + X51 + 3 X65 + X62 <= 4
CA5: X15 + 3 X57 + X27 + X51 + 3 X75 + X72 <= 4
C16: X15 + 3 X58 + X28 + X51 + 3 X85 + X82 <= 4
C16: X17 + 3 X73 + X23 + X71 + 3 X37 + X32 <= 4
C16: X17 + 3 X74 + X24 + X71 + 3 X47 + X42 <= 4
C16: X17 + 3 X76 + X26 + X71 + 3 X67 + X62 <= 4
C16: X18 + 3 X38 + X23 + X81 + 3 X83 + X32 <= 4
C16: X18 + 3 X48 + X24 + X81 + 3 X84 + X42 <= 4
C16: X18 + 3 X68 + X26 + X81 + 3 X86 + X62 <= 4
C17: X23 + 3 X24 + X14 + X32 + 3 X42 + X41 <= 4
C18: X23 + 3 X35 + X15 + X32 + 3 X53 + X51 <= 4
C19: X23 + 3 X37 + X17 + X32 + 3 X73 + X71 <= 4
C19: X23 + 3 X38 + X18 + X32 + 3 X83 + X81 <= 4
C20: X24 + 3 X34 + X13 + X42 + 3 X43 + X31 <= 4
C21: X24 + 3 X45 + X15 + X42 + 3 X54 + X51 <= 4
C22: X24 + 3 X47 + X17 + X42 + 3 X74 + X71 <= 4
C22: X24 + 3 X48 + X18 + X42 + 3 X84 + X81 <= 4
C23: X25 + 3 X35 + X13 + X52 + 3 X53 + X31 <= 4
C24: X25 + 3 X45 + X14 + X52 + 3 X54 + X41 <= 4
C25: X25 + 3 X57 + X17 + X52 + 3 X75 + X71 <= 4
C25: X25 + 3 X58 + X18 + X52 + 3 X85 + X81 <= 4
C26: X26 + 3 X36 + X13 + X62 + 3 X63 + X61 <= 4
C27: X26 + 3 X46 + X14 + X62 + 3 X64 + X41 <= 4
C28: X26 + 3 X56 + X15 + X62 + 3 X65 + X51 <= 4
```

```
C27: X26 + 3 X67 + X17 + X62 + 3 X76 + X71 <= 4
C28: X26 + 3 X68 + X18 + X62 + 3 X86 + X81 <= 4
C29: X13 + X31 + X42 + X24 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
C30: X13 + X31 + X52 + X25 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
C31: X13 + X31 + X62 + X26 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
CC0: X13 + X31 + X72 + X27 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
CC1: X13 + X31 + X82 + X28 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
C32: X14 + X41 + X32 + X23 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
C33: X14 + X41 + X52 + X25 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
C34: X14 + X41 + X62 + X26 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
CC3: X14 + X41 + X72 + X27 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
CC4: X14 + X41 + X82 + X28 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
C35: X15 + X51 + X32 + X23 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
C36: X15 + X51 + X42 + X24 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
C37: X15 + X51 + X62 + X26 + 2 ( X34 + X35 + X36 + X45
```

```
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
CC6: X15 + X51 + X72 + X27 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
CC7: X15 + X51 + X82 + X28 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
CC6: X17 + X71 + X32 + X23 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
C37: X17 + X71 + X42 + X24 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
CC6: X17 + X71 + X62 + X26 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
CC7: X17 + X71 + X82 + X28 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
CD6: X18 + X81 + X32 + X23 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
C37: X18 + X81 + X42 + X24 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
CC6: X18 + X81 + X62 + X26 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
CC7: X18 + X81 + X72 + X27 + 2 ( X34 + X35 + X36 + X45
+ X46 + X56 + X43 + X53 + X63 + X54 + X64 + X65 + X37 + X38
+ X47 + X48 + X57 + X58 + X67 + X68 + X73 + X83 + X74 + X84
+ X75 + X85 + X76 + X86 ) <= 11
*
* ACFT ASSIGNED ONLY TO ACTIVE DEPOTS
*
C41: Y1 - M1 <= 0
C42: Y2 - M2 <= 0
C43: M1 - 10 Y1 <= 0
C44: M2 - 10 Y2 <= 0
*
* BOUNDS ON FLEET SIZE
*
```

```
C45: M1 <= 4
C46: M2 <= 4
C47: Y1 + Y2 >= 1
```

Region 1 with optimal depot.

Laporte formulation output (of the input file on the previous pages):

```
"REG11 "
 129,  63,  6792.0000
"X12     ",      0.0000,   764.0000
"X13     ",      0.0000,   496.0000
"X14     ",      1.0000,   541.0000
"X15     ",      0.0000,     0.0000
"X16     ",      0.0000,   764.0000
"X17     ",      1.0000,   578.0000
"X18     ",      0.0000,   578.0000
"X23     ",      0.0000,   419.0000
"X24     ",      0.0000,   621.0000
"X25     ",      0.0000,   764.0000
"X26     ",      0.0000,     0.0000
"X27     ",      0.0000,   608.0000
"X28     ",      0.0000,   608.0000
"X34     ",      0.0000,   445.0000
"X35     ",      0.0000,   496.0000
"X36     ",      0.0000,   419.0000
"X37     ",      0.0000,   454.0000
"X38     ",      0.0000,   454.0000
"X45     ",      0.0000,   541.0000
"X46     ",      0.0000,   621.0000
"X47     ",      0.0000,   190.0000
"X48     ",      1.0000,   190.0000
"X56     ",      0.0000,   764.0000
"X57     ",      0.0000,   578.0000
"X58     ",      0.0000,   578.0000
"X67     ",      0.0000,   608.0000
"X68     ",      0.0000,   608.0000
"X21     ",      0.0000,   764.0000
"X31     ",      1.0000,   496.0000
"X41     ",      0.0000,   541.0000
"X51     ",      1.0000,     0.0000
"X61     ",      0.0000,   764.0000
"X71     ",      0.0000,   578.0000
"X81     ",      0.0000,   578.0000
"X32     ",      0.0000,   419.0000
"X42     ",      0.0000,   621.0000
"X52     ",      0.0000,   764.0000
"X62     ",      0.0000,     0.0000
"X72     ",      0.0000,   608.0000
"X82     ",      0.0000,   608.0000
"X43     ",      0.0000,   445.0000
"X53     ",      0.0000,   496.0000
"X63     ",      1.0000,   419.0000
"X73     ",      0.0000,   454.0000
"X83     ",      0.0000,   454.0000
"X54     ",      0.0000,   541.0000
```

Output explanation:

Since the MSF/CW output does not include depot cost, the objective function value for comparitive purposes is 6792-3382, or 3410.

Node assignments:
1,5 TCM
2,6 SUU
3 LMT
4 BOI
7,8 MUO

Arc value is 1 if used.

```
"X64      ",     0.0000,   621.0000
"X74      ",     0.0000,   190.0000
"X84      ",     0.0000,   190.0000
"X65      ",     0.0000,   764.0000
"X75      ",     0.0000,   578.0000
"X85      ",     1.0000,   578.0000
"X76      ",     1.0000,   608.0000
"X86      ",     0.0000,   608.0000
"Y1       ",     1.0000,  3382.0000  Depot is used if value
"Y2       ",     0.0000,  3382.0000  is 1.
"M1       ",     2.0000,     0.0000  Num of aircraft at a
"M2       ",     0.0000,     0.0000  depot.
"D3       ",  2104.0000,     0.0000  Odometer variable
"D4       ",   541.0000,     0.0000  values.
"D5       ",  1309.0000,     0.0000
"D6       ",  1685.0000,     0.0000
"D7       ",   731.0000,     0.0000
"C1       ",     0.0000,     0.0000  Constraint values and
"C2       ",     0.0000,     0.0000  slack.
"C3       ",     1.0000,     1.0000
"C4       ",     1.0000,     1.0000
"C5       ",     1.0000,     1.0000
"C6       ",     1.0000,     1.0000
"C6A      ",     1.0000,     1.0000
"C6B      ",     1.0000,     1.0000
"C7       ",     0.0000,     0.0000
"C8       ",     0.0000,     0.0000
"C9       ",     1.0000,     1.0000
"C10      ",     1.0000,     1.0000
"C11      ",     1.0000,     1.0000
"C12      ",     1.0000,     1.0000
"C12A     ",     1.0000,     1.0000
"C12B     ",     1.0000,     1.0000
"C48      ", -1563.0000,  2155.0000
"C49      ",  1563.0000,  2155.0000
"C50      ",  -795.0000,  2104.0000
"C51      ",   795.0000,  2104.0000
"C52      ",  2181.0000,  2181.0000
"C53      ",   419.0000,  2181.0000
"CE3      ", -1373.0000,  2146.0000
"CE4      ",  1373.0000,  2146.0000
"CE5      ", -1373.0000,  2146.0000
"CE6      ",  1373.0000,  2146.0000
"C54      ",   768.0000,  2059.0000
"C55      ",  -768.0000,  2059.0000
"C56      ",  1144.0000,  1979.0000
"C57      ", -1144.0000,  1979.0000
"CE8      ",   190.0000,  2410.0000
"CE9      ",  -190.0000,  2410.0000
"CE1      ",   190.0000,  2410.0000
"CE2      ",  2410.0000,  2410.0000
"C58      ",   376.0000,  1836.0000
"C59      ",  -376.0000,  1836.0000
```

```
"C60      ",  -578.0000,  2022.0000
"C61      ",   578.0000,  2022.0000
"C62      ",  2022.0000,  2022.0000
"C63      ",   578.0000,  2022.0000
"C64      ",  1646.0000,  2022.0000
"C65      ",   954.0000,  2022.0000
"C66      ",  -954.0000,  2022.0000
"C67      ",   954.0000,  2022.0000
"C82      ", -2104.0000,     0.0000
"C83      ",    -0.0000,     0.0000
"C84      ", -1685.0000,     0.0000
"CG4      ",  -153.0000,     0.0000
"CG5      ",  -731.0000,     0.0000
"C86      ", -2104.0000,     0.0000
"C87      ",  -541.0000,     0.0000
"C88      ", -1309.0000,     0.0000
"CG8      ",  -731.0000,     0.0000
"CG9      ".  -731.0000,     0.0000
"C89      ",  2600.0000,  2600.0000
"C90      ",   541.0000,  2600.0000
"C91      ",  1685.0000,  2600.0000
"CH1      ",   731.0000,  2600.0000
"CH2      ",   731.0000,  2600.0000
"C92      ",  2104.0000,  2600.0000
"C93      ",   541.0000,  2600.0000
"C94      ",  1309.0000,  2600.0000
"CH4      ",   731.0000,  2600.0000
"CH5      ",   731.0000,  2600.0000
"C76      ",     1.0000,     4.0000
"C78      ",     2.0000,     4.0000
"C77      ",     1.0000,     4.0000
"CG7      ",     1.0000,     4.0000
"C79      ",     1.0000,     4.0000
"C13      ",     1.0000,     4.0000
"C80      ",     1.0000,     4.0000
"CH0      ",     2.0000,     4.0000
"C14      ",     1.0000,     4.0000
"C15      ",     1.0000,     4.0000
"CA5      ",     1.0000,     4.0000
"C16      ",     2.0000,     4.0000
"C16      ",     1.0000,     4.0000
"C16      ",     1.0000,     4.0000
"C16      ",     2.0000,     4.0000
"C16      ",     0.0000,     4.0000
"C16      ",     1.0000,     4.0000
"C16      ",     0.0000,     4.0000
"C17      ",     1.0000,     4.0000
"C18      ",     1.0000,     4.0000
"C19      ",     1.0000,     4.0000
"C19      ",     0.0000,     4.0000
"C20      ",     1.0000,     4.0000
"C21      ",     1.0000,     4.0000
"C22      ",     1.0000,     4.0000
```

```
"C22       ",     1.0000,     4.0000
"C23       ",     1.0000,     4.0000
"C24       ",     1.0000,     4.0000
"C25       ",     1.0000,     4.0000
"C25       ",     1.0000,     4.0000
"C26       ",     1.0000,     4.0000
"C27       ",     1.0000,     4.0000
"C28       ",     1.0000,     4.0000
"C27       ",     2.0000,     4.0000
"C28       ",     0.0000,     4.0000
"C29       ",     9.0000,    11.0000
"C30       ",     9.0000,    11.0000
"C31       ",     9.0000,    11.0000
"CC0       ",     9.0000,    11.0000
"CC1       ",     9.0000,    11.0000
"C32       ",     9.0000,    11.0000
"C33       ",     9.0000,    11.0000
"C34       ",     9.0000,    11.0000
"CC3       ",     9.0000,    11.0000
"CC4       ",     9.0000,    11.0000
"C35       ",     9.0000,    11.0000
"C36       ",     9.0000,    11.0000
"C37       ",     9.0000,    11.0000
"CC6       ",     9.0000,    11.0000
"CC7       ",     9.0000,    11.0000
"CC6       ",     9.0000,    11.0000
"C37       ",     9.0000,    11.0000
"CC6       ",     9.0000,    11.0000
"CC7       ",     9.0000,    11.0000
"CD6       ",     8.0000,    11.0000
"C37       ",     8.0000,    11.0000
"CC6       ",     8.0000,    11.0000
"CC7       ",     8.0000,    11.0000
"C41       ",    -1.0000,     0.0000
"C42       ",     0.0000,     0.0000
"C43       ",    -8.0000,     0.0000
"C44       ",     0.0000,     0.0000
"C45       ",     2.0000,     4.0000
"C46       ",     0.0000,     4.0000
"C47       ",     1.0000,     1.0000
```

Region 1 with 1 depot.

```
MSF output:                              Output Explanation:

 47.08    122.28    1                    1 TCM Lat/Long, service freq
 38.15    121.55    1                    2 SUU  "
 42.09    121.44    1                    3 LMT  "
 43.33    116.13    1                    4 BOI  "
 43.02    115.52    2                    5 MUO  "
     0
   763     0
   495   419     0                       Distance matrix + 150 miles
   541   621   445     0
   578   607   454   189     0
 BEST WEIGHT=              4303          Forest cost
 EMANATING NODES ON TOP
 INCIDENT NODES BELOW
     2     3     4     3                 Forest structure by node #
     3     4     5     1                 (2 connects to 3, 3 connects
                                         to 4, etc.)
```

```
CW output:

 INPUT LAT, LONG, CLUSTER
 38.15    121.55    1                    1 SUU (only depot selected)
 47.08    122.28    1                    2 TCM
 42.09    121.44    1                    3 LMT
 43.33    116.13    1                    4 BOI
 43.02    115.52    2                    5 MUO
 43.02    115.52    2                    6 MUO
    0
  763   0
  419 495   0                            Distance Matrix
  621 541 445   0
  607 578 454 189   0
  607 578 454 189   0   0
 ARCS IN THE SOLUTION
   5  4                                  Route structure by node #
   4  2                                  (5 connects to 4, 4 connects
   3  2                                  to 2, etc.)
   3  1
   5  1
   6  1 TWICE
 THE TOTAL COST=                         Route cost in statute miles.
   3465                                  note that 150 * the number
                                         of legs (7 in this case)
                                         must be subtracted for
                                         actual milage.

                                         Heuristic error:
                                         (3465-3410)/3410 = 1.61%
```

Region 1 with 2 depots forced.

Laporte output:

```
"REG12"
 128,  63,  9554.0000
"X12     ",      0.0000,    764.0000
"X13     ",      0.0000,    496.0000
"X14     ",      1.0000,    541.0000
"X15     ",      1.0000,      0.0000
"X16     ",      0.0000,    764.0000
"X17     ",      0.0000,    578.0000
"X18     ",      0.0000,    578.0000
"X23     ",      0.0000,    419.0000
"X24     ",      0.0000,    621.0000
"X25     ",      0.0000,    764.0000
"X26     ",      1.0000,      0.0000
"X27     ",      1.0000,    608.0000
"X28     ",      0.0000,    608.0000
"X34     ",      0.0000,    445.0000
"X35     ",      0.0000,    496.0000
"X36     ",      0.0000,    419.0000
"X37     ",      0.0000,    454.0000
"X38     ",      0.0000,    454.0000
"X45     ",      0.0000,    541.0000
"X46     ",      0.0000,    621.0000
"X47     ",      0.0000,    190.0000
"X48     ",      1.0000,    190.0000
"X56     ",      0.0000,    764.0000
"X57     ",      0.0000,    578.0000
"X58     ",      0.0000,    578.0000
"X67     ",      0.0000,    608.0000
"X68     ",      0.0000,    608.0000
"X21     ",      0.0000,    764.0000
"X31     ",      0.0000,    496.0000
"X41     ",      0.0000,    541.0000
"X51     ",      1.0000,      0.0000
"X61     ",      0.0000,    764.0000
"X71     ",      0.0000,    578.0000
"X81     ",      1.0000,    578.0000
"X32     ",      1.0000,    419.0000
"X42     ",      0.0000,    621.0000
"X52     ",      0.0000,    764.0000
"X62     ",      1.0000,      0.0000
"X72     ",      0.0000,    608.0000
"X82     ",      0.0000,    608.0000
"X43     ",      0.0000,    445.0000
"X53     ",      0.0000,    496.0000
"X63     ",      0.0000,    419.0000
"X73     ",      1.0000,    454.0000
"X83     ",      0.0000,    454.0000
"X54     ",      0.0000,    541.0000
"X64     ",      0.0000,    621.0000
```

Output explanation:

Comparative cost
(without depots) is 9554
- 2(3382)=2790.

Node assignments:
1,5 TCM
2,6 SUU
3 LMT
4 BOI
7,8 MUO

```
"X74      ",      0.0000,   190.0000
"X84      ",      0.0000,   190.0000
"X65      ",      0.0000,   764.0000
"X75      ",      0.0000,   578.0000
"X85      ",      0.0000,   578.0000
"X76      ",      0.0000,   608.0000
"X86      ",      0.0000,   608.0000
"Y1       ",      1.0000,  3382.0000
"Y2       ",      1.0000,  3382.0000
"M1       ",      2.0000,     0.0000
"M2       ",      2.0000,     0.0000
"D3       ",   2181.0000,     0.0000
"D4       ",    541.0000,     0.0000
"D5       ",    684.0000,     0.0000
"D6       ",   2520.0000,     0.0000  The constraint output is
"D7       ",   1727.0000,     0.0000  deleted for brevity.
```

Region 1 with 2 depots

MSF output:

```
 47.08    122.28   1
 38.15    121.55   1
 42.09    121.44   1
 43.33    116.13   1
 43.02    115.52   2
     0
   763     0
   495   419     0
   541   621   445     0
   578   607   454   189     0
 BEST WEIGHT=           3389
 EMANATING NODES ON TOP
 INCIDENT NODES BELOW
     2     3     4
     3     4     5
```

Output explanation (where different from previous):
1 TCM
2 SUU
3 LMT
4 BOI
5 MUO

SUU is the only depot with emanating routes.

CW output:

SUU only is run since TCM depot has no routes.

```
 INPUT LAT, LONG, CLUSTER
 38.15    121.55   1
 42.09    121.44   1
 43.33    116.13   1
 43.02    115.52   2
 43.02    115.52   2
    0
  419   0
  621 445   0
  607 454 189   0
  607 454 189   0   0
 ARCS IN THE SOLUTION
   4  3
   3  2
   2  1
   4  1
   5  1 TWICE
 THE TOTAL COST=
   2874
```

Heuristic error:
(2874-2790)/2790 = 3%

Region 2 with optimal depot:

Laporte formulation output:

```
"REG21 "
 131,  66,  6545.0000
"X12     ",     0.0000,   778.0000
"X13     ",     1.0000,   402.0000
"X14     ",     0.0000,   705.0000
"X15     ",     0.0000,     0.0000
"X16     ",     0.0000,   778.0000
"X17     ",     0.0000,   517.0000
"X18     ",     1.0000,   696.0000
"X23     ",     0.0000,   877.0000
"X24     ",     0.0000,   331.0000
"X25     ",     0.0000,   778.0000
"X26     ",     0.0000,     0.0000
"X27     ",     0.0000,   410.0000
"X28     ",     0.0000,   437.0000
"X34     ",     0.0000,   863.0000
"X35     ",     1.0000,   402.0000
"X36     ",     0.0000,   877.0000
"X37     ",     0.0000,   639.0000
"X38     ",     0.0000,   692.0000
"X45     ",     0.0000,   705.0000
"X46     ",     0.0000,   331.0000
"X47     ",     1.0000,   378.0000
"X48     ",     0.0000,   556.0000
"X56     ",     0.0000,   778.0000
"X57     ",     0.0000,   517.0000
"X58     ",     0.0000,   696.0000
"X67     ",     0.0000,   410.0000
"X68     ",     0.0000,   437.0000
"X78     ",     0.0000,   424.0000
"X21     ",     0.0000,   778.0000
"X31     ",     0.0000,   402.0000
"X41     ",     0.0000,   705.0000
"X51     ",     1.0000,     0.0000
"X61     ",     0.0000,   778.0000
"X71     ",     1.0000,   517.0000
"X81     ",     0.0000,   696.0000
"X32     ",     0.0000,   877.0000
"X42     ",     0.0000,   331.0000
"X52     ",     0.0000,   778.0000
"X62     ",     0.0000,     0.0000
"X72     ",     0.0000,   410.0000
"X82     ",     0.0000,   437.0000
"X43     ",     0.0000,   863.0000
"X53     ",     0.0000,   402.0000
"X63     ",     0.0000,   877.0000
"X73     ",     0.0000,   639.0000
"X83     ",     0.0000,   692.0000
"X54     ",     0.0000,   705.0000
```

Output explanation
(where different from
previous):

Comparative cost is
6545-3382 = 3163

Node assignment:
1,5 OFF
2,6 FFO
3 IAB
4 BTL
7 BMI
8 HOP

```
"X64      ",      1.0000,   331.0000
"X74      ",      0.0000,   378.0000
"X84      ",      0.0000,   556.0000
"X65      ",      0.0000,   778.0000
"X75      ",      0.0000,   517.0000
"X85      ",      0.0000,   696.0000
"X76      ",      0.0000,   410.0000
"X86      ",      1.0000,   437.0000
"X87      ",      0.0000,   424.0000
"Y1       ",      1.0000,  3382.0000
"Y2       ",      0.0000,  3382.0000
"M1       ",      2.0000,     0.0000
"M2       ",      0.0000,     0.0000
"D3       ",   2080.0000,     0.0000
"D4       ",   1644.0000,     0.0000
"D5       ",   2482.0000,     0.0000
"D6       ",   1015.0000,     0.0000
"D7       ",   2022.0000,     0.0000  Constraint activity
"D8       ",    578.0000,     0.0000  deleted for brevity.
```

Region 2 with 1 depot.

MSF output:

```
 41.07     95.54    1
 39.50     84.03    1
 37.37     97.16    1
 42.18     85.14    1
 40.29     88.55    1
 36.40     87.29    1
     0
   778     0
   402   877     0
   705   331   863     0
   517   410   639   378     0
   696   437   692   556   424     0
 BEST WEIGHT=          3981
 EMANATING NODES ON TOP
 INCIDENT NODES BELOW
     1     1     5     4     5
     3     5     4     2     6
```

Output explanation where different:
1 OFF
2 FFO
3 IAB
4 BTL
5 BMI
6 HOP

CW output:

```
 INPUT LAT, LONG, CLUSTER
 41.07     95.54    1
 39.50     84.03    1
 37.37     97.16    1
 42.18     85.14    1
 40.29     88.55    1
 36.40     87.29    1
    0
  778   0
  402 877   0
  705 331 863   0
  517 410 639 378   0
  696 437 692 556 424   0
 ARCS IN THE SOLUTION
   4  2
   6  2
   5  4
   3  1 TWICE
   5  1
   6  1
 THE TOTAL COST=

   3163
```

Heuristic error:

0%

Region 2 with 2 depots forced:

Laporte formulation output:

```
"REG22"
 130,  66,  9138.0000
"X12     ",      0.0000,   778.0000
"X13     ",      0.0000,   402.0000
"X14     ",      0.0000,   705.0000
"X15     ",      1.0000,     0.0000
"X16     ",      0.0000,   778.0000
"X17     ",      0.0000,   517.0000
"X18     ",      0.0000,   696.0000
"X23     ",      0.0000,   877.0000
"X24     ",      1.0000,   331.0000
"X25     ",      0.0000,   778.0000
"X26     ",      0.0000,     0.0000
"X27     ",      0.0000,   410.0000
"X28     ",      0.0000,   437.0000
"X34     ",      0.0000,   863.0000
"X35     ",      0.0000,   402.0000
"X36     ",      0.0000,   877.0000
"X37     ",      0.0000,   639.0000
"X38     ",      0.0000,   692.0000
"X45     ",      0.0000,   705.0000
"X46     ",      0.0000,   331.0000
"X47     ",      1.0000,   378.0000
"X48     ",      0.0000,   556.0000
"X56     ",      0.0000,   778.0000
"X57     ",      0.0000,   517.0000
"X58     ",      0.0000,   696.0000
"X67     ",      0.0000,   410.0000
"X68     ",      0.0000,   437.0000
"X78     ",      1.0000,   424.0000
"X21     ",      0.0000,   778.0000
"X31     ",      1.0000,   402.0000
"X41     ",      0.0000,   705.0000
"X51     ",      0.0000,     0.0000
"X61     ",      0.0000,   778.0000
"X71     ",      0.0000,   517.0000
"X81     ",      0.0000,   696.0000
"X32     ",      0.0000,   877.0000
"X42     ",      0.0000,   331.0000
"X52     ",      0.0000,   778.0000
"X62     ",      1.0000,     0.0000
"X72     ",      0.0000,   410.0000
"X82     ",      0.0000,   437.0000
"X43     ",      0.0000,   863.0000
"X53     ",      1.0000,   402.0000
"X63     ",      0.0000,   877.0000
"X73     ",      0.0000,   639.0000
"X83     ",      0.0000,   692.0000
"X54     ",      0.0000,   705.0000
```

Output explanation as necessary:

Comparative cost is
9138-6764 = 2374

Node assignment:

1,5 OFF
2,6 FFO
3 IAB
4 BTL
7 BMI
8 HOP

```
"X64      ",     0.0000,   331.0000
"X74      ",     0.0000,   378.0000
"X84      ",     0.0000,   556.0000
"X65      ",     0.0000,   778.0000
"X75      ",     0.0000,   517.0000
"X85      ",     0.0000,   696.0000
"X76      ",     0.0000,   410.0000
"X86      ",     1.0000,   437.0000
"X87      ",     0.0000,   424.0000
"Y1       ",     1.0000,  3382.0000
"Y2       ",     1.0000,  3382.0000
"M1       ",     1.0000,     0.0000
"M2       ",     1.0000,     0.0000
"D3       ",  2104.0000,     0.0000
"D4       ",   621.0000,     0.0000
"D5       ",    38.0000,     0.0000
"D6       ",  1860.0000,     0.0000
"D7       ",   999.0000,     0.0000  Constraint activity
"D8       ",  1423.0000,     0.0000  deleted for brevity.
```

Region 2 with 2 depots.

```
MSF output:                          Output explanation as
                                     required:
 41.07    95.54   1                  1 OFF
 39.50    84.03   1                  2 FFO
 37.37    97.16   1                  3 IAB
 42.18    85.14   1                  4 BTL
 40.29    88.55   1                  5 BMI
 36.40    87.29   1                  6 HOP
     0
   778    0
   402  877    0
   705  331  863    0
   517  410  639  378    0
   696  437  692  556  424    0
 BEST WEIGHT=         2575
 EMANATING NODES ON TOP
 INCIDENT NODES BELOW
     2    4    1    5                FFO serves 3 bases
     4    5    3    6                OFF serves 1 base

--------------------------------------
```

```
CW output:

 INPUT LAT, LONG, CLUSTER
 39.50    84.03   1                  1 FFO
 42.18    85.14   1                  2 BTL
 40.29    88.55   1                  3 BMI
 36.40    87.29   1                  4 HOP
    0
  331   0
  410 378   0
  437 556 424   0
 ARCS IN THE SOLUTION
   4  3
   3  2
   2  1
   4  1
 THE TOTAL COST=                     Routing from OFF to
   1570                              IAB and return is
                                     trivial and = 804. Total
                                     = 804 + 1570 = 2374

                                     Heuristic error:
                                            0%
```

Region 3 with optimal depot.

Laporte formulation output:

```
"REG31"
 129,  63,  6071.0000
"X12     ",       0.0000,   357.0000
"X13     ",       0.0000,   319.0000
"X14     ",       0.0000,   345.0000
"X15     ",       0.0000,     0.0000
"X16     ",       0.0000,   357.0000
"X17     ",       0.0000,   528.0000
"X18     ",       0.0000,   528.0000
"X23     ",       1.0000,   496.0000
"X24     ",       0.0000,   546.0000
"X25     ",       0.0000,   357.0000
"X26     ",       1.0000,     0.0000
"X27     ",       1.0000,   323.0000
"X28     ",       0.0000,   323.0000
"X34     ",       1.0000,   351.0000
"X35     ",       0.0000,   319.0000
"X36     ",       0.0000,   496.0000
"X37     ",       0.0000,   668.0000
"X38     ",       0.0000,   668.0000
"X45     ",       1.0000,   345.0000
"X46     ",       0.0000,   546.0000
"X47     ",       0.0000,   711.0000
"X48     ",       0.0000,   711.0000
"X56     ",       0.0000,   357.0000
"X57     ",       0.0000,   528.0000
"X58     ",       1.0000,   528.0000
"X67     ",       0.0000,   323.0000
"X68     ",       0.0000,   323.0000
"X21     ",       0.0000,   357.0000
"X31     ",       0.0000,   319.0000
"X41     ",       0.0000,   345.0000
"X51     ",       0.0000,     0.0000
"X61     ",       0.0000,   357.0000
"X71     ",       0.0000,   528.0000
"X81     ",       0.0000,   528.0000
"X32     ",       0.0000,   496.0000
"X42     ",       0.0000,   546.0000
"X52     ",       0.0000,   357.0000
"X62     ",       1.0000,     0.0000
"X72     ",       1.0000,   323.0000
"X82     ",       1.0000,   323.0000
"X43     ",       0.0000,   351.0000
"X53     ",       0.0000,   319.0000
"X63     ",       0.0000,   496.0000
"X73     ",       0.0000,   668.0000
"X83     ",       0.0000,   668.0000
"X54     ",       0.0000,   345.0000
"X64     ",       0.0000,   546.0000
```

Explanation as necessary:

Comparative is 6071-3382 = 2689.

Node assignment:
1,5 CHS
2,6 NIP
3 CLT
4 NCA
7,8 MCF

```
"X74      ",     0.0000,   711.0000
"X84      ",     0.0000,   711.0000
"X65      ",     0.0000,   357.0000
"X75      ",     0.0000,   528.0000
"X85      ",     0.0000,   528.0000
"X76      ",     0.0000,   323.0000
"X86      ",     0.0000,   323.0000
"Y1       ",     0.0000,  3382.0000
"Y2       ",     1.0000,  3382.0000
"M1       ",     0.0000,     0.0000
"M2       ",     3.0000,     0.0000
"D3       ",   496.0000,     0.0000
"D4       ",  1404.0000,     0.0000
"D5       ",  1749.0000,     0.0000
"D6       ",   205.0000,     0.0000  Constraint activity
"D7       ",  2277.0000,     0.0000  deleted for brevity.
```

Region 3 with 1 depot.

MSF output:

```
 32.53     80.02   1
 30.14     81.41   1
 35.13     80.56   1
 34.43     77.26   1
 27.50     82.31   2
     0
   357     0
   319   496     0
   345   546   351     0
   528   323   668   711     0
 BEST WEIGHT=          2381
 EMANATING NODES ON TOP
 INCIDENT NODES BELOW
     1     1     1     2
     3     4     2     5
```

Explanation as necessary:

1 CHS
2 NIP
3 CLT
4 NCA
5 MCF

CHS chosen

CW output:

```
 INPUT LAT, LONG, CLUSTER
 32.53     80.02   1
 30.14     81.41   1
 35.13     80.56   1
 34.43     77.26   1
 27.50     82.31   2
 27.50     82.31   2
    0
  357   0
  319 496   0
  345 546 351   0
  528 323 668 711   0
  528 323 668 711   0    0
 ARCS IN THE SOLUTION
   5  2
   4  3
   3  2
   4  1
   5  1
   6  1 TWICE
 THE TOTAL COST=
   3099
```

1 CHS
2 NIP
3 CLT
4 NCA
5 MCF
6 MCF

Heuristic error:
(3099-2689)/2689 =
15.25%

Region 3 with 2 depots forced.

Laporte formulation output:

```
"REG32"
 128,  63,  9071.0000
"X12     ",      0.0000,   357.0000
"X13     ",      1.0000,   319.0000
"X14     ",      0.0000,   345.0000
"X15     ",      1.0000,     0.0000
"X16     ",      0.0000,   357.0000
"X17     ",      0.0000,   528.0000
"X18     ",      0.0000,   528.0000
"X23     ",      0.0000,   496.0000
"X24     ",      0.0000,   546.0000
"X25     ",      0.0000,   357.0000
"X26     ",      1.0000,     0.0000
"X27     ",      1.0000,   323.0000
"X28     ",      0.0000,   323.0000
"X34     ",      1.0000,   351.0000
"X35     ",      0.0000,   319.0000
"X36     ",      0.0000,   496.0000
"X37     ",      0.0000,   668.0000
"X38     ",      0.0000,   668.0000
"X45     ",      0.0000,   345.0000
"X46     ",      0.0000,   546.0000
"X47     ",      0.0000,   711.0000
"X48     ",      0.0000,   711.0000
"X56     ",      0.0000,   357.0000
"X57     ",      0.0000,   528.0000
"X58     ",      0.0000,   528.0000
"X67     ",      0.0000,   323.0000
"X68     ",      1.0000,   323.0000
"X21     ",      0.0000,   357.0000
"X31     ",      0.0000,   319.0000
"X41     ",      1.0000,   345.0000
"X51     ",      1.0000,     0.0000
"X61     ",      0.0000,   357.0000
"X71     ",      0.0000,   528.0000
"X81     ",      0.0000,   528.0000
"X32     ",      0.0000,   496.0000
"X42     ",      0.0000,   546.0000
"X52     ",      0.0000,   357.0000
"X62     ",      0.0000,     0.0000
"X72     ",      1.0000,   323.0000
"X82     ",      1.0000,   323.0000
"X43     ",      0.0000,   351.0000
"X53     ",      0.0000,   319.0000
"X63     ",      0.0000,   496.0000
"X73     ",      0.0000,   668.0000
"X83     ",      0.0000,   668.0000
"X54     ",      0.0000,   345.0000
"X64     ",      0.0000,   546.0000
```

Explanation as necessary:

Comparative cost is
9071-6764 = 2307

Node assgnment:
1,5 CHS
2,6 NIP
3 CLT
4 NCA
7,8 MCF

```
"X74      ",      0.0000,   711.0000
"X84      ",      0.0000,   711.0000
"X65      ",      0.0000,   357.0000
"X75      ",      0.0000,   528.0000
"X85      ",      0.0000,   528.0000
"X76      ",      0.0000,   323.0000
"X86      ",      0.0000,   323.0000
"Y1       ",      1.0000,  3382.0000
"Y2       ",      1.0000,  3382.0000
"M1       ",      2.0000,     0.0000
"M2       ",      2.0000,     0.0000
"D3       ",   1904.0000,     0.0000
"D4       ",   2255.0000,     0.0000
"D5       ",      0.0000,     0.0000
"D6       ",    201.0000,     0.0000  Constraint activity
"D7       ",    729.0000,     0.0000  deleted for brevity.
```

Region 3 with 2 depots.

MSF output:

```
 32.53    80.02   1
 30.14    81.41   1
 35.13    80.56   1
 34.43    77.26   1
 27.50    82.31   2
     0
   357    0
   319  496    0
   345  546  351    0
   528  323  668  711    0
 BEST WEIGHT=         1310
 EMANATING NODES ON TOP
 INCIDENT NODES BELOW
     1    2    1
     3    5    4
```

Explanation as
necessary:
1 CHS
2 NIP
3 CLT
4 NCA
5 MCF

CW output is not included as the routing from CHS - CLT - NCA - CHS is trivial (equals 1015), and 2 round trips from CHS to MCF equal 1292. The total is 2307, which is 0% from optimal.

Appendix D: Spanning Forest Data Set

1	2	3	4
38.15	121.55	1	SUU/F-1
29.22	98.35	4	SKF/F-2
39.11	76.40	12	BWI/F-3
47.08	122.28	2	TCM/C-4
32.41	117.12	1	NZY/C-5
39.46	104.53	2	DEN/C-6
41.07	95.54	4	OFF/C-7
39.50	84.03	12	FFO/C-8
42.09	70.56	2	NZW/C-9
36.56	76.17	2	NGU/C-10
32.53	80.02	2	CHS/C-11
30.14	81.41	2	NIP/C-12
40.47	111.58	2	SLC/C-13
36.14	115.02	1	LSV/C-14
33.32	112.23	1	LUF/C-15
35.03	106.34	1	ABQ/C-16
31.48	106.23	1	ELP/C-17
32.46	97.26	2	FWH/C-18
35.25	97.23	2	TIK/C-19
34.54	92.08	1	LRF/C-20
35.02	89.58	1	MEM/C-21
37.37	97.16	2	IAB/C-22
38.32	89.51	2	BLV/C-23
42.05	87.49	1	NBU/C-24
38.10	85.44	2	SDF/C-25
43.14	75.24	2	RME/C-26
29.50	90.01	1	NBG/C-27
27.50	82.31	2	MCF/C-28
25.29	80.23	2	HST/C-29
33.54	84.31	2	NCQ/C-30
38.40	121.23	2	MCC-31
37.17	120.31	2	MCE-32
36.20	119.57	2	NLC-33
37.53	121.14	2	SCK-34
36.46	119.43	2	FAT-35
36.35	121.50	2	MRY-36
42.09	121.44	1	LMT-37
39.29	119.46	1	RNO-38
39.24	118.41	1	NFL-39
46.34	120.32	2	YKM-40
47.37	117.31	2	GEG-41
46.15	119.06	1	PSC-42
43.33	116.13	1	BOI-43
43.02	115.52	1	MUO-44
32.50	115.40	1	NJK-45
32.39	114.36	1	NYL-46
35.41	117.41	1	NID-47
34.17	116.10	1	NXP-48
34.51	116.47	1	DAG-49

34.12	119.12	1	OXR-50
34.54	117.52	1	EDW-51
34.43	120.34	2	VBG-52
41.09	104.49	2	CYS-53
44.08	103.06	2	RCA-54
48.24	101.21	2	MIB-55
47.57	97.24	2	RDR-56
47.30	111.11	2	GFA-57
43.31	112.04	1	IDA-58
45.48	108.32	1	BIL-59
46.36	111.59	1	HLN-60
49.54	97.14	1	YWG-61
34.39	98.24	2	FSI-62
32.30	93.40	2	BAD-63
31.21	100.29	2	SJT-64
32.25	99.51	2	DYS-65
31.04	97.50	2	GRK-66
30.12	97.41	2	BSM-67
34.40	99.16	1	LTS-68
32.19	90.05	1	JAN-69
31.19	92.32	1	AEX-70
35.20	94.22	1	FSM-71
34.29	93.06	1	HOT-72
29.36	95.09	1	EFD-73
32.51	106.06	1	HMN-74
32.09	110.52	1	DMA-75
34.23	103.19	1	CVS-76
29.22	100.47	1	DLV-77
33.59	98.29	1	SPS-78
33.35	102.02	1	REE-79
35.13	101.43	1	AMA-80
41.32	93.39	1	DSM-81
41.53	91.42	1	CID-82
41.26	90.30	1	MLI-83
43.57	90.44	1	CMY-84
44.53	93.13	1	MSP-85
43.34	96.44	1	FSD-86
42.24	96.23	1	SUX-87
39.22	94.54	1	FLV-88
39.03	96.46	1	FRI-89
38.51	94.33	1	GVW-90
38.57	95.39	1	FOE-91
37.44	92.08	1	TBN-92
35.58	89.57	2	BYH-93
38.44	93.33	2	SZL-94
38.34	90.09	4	CPS-95
42.57	87.53	1	MKE-96
42.18	85.14	1	BTL-97
41.35	83.48	1	TOL-98
41.01	83.41	1	FDY-99
41.25	81.51	1	CLE-100
40.29	80.14	1	PIT-101
39.49	82.56	1	LCK-102

40.49	82.30	1	MFD-103
40.58	85.11	1	FWA-104
40.38	86.09	1	GUS-105
39.27	87.18	1	HUF-106
40.29	88.55	1	BMI-107
39.09	86.37	1	BMG-108
39.06	84.25	1	LUK-109
36.40	87.29	1	HOP-110
35.24	86.05	1	TUH-111
35.49	84.00	1	TYS-112
38.22	81.36	1	CUW-113
41.35	71.25	2	OQW-114
41.04	73.42	2	HPN-115
43.07	76.06	2	SYR-116
44.03	75.44	2	GTB-117
42.45	73.48	2	ALB-118
42.11	72.31	2	CEF-119
40.44	73.25	2	FRG-120
41.30	74.06	2	SWF-121
42.12	75.59	2	BGM-122
42.56	78.44	2	BUF-123
43.07	77.40	2	ROC-124
41.16	72.53	2	HVN-125
41.19	72.02	2	GON-126
41.56	72.41	2	BDL-127
44.39	73.28	2	PBG-128
44.28	73.09	2	BTV-129
42.56	71.26	2	MHT-130
43.04	70.49	2	PSM-131
43.53	69.56	2	NHZ-132
44.48	68.50	2	BGR-133
46.57	67.53	2	LIZ-134
41.40	70.31	2	FMH-135
37.05	76.21	12	LFI-136
34.40	86.41	4	HUA-137
38.08	78.27	2	CHO-138
38.17	76.24	2	NHK-139
38.15	78.53	2	SHD-140
37.19	79.58	2	ROA-141
39.38	79.54	2	MGW-142
39.42	77.43	2	HGR-143
40.51	77.51	2	UNV-144
41.20	75.43	2	AVP-145
40.11	76.45	2	MDT-146
33.40	78.55	2	MYR-147
33.57	80.28	2	SSC-148
33.22	81.58	2	AGS-149
33.39	88.27	2	CBM-150
33.33	86.45	2	BHM-151
33.35	85.51	2	ANB-152
32.28	80.43	2	NBC-153
31.53	81.34	2	LHW-154
32.38	83.35	2	WRB-155

32.20	84.59	2	LSF-156
32.22	86.21	2	MXF-157
32.20	88.44	2	MEI-158
31.16	85.42	2	OZR-159
31.32	84.12	2	ABY-160
24.35	81.41	2	NOX-161
26.41	80.06	2	PBI-162
28.14	80.36	2	COF-163
28.25	81.19	2	MCO-164
30.24	88.55	2	BIX-165
30.21	87.19	2	NPA-166
30.29	86.31	2	VPS-167
30.04	85.34	2	PAM-168
30.58	83.11	1	VAD-169
30.23	84.21	1	TLH-170
34.54	76.53	2	NKT-171
34.43	77.26	2	NCA-172
34.54	82.13	2	GSP-173
35.26	82.32	2	AVL-174
36.29	82.25	2	TRI-175
37.31	77.19	2	RIC-176
35.20	77.58	2	GSB-177
35.10	79.01	2	POB-178
35.13	80.56	2	CLT-179
36.06	79.56	2	GSO-180
35.53	78.47	2	RDU-181

Columns:
1 Latitude
2 Longitude
3 Frequency in visits per 2 weeks
4 ICAO and program assignment number

Appendix E: MSF and CW Output

11 Depot Model

MSF:

Note, the number assignments are given in Appendix D.

```
BEST WEIGHT=      279481
DEPOTS=
    1    2    3    5    7    8    9   11   12   20   26
EMINATING NODES ON TOP
INCIDENT NODES BELOW
   26    9    1    1    9  114  126  125  115  115
  116  135   31   34  114  126  125  115  120  121

  125  127   11    8   34   32   35   26    8    9
  127  119  153  109   32   35   33  117  102  130

  130   20  116  122    3  153    3  143  131  102
  131   72  122  145  139  154  143  146  132  103

  103  103   99  139  176  136  146  176  138  119
  100   99   98  176  136   10  144  138  140  118

   11    2   67   99  104  116  124  132   11   32
  148   67   66  104  105  124  123  133  147   36

  140  141  180  181  181  177  172  180  179  173
  141  180  181  178  177  172  171  179  173  174

  174  174   98    5   45   72    7   87  109   25
  175  112   97   45   46   71   87   86   25  108

  108  153   12  169  160  156  160  170  168  167
  106  149  169  160  156  157  170  168  167  166

  167  157  151  151  137  152  160  166  165  151
  159  151  152  137  111   30  155  165   27  150

  150  158   31   38   45   48   49   51   51   50
  158   69   38   39   48   49   51   47   50   52

  100  101  106  107   83   82  141  111   66   18
  101  142  107   83   82   81  113  110   18   78

   78   62   62  117  128   20   21  107   24   12
   62   68   19  128  129   21   93   24   96  164

  164  164  163  162   29    7   88   88   90   91
  163   28  162   29  161   88   90   91   94   89

   89   94   92   95    2   78   65   49   72   63
```

```
   22    92    95    23    77    65    64    14    63    70

   46    15    68    80    76    82    84   133    67    76
   15    75    80    76    79    84    85   134    73    16

   16    74    38    39    44    44    58    58    60    43
   74    17    37    44    43    58    13    60    57    42

   42    40    42    86    56    56    55    54    53    54
   40     4    41    56    61    55    54    53     6    59
```

CW for 11 Depot:

SKF data file.

```
   1        2      3    4          5              6

 29.22     98.35   1   SKF/F-2   1             KELLY
 31.48    106.23   2   ELP/C-17  2,3           FT BLISS
 32.46     97.26   4   FWH/C-18  4,5,6,7       CARSWELL
 35.25     97.23   4   TIK/C-19  8,9,10,11     TINKER
 35.03    106.34   2   ABQ/C-16  12,13         KIRTLAND
 34.39     98.24   4   FSI-62    14,15,16,17   FT SILL
 31.21    100.29   4   SJT-64    18,19,20,21   GOODFELLOW
 32.25     99.51   4   DYS-65    22,23,24,25   DYESS
 31.04     97.50   4   GRK-66    26,27,28,29   FT HOOD
 30.12     97.41   4   BSM-67    30,31,32,33   BERGSTROM
 34.40     99.16   2   LTS-68    34,35         ALTUS
 29.36     95.09   2   EFD-73    36,37         ELLINGTON
 32.51    106.06   2   HMN-74    38,39         HOLLOMAN
 34.23    103.19   2   CVS-76    40,41         CANNON
 29.22    100.47   1   DLF-77    42            LAUGHLIN
 33.59     98.29   1   SPS-78    43            SHEPPARD
 33.35    102.02   1   REE-79    44            REESE
 35.13    101.43   1   AMA-80    45            AMARILLO
```

Column explanation for all CW data files:
1 Latitude
2 Longitude
3 Visits per 4 week period
4 ICAO Identifier and CONUS system number
5 Number assignments for CW runs
6 Name

SKF output file:

```
 ARCS IN THE SOLUTION
  38 12
  39 13
  38  2
```

```
 39  3
 40 12
 41 13
 45 40
 14  8
 15  9
 16 10
 17 11
 44 41
 34 14
 35 15
 43 16
  8  4
  9  5
 10  6
 11  7
 45 22
 34 23
 35 24
 44 25
 23 18
 24 19
 20 17
 43 21
 26  4
 27  5
 28  6
 29  7
 30 26
 31 27
 32 28
 33 29
 36 32
 37 33
 42  2
  3  1
 18  1
 19  1
 20  1
 21  1
 22  1
 25  1
 30  1
 31  1
 36  1
 37  1
 42  1
THE TOTAL COST=
 14505
```

Cost explanation:
-Run was made over 4 week period
-50 legs (arcs) in solution

Weekly milage =

$$\frac{(14505-150*50)}{4} = 1751$$

Example output interpretation is done by matching ICAO's with solution arcs:

```
Route 1:  SKF-DLF-ELP-HMN-ABQ-CVS-AMA-DYS-SKF
            1  42   2  38  12  40  45  22   1
Route 2:  SKF-ELP-HMN-ABQ-CVS-AMA-DYS-SKF
            1   3  39  13  41  44  25   1
Route 3:  SKF-BSM-GRK-FWH-TIK-FSI-LTS-DYS-SJT-SKF
            1  30  26   4   8  14  34  23  18   1
Route 4:  SKF-BSM-GRK-FWH-TIK-FSI-LTS-DYS-SJT-SKF
            1  31  27   5   9  15  35  24  19   1
Route 5:  SKF-EFD-BSM-GRK-FWH-TIK-FSI-SPS-SJT-SKF
            1  36  32  28   6  10  16  43  21   1
Route 6:  SKF-EFD-BSM-GRK-FWH-TIK-FSI-SJT-SKF
            1  37  33  29   7  11  17  20   1
-------------------------------------
```

CHS data file (11 depot):

Frequency based on weekly rate.

```
 32.53     80.02    1    CHS/C-11   1 CHARLESTON
 33.40     78.55    1    MYR-147    2 MYRTLE BEACH
 33.57     80.23    1    SSC-148    3 SHAW
 33.22     81.58    1    AGS-149    4 FT GORDON
 32.28     80.43    1    NBC-153    5 BEAUFORT
 31.53     81.34    1    LHW-154    6 FT STEWART
```

CHS output file.

```
 ARCS IN THE SOLUTION
   6  4
   4  3
   6  5
   3  2                             Cost explanation:
   2  1                             -6 arcs in solution
   5  1                             Weekly milage =
 THE TOTAL COST=
 1387                               1387-(6*150)=  487
```

Example output interpretation:

```
Route 1:  CHS-NBC-LWH-AGS-SSC-MYR-CHS
            1   5   6   4   3   2   1

-------------------------------------------
```

BWI data file (11 depot):

Frequency based on 2 week rate.

```
 39.11     76.40    1    BWI/F-3  1      BALTIMORE
 36.56     76.17    2    NGU/C-10 2,3    NORFOLK
 35.49     84.00    1    TYS-112  4      KNOXVILLE
 38.22     81.36    1    CUW-113  5      CHARLESTON WV
 37.05     76.21   12    LFI-136  6-17   LANGLEY
```

```
38.08     78.27    2    CHO-138  18,19 CHARLOTTESVILLE
38.17     76.24    2    NHK-139  20,21 PAX RIVER
38.15     78.53    2    SHD-140  22,23 SHENENDOAH
37.19     79.58    2    ROA-141  24,25 ROANOKE
39.42     77.43    2    HGR-143  26,27 HAGERSTOWN
40.51     77.51    2    UNV-144  28,29 STATE COLLEGE
40.11     76.45    2    MDT-146  30,31 HARRISBURG
34.54     76.53    2    NKT-171  32,33 CHERRY POINT
34.43     77.26    2    NCA-172  34.35 JACKSONVILLE
34.54     82.13    2    GSP-173  36,37 GREENSVILLE
35.26     82.32    2    AVL-174  38,39 ASHEVILLE
36.29     82.25    2    TRI-175  40,41 BRISTOL
37.31     77.19    2    RIC-176  42,43 RICHMOND
35.20     77.58    2    GSB-177  44,45 GOLDSBORO
35.10     79.01    2    POB-178  46,47 POPE
35.13     80.56    2    CLT-179  48,49 CHARLOTTE
36.06     79.56    2    GSO-180  50,51 GREENSBORO
35.53     78.47    2    RDU-181  52,53 RALIEGH
```

BWI output file:

```
 ARCS IN THE SOLUTION
  38 36
  39 37
  38  4
  40  4
  48 36
  49 37
  41 39
  34 32
  35 33
  48 46
  49 47
  44 34
  45 35
  47 44
  52 46
  50 40
  53 45
  53 51
  51 24
  24  5
  33  2
   6  2
   7  3
  41 22
  25 23
  25 18
  42  3
  43  8
  42 18
  43 19
  20  7
```

```
  21   8
  30  28
  31  29
  28  26
  29  27
  26  23
  27  19
   5   1
   6   1
   9   1 TWICE
  10   1 TWICE
  11   1 TWICE
  12   1 TWICE
  13   1 TWICE
  14   1 TWICE
  15   1 TWICE
  16   1 TWICE
  17   1 TWICE
  20   1
  21   1
  22   1
  30   1
  31   1
  32   1
  50   1
  52   1
 THE TOTAL COST=
  17177
```

Cost explanation:
-Run was made over
 2 week period
-66 arcs in solution

Weekly milage=

$$\frac{17177-(150*66)}{2} = 3638$$

SUU data file (11 depot):

Frequency based on 2 week rate.

```
 38.15    121.55   1   SUU/F-1   1     TRAVIS
 38.40    121.23   2   MCC-31    2,3   MCCLELLAN
 37.17    120.31   2   MCE-32    4,5   MERCED
 36.20    119.57   2   NLC-33    6,7   LEMOORE
 37.53    121.14   2   SCK-34    8,9   STOCKTON
 36.46    119.43   2   FAT-35    10,11 FRESNO
 36.35    121.50   2   MRY-36    12,13 MONTERRY
 42.09    121.44   1   LMT-37    14    KLAMATH FALLS
 39.29    119.46   1   RNO-38    15    RENO
 39.24    118.41   1   NFL-39    16    FALLON
 40.47    111.58   2   SLC/C-13  17,18 SALT LAKE CITY
 47.08    122.28   2   TCM/C-4   19,20 MCCHORD
 46.34    120.32   2   YKM-40    21,22 YAKIMA
 47.37    117.31   2   GEG-41    23,24 SPOKANE
 46.15    119.06   1   PSC-42    25    PASCO
 43.33    116.13   1   BOI-43    26    BOISE
 43.02    115.52   1   MUO-44    27    MT HOME
 47.30    111.11   2   GFA-57    28,29 MALMSTROM
 43.31    112.04   1   IDA-58    30    IDAHO FALLS
```

```
 46.36   111.59   1   HLN-60   31    HELENA
```

SUU output file:

```
 ARCS IN THE SOLUTION
  31 28
  28 23
  29 24
  30 29
  25 23
  21 19
  22 20
  27 26
  27 17
  21 18
  20 14
  17 16
  10  6
  11  7
  26 15
  10  4
  11  5
  12  6
  13  7
   8  4
   9  5
  15  2
  22  3
   2  1
   3  1
   8  1
   9  1
  12  1
  13  1
  14  1
  16  1
  18  1
  19  1
  24  1
  25  1
  30  1
  31  1
 THE TOTAL COST=
  14557
```

Cost explanation:
-Run was made over 2 week period.
-37 arcs in solution

Weekly milage:

$$\frac{14557-(150*37)}{2} = 4504$$

NZY data file (11 depot):

Frequency based on 2 week rate:

```
 32.41   117.12   1   NZY/C-5  1     NORTH ISLAND
 36.14   115.02   1   LSV/C-14 2     LAS VEGAS
 33.32   112.23   1   LUF/C-15 3     LUKE
```

```
 32.50    115.40    1    NJK-45    4      EL CENTRO
 32.39    114.36    1    NYL-46    5      YUMA
 35.41    117.41    1    NID-47    6      CHINA LAKE
 34.17    116.10    1    NXP-48    7      29 PALMS
 34.51    116.47    1    DAG-49    8      DAGGETT
 34.12    119.12    1    OXR-50    9      OXNARD
 34.54    117.52    1    EDW-52    10     EDWARDS
 34.43    120.34    2    VBG-51    11,12  VANDENBERG
 32.09    110.52    1    DMA-75    13     DAVIS-MONTHAN
```

NZY output file:

```
 ARCS IN THE SOLUTION
  13  3
   6  2
   3  2
  10  6
  11  9
  13  5
  10  8
   8  7
   9  4
   4  1
   5  1
   7  1
  11  1
  12  1 TWICE
 THE TOTAL COST=
    4546
```

Cost explanation:
-Run made over 2 week period
-15 arcs in solution

Weekly milage:

$$\frac{4546-(15*150)}{2} = 1148$$

OFF data file (11 depot):

Frequency based on <u>every other month</u> due to infrequent service at YWG.

```
 41.07     95.54    1    OFF/C-7   1       OFFUTT
 37.37     97.16    8    IAB/C-22  2-9     MCCONNELL
 38.32     89.51    8    BLV/C-23  10-17   SCOTT
 43.34     96.44    4    FSD-86    18-21   SIOUX FALLS
 42.24     96.23    4    SUX-87    22-25   SIOUX CITY
 39.22     94.54    4    FLV-88    26-29   FT LEAVENWORTH
 39.03     96.46    4    FRI-89    30-33   FT RILEY
 38.51     94.33    4    GVW-90    34-37   KANSAS CITY
 38.57     95.39    4    FOE-91    38-41   FORBES
 37.44     92.08    4    TBN-92    42-45   FORNEY
 38.44     93.33    8    SZL-94    46-53   WHITEMAN
 38.34     90.09    16   CPS-95    54-69   E ST LOUIS
 48.24    101.21    8    MIB-55    70-77   MINOT
 47.57     97.24    8    RDR-56    78-85   GRAND FORKS
 49.54     97.14    1    YWG-61    86      WINNEPEG
 39.46    104.53    8    DEN/C-6   87-94   DENVER
 41.09    104.49    8    CYS-53    95-102   CHEYENNE
```

```
 44.08   103.06   8   RCA-54   103-110 ELLSWORTH
 45.48   108.32   4   BIL-59   111-114 BILLINGS
```

OFF output file:

```
ARCS IN THE SOLUTION
 86 70
 86 78
111 71
112 72
113 73
114 74
 79 71
 80 72
 81 73
 82 74
 83 75
 84 76
 85 77
 95 87
 96 88
 97 89
 98 90
 99 91
100 92
101 93
102 94
111103
112104
113105
114106
 54 10
 55 11
 56 12
 57 13
 58 14
 59 15
 60 16
 61 17
107 70
108 75
109 76
110 77
 42 10
 43 11
 44 12
 45 13
 46 42
 47 43
 48 44
 49 45
 58 50
 59 51
```

```
60 52
61 53
78 18
83 19
84 20
85 21
46 34
47 35
48 36
49 37
30  2
31  3
32  4
33  5
87  2
88  3
89  4
90  5
91  6
92  7
93  8
94  9
38  6
39  7
40  8
41  9
34 26
35 27
36 28
37 29
22 18
23 19
24 20
25 21
14  1
15  1
16  1
17  1
22  1
23  1
24  1
25  1
26  1
27  1
28  1
29  1
30  1
31  1
32  1
33  1
38  1
39  1
40  1
```

```
 41  1
 50  1
 51  1
 52  1
 53  1
 54  1
 55  1
 56  1
 57  1
 62  1 TWICE
 63  1 TWICE
 64  1 TWICE
 65  1 TWICE
 66  1 TWICE
 67  1 TWICE
 68  1 TWICE
 69  1 TWICE
 79  1
 80  1
 81  1
 82  1
 95  1
 96  1
 97  1
 98  1
 99  1
100  1
101  1
102  1
103  1
104  1
105  1
106  1
107  1
108  1
109  1
110  1
THE TOTAL COST=
 56556
-----------------------------------
```

Cost explanation:
-Run made over 8 weeks
-145 arcs in solution

Weekly milage=

$$\frac{56556-(145*150)}{8} = 4351$$

FFO data file (11 depot):

```
 39.50    84.03   1   FFO/C-8  1   WRIGHT-PATT
 42.05    87.49   1   NBU/C-24 2   GLENVIEW
 38.10    85.44   2   SDF/C-25 3,4 STANDIFORD
 41.32    93.39   1   DSM-81   5   DES MOINES
 41.53    91.42   1   CID-82   6   CEDAR RAPIDS
 41.26    90.30   1   MLI-83   7   MOLINE
 43.57    90.44   1   CMY-84   8   FT MCCOY
 44.53    93.13   1   MSP-85   9   MINNEAPOLIS
 42.57    87.53   1   MKE-96   10  MILWAUKEE
 42.18    85.14   1   BTL-97   11  BATTLE CREEK
```

```
 41.35     83.48    1   TOL-98    12  TOLEDO
 41.01     83.41    1   FDY-99    13  FINDLAY
 41.25     81.51    1   CLE-100   14  CLEVELAND
 40.29     80.14    1   PIT-101   15  PITTSBURGH
 39.49     82.56    1   LCK-102   16  COLUMBUS
 40.49     82.30    1   MFD-103   17  MANSFIELD
 40.58     85.11    1   FWA-104   18  FORT WAYNE
 40.38     86.09    1   GUS-105   19  GRISSOM
 39.27     87.18    1   HUF-106   20  TERRE HAUTE
 40.29     88.55    1   BMI-107   21  BLOOMINGTON IL
 39.09     86.37    1   BMG-108   22  BLOOMINGTON IN
 39.06     84.25    1   LUK-109   23  CINCINATI
 39.38     79.54    2   MGW-142   24,25 MORGANTOWN
```

FFO output file:

```
 ARCS IN THE SOLUTION
    9  8
    9  5
    6  5
    7  6
   10  8
   21  7
   24 15
   11  2
   22 20
   15 14
   19  2
   12 11
   17 14
   22  3
   20 19
   13 12
   23  3
   18 13
   24  4
   25 16
    4  1
   10  1
   16  1
   17  1
   18  1
   21  1
   23  1
   25  1
 THE TOTAL COST=
     7529
```

Cost explanation:
-Run made over 2 weeks
-28 arcs in solution

Weekly milage =

$$\frac{7529-(28*150)}{2} = 1665$$

LRF data file (11 depot):

Frequency based on 2 week rate.

```
 34.54     92.08    1    LRF/C-20  1    LITTLE ROCK
 35.02     89.58    1    MEM/C-21  2    MEMPHIS
 32.30     93.40    2    BAD-63    3,4  BARKSDALE
 31.19     92.32    1    AEX-70    5    ENGLAND
 35.20     94.22    1    FSM-71    6    FT SMITH
 34.29     93.06    1    HOT-72    7    HOT SPRINGS
 35.58     89.57    2    BYH-93    8,9  BLYTHEVILLE
```

LRF output file:

```
ARCS IN THE SOLUTION
   5  3
   8  2
   6  3
   7  4                                 Cost explanation:
   5  2                                 -run made over 2 weeks
   9  4                                 -10 arcs in soluton
   6  1
   7  1                                 Weekly cost=
   8  1
   9  1                                 3099-(10*15) =    800
 THE TOTAL COST=                             2
   3099
------------------------------------
```

NIP data file (11 depot):

Frequency based on 2 week rate.

```
 30.14     81.41    1    NIP/C-12 1      JACKSONVILLE
 29.50     90.01    1    NBG/C-27 2      NEW ORLEANS
 27.50     82.31    2    MCF/C-28 3,4    MACDILL
 25.29     80.23    2    HST/C-29 5,6    HOMESTEAD
 33.54     84.31    2    NCQ/C-30 7,8    DOBBINS
 32.19     90.05    1    JAN-69   9      JACKSON
 36.40     87.29    1    HOP-110  10     FT CAMPBELL
 35.24     86.05    1    TUH-111  11     TULLAHOMA
 34.40     86.41    4    HUA-137  12-15  HUNTSVILLE
 33.39     88.27    2    CBM-150  16,17  COLUMBUS
 33.33     86.45    2    BHM-151  18,19  BIRMINGHAM
 33.35     85.51    2    ANB-152  20,21  ANNISTON
 32.38     83.35    2    WRB-155  22,23  ROBINS
 32.20     84.59    2    LSF-156  24,25  LAWSON
 32.22     86.21    2    MXF-157  26,27  MAXWELL
 32.20     88.44    2    MEI-158  28,29  MERIDIAN
 31.16     85.42    2    OZR-159  30,31  FT RUCKER
 31.32     84.12    2    ABY-160  32,33  ALBANY
 24.35     81.41    2    NOX-161  34,35  KEY WEST
 26.41     80.06    2    PBI-162  36,37  PALM BEACH
 28.14     80.36    2    COF-163  38,39  PATRICK
 28.25     81.19    2    MCO-164  40,41  ORLANDO
 30.24     88.55    2    BIX-165  42,43  KEESLER
 30.21     87.19    2    NPA-166  44,45  PENSACOLA
```

```
30.29    86.31    2    VPS-167   46,47 EGLIN
30.04    85.34    2    PAM-168   48,49 TYNDALL
30.58    83.11    1    VAD-169   50    MOODY
30.23    84.21    1    TLH-170   51    TALLAHASSEE
```

NIP output file:

```
ARCS IN THE SOLUTION
 28  9
 11 10
 42  2
 16  9
 12 10
 29 17
 16 12
 17 13
 29  2
 18 13
 19 14
 44 42
 45 43
 20 14
 21 15
 26 19
 15  7
 46 43
 27 21
 20  8
 36  5
 37  6
 45 27
 30 26
 47 30
 48 47
 31 24
 22  8
 49 31
 24 23
 32 25
 51 49
 38 36
 39 37
  5  3
  6  4
 33 23
 40 38
 41 39
 50 32
 25  3
  4  1
  7  1
 11  1
 18  1
```

```
 22  1
 28  1
 33  1
 34  1 TWICE
 35  1 TWICE
 40  1
 41  1
 44  1
 46  1
 48  1
 50  1
 51  1
THE TOTAL COST=
 16100
--------------------------------------
```

Cost explanation:
-Run over 2 week period
-59 arcs in solution

Weekly milage=

$$\frac{16100-(59*150)}{2} = 3625$$

NZW data file (11 depots):

Frequency based on weekly rate.

```
 42.09    70.56    1   NZW/C-9  1  BOSTON
 41.35    71.25    1   OQW-114  2  QUONSET STATE
 41.04    73.42    1   HPN-115  3  WHITE PLAINS
 42.45    73.48    1   ALB-118  4  ALBANY
 42.11    72.31    1   CEF-119  5  WESTOVER
 40.44    73.25    1   FRG-120  6  FARMINGTON
 41.30    74.06    1   SWF-121  7  STEWART
 41.16    72.53    1   HVN-125  8  NEW HAVEN
 41.19    72.02    1   GON-126  9  GROTON
 41.56    72.41    1   BDL-127  10 BRADLEY
 42.56    71.26    1   MHT-130  11 MANCHESTER
 43.04    70.49    1   PSM-131  12 PEASE
 43.53    69.56    1   NHZ-132  13 BRUNSWICK
 44.48    68.50    1   BGR-133  14 BANGOR
 46.57    67.53    1   LIZ-134  15 LORING
 41.40    70.31    1   FMH-135  16 OTIS
```

NZW output file:

```
 ARCS IN THE SOLUTION
  15 14
   6  3
   7  3
  15 13
   7  4
   8  6
  10  4
   9  8
  10  5
  13 12
   9  2
  12 11
  16  2
```

```
   5  1                              Cost explanation:
  11  1                              -Runs made over 1 week
  14  1                              -17 arcs in solution
  16  1
 THE TOTAL COST=                     Weekly milage =
   3852                              3852-(17*150) = 1302
------------------------------------
```

RME data file (11 depot):

Frequency based on weekly rate.

```
 43.14    75.24   1   RME/C-26 1  GRIFFIS
 43.07    76.06   1   SYR-116  2  SYRACUSE
 44.03    75.44   1   GTB-117  3  WHEELER SACK
 42.12    75.59   1   BGM-122  4  BINGHAMTON
 42.56    78.44   1   BUF-123  5  BUFFALO
 43.07    77.40   1   ROC-124  6  ROCHESTER
 44.39    73.28   1   PBG-128  7  PLATTSBURGH
 44.28    73.09   1   BTV-129  8  BURLINGTON
 41.20    75.43   1   AVP-145  9  WILKES-BARRE
```

RME output file:

```
 ARCS IN THE SOLUTION
   8  7
   6  5
   9  4                          Cost explanation:
   9  5                          -Runs made over one week
   7  3                          -9 arcs in solution
   6  3
   4  2                          Weekly milage=
   2  1                          2149-(9*150) =  799
   8  1
 THE TOTAL COST=
   2149
```

----

11 Depot summary:

Depot	Weekly Milage
SKF	1751
CHS	487
BWI	3638
SUU	4504
NZY	1148
OFF	4351
FFO	1665
LRF	800
NIP	3625
NZW	1302
RME	799

TOTAL = 24070

YEARLY TOTAL
1,251,640

10 Depot Model

```
MSF:

BEST WEIGHT=      294024
DEPOTS=
    1    2    3    7    8    9   11   12   20   26
EMINATING NODES ON TOP
INCIDENT NODES BELOW
   26    9    1    1    9  114  126  125  115  115
  116  135   31   34  114  126  125  115  120  121

  125  127   11    8   34   32   35   26    8    9
  127  119  153  109   32   35   33  117  102  130

  130   20  116  122    3  153    3  143  131  102
  131   72  122  145  139  154  143  146  132  103

  103  103   99  139  176  136  146  176  138  119
  100   99   98  176  136   10  144  138  140  118

   11    2   67   99  104  116  124  132   11   32
  148   67   66  104  105  124  123  133  147   36

  140  141  180  181  181  177  172  180  179  173
  141  180  181  178  177  172  171  179  173  174

  174  174   98   72    7   87  109   25  108  153
  175  112   97   71   87   86   25  108  106  149

   12  169  160  156  160  170  168  167  167  157
  169  160  156  157  170  168  167  166  159  151

  151  151  137  152  160  166  165  151  150  158
  152  137  111   30  155  165   27  150  158   69

   31   38  100  101  106  107   83   82  141   33*
   38   39  101  142  107   83   82   81  113   52*

   52   50   51   51   49   48   45   45  111   66
   50   51   47   49   48   45   46    5  110   18

   18   78   62   62  117  128   20   21  107   24
   78   62   68   19  128  129   21   93   24   96

   12  164  164  163  162   29    7   88   88   90
  164  163   28  162   29  161   88   90   91   94

   91   89   94   92   95    2   78   65   49   72
   89   22   92   95   23   77   65   64   14   63

   63   46   15   68   80   76   82   84  133   67
   70   15   75   80   76   79   84   85  134   73
```

```
76   16   74   38   39   44   44   58   58   60
16   74   17   37   44   43   58   13   60   57

43   42   40   42   86   56   56   55   54   53
42   40    4   41   56   61   55   54   53    6

54
59
```

* Note the asterisked entry; it is the only link that is different from the 11 depot model. The consequence is the joining of the NZY tree to the SUU tree.

New SUU CW.

Data file:

Frequency based on 2 week rate.

```
38.15   121.55   1   SUU/F-1   1      TRAVIS
38.40   121.23   2   MCC-31    2,3    MCCLELLAN
37.17   120.31   2   MCE-32    4,5    MERCED
36.20   119.57   2   NLC-33    6,7    LEMOORE
37.53   121.14   2   SCK-34    8,9    STOCKTON
36.46   119.43   2   FAT-35    10,11  FRESNO
36.35   121.50   2   MRY-36    12,13  MONTERRY
42.09   121.44   1   LMT-37    14     KLAMATH FALLS
39.29   119.46   1   RNO-38    15     RENO
39.24   118.41   1   NFL-39    16     FALLON
40.47   111.58   2   SLC/C-13  17,18  SALT LAKE CITY
47.08   122.28   2   TCM/C-4   19,20  MCCHORD
46.34   120.32   2   YKM-40    21,22  YAKIMA
47.37   117.31   2   GEG-41    23,24  SPOKANE
46.15   119.06   1   PSC-42    25     PASCO
43.33   116.13   1   BOI-43    26     BOISE
43.02   115.52   1   MUO-44    27     MT HOME
47.30   111.11   2   GFA-57    28,29  MALMSTROM
43.31   112.04   1   IDA-58    30     IDAHO FALLS
46.36   111.59   1   HLN-60    31     HELENA
32.41   117.12   2   NZY/C-5   32,33  NORTH ISLAND
36.14   115.02   1   LSV/C-14  34     LAS VEGAS
33.32   112.23   1   LUF/C-15  35     LUKE
32.50   115.40   1   NJK-45    36     EL CENTRO
32.39   114.36   1   NYL-46    37     YUMA
35.41   117.41   1   NID-47    38     CHINA LAKE
34.17   116.10   1   NXP-48    39     29 PALMS
34.51   116.47   1   DAG-49    40     DAGGETT
34.12   119.12   1   OXR-50    41     OXNARD
34.54   117.52   1   EDW-52    42     EDWARDS
34.43   120.34   2   VBG-51    43,44  VANDENBERG
32.09   110.52   1   DMA-75    45     DAVIS-MONTHAN
```

New SUU output file:

```
 ARCS IN THE SOLUTION
  31 28
  45 35
  28 23
  29 24
  30 29
  25 23
  45 37
  21 19
  22 20
  37 36
  27 26
  36 32
  39 33
  27 17
  40 39
  40 34
  42 33
  42 38
  21 18
  20 14
  43 41
  17 16
  44 38
  41  6
  10  6
  11  7
  26 15
  43 12
  10  4
  11  5
  13  7
   8  4
   9  5
  15  2
  22  3
   2  1
   3  1
   8  1
   9  1
  12  1
  13  1
  14  1
  16  1
  18  1
  19  1
  24  1
  25  1
  30  1
  31  1
```

```
 32  1
 34  1
 35  1
 44  1
THE TOTAL COST=
 20187
```

Cost explanation:
-Runs over 2 weeks
-53 arcs in solution

Weekly milage=

$$\frac{20187-(53*150)}{2} = 6119$$

----

10 Depot summary:

11 depot weekly miles	24070	
minus old SUU and NZY	-4504	
	-1148	
plus new SUU	+6119	Yearly milage:
new weekly milage	24537	1,275,924

9 Depot Model

```
MSF:

BEST WEIGHT=      309987
DEPOTS=
    1    2    3    7    8    9   11   12   26
EMINATING NODES ON TOP
INCIDENT NODES BELOW
   26    9    1    1    9  114  126  125  115  115
  116  135   31   34  114  126  125  115  120  121

  125  127   11    8   34   32   35   26    8    9
  127  119  153  109   32   35   33  117  102  130

  130  116  122    3  153    3  143  131  102  103
  131  122  145  139  154  143  146  132  103  100

  103   99  139  176  136  146  176  138  119   11
   99   98  176  136   10  144  138  140  118  148

    2   67   99  104  116  124  132   11   32  140
   67   66  104  105  124  123  133  147   36  141

  141  180  181  181  177  172  180  179  173  174
  180  181  178  177  172  171  179  173  174  175

  174   98    7   87  109   25  108  153   12  169
  112   97   87   86   25  108  106  149  169  160

  160  156  160  170  168  167  167  157  151  151
  156  157  170  168  167  166  159  151  152  137

  137  152  160  166  165  151  150  158   31   38
  111   30  155  165   27  150  158   69   38   39

  100  101  106  107   83   82  141   33   52   50
  101  142  107   83   82   81  113   52   50   51

   51   51   49   48   45   45  111   66   18   78
   47   49   48   45   46    5  110   18   78   62

   62   62  117  128  107   24   12  164  164  163
   68   19  128  129   24   96  164  163   28  162

  162   29  150*   21   21   20   72    7   88   88
   29  161   21*   93   20   72   71   88   90   91

   90   91   89   94   92   95    2   78   65   49
   94   89   22   92   95   23   77   65   64   14

   72   63   46   15   68   80   76   82   84  133
   63   70   15   75   80   76   79   84   85  134
```

```
67   76   16   74   38   39   44   44   58   58
73   16   74   17   37   44   43   58   13   60

60   43   42   40   42   86   56   56   55   54
57   42   40    4   41   56   61   55   54   53

53   54
 6   59
```

* Asterisk indicates the link which combines LRF stations into NIP. The only new route structure which requires CW computation is NIP.

New NIP CW:

Data file:

Frequency based on 2 week rate.

```
 30.14     81.41    1   NIP/C-12 1      JACKSONVILLE
 29.50     90.01    1   NBG/C-27 2      NEW ORLEANS
 27.50     82.31    2   MCF/C-28 3,4    MACDILL
 25.29     80.23    2   HST/C-29 5,6    HOMESTEAD
 33.54     84.31    2   NCQ/C-30 7,8    DOBBINS
 32.19     90.05    1   JAN-69   9      JACKSON
 36.40     87.29    1   HOP-110  10     FT CAMPBELL
 35.24     86.05    1   TUH-111  11     TULLAHOMA
 34.40     86.41    4   HUA-137  12-15  HUNTSVILLE
 33.39     88.27    2   CBM-150  16,17  COLUMBUS
 33.33     86.45    2   BHM-151  18,19  BIRMINGHAM
 33.35     85.51    2   ANB-152  20,21  ANNISTON
 32.38     83.35    2   WRB-155  22,23  ROBINS
 32.20     84.59    2   LSF-156  24,25  LAWSON
 32.22     86.21    2   MXF-157  26,27  MAXWELL
 32.20     88.44    2   MEI-158  28,29  MERIDIAN
 31.16     85.42    2   OZR-159  30,31  FT RUCKER
 31.32     84.12    2   ABY-160  32,33  ALBANY
 24.35     81.41    2   NOX-161  34,35  KEY WEST
 26.41     80.06    2   PBI-162  36,37  PALM BEACH
 28.14     80.36    2   COF-163  38,39  PATRICK
 28.25     81.19    2   MCO-164  40,41  ORLANDO
 30.24     88.55    2   BIX-165  42,43  KEESLER
 30.21     87.19    2   NPA-166  44,45  PENSACOLA
 30.29     86.31    2   VPS-167  46,47  EGLIN
 30.04     85.34    2   PAM-168  48,49  TYNDALL
 30.58     83.11    1   VAD-169  50     MOODY
 30.23     84.21    1   TLH-170  51     TALLAHASSEE
 34.54     92.08    1   LRF/C-20 52     LITTLE ROCK
 35.02     89.58    1   MEM/C-21 53     MEMPHIS
 32.30     93.40    2   BAD-63   54,55  BARKSDALE
 31.19     92.32    1   AEX-70   56     ENGLAND
 35.20     94.22    1   FSM-71   57     FT SMITH
```

```
 34.29     93.06    1    HOT-72    58     HOT SPRINGS
 35.58     89.57    2    BYH-93    59,60  BLYTHEVILLE
```

New NIP output file:

```
 ARCS IN THE SOLUTION
  58 57
  57 52
  58 54
  56 55
  59 53
  55 53
  60 10
  60 16
  28  9
  11 10
  42  2
  16  9
  29 17
  17 12
  29  2
  18 12
  19 13
  44 42
  45 43
  20 13
  21 14
  26 19
  14  7
  15  8
  46 43
  27 15
  36  5
  37  6
  45 26
  24 21
  30 27
  47 30
  48 47
  25  8
  31 24
  22  7
  49 31
  25 23
  51 49
  38 36
  39 37
   5  3
   6  4
  32 22
  40 38
  41 39
  50 33
```

```
 33  3
  4  1
 11  1
 18  1
 20  1
 23  1
 28  1
 32  1
 34  1 TWICE
 35  1 TWICE
 40  1
 41  1
 44  1
 46  1
 48  1
 50  1
 51  1
 52  1
 54  1
 56  1
 59  1
THE TOTAL COST=
 21521
---------------------------------
```

Cost explanation:
-Runs over 2 weeks
-70 arcs in solution

Weekly milage =

$$\frac{21521-(70*150)}{2} = 5510$$

9 Depot Summary:

10 depot weekly miles	24537	
minus old NIP and LRF	-3625	
	- 800	
plus new NIP	+5510	Yearly milage
new weekly milage	25622	1,332,344

8 Depot Model

```
MSF:

BEST WEIGHT=      332287
DEPOTS=
    1    2    3    7    8    9   12   26
EMINATING NODES ON TOP
INCIDENT NODES BELOW
   26    9    1    1    9  114  126  125  115  115
  116  135   31   34  114  126  125  115  120  121

  125  127    8   34   32   35   26    8    9  130
  127  119  109   32   35   33  117  102  130  131

  116  122    3    3  143  131  102  103  103   99
  122  145  139  143  146  132  103  100   99   98

  139  176  136  146  176  138  119    2   67   99
  176  136   10  144  138  140  118   67   66  104

  104  116  124  132   32  140  141  180  181  181
  105  124  123  133   36  141  180  181  178  177

  177  172  180  179  173  174  174   98  179* 148
  172  171  179  173  174  175  112   97  148*  11

   11  153   11    7   87  109   25  108  148   12
  153  154  147   87   86   25  108  106  149  169

  169  160  156  160  170  168  167  167  157  151
  160  156  157  170  168  167  166  159  151  152

  151  137  152  160  166  165  151  150  158   31
  137  111   30  155  165   27  150  158   69   38

   38  100  101  106  107   83   82  141   33   52
   39  101  142  107   83   82   81  113   52   50

   50   51   51   49   48   45   45  111   66   18
   51   47   49   48   45   46    5  110   18   78

   78   62   62  117  128  107   24   12  164  164
   62   68   19  128  129   24   96  164  163   28

  163  162   29  150   21   21   20   72    7   88
  162   29  161   21   93   20   72   71   88   90

   88   90   91   89   94   92   95    2   78   65
   91   94   89   22   92   95   23   77   65   64

   49   72   63   46   15   68   80   76   82   84
   14   63   70   15   75   80   76   79   84   85
```

```
133   67   76   16   74   38   39   44   44   58
134   73   16   74   17   37   44   43   58   13

 58   60   43   42   40   42   86   56   56   55
 60   57   42   40    4   41   56   61   55   54

 54   53   54
 53    6   59
```

*Asterisk denotes new link from 9 depot MSF. This link combines CHS into BWI; BWI routes require altering.

New BWI CW:

Data file:

Frequency based on 2 week rate.

```
 39.11    76.40   1   BWI/F-3  1      BALTIMORE
 36.56    76.17   2   NGU/C-10 2,3    NORFOLK
 35.49    84.00   1   TYS-112  4      KNOXVILLE
 38.22    81.36   1   CUW-113  5      CHARLESTON WV
 37.05    76.21  12   LFI-136  6-17   LANGLEY
 38.08    78.27   2   CHO-138  18,19  CHARLOTTESVILLE
 38.17    76.24   2   NHK-139  20,21  PAX RIVER
 38.15    78.53   2   SHD-140  22,23  SHENENDOAH
 37.19    79.58   2   ROA-141  24,25  ROANOKE
 39.42    77.43   2   HGR-143  26,27  HAGERSTOWN
 40.51    77.51   2   UNV-144  28,29  STATE COLLEGE
 40.11    76.45   2   MDT-146  30,31  HARRISBURG
 34.54    76.53   2   NKT-171  32,33  CHERRY POINT
 34.43    77.26   2   NCA-172  34,35  JACKSONVILLE
 34.54    82.13   2   GSP-173  36,37  GREENSVILLE
 35.26    82.32   2   AVL-174  38,39  ASHEVILLE
 36.29    82.25   2   TRI-175  40,41  BRISTOL
 37.31    77.19   2   RIC-176  42,43  RICHMOND
 35.20    77.58   2   GSB-177  44,45  GOLDSBORO
 35.10    79.01   2   POB-178  46,47  POPE
 35.13    80.56   2   CLT-179  48,49  CHARLOTTE
 36.06    79.56   2   GSO-180  50,51  GREENSBORO
 35.53    78.47   2   RDU-181  52,53  RALIEGH
 32.53    80.02   2   CHS/C-11 54,55  CHARLESTON
 33.40    78.55   2   MYR-147  56,57  MYRTLE BEACH
 33.57    80.28   2   SSC-148  58,59  SHAW
 33.22    81.58   2   AGS-149  60,61  FT GORDON
 32.28    80.43   2   NBC-153  62,63  BEAUFORT
 31.53    81.34   2   LHW-154  64,65  FT STEWART
```

New BWI output file:

```
ARCS IN THE SOLUTION
 64 62
```

```
65 63
64 60
65 61
62 54
63 55
60 58
61 59
38 36
39 37
38  4
56 54
57 55
40  4
48 36
49 37
41 39
58 46
59 47
56 34
57 35
50 48
51 49
44 32
45 33
40  5
52 44
53 45
52 51
50 24
53 25
33  2
 6  2
 7  3
24 22
25 23
23 18
42  3
43  6
42 19
20  7
21  8
30 28
31 29
28 26
29 27
26 19
27  8
 5  1
 9  1 TWICE
10  1 TWICE
11  1 TWICE
12  1 TWICE
13  1 TWICE
```

```
 14  1 TWICE
 15  1 TWICE
 16  1 TWICE
 17  1 TWICE
 18  1
 20  1
 21  1
 22  1
 30  1
 31  1
 32  1
 34  1
 35  1
 41  1
 43  1
 46  1
 47  1
THE TOTAL COST=
 21330
```

Cost explanation:
-Runs made over 2 weeks
-80 arcs in solution

Weekly cost =
$$\frac{21330-(80*150)}{2} = 4665$$

----

8 Depot summary

9 depot weekly milage	25622	
minus old CHS and BWI	- 487	
	-3638	
plus new BWI	+4665	Yearly milage:
new weekly milage	26162	1,360,424

7 Depot Model

```
MSF:

BEST WEIGHT=      358419
DEPOTS=
    1    2    3    7    8    9   12
EMINATING NODES ON TOP
INCIDENT NODES BELOW
    9    1    1    9  114  126  125  115  115  125
  135   31   34  114  126  125  115  120  121  127

  127    8   34   32   35    8    9  130    3    3
  119  109   32   35   33  102  130  131  139  143

  143  131  102  103  103   99  139  176  136  146
  146  132  103  100   99   98  176  136   10  144

  176  138  119    2   67   99  104  132  121* 145
  138  140  118   67   66  104  105  133  145* 122

  122  116   26  116  124   32  140  141  180  181
  116   26  117  124  123   36  141  180  181  178

  181  177  172  180  179  173  174  174   98  179
  177  172  171  179  173  174  175  112   97  148

  148   11  153   11    7   87  109   25  108  148
   11  153  154  147   87   86   25  108  106  149

   12  169  160  156  160  170  168  167  167  157
  169  160  156  157  170  168  167  166  159  151

  151  151  137  152  160  166  165  151  150  158
  152  137  111   30  155  165   27  150  158   69

   31   38  100  101  106  107   83   82  141   33
   38   39  101  142  107   83   82   81  113   52

   52   50   51   51   49   48   45   45  111   66
   50   51   47   49   48   45   46    5  110   18

   18   78   62   62  117  128  107   24   12  164
   78   62   68   19  128  129   24   96  164  163

  164  163  162   29  150   21   21   20   72    7
   28  162   29  161   21   93   20   72   71   88

   88   88   90   91   89   94   92   95    2   78
   90   91   94   89   22   92   95   23   77   65

   65   49   72   63   46   15   68   80   76   82
   64   14   63   70   15   75   80   76   79   84
```

```
 84  133   67   76   16   74   38   39   44   44
 85  134   73   16   74   17   37   44   43   58

 58   58   60   43   42   40   42   86   56   56
 13   60   57   42   40    4   41   56   61   55

 55   54   53   54
 54   53    6   59
```

* New link joins RME locations into NZW route system. New NZW route system required.

New NZW CW:

Data set:

Frequency based on weekly rate.

```
 42.09     70.56    1    NZW/C-9   1  SOUTH WEYMOUTH
 41.35     71.25    1    OQW-114   2  QUONSET STATE
 41.04     73.42    1    HPN-115   3  WHITE PLAINS
 42.45     73.48    1    ALB-118   4  ALBANY
 42.11     72.31    1    CEF-119   5  WESTOVER
 40.44     73.25    1    FRG-120   6  FARMINGTON
 41.30     74.06    1    SWF-121   7  STEWART
 41.16     72.53    1    HVN-125   8  NEW HAVEN
 41.19     72.02    1    GON-126   9  GROTON
 41.56     72.41    1    BDL-127   10 BRADLEY
 42.56     71.26    1    MHT-130   11 MANCHESTER
 43.04     70.49    1    PSM-131   12 PEASE
 43.53     69.56    1    NHZ-132   13 BRUNSWICK
 44.48     68.50    1    BGR-133   14 BANGOR
 46.57     67.53    1    LIZ-134   15 LORING
 41.40     70.31    1    FMH-135   16 OTIS
 43.14     75.24    1    RME/C-26  17 GRIFFIS
 43.07     76.06    1    SYR-116   18 SYRACUSE
 44.03     75.44    1    GTB-117   19 WHEELER SACK
 42.12     75.59    1    BGM-122   20 BINGHAMTON
 42.56     78.44    1    BUF-123   21 BUFFALO
 43.07     77.40    1    ROC-124   22 ROCHESTER
 44.39     73.28    1    PBG-128   23 PLATTSBURGH
 44.28     73.09    1    BTV-129   24 BURLINGTON
 41.20     75.43    1    AVP-145   25 WILKES-BARRE
```

New NZW output file:

```
 ARCS IN THE SOLUTION
  22 21
  21 18
  22 19
  18 17
  25 20
```

```
  15 14
  20 17
  24 23
  23 19
   6  3
   7  3
  15 13
   7  4
   8  6
  10  4
   9  8
  10  5
  13 12
   9  2
  12 11
  16  2
   5  1
  11  1
  14  1
  16  1
  24  1
  25  1
 THE TOTAL COST=
    6415
```

Cost explanation:
-Runs made over 1 week
-27 arcs in solution

Weekly milage =

6415-(27*150) = 2365

----

7 Depot summary

8 depot weekly milage	26162	
minus old RME and NZW	- 799	
	-1302	
plus new NZW	+2365	Yearly milage:
new weekly milage	26426	1,374,152

6 Depot Model

```
MSF:

BEST WEIGHT=       387217
DEPOTS=
     1     2     3     7     8    12
EMINATING NODES ON TOP
INCIDENT NODES BELOW
     1     1     8    34    32    35     8     3     3   143
    31    34   109    32    35    33   102   139   143   146

   102   103   103    99   139   176   136   146   176   138
   103   100    99    98   176   136    10   144   138   140

     2    67    99   104    32   140   141   180   181   181
    67    66   104   105    36   141   180   181   178   177

   177   172   180   179   173   174   174    98   179   148
   172   171   179   173   174   175   112    97   148    11

    11   153    11     7    87   109    25   108   148   146*
   153   154   147    87    86    25   108   106   149   145*

   145   122   116    26   116   124   145   121   115   115
   122   116    26   117   124   123   121   115   120   125

   125   126   114     9   125   127     9   130   131   119
   126   114     9   135   127   119   130   131   132   118

   132    12   169   160   156   160   170   168   167   167
   133   169   160   156   157   170   168   167   166   159

   157   151   151   137   152   160   166   165   151   150
   151   152   137   111    30   155   165    27   150   158

   158    31    38   100   101   106   107    83    82   141
    69    38    39   101   142   107    83    82    81   113

    33    52    50    51    51    49    48    45    45   111
    52    50    51    47    49    48    45    46     5   110

    66    18    78    62    62   117   128   107    24    12
    18    78    62    68    19   128   129    24    96   164

   164   164   163   162    29   150    21    21    20    72
   163    28   162    29   161    21    93    20    72    71

     7    88    88    90    91    89    94    92    95     2
    88    90    91    94    89    22    92    95    23    77

    78    65    49    72    63    46    15    68    80    76
    65    64    14    63    70    15    75    80    76    79
```

82	84	133	67	76	16	74	38	39	44
84	85	134	73	16	74	17	37	44	43

44	58	58	60	43	42	40	42	86	56
58	13	60	57	42	40	4	41	56	61

56	55	54	53	54
55	54	53	6	59

*New link from 7 depot MSF. Depot at NZW is eliminated; depot at BWI enlarges.

New BWI CW:

Data set.

Frequency based on 2 week rate.

39.11	76.40	1	BWI/F-3	1	BALTIMORE
36.56	76.17	2	NGU/C-10	2,3	NORFOLK
35.49	84.00	1	TYS-112	4	KNOXVILLE
38.22	81.36	1	CUW-113	5	CHARLESTON WV
37.05	76.21	12	LFI-136	6-17	LANGLEY
38.08	78.27	2	CHO-138	18,19	CHARLOTTESVILLE
38.17	76.24	2	NHK-139	20,21	PAX RIVER
38.15	78.53	2	SHD-140	22,23	SHENENDOAH
37.19	79.58	2	ROA-141	24,25	ROANOKE
39.42	77.43	2	HGR-143	26,27	HAGERSTOWN
40.51	77.51	2	UNV-144	28,29	STATE COLLEGE
40.11	76.45	2	MDT-146	30,31	HARRISBURG
34.54	76.53	2	NKT-171	[illegible],33	CHERRY POINT
34.43	77.26	2	NCA-172	34,35	JACKSONVILLE
34.54	82.13	2	GSP-173	36,37	GREENSVILLE
35.26	82.32	2	AVL-174	38,39	ASHEVILLE
36.29	82.25	2	TRI-175	40,41	BRISTOL
37.31	77.19	2	RIC-176	42,43	RICHMOND
35.20	77.58	2	GSB-177	44,45	GOLDSBORO
35.10	79.01	2	POB-178	46,47	POPE
35.13	80.56	2	CLT-179	48,49	CHARLOTTE
36.06	79.56	2	GSO-180	50,51	GREENSBORO
35.53	78.47	2	RDU-181	52,53	RALIEGH
32.53	80.02	2	CHS/C-11	54,55	CHARLESTON
33.40	78.55	2	MYR-147	56,57	MYRTLE BEACH
33.57	80.28	2	SSC-148	58,59	SHAW
33.22	81.58	2	AGS-149	60,61	FT GORDON
32.28	80.43	2	NBC-153	62,63	BEAUFORT
31.53	81.34	2	LHW-154	64,65	FT STEWART
42.09	70.56	2	NZW/C-9	66,67	SOUTH WEYMOUTH
41.35	71.25	2	OQW-114	68,69	QUONSET STATE
41.04	73.42	2	HPN-115	70,71	WHITE PLAINS
42.45	73.48	2	ALB-118	72,73	ALBANY
42.11	72.31	2	CEF-119	74,75	WESTOVER

```
 40.44     73.25    2    FRG-120  76,77  FARMINGTON
 41.30     74.06    2    SWF-121  78,79  STEWART
 41.16     72.53    2    HVN-125  80,81  NEW HAVEN
 41.19     72.02    2    GON-126  82,83  GROTON
 41.56     72.41    2    BDL-127  84,85  BRADLEY
 42.56     71.26    2    MHT-130  86,87  MANCHESTER
 43.04     70.49    2    PSM-131  88,89  PEASE
 43.53     69.56    2    NHZ-132  90,91  BRUNSWICK
 44.48     68.50    2    BGR-133  92,93  BANGOR
 46.57     67.53    2    LIZ-134  94,95  LORING
 41.40     70.31    2    FMH-135  96,97  OTIS
 43.14     75.24    2    RME/C-26 98,99  GRIFFIS
 43.07     76.06    2    SYR-116  100,101  SYRACUSE
 44.03     75.44    2    GTB-117  102,103  WHEELER SACK
 42.12     75.59    2    BGM-122  104,105  BINGHAMTON
 42.56     78.44    2    BUF-123  106,1C7  BUFFALO
 43.07     77.40    2    ROC-124  108,109  ROCHESTER
 44.39     73.28    2    PBG-128  110,111  PLATTSBURGH
 44.28     73.09    2    BTV-129  112,113  BURLINGTON
 41.20     75.43    2    AVP-145  114,115  WILKES-BARRE
```

New BWI output file:

```
ARCS IN THE SOLUTION
  94 92
  95 93
  64 62
  65 63
  64 60
  65 61
  92 90
  93 91
  62 54
  63 55
  60 58
  61 59
  90 88
  91 89
  38 36
  39 37
 112110
 113111
 112 94
 113 95
  38  4
  56 54
  57 55
  40  4
  48 36
  49 37
  41 39
  96 66
```

```
 97 67
 86 66
 87 67
 96 68
 97 69
 58 46
 59 47
 56 34
 57 35
 86 74
 87 75
 82 68
 83 69
102 98
103 99
 84 74
 85 75
 50 48
 51 49
102100
103101
 44 32
 45 33
108106
109107
 40  5
 84 72
 85 73
 82 80
 83 81
 52 44
 53 45
 52 51
108 98
109 99
104100
105101
 50 24
 78 72
 79 73
 76 70
 77 71
 53 25
 33  2
114104
115105
  6  2
  7  3
 24 22
 25 23
106 28
107 29
 23 18
```

```
 42  3
 43  6
 42 19
114 30
115 31
 20  7
 21  8
 28 26
 29 27
 76  8
 77  9
  5  1
  9  1
 10  1 TWICE
 11  1 TWICE
 12  1 TWICE
 13  1 TWICE
 14  1 TWICE
 15  1 TWICE
 16  1 TWICE
 17  1 TWICE
 18  1
 19  1
 20  1
 21  1
 22  1
 26  1
 27  1
 30  1
 31  1
 32  1
 34  1
 35  1
 41  1
 43  1
 46  1
 47  1
 70  1
 71  1
 78  1
 79  1
 80  1
 81  1
 88  1
 89  1
110  1
111  1
THE TOTAL COST=
 36542
-----------------------------------
6 Depot summary:
```

Cost explanation:
-Run made over 2 weeks
-136 arcs in solution

Weekly milage =

$$\frac{36542-(136*150)}{2} = 8071$$

7 depot weekly milage	26426	
minus old NZW and BWI	-2365	
	-4665	
plus new BWI	+8071	Yearly milage:
6 depot weekly cost	27467	1,428,284

5 Depot Model

```
MSF:

BEST WEIGHT=       449824
DEPOTS=
    1    2    3    7   12
EMINATING NODES ON TOP
INCIDENT NODES BELOW
    1    1   34   32   35    3    3  143  139  176
   31   34   32   35   33  139  143  146  176  136

  136  146  176  138    2   67   32  140  141  180
   10  144  138  140   67   66   36  141  180  181

  181  181  177  172  180  179  173  174  174  179
  178  177  172  171  179  173  174  175  112  148

  148   11  153   11    7   87  148  146  145  122
   11  153  154  147   87   86  149  145  122  116

  116   26  116  124  145  121  115  115  125  126
   26  117  124  123  121  115  120  125  126  114

  114    9  125  127    9  130  131  119  132   12
    9  135  127  119  130  131  132  118  133  169

  169  160  156  160  170  168  167  167  157  151
  160  156  157  170  168  167  166  159  151  152

  151  137  152  160  166  165  151  150  158   31
  137  111   30  155  165   27  150  158   69   38

   38  140  142  101  100  103   99  103  102    8
   39  142  101  100  103   99   98  102    8  109

   99  104   98  109   25  108  106  107   83  141
  104  105   97   25  108  106  107   83   82  113

   33   52   50   51   51   49   48   45   45  111
   52   50   51   47   49   48   45   46    5  110

   66   18   78   62   62  117  128    7  107   24
   18   78   62   68   19  128  129   81   24   96

   12  164  164  163  162   29  150   21   21   20
  164  163   28  162   29  161   21   93   20   72

   72    7   88   88   90   91   89   94   92   95
   71   88   90   91   94   89   22   92   95   23

    2   78   65   49   72   63   46   15   68   80
   77   65   64   14   63   70   15   75   80   76
```

76	82	133	67	76	16	74	86	38	39
79	84	134	73	16	74	17	85	37	44

44	44	58	58	60	43	42	40	42	85
43	58	13	60	57	42	40	4	41	56

56	56	55	54	53	54
61	55	54	53	6	59

Note, there are numerous changes due to splitting of FFO service locations to both OFF and BWI. New CW computations are required for OFF and BWI.

New BWI CW:

Data set:

Frequency based on 2 week rate.

39.11	76.40	1	BWI/F-3	1	BALTIMORE
36.56	76.17	2	NGU/C-10	2,3	NORFOLK
35.49	84.00	1	TYS-112	4	KNOXVILLE
38.22	81.36	1	CUW-113	5	CHARLESTON WV
37.05	76.21	12	LFI-136	6-17	LANGLEY
38.08	78.27	2	CHO-138	18,19	CHARLOTTESVILLE
38.17	76.24	2	NHK-139	20,21	PAX RIVER
38.15	78.53	2	SHD-140	22,23	SHENENDOAH
37.19	79.58	2	ROA-141	24,25	ROANOKE
39.42	77.43	2	HGR-143	26,27	HAGERSTOWN
40.51	77.51	2	UNV-144	28,29	STATE COLLEGE
40.11	76.45	2	MDT-146	30,31	HARRISBURG
34.54	76.53	2	NKT-171	32,33	CHERRY POINT
34.43	77.26	2	NCA-172	34,35	JACKSONVILLE
34.54	82.13	2	GSP-173	36,37	GREENSVILLE
35.26	82.32	2	AVL-174	38,39	ASHEVILLE
36.29	82.25	2	TRI-175	40,41	BRISTOL
37.31	77.19	2	RIC-176	42,43	RICHMOND
35.20	77.58	2	GSB-177	44,45	GOLDSBORO
35.10	79.01	2	POB-178	46,47	POPE
35.13	80.56	2	CLT-179	48,49	CHARLOTTE
36.06	79.56	2	GSO-180	50,51	GREENSBORO
35.53	78.47	2	RDU-181	52,53	RALIEGH
32.53	80.02	2	CHS/C-11	54,55	CHARLESTON
33.40	78.55	2	MYR-147	56,57	MYRTLE BEACH
33.57	80.28	2	SSC-148	58,59	SHAW
33.22	81.58	2	AGS-149	60,61	FT GORDON
32.28	80.43	2	NBC-153	62,63	BEAUFORT
31.53	81.34	2	LHW-154	64,65	FT STEWART
42.09	70.56	2	NZW/C-9	66,67	SOUTH WEYMOUTH
41.35	71.25	2	OQW-114	68,69	QUONSET STATE
41.04	73.42	2	HPN-115	70,71	WHITE PLAINS
42.45	73.48	2	ALB-118	72,73	ALBANY

```
42.11    72.31   2   CEF-119   74,75   WESTOVER
40.44    73.25   2   FRG-120   76,77   FARMINGTON
41.30    74.06   2   SWF-121   78,79   STEWART
41.16    72.53   2   HVN-125   80,81   NEW HAVEN
41.19    72.02   2   GON-126   82,83   GROTON
41.56    72.41   2   BDL-127   84,85   BRADLEY
42.56    71.26   2   MHT-130   86,87   MANCHESTER
43.04    70.49   2   PSM-131   88,89   PEASE
43.53    69.56   2   NHZ-132   90,91   BRUNSWICK
44.48    68.50   2   BGR-133   92,93   BANGOR
46.57    67.53   2   LIZ-134   94,95   LORING
41.40    70.31   2   FMH-135   96,97   OTIS
43.14    75.24   2   RME/C-26  98,99   GRIFFIS
43.07    76.06   2   SYR-116   100,101  SYRACUSE
44.03    75.44   2   GTB-117   102,103  WHEELER SACK
42.12    75.59   2   BGM-122   104,105  BINGHAMTON
42.56    78.44   2   BUF-123   106,107  BUFFALO
43.07    77.40   2   ROC-124   108,109  ROCHESTER
44.39    73.28   2   PBG-128   110,111  PLATTSBURGH
44.28    73.09   2   BTV-129   112,113  BURLINGTON
41.20    75.43   2   AVP-145   114,115  WILKES-BARRE
39.50    84.03  12   FFO/C-8   116-127  WRIGHT-PATT
42.05    87.49   1   NBU/C-24  128      GLENVIEW
38.10    85.44   2   SDF/C-25  129,130  STANDIFORD
41.53    91.42   1   CID-82    131      CEDAR RAPIDS
41.26    90.30   1   MLI-83    132      MOLINE
43.57    90.44   1   CMY-84    133      FT MCCOY
42.18    85.14   1   BTL-97    134      BATTLE CREEK
41.35    83.48   1   TOL-98    135      TOLEDO
41.01    83.41   1   FDY-99    136      FINDLAY
41.25    81.51   1   CLE-100   137      CLEVELAND
40.29    80.14   1   PIT-101   138      PITTSBURGH
39.49    82.56   1   LCK-102   139      COLUMBUS
40.49    82.30   1   MFD-103   140      MANSFIELD
40.58    85.11   1   FWA-104   141      FORT WAYNE
40.38    86.09   1   GUS-105   142      GRISSOM
39.27    87.18   1   HUF-106   143      TERRE HAUTE
40.29    88.55   1   BMI-107   144      BLOOMINGTON IL
39.09    86.37   1   BMG-108   145      BLOOMINGTON IN
39.06    84.25   1   LUK-109   146      CINCINATI
39.38    79.54   2   MGW-142   147,148  MORGANTOWN
42.57    87.53   1   MKE-96    149      MILWAUKEE
```

New BWI output file:

```
ARCS IN THE SOLUTION
132131
133131
144132
149128
 94 92
 95 93
145143
```

```
 64 62
 65 63
143128
149134
 64 60
 65 61
 92 90
 93 91
145129
 62 54
 63 55
142141
142130
 60 58
 61 59
146130
 90 88
 91 89
 38 36
 39 37
112110
113111
112 94
113 95
141135
 38  4
 56 54
 57 55
136135
146116
 40  4
 48 36
 49 37
 41 39
 96 66
 97 67
 86 66
 87 67
 96 68
 97 69
140117
 58 46
 59 47
 56 34
 57 35
 86 74
 87 75
140139
 82 68
 83 69
102 98
103 99
 84 74
```

```
 85 75
 50 48
 51 49
137117
102100
103101
118 40
119 41
 44 32
 45 33
108106
109107
119  5
 84 72
 85 73
 82 80
 83 81
 52 44
 53 45
108 98
109 99
104100
105101
138137
 78 72
 79 73
 76 70
 77 71
 52 24
 53 25
147120
148121
120 24
121 25
122106
123107
 32  2
 33  3
  6  2
  7  3
 22  5
114 70
115 71
124 23
 23 18
138 28
 42  8
 43  9
125 19
124 29
114 29
 42 19
115 30
```

```
 20   8
 21   9
 31  28
139  26
125  27
126  43
127  10
127  30
  6   1
  7   1
 10   1
 11   1 TWICE
 12   1 TWICE
 13   1 TWICE
 14   1 TWICE
 15   1 TWICE
 16   1 TWICE
 17   1 TWICE
 18   1
 20   1
 21   1
 22   1
 26   1
 27   1
 31   1
 34   1
 35   1
 46   1
 47   1
 50   1
 51   1
 76   1
 77   1
 78   1
 79   1
 80   1
 81   1
 88   1
 89   1
104   1
105   1
110   1
111   1
116   1
118   1
122   1
123   1
126   1
129   1
133   1
134   1
136   1
144   1
```

Cost explanation:
-Runs over 2 weeks
-175 arcs in solution

```
147  1
148  1
THE TOTAL COST=
 53407
```

Weekly milage:

$$\frac{53407-(175*150)}{2} = 13579$$

New OFF CW:

Data set.

Frequency based on 8 week rate.

```
 41.07    95.54   1   OFF/C-7  1       OFFUTT
 37.37    97.16   8   IAB/C-22 2-9     MCCONNELL
 38.32    89.51   8   BLV/C-23 10-17   SCOTT
 43.34    96.44   4   FSD-86   18-21   SIOUX FALLS
 42.24    96.23   4   SUX-87   22-25   SIOUX CITY
 39.22    94.54   4   FLV-88   26-29   FT LEAVENWORTH
 39.03    96.46   4   FRI-89   30-33   FT RILEY
 38.51    94.33   4   GVW-90   34-37   KANSAS CITY
 38.57    95.39   4   FOE-91   38-41   FORBES
 37.44    92.08   4   TBN-92   42-45   FORNEY
 38.44    93.33   8   SZL-94   46-53   WHITEMAN
 38.34    90.09   16  CPS-95   54-69   E ST LOUIS
 48.24   101.21   8   MIB-55   70-77   MINOT
 47.57    97.24   8   RDR-56   78-85   GRAND FORKS
 49.54    97.14   1   YWG-61   86      WINNEPEG
 39.46   104.53   8   DEN/C-6  87-94   DENVER
 41.09   104.49   8   CYS-53   95-102   CHEYENNE
 44.08   103.06   8   RCA-54   103-110 ELLSWORTH
 45.48   108.32   4   BIL-59   111-114 BILLINGS
 41.32    93.39   4   DSM-81   115-118 DES MOINES
 44.53    93.13   4   MSP-85   119-122 MINNEAPOLIS
```

New OFF output file:

```
ARCS IN THE SOLUTION
 86 70
 86 78
111 71
112 72
113 73
114 74
 79 71
 80 72
 81 73
 82 74
 83 75
 84 76
 85 77
 95 87
 96 88
 97 89
 98 90
```

```
 99 91
100 92
101 93
102 94
111103
112104
113105
114106
 54 10
 55 11
 56 12
 57 13
 58 14
 59 15
 60 16
 61 17
107 70
108 75
109 76
110 77
 42 10
 43 11
 44 12
 45 13
119 78
120 83
121 84
122 85
 46 42
 47 43
 48 44
 49 45
 58 50
 59 51
 60 52
 61 53
 46 34
 47 35
 48 36
 49 37
 30  2
 31  3
 32  4
 33  5
 87  2
 88  3
 89  4
 90  5
 91  6
 92  7
 93  8
 94  9
 38  6
```

```
 39  7
 40  8
 41  9
108 18
109 19
110 20
 34 26
 35 27
 36 28
 37 29
115 14
116 15
117 16
118 17
 95 21
 22 21
 96 23
 97 24
 98 25
 18  1
 19  1
 20  1
 22  1
 23  1
 24  1
 25  1
 26  1
 27  1
 28  1
 29  1
 30  1
 31  1
 32  1
 33  1
 38  1
 39  1
 40  1
 41  1
 50  1
 51  1
 52  1
 53  1
 54  1
 55  1
 56  1
 57  1
 62  1 TWICE
 63  1 TWICE
 64  1 TWICE
 65  1 TWICE
 66  1 TWICE
 67  1 TWICE
 68  1 TWICE
```

```
 69  1 TWICE
 79  1
 80  1
 81  1
 82  1
 99  1
100  1
101  1
102  1
103  1
104  1
105  1
106  1
107  1
115  1
116  1                        Cost explanation:
117  1                        -Runs over 8 weeks
118  1                        -153 arcs in solution
119  1
120  1                        Weekly milage =
121  1
122  1                        58931-(153*150) =  4498
THE TOTAL COST=                     8
 58931
------------------------------------
5 Depot Summary:

 6 depot weekly milage          27467
 minus old FFO, OFF, and BWI    -1665
                                -4351
                                -8071
 plus new OFF and BWI           +4498
                               +13579       Yearly Milage:
  5 depot weekly milage         31457       1,635,764
```

Depot Closure Resequence Computations

11 Depot Weekly Milage.	24070
Close RME and old NZW routes	-799
	-1302
Add enlarged NZW routes (7 dep)	+2365
10 Depot Weekly milage	24334

Recommended 10 Depot yearly milage 1,265,368
(additional miles = 13728)

Recommended10 Depot Weekly Milage	24334
Close NZY and old SUU routes	-1148
	-4504
Add enlarged SUU routes (10 dep)	+6119
9 Depot Weekly milage	24801

Recommended 9 Depot yearly milage 1,289,652
(additional miles = 24284)

Recommended 9 Depot Weekly Milage	24801
Close CHS and old BWI routes	-487
	-3638
Add enlarged BWI routes (8 dep)	+4665
8 Depot Weekly milage	25341

Recommended 8 Depot yearly milage 1,317,732
(additional miles = 28080)

Recommended 8 Depot Weekly Milage	25341
Close NZW and old BWI routes	-2365
	-4665
Add enlarged BWI routes (6 dep)	+8071
7 Depot Weekly milage	26382

Recommended 7 Depot yearly milage 1,371,864
(additional miles = 54132)

Recommended 7 Depot Weekly Milage	26382
Close LRF and old NIP routes	-800
	-3625
Add enlarged NIP routes (9 dep)	+5510
6 Depot Weekly milage	27467

Recommended 6 Depot yearly milage 1,428,284
(additional miles = 56420)

5 Depot recommendation is unchanged:
Yearly milage 1,635,764
(additional miles = 207,480)

Appendix F: Near Term Output

MSF:

BWI locations are effectively removed by setting their latitude and longitude equal to that of Baltimore.

```
BEST WEIGHT=      210625
DEPOTS=
    1    2    3    4    5    7    8    9   11   12
EMINATING NODES ON TOP
INCIDENT NODES BELOW
    3    3    3    3    3    3    3    3    3    3
   10   26  100  101  102  103  111  112  113  116

    3    3    3    3    3    3    3    3    3    3
  117  122  123  124  136  137  138  139  140  141

    3    3    3    3    3    9    1    1    9  114
  142  143  144  145  146  135   31   34  114  126

  126  125  115  115  125  127   11    8   34   32
  125  115  120  121  127  119  153  109   32   35

   35    9  130  153  131  119   11    2   67    8
   33  130  131  154  132  118  148   67   66   99

   99   99  104  132   11   32   98    5   45    7
   98  104  105  133  147   36   97   45   46   87

   87  109   25  108  153    4   40   12  169  160
   86   25  108  106  149   40   42  169  160  156

  156  160  170  168  167  167  157  151  152  160
  157  170  168  167  166  159  151  152   30  155

  166  165  151  150  158   31   38   45   48   49
  165   27  150  158   69   38   39   48   49   51

   51   51   50  106  107   83   82   66   18   78
   47   50   52  107   83   82   81   18   78   62

   62   62   42  118  129  107   24   12  164  164
   68   19   41  129  128   24   96  164  163   28

  163  162   29  150   21   21   20   72    7   88
  162   29  161   21   93   20   72   71   88   90

   88   90   91   89   94   92   95    2   78   65
   91   94   89   22   92   95   23   77   65   64

   49   72   63   46   15   25   68   80   76   82
   14   63   70   15   75  110   80   76   79   84
```

```
 84  133   67   76   16   74   38   42   43   44
 85  134   73   16   74   17   37   43   44   58

 58   58   60   57   86   56   56   55   54   53
 13   60   57   59   56   61   55   54   53    6
```

CW:

FFO Data set.

Frequencies based on 2 week rate.

```
 39.50    84.03   1   FFO/C-8  1    WRIGHT-PATTERSON
 42.05    87.49   1   NBU/C-24 2    GLENVIEW
 38.10    85.44   2   SDF/C-25 3,4  STANDIFORD
 41.32    93.39   1   DSM-81   5    DES MOINES
 41.53    91.42   1   CID-82   6    CEDAR RAPIDS
 41.26    90.30   1   MLI-83   7    MOLINE
 43.57    90.44   1   CMY-84   8    FT MCCOY
 44.53    93.13   1   MSP-85   9    MINNEAPOLIS
 42.57    87.53   1   MKE-96   10   MILWAUKEE
 42.18    85.14   1   BTL-97   11   BATTLE CREEK
 41.35    83.48   1   TOL-98   12   TOLEDO
 41.01    83.41   1   FDY-99   13   FINDLAY
 40.58    85.11   1   FWA-104  14   FT WAYNE
 40.38    86.09   1   GUS-105  15   GRISSOM
 39.27    87.18   1   HUF-106  16   TERRE HAUTE
 40.29    88.55   1   BMI-107  17   BLOOMINGTON IL
 39.09    86.37   1   BMG-108  18   BLOOMINGTON IN
 39.06    84.25   1   LUK-109  19   CINCINNATI
 36.40    87.29   1   HOP-110  20   FT CAMPBELL
```

FFO output file:

```
 ARCS IN THE SOLUTION
    9  8
    9  5
    6  5
    7  6
   10  8
   17  7
   11  2
   20  3
   18 16
   20 16
   15  2
   12 11
   15 14
   13 12
   19  3
   14  4
```

```
  4  1                             Cost explanation:
 10  1                             -run over 2 weeks
 13  1                             -22 arcs in solution
 17  1
 18  1                             Weekly milage =
 19  1
THE TOTAL COST=                    6194-(22*150) =  1447 sm/wk
  6194                                   2
```

Wright-Patt route interpretation (2 week period):

```
R1:  FFO-BMI-MLI-CID-DSM-MSP-CMY-MKE-FFO
      1   17   7   6   5   9   8   10  1

R2:  FFO-FDY-TOL-BTL-NBU-GUS-FWA-SDF-FFO
      1   13  12  11  2   15  14  4   1

R3:  FFO-BMG-HUF-HOP-SDF-LUK-FFO
      1   18  16  20  3   19  1
-------------------------------------
```

NZY data set.

Frequency based on 2 week rate.

```
 32.41    117.12   1   NZY/C-5  1      NORTH ISLAND
 36.14    115.02   1   LSV/C-14 2      NELLIS
 33.32    112.23   1   LUF/C-15 3      LUKE
 32.50    115.40   1   NJK-45   4      EL CENTRO
 32.39    114.36   1   NYL-46   5      YUMA
 35.41    117.41   1   NID-47   6      CHINA LAKE
 34.17    116.10   1   NXP-48   7      TWENTYNINE PALMS
 34.51    116.47   1   DAG-49   8      BARSTOW
 34.12    119.12   1   OXR-50   9      OXNARD
 34.54    117.52   1   EDW-52   10     EDWARDS
 34.43    120.34   2   VBG-51   11,12  VANDENBERG
 32.09    110.52   1   DMA-75   13     DAVIS-MONTHAN
```

NZY output file:

```
 ARCS IN THE SOLUTION
  13  3
   6  2
   3  2
  10  6
  11  9
  13  5
  10  8
   8  7
   9  4
   4  1                          Cost explanation
   5  1                          -run over 2 weeks
   7  1                          -15 arcs in solution
```

```
 11  1
 12  1 TWICE
THE TOTAL COST=
  4546
```

Weekly milage =

$$\frac{4546-(15*150)}{2} = 1148 \text{ sm/wk}$$

North Island route interpretation (2 week period):

```
R1:  NZY-NYL-DMA-LUF-LSV-NID-EDW-DAG-NXP-NZY
      1   5   13  3   2   6   10  8   7   1

R2:  NZY-VBG-OXR-NJK-NZY
      1   11  9   4   1

R3:  NZY-VBG-NZY
      1   12  1
-----------------------------------
```

SUU data set.

Frequency based on 2 week rate.

```
 38.15   121.55   1   SUU/F-1  1       TRAVIS
 38.40   121.23   2   MCC-31   2,3     MCCLELLAN
 37.17   120.31   2   MCE-32   4,5     MERCED
 36.20   119.57   2   NLC-33   6,7     LEMORE
 37.53   121.14   2   SCK-34   8,9     STOCKTON
 36.46   119.43   2   FAT-35   10,11   FRESNO
 36.35   121.50   2   MRY-36   12,13   MONTEREY
 42.09   121.44   1   LMT-37   14      KLAMATH FALLS
 39.29   119.46   1   RNO-38   15      RENO
 39.24   118.41   1   NFL-39   16      FALLON
```

SUU output file.

```
 ARCS IN THE SOLUTION
  10  6
  11  7
  16 15
  16 14
  10  4
  11  5
  12  6
  13  7
   8  4
   9  5
  15  2
   8  2
   9  3
   3  1
  12  1
  13  1
  14  1
 THE TOTAL COST= 4105
```

Cost explanation:
-run over 2 weeks
-17 arcs in solution

Weekly milage =

$$\frac{4105-(17*150)}{2} = 778$$

Travis route interpretation (2 week period).

```
R1:  SUU-LMT-NFL-RNO-MCC-SCK-MCE-FAT-NLC-MRY-SUU
      1   14  16  15  2   8   4   10  6   12  1

R2:  SUU-MCC-SCK-MCE-FAT-NLC-MRY-SUU
      1   3   9   5   11  7   13  1
```

TCM data set.

Frequency based on 2 week period.

```
 47.08   122.28   1   TCM/C-4   1      MCCHORD
 46.34   120.32   2   YKM-40    2,3    YAKIMA
 47.37   117.31   2   GEG-41    4,5    FAIRCHILD
 46.15   119.06   1   PSC-42    6      PASCO
 43.33   116.13   1   BOI-43    7      BOISE
 43.02   115.52   1   MUO-44    8      MT HOME
 40.47   111.58   2   SLC/C-13  9,10   SALT LAKE CITY
 47.30   111.11   2   GFA-57    11,12  GREAT FALLS
 43.31   112.04   1   IDA-58    13     IDAHO FALLS
 45.48   108.32   1   BIL-59    14     BILLINGS
 46.36   111.59   1   HLN-60    15     HELENA
```

TCM output file.

```
 ARCS IN THE SOLUTION
  13  9
  14 11
  14 13
  15 12
  10  8
  10  7
  12  4
   7  5
   8  6
   6  2
  15  3
   2  1
   3  1
   4  1
   5  1
   9  1
  11  1
 THE TOTAL COST=
   6959
```

Cost explanation:
-run made over 2 weeks
-17 arcs in solution

Weekly milage =

$$\frac{6959-(17*150)}{2} = 2205$$

McChord route interpretation (2 week period).

```
R1:  TCM-SLC-IDA-BIL-GFA-TCM
      1   9   13  14  11  1
```

```
R2:  TCM-YKM-HLN-GFA-GEG-TCM
      1   3   15  12  4   1

R3:  TCM-GEG-BOI-SLC-MUO-PSC-YKM-TCM
      1   5   7   10  8   6   2   1
----------------------------------------
```

OFF data set.

Frequency based on 8 week rate.

```
 41.07    95.54   1   OFF/C-7  1       OFFUTT
 37.37    97.16   8   IAB/C-22 2-9     MCCONNELL
 38.32    89.51   8   BLV/C-23 10-17   SCOTT
 43.34    96.44   4   FSD-86   18-21   SIOUX FALLS
 42.24    96.23   4   SUX-87   22-25   SIOUX CITY
 39.22    94.54   4   FLV-88   26-29   FT LEAVENWORTH
 39.03    96.46   4   FRI-89   30-33   FT RILEY
 38.51    94.33   4   GVW-90   34-37   KANSAS CITY
 38.57    95.39   4   FOE-91   38-41   FORBES
 37.44    92.08   4   TBN-92   42-45   FORNEY
 38.44    93.33   8   SZL-94   46-53   WHITEMAN
 38.34    90.09   16  CPS-95   54-69   E ST LOUIS
 48.24   101.21   8   MIB-55   70-77   MINOT
 47.57    97.24   8   RDR-56   78-85   GRAND FORKS
 49.54    97.14   1   YWG-61   86      WINNEPEG
 39.46   104.53   8   DEN/C-6  87-94   DENVER
 41.09   104.49   8   CYS-53   95-102   CHEYENNE
 44.08   103.06   8   RCA-54   103-110 ELLSWORTH
```

OFF output file.

```
ARCS IN THE SOLUTION
 86 70
 86 78
 79 71
 80 72
 81 73
 82 74
 83 75
 84 76
 85 77
 95 87
 96 88
 97 89
 98 90
 99 91
100 92
101 93
102 94
 54 10
 55 11
 56 12
```

```
 57 13
 58 14
 59 15
 60 16
 61 17
103 70
104 71
105 72
106 73
107 74
108 75
109 76
110 77
 42 10
 43 11
 44 12
 45 13
 46 42
 47 43
 48 44
 49 45
 58 50
 59 51
 60 52
 61 53
 78 18
 79 19
 80 20
 81 21
 46 34
 47 35
 48 36
 49 37
 30  2
 31  3
 32  4
 33  5
 87  2
 88  3
 89  4
 90  5
 91  6
 92  7
 93  8
 94  9
 38  6
 39  7
 40  8
 41  9
 34 26
 35 27
 36 28
 37 29
```

```
 22 18
 23 19
 24 20
 25 21
 14  1
 15  1
 16  1
 17  1
 22  1
 23  1
 24  1
 25  1
 26  1
 27  1
 28  1
 29  1
 30  1
 31  1
 32  1
 33  1
 38  1
 39  1
 40  1
 41  1
 50  1
 51  1
 52  1
 53  1
 54  1
 55  1
 56  1
 57  1
 62  1 TWICE
 63  1 TWICE
 64  1 TWICE
 65  1 TWICE
 66  1 TWICE
 67  1 TWICE
 68  1 TWICE
 69  1 TWICE
 82  1
 83  1
 84  1
 85  1
 95  1
 96  1
 97  1
 98  1
 99  1
100  1
101  1
102  1
103  1
```

```
104  1
105  1
106  1
107  1
108  1
109  1
110  1
THE TOTAL COST=
 54496
```

Cost explanation:
-run over 8 weeks
-141 arcs in solution

Weekly milage =

$$\frac{54496-(141*150)}{8} = 4168$$

Offutt route interpretation (8 week period).

```
R1: OFF-SUX-FSD-RDR-YWG-MIB-RCA-OFF
     1   22  18  78  86  70 103  1

R2: OFF-SUX-FSD-RDR-MIB-RCA-OFF
     1   23  19  79  71 104  1
R3:  1   24  20  80  72 105  1
R4:  1   25  21  81  73 106  1

R5: OFF-RDR-MIB-RCA-OFF
     1   82  74 107  1
R6:  1   83  75 108  1
R7:  1   84  76 109  1
R8:  1   85  77 110  1

R9:   OFF-CYS-DEN-IAB-FRI-OFF
       1   95  87  2   30  1
R10:   1   96  88  3   31  1
R11:   1   97  89  4   32  1
R12:   1   98  90  5   33  1

R13:  OFF-CYS-DEN-IAB-FOE-OFF
       1   99  91  6   38  1
R14:   1  100  92  7   39  1
R15:   1  101  93  8   40  1
R16:   1  102  94  9   41  1

R17:  OFF-CPS-BLV-TBN-SZL-GVW-FLV-OFF
       1   54  10  42  46  34  26  1
R18:   1   55  11  43  47  35  27  1
R19:   1   56  12  44  48  36  28  1
R20:   1   57  13  45  49  37  29  1

R21:  OFF-SZL-CPS-BLV-OFF
       1   50  58  14  1
R22:   1   51  59  15  1
R23:   1   52  60  16  1
R24:   1   53  61  17  1

R25-R32.   OFF-CPS-OFF
            1  62-69  1
------------------------------------
```

NZW data set.

Frequency based on weekly rate.

```
 42.09    70.56    1    NZW/C-9   1  BOSTON
 41.35    71.25    1    OQU-114   2  QUONSET STATE
 41.04    73.42    1    HPN-115   3  WHITE PLAINS
 42.45    73.48    1    ALB-118   4  ALBANY
 42.11    72.31    1    CEF-119   5  WESTOVER
 40.44    73.25    1    FRG-120   6  FARMINGTON
 41.30    74.06    1    SWF-121   7  STEWART
 41.16    72.53    1    HVN-125   8  NEW HAVEN
 41.19    72.02    1    GON-126   9  GROTON
 41.56    72.41    1    BDL-127   10 BRADLEY
 42.56    71.26    1    MHT-130   11 MANCHESTER
 43.04    70.49    1    PSM-131   12 PEASE
 43.53    69.56    1    NHZ-132   13 BRUNSWICK
 44.48    68.50    1    BGR-133   14 BANGOR
 46.57    67.53    1    LIZ-134   15 LORING
 41.40    70.31    1    FMH-135   16 OTIS
 44.39    73.28    1    PBG-128   17 PLATTSBURGH
 44.28    73.09    1    BTV-129   18 BURLINGTON
```

NZW output file.

```
 ARCS IN THE SOLUTION
  15 14
  18 17
   6  3
   7  3
  17 15
  14 13
   7  4
   8  6
  10  4
   9  8
  10  5
  13 12
  18 11
   9  2
  16  2
   5  1
  11  1
  12  1
  16  1
 THE TOTAL COST=
   4290
```

Cost explanation:
-run made over 1 week
-19 arcs in solution

Weekly milage =

4290-(19*150) = 1440

Boston (South Weymouth) route interpretation (1 week period)

```
R1: NZW-PSM-NHZ-BGR-LIZ-PBG-BTV-MHT-NZW
     1   12  13  14  15  17  18  11  1
```

```
R2: NZW-FMH-OQU-GON-HVN-FRG-HPN-SWF-ALB-BDL-CEF-NZW
     1   16  2   9   8   6   3   7   4   10  5   1
-----------------------------------------
```

BWI data set.

Frequency based on 2 week rate.

```
 39.11    76.40   1   BWI/F-3  1     BALTIMORE
 39.50    84.03  12   FFO/C-8  2-13  WRIGHT-PATT
 36.56    76.17   2   NGU/C-10 14,15 NORFOLK
 43.14    75.24   2   RME/C-26 16,17 GRIFFISS
 41.25    81.51   1   CLE-100  18    CLEVLAND
 40.29    80.14   1   PIT-101  19    PITTSBURGH
 39.49    82.56   1   LCK-102  20    COLUMBUS
 40.49    82.30   1   MFD-103  21    MANSFIELD
 35.24    86.05   1   TUH-111  22    TULLAHOMA
 35.49    84.00   1   TYS-112  23    KNOXVILLE
 38.22    81.36   1   CRW-113  24    CHARLESTON WV
 43.07    76.06   2   SYR-116  25,26 SYRACUSE
 44.03    75.44   2   GTB-117  27,28 WHEELER SACK
 42.12    75.59   2   BGM-122  29,30 BINGHAMTON
 42.56    78.44   2   BUF-123  31,32 BUFFALO
 43.07    77.40   2   ROC-124  33,34 ROCHESTER
 37.05    76.21  12   LFI-136  35-46 LANGLEY
 34.40    86.41   4   HUA-137  47-50 HUNTSVILLE
 38.08    78.27   2   CHO-138  51,52 CHARLOTTESVILLE
 38.17    76.24   2   NHK-139  53,54 PATUXENT
 38.15    78.53   2   SHD-140  55,56 SHENENDOAH
 37.19    79.58   2   ROA-141  57,58 ROANOKE
 39.38    79.54   2   MGW-142  59,60 MORGANTOWN
 39.42    77.43   2   HGR-143  61,62 HAGERSTOWN
 40.51    77.51   2   UNV-144  63,64 STATE COLLEGE
 41.20    75.43   2   AVP-145  65,66 WILKES-BARRE
 40.11    76.45   2   MDT-146  67,68 HARRISBURG
 34.54    76.53   2   NKT-171  69,70 CHERRY POINT
 34.43    77.26   2   NCA-172  71,72 JACKSONVILLE
 34.54    82.13   2   GSP-173  73,74 GREENSVILLE
 35.26    82.32   2   AVL-174  75,76 ASHEVILLE
 36.29    82.25   2   TRI-175  77,78 BRISTOL
 37.31    77.19   2   RIC-176  79,80 RICHMOND
 35.20    77.58   2   GSB-177  81,82 GOLDSBORO
 35.10    79.01   2   POB-178  83,84 POPE
 35.13    80.56   2   CLT-179  85,86 CHARLOTTE
 36.06    79.56   2   GSO-180  87,88 GREENSBORO
 35.53    78.47   2   RDU-181  89,90 RALIEGH
```

BWI output file.

```
ARCS IN THE SOLUTION
 47 22
 47 23
 75 48
```

76	49
73	48
74	49
77	23
78	50
85	73
86	74
22	2
50	3
21	2
71	69
72	70
27	16
28	17
85	83
86	84
18	3
27	25
28	26
87	75
88	76
81	71
82	72
20	18
24	4
33	31
34	32
89	81
90	82
33	16
34	17
29	25
30	26
19	4
57	24
89	58
59	5
60	6
58	5
31	7
32	8
69	14
70	15
35	15
57	55
90	6
56	9
55	51
56	52
63	19
79	36
80	37
64	9

```
 65  63
 66  64
 79  52
 67  66
 53  37
 54  38
 61  10
 62  11
 80  10
 38  11
 39  12
 40  13
 68  12
  7   1
  8   1
 13   1
 14   1
 20   1
 21   1
 29   1
 30   1
 35   1
 36   1
 39   1
 40   1
 41   1 TWICE
 42   1 TWICE
 43   1 TWICE
 44   1 TWICE
 45   1 TWICE
 46   1 TWICE
 51   1
 53   1
 54   1
 59   1
 60   1
 61   1
 62   1
 65   1
 67   1
 68   1
 77   1
 78   1
 83   1
 84   1
 87   1
 88   1
THE TOTAL COST=
 35495
```

Cost explanation:
-run over 2 weeks
-109 arcs in solution

Weekly milage =

$$\frac{35495-(109*150)}{2} = 9572$$

Baltimore route interpretation (2 week period).

```
R1: BWI-TRI-TYS-HUA-TUH-FFO-MFD-BWI
     1  77  23  47  22  2   21  1

R2: BWI-BGM-SYR-GTB-RME-ROC-BUF-FFO-BWI
     1  30  26  28  17  34  32  8   1

R3: BWI-BGM-SYR-GTB-RME-ROC-BUF-FFO-BWI
     1  29  25  27  16  33  31  7   1

R4: BWI-NGK-LFI-FFO-HGR-BWI
     1  54  38  11  62  1

R5: BWI-LFI-FFO-MDT-BWI
     1  39  12  68  1

R6: BWI-LFI-FFO-BWI
     1  40  13  1

R7: BWI-GSO-AVL-HUA-GSP-CLT-POB-BWI
     1  87  75  48  73  85  83  1

R8: BWI-GSO-AVL-HUA-GSP-CLT-POB-BWI
     1  88  76  49  74  86  84  1

R9: BWI-TRI-HUA-FFO-CLE-LCK-BWI
     1  78  50  3   18  20  1

R10: BWI-MGW-FFO-ROA-RDU-GSB-NCA-NKT-NGU-BWI
      1  59  5   58  89  81  71  69  14  1

R11: BWI-MGW-FFO-RDU-GSB-NCA-NKT-NGU-LFI-BWI
      1  60  6   90  82  72  70  15  35  1

R12: BWI-AVP-UNV-PIT-FFO-CRW-ROA-SHD-CHO-BWI
      1  65  63  19  4   24  57  55  51  1

R13: BWI-MDT-AVP-UNV-FFO-SHD-CHO-RIC-LFI-BWI
      1  67  66  64  9   56  52  79  36  1

R14: BWI-HGR-FFO-RIC-LFI-NHK-BWI
      1  61  10  80  37  53  1

R15-R20:  BWI-LFI-BWI
           1  41-46  1
-----------------------------------
```

NIP data set.

Frequency based on 2 week rate.

30.14	81.41	1	NIP/C-12	1	JACKSONVILLE
29.50	90.01	1	NBG/C-27	2	NEW ORLEANS
27.50	82.31	2	MCF/C-28	3,4	MACDILL

```
25.29     80.23    2    HST/C-29      5,6   HOMESTEAD
33.54     84.31    2    NCQ/C-30      7,8   DOBBINS
32.19     90.05    1    JAN-69        9     JACKSON
33.39     88.27    2    CBM-150       10,11 COLUMBUS
33.33     86.45    2    BHM-151       12,13 BIRMINGHAM
33.35     85.51    2    ANB-152       14,15 ANNISTON
32.38     83.35    2    WRB-155       16,17 ROBINS
32.20     84.59    2    LSF-156       18,19 LAWSON
32.22     86.21    2    MXF-157       20,21 MAXWELL
32.20     88.44    2    MEI-158       22,23 MERIDIAN
31.16     85.42    2    OZR-159       24,25 FT RUCKER
31.32     84.12    2    ABY-160       26,27 ALBANY
24.35     81.41    2    NOX-161       28,29 KEY WEST
26.41     80.06    2    PBI-162       30,31 PALM BEACH
28.14     80.36    2    COF-163       32,33 PATRICK
28.25     81.19    2    MCO-164       34,35 ORLANDO
30.24     88.55    2    BIX-165       36,37 KEESLER
30.21     87.19    2    NPA-166       38,39 PENSACOLA
30.29     86.31    2    VPS-167       40,41 EGLIN
30.04     85.34    2    PAM-168       42,43 TYNDALL
30.58     83.11    1    VAD-169       44    MOODY
30.23     84.21    1    TLH-170       45    TALLAHASSEE
34.54     92.08    1    LRF/C-20      46    LITTLE ROCK
35.02     89.58    1    MEM/C-21      47    MEMPHIS
32.30     93.40    2    BAD-63        48,49 BARKSDALE
31.19     92.32    1    AEX-70        50    ENGLAND
35.20     94.22    1    FSM-71        51    FT SMITH
34.29     93.06    1    HOT-72        52    HOT SPRINGS
35.58     89.57    2    BYH-93        53,54 BLYTHEVILLE
```

NIP output file.

```
 ARCS IN THE SOLUTION
  52 51
  51 46
  52 48
  50 49
  53 47
  49 47
  54 10
  54  9
  22  9
  36  2
  23 11
  23  2
  37 22
  12 10
  13 11
  38 36
  14 13
  40 39
  20 15
  15  7
```

```
  30   5
  31   6
  39  20
  24  21
  21  18
  40  25
  41  24
  42  41
  18   8
  19   7
  16   8
  43  25
  45  42
  32  30
  33  31
   5   3
   6   4
  26  16
  27  17
  34  32
  35  33
  44  27
  44   3
   4   1
  12   1
  14   1
  17   1
  19   1
  26   1
  28   1  TWICE
  29   1  TWICE
  34   1
  35   1
  37   1
  38   1
  43   1                   Cost explanation:
  45   1                   -run over 2 weeks.
  46   1                   -63 arcs in solution
  48   1
  50   1                   Weekly cost =
  53   1
 THE TOTAL COST=           19155-(63*150) =  4853
  19155                          2
---------------------------------------
```

The routes of SKF and CHS are identical to the 11 depot model in Appendix E (page 114). The route interpretations are also provided there.

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