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IMPLEMENTATION OF THE METAHEURISTIC
TABU SEARCH IN ROUTE SELECTION
FOR MOBILITY ANALYSIS SUPPORT SYSTEM

THESIS

David M. Ryer, Major, USAF

AFIT/GOA/ENS/99M-07

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NAME: David M. Ryer, Major, USAF **CLASS:** GOA-99M

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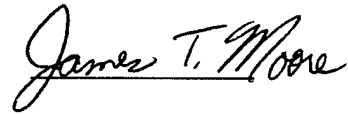
DEFENSE DATE: 2 March 1999

COMMITTEE: NAME/TITLE/DEPARTMENT

Advisor T. Glenn Bailey, Lieutenant Colonel, USAF
Assistant Professor of Operations Research
Department of Operational Sciences
Air Force Institute of Technology

SIGNATURE


Reader James T. Moore
Associate Professor of Operations Research
Department of Operational Sciences
Air Force Institute of Technology



Reader William B. Carlton, Lieutenant Colonel (P), USA
Adjunct Assistant Professor of Operations Research
Department of Operational Sciences
Air Force Institute of Technology



The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U. S. Government.

IMPLEMENTATION OF THE METAHEURISTIC
TABU SEARCH IN ROUTE SELECTION
FOR MOBILITY ANALYSIS SUPPORT SYSTEM

THESIS

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

David M. Ryer, B.S.
Major, USAF

March 1999

Approved for public release; distribution unlimited

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Abstract

This thesis employs a reactive tabu search heuristic implemented in the Java programming language to solve a real world variation of the vehicle routing problem with the objective of providing quality routes to Mobility Analysis Support System (MASS). MASS is a stochastic simulation model used extensively by Air Mobility Command (AMC) to analyze strategic airlift capabilities and future procurement decisions. This dynamic real world problem of strategic and tactical airlift possesses a number of side constraints such as vehicle capacities, route length and time windows in a sizeable network with multiple depots and a large fleet of heterogeneous vehicles. Finding optimal solutions to this problem is currently not practical. Currently, MASS requires all possible routes used in its simulation to be manually selected. As a result, the route selection process is a tedious and time consuming process that relies on experience and past performance of the model to obtain quality routes for the mobility system.

Chapter 1

1.1 Introduction

Mobility Analysis Support System (MASS) is a simulation model used extensively by Air Mobility Command (AMC) to analyze strategic airlift capabilities and future procurement decisions, whose routes are calculated by an experienced analyst through trial and error. This thesis employs a reactive tabu search heuristic implemented in the Java programming language to solve the vehicle routing problem with the objective of providing quality routes to MASS that are as good or better than those currently used.

1.2 Background

Most vehicle routing problems (VRP's) are NP-hard combinatorial problems for which no polynomially bounded algorithm has yet been found (Baker 1986). Convergent algorithms can rarely solve problems larger than 50 customers, and often require relatively few side constraints (Gendreau et al. 1997). Unfortunately, real world problems such as strategic airlift possess a number of side constraints such as precedence, route and vehicle capacities, route length and time windows in a sizeable network with multiple depots, and a large fleet of heterogeneous vehicles. Therefore, finding optimal solutions using such techniques as branch and bound or dynamic programming is currently not practical.

On the other hand, many heuristic approaches can provide excellent solutions with reasonable computational times. Greedy algorithms, which prove to be very useful in simpler problems, fail to achieve the desired results with respect to solution quality, while simulated annealing (SA) displays large variance with regard to computational time

and quality due to the random nature of its search strategy (Osman 1993). Genetic algorithms (GAs) are difficult to apply to VRP's with capacity, distance, and time window constraints because they were designed to solve numerical optimization problems rather than combinatorial optimization problems (Gendreau et al. 1997). Conversely, tabu search (TS) has provided excellent results on this type of problem with the implementation of *intensification* and *diversification* strategies (Gendreau et al. 1997). Intensification uses choice rules to encourage move combinations that incorporate good solution features, while diversification forces the solution search to unexplored regions or to solutions significantly different than those already found (Glover and Laguna 1997). The literature shows TS is a robust approach to solving many variations of the VRP and dominates current studies of routing problems (Gendreau et al. 1997, Xu and Kelly 1996, Rochat and Semet 1994, Renaud et al. 1996, Osman 1993, Garcia et al. 1994, Chiang and Russell 1997, Carlton 1995).

Recent modeling efforts in the military airlift community emphasize simulation over optimization, in part due to the ease in which simulation can represent the stochastic nature of the problems being studied (Rosenthal et al. 1997, Morton et al. 1996). However, more recent efforts look at combining simulation and optimization, particularly with regard to the Air Mobility Command's legacy model Mobility Analysis Support System (MASS). MASS simulates the strategic airlift environment for analysis of doctrine, strategic airlift capability, current AMC airlift assets and future AMC acquisitions. This simulation analysis supports the activities of the AMC Commander, the United States Transportation Command (USTRANSCOM), and a wide variety of theater and campaign level commanders. In addition, proprietary organizations like

Lockheed-Martin and Boeing use MASS to analyze future airlift systems. Possessing a global domain, MASS simulates up to 300 bases at any latitude and longitude in the world, using up to ten types of aircraft, with the entire fleet of strategic airlift aircraft tracked by tail number and cargo classified by weight, dimension and special handling instructions (Boeing 1996). In short, the model's domain is the world and it spans all strategic aircraft in the USAF inventory and CRAF with virtually every cargo combination (Boeing 1996).

The primary component of MASS is the Airlift Flow Model (AFM), which orchestrates the simulation of mission events throughout the entire system. Supporting this core element are various loading, ground crew, command and control, and tanker models. Current validation efforts include output comparisons between MASS and the Naval Postgraduate School/RAND Mobility Optimizer (NRMO) by crossfeeding relative information between the two models in a series of repetitive simulations and then observing if the two models converge on the same solution (Wright 1998).

Extending the work of Ryan (1999) and Carlton (1995), we implement the metaheuristic of reactive TS (RTS) in an object-oriented (OO) programming language. The RTS route solution represents the input to MASS for comparison with current routing selection methods. Our goal is to improve the route selection process used for MASS by using RTS-based routing inputs instead of NRMO or manually derived routing solutions.

1.3 Scope

Earlier attempts at route generators employ the optimal k-shortest path method and route length restrictions representing aircraft type maximum flight legs. This effort, coded in two separate computer-programming languages, has shown limited results in large realistic scenarios (Rink 1998). Extending this effort to include additional route selection criteria requires an efficient and robust method currently not achievable by convergent algorithms. In order to improve the overall quality of route selection, AMC Studies and Analysis (XPY) proposes adding international airspace routing constraints, crew staging and air-refueling constraints to the routing problem formulation.

Following the hierarchy scheme introduced by Carlton (1995) this problem can be treated as a VRP with multiple depots (MD), multiple non-homogenous vehicles ($M\bar{H}V$), and route length constraints (RL). As with most heuristic techniques, the algorithm, once constructed, will have to be fine-tuned to accurately represent the most important routing considerations as modeled by MASS.

Chapter 2

2.1 Air Mobility Command's Mobility Model - MASS

Currently route segments are fed into MASS in an ordered list (one of many input files required for a single simulation run) determined solely by the user. The Aircraft Routing Algorithm (ARA) of MASS checks these route segments in file order for a feasible crew plan. Then the Aircraft Flight Plan Algorithm (AFPA) determines if a route can be feasibly mission planned (flying hour availability, aircraft target use rate, route length, ramp space or maximum on ground (MOG)) (Boeing 1996). If this route segment is not feasible, then the next route in the file is checked. If no feasible route segment is found, the planning phase returns to a previous planned enroute segment and restarts the process. If no feasible crew plan or mission plan exists on the routes provided, the aircraft is scheduled for a "Part IV" mission; i.e., it flies from its present position to its home station base as a recovery.

Because of the importance of crew feasibility in MASS, a constraint to this problem prioritizes routes with available crews to avoid unnecessary recovery missions. Listed in the order of importance, the following considerations must be evaluated by any route generator: distance, route length restriction, crew availability, route or airspace restrictions, winds, and air refueling capability. All locations that make up a route (Home Station, Onload, Offload, Enroute, and Recovery) are further characterized by the geographical region in which they are located (Figure 1).

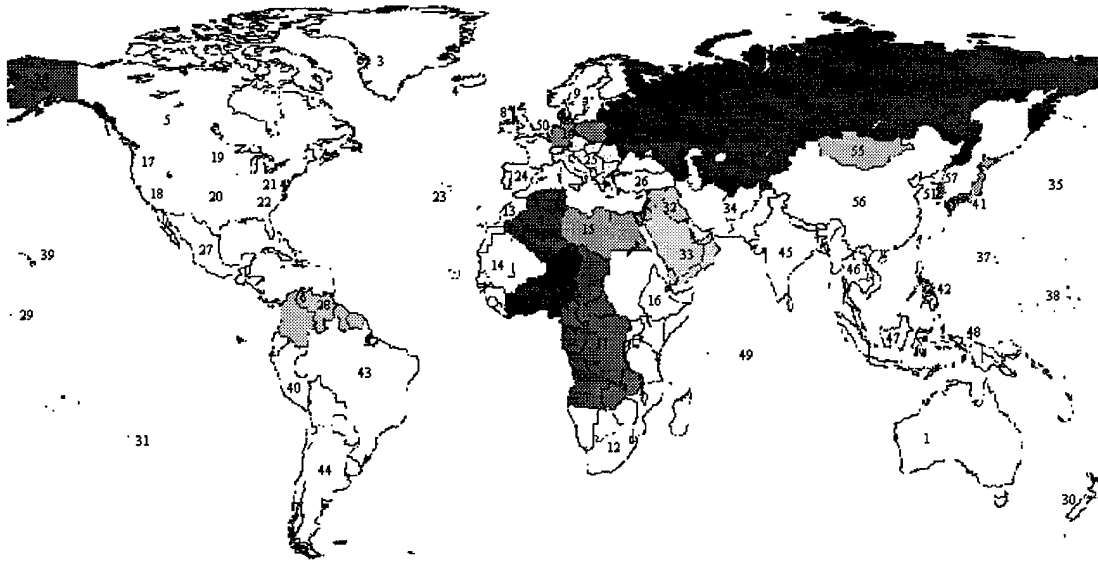


Figure 1. MASS Regions

In order to avoid the task of explicitly listing all possible route permutations from each on-load base to each off-load base, the Airlift Flow Model (AFM) deals with region pairs. With this representation, it is not necessary to specify every possible route joining the departure base to the destination base, but instead only the routes joining the respective regions (Brigantic 1998).

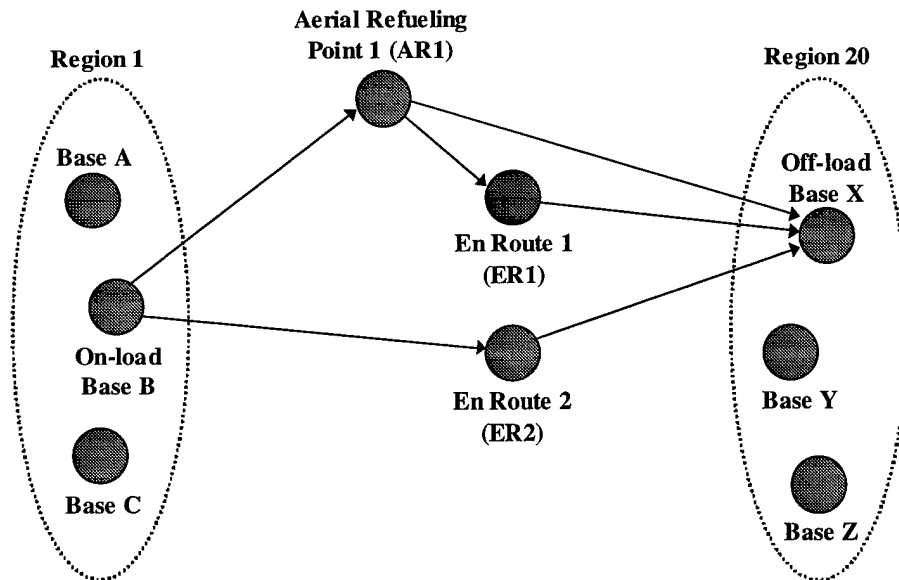


Figure 2. Routes that Link Region Pairings

2.2 Problem Formulation – The Vehicle Routing Problem

The VRP can be viewed as an extension of the basic traveling salesman problem (TSP) that adds capacity constraints to multiple salesman or vehicles. (For a more in-depth discussion on building the formulation for this family of problems see Appendix A.) The VRP involves w vehicles leaving a depot and servicing n customers, each with a unique demand d_i . Each vehicle v has a limited capacity K_v and maximum time length for a route T_v that constrains their closed delivery routes. This particular instance of the VRP is commonly known as the general vehicle routing problem (GVRP). If the route length or range constraints are removed, then we refer to this problem as the standard vehicle routing problem (SVRP) (Bodin et al. 1983). We also define the time required for vehicle v to deliver or service at node i as s_i^v , travel time for vehicle v from node i to node j as t_{ij}^v , $x_{ij}^v = 1$ if arc i - j is used by vehicle v ($x_{ij}^v = 0$, otherwise), and c_{ij} as the cost of travelling from node i to node j .

$$\text{Minimize } \sum_{i=1}^n \sum_{j=1}^n \sum_{v=1}^w c_{ij} x_{ij}^v \quad (1)$$

$$\text{Subject to } \sum_{i=1}^n \sum_{v=1}^w x_{ij}^v = 1 \quad (j = 2, \dots, n) \quad (2)$$

$$\sum_{j=1}^n \sum_{v=1}^w x_{ij}^v = 1 \quad (i = 2, \dots, n) \quad (3)$$

$$\sum_{i=1}^n x_{ip}^v - \sum_{j=1}^n x_{pj}^v = 0 \quad (v = 1, \dots, w; p = 1, \dots, n) \quad (4)$$

$$\sum_{i=1}^n d_i \left(\sum_{j=1}^n x_{ij}^v \right) \leq K_v \quad (v = 1, \dots, w) \quad (5)$$

$$\sum_{i=1}^n s_i^v \sum_{j=1}^n x_{ij}^v + \sum_{i=1}^n \sum_{j=1}^n t_{ij}^v x_{ij}^v \leq T_v \quad (v = 1, \dots, w) \quad (6)$$

$$\sum_{j=2}^n x_{1j}^v \leq 1 \quad (v = 1, \dots, w) \quad (7)$$

$$\sum_{i=2}^n x_{i1}^v \leq 1 \quad (v = 1, \dots, w) \quad (8)$$

$$X \in S \quad x_{ij}^v = 0 \text{ or } 1 \quad \text{for all } i, j, v$$

The objective function (1) minimizes the cost (travel distance) for all vehicles. Equations (2) and (3) ensure every customer is visited by one and only one vehicle. We assume that a customer's demand does not exceed vehicle capacity and each customer is fully serviced by its one visiting vehicle. Equation (4) checks the continuity of our routes while (5) maintains the capacity constraint on all of the vehicles. Since we represent route length restrictions by time, (6) ensures maximum route times are not exceeded. Equations (7) and (8) insure we do not exceed vehicle fleet size. Next, let $N^v \subseteq N$ represent the nodes from N assigned to vehicle v such that for any vehicle v that is not used, $N^v = \emptyset$; $N^1 \cup N^2 \cup \dots \cup N^{nw} = N$; and, $N^1 \cap N^2 \cap \dots \cap N^{nw} = \emptyset$. The subtour breaking constraints are then defined and included in the model as

$$x_{ij}^v : \sum_{i \in Q} \sum_{j \notin Q} x_{ij} \geq 1 \text{ for every nonempty subset } Q \text{ of } N^v \quad \forall v = 1..nw.$$

This states that for every proper subset Q of nodes must be connected to the other nodes in the network of the solution.

We eliminate some redundant constraints by recognizing that (2) and (4) enforces (3), while (4) and (7) imply (8) (Bodin et al. 1983).

Finally, we add time window considerations to the VRP. Let a_j represent the arrival time to node j , e_j the earliest delivery time allowable, and l_j the no-later-than-time for delivery such that

$$a_j = \sum_v \sum_i (a_i + s_i^v + t_{ij}^v) x_{ij}^v \quad (j = 1, \dots, n)$$

$$a_1 = 0$$

$$e_j \leq a_j \leq l_j \quad (j = 2, \dots, n).$$

For each j , one of the x_{ij}^v variables equals 1, so a_j sums the previous arrival time (a_i), the service time at node i (s_i^v), and the travel time from i to j (t_{ij}^v). Alternatively, from Bodin et al. (1983), we can use the linear representation of time windows constraint in the formulation

$$\left. \begin{aligned} a_j &\geq (a_i + s_i^v + t_{ij}^v) - (1 - x_{ij}^v) T_{max}^v \\ a_j &\leq (a_i + s_i^v + t_{ij}^v) + (1 - x_{ij}^v) T_{max}^v \end{aligned} \right\} \quad \forall i, j, v$$

When $x_{ij}^v = 1$, a_j is equal to the summation of the previous arrival time, previous service time and the travel time between the nodes. Conversely, when $x_{ij}^v = 0$ the constraints are redundant.

There are many alterations that could be added to this formulation to represent common real world problems. One such consideration takes into account the duty limitations of the crew that flies the vehicles. This can be done through inserting rest nodes that must be visited during the route that incur no travel cost, but impose service time equal to the mandatory rest break. Hard time windows for these rest nodes insure that the maximum duty hours will not be exceeded.

While the time windows defined in this formulation are hard, modeling the early time window as “soft” allows vehicles to arrive early, thus introducing a waiting time. Therefore, we use arrival times to calculate a waiting time that must be included in the precedence constraints along with service time and travel time.

Several changes are made to finalize the formulation of the strategic airlift system as modeled by MASS. First, we eliminate or soften time window constraints for the depots unless they are fixed and implement a version of the route length constraint (6) to insure route length limitations for a particular aircraft are not exceeded.

2.3 Methodology

The intent of this project is to explore the application of the Reactive Tabu Search (RTS) metaheuristic to routing problems, specifically the vehicle routing problem with time windows (VRPTW). This project has been coded in the object-oriented (OO) Java programming language for several reasons. First, the OO design of software allows us to reuse and modify existing code and libraries to reduce development time of new software. Second, Java programs are portable (Flanagan 1997). Finally, as an added benefit, the documentation tool, javadoc, links program documentation directly to the code for a hassle free method of updating and maintaining documentation. Javadoc extracts embedded comments in the code and creates an html file that is viewable with a web browser. This tool allows you to automatically create and maintain a single source file for accurate and useful documentation in the form of a web page (Eckel 1998).

The Java program represents a continuation of RTS code improvements starting with Carlton’s (1995) C code through Ryan et al. (1999) MODSIM implementation.

RTS follows the basic TS scheme but adjusts the tabu length based on the quality of the search, as determined by the number of iterations before a solution is revisited. (For example, a “high quality” search typically does not tend to revisit past solutions.) When the search moves to a neighbor solution that has been visited within the designated number of iterations or cycle length, the tabu length is increased by a multiplicative factor.

Conversely, if the solution has not been visited previously, tabu length is decreased by the multiplicative factor. When a solution is revisited within the *maximum cycle length*, a moving average of cycle lengths is calculated. If this average is less than the number of iterations without a change in tabu length, the current tabu length is decreased by the multiplicative factor. This concept from Battiti and Tecchiolli (1994) enforces the ultimate objective a broad exploration of the search space.

Finally, if all candidate solutions are tabu and aspiration criteria is not met, the search escapes to a solution with the smallest move value regardless of tabu status and then decreases the tabu length. This entire search routine is then continued for a designated number of iterations.

2.3.1 Tour Structure

The objective of the VRPTW is to find a tour in which each customer is visited within its stated time window by one vehicle, with a finite capacity, while minimizing the total cost. A tour is defined by the order in which the n customers are served by the m vehicles and is represented as an ordered list of the sequence of customers and vehicles, or “disjunctive graph” (Figure 3).

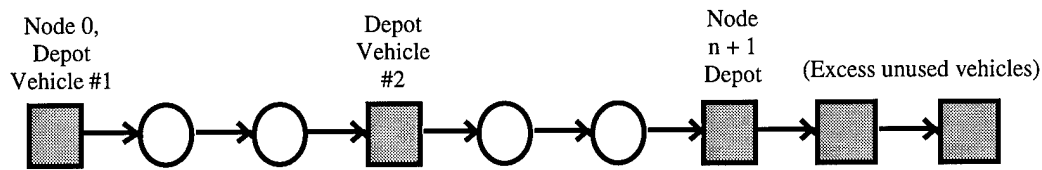


Figure 3. Disjunctive Graph representation of Tour

Positions 0 and $n + 1$ in this sequence represent depots, but are internally modeled as vehicles. Initially, the customers occupy positions between 1 and n_j . Excess vehicles occupy positions after the last depot.

2.3.2 Starting Solution

Several methods are used to generate starting, but not necessarily feasible, solutions for the RTS algorithm. The time window “midpoint” is defined as halfway between the end service time (a no later than time) and the earlier begin service time (a no earlier than time) for a particular customer. In order starting tour (OST), we generate a “starting solution” by sorting the customers into an increasing time window midpoint value while enforcing the time window feasibility condition. Since the RTS is not limited to feasible starting solutions, the initial solution can sequentially read the initial list of customers (OST OFF), or this list can be randomly reordered and read to create a random-starting tour (RST) with a different starting point (and possibly an improved solution).

2.3.3 Solution Neighborhood

This search routine uses a disjunctive graph formulation internally to represent solution tours. From this representation the solution neighborhood is defined by the use of swap and insertion moves. A swap move is performed by exchanging the position of two adjacent nodes, while an insertion uses a series of successive swap moves to relocate a specific customer forwards or backwards in the tour by a number of steps called the insertion depth (d).

Through the systematic use of these moves the RTS explores the vast solution space of the VRPTW. Starting with the initial solution, the algorithm searches insertion depths $d \geq 1$ later in the tour (for customers 1 to $n-1$) and explores earlier insertions for depths $d \leq -2$ (for customers 3 to n), comparing the candidate's change in objective function from that of the incumbent tour. To reduce the vast set of candidate moves in a neighborhood, redundant tours are eliminated and the restriction of strong time window infeasibility is applied.

Redundant tours are tracked through the use of a two-attribute hashing scheme. The first attribute, *hashing function* ($f(T)$), is the objective function value $Z(T)$. The second attribute, the *tour hashing value* (thv), takes the tour vector and calculates an integer value based on random integer values, $\Psi(i)$, and the index of the customer assigned to tour position i , τ_i (Woodruff and Zemel 1993), such that

$$thv(T) = \sum_{i=0}^n \Psi(\tau_i) * \Psi(\tau_{i+1}).$$

The tour hashing value attempts to minimize the possibility of a *collision*, or the incorrect identification of two tours as being identical or redundant when in fact they are distinct.

Additional attributes used to identify a solution are the tour cost, travel time, time window penalty, and total penalties. These integer values are concatenated in a string object that is uniquely identified in the Java programming language (java.util package) using the Hashtable class (Grand and Knudsen 1997). This unique numerical value is the “key” to identifying past solutions efficiently as well as accessing the “hash record”, where solution attributes are stored in their original form.

Strong window infeasibility states that whenever a vehicle leaves one node it can never arrive at the next node within its desired time window. Conversely, weak time window infeasible tours occur when only some departure times preclude a timely arrival at the next node. Unlike strong time window infeasibility, weak time window infeasible tours are evaluated in the search since insertion moves can ultimately reduce the amount of infeasibility in the overall tour. This is critical since past research has shown that feasible solution regions are isolated or disjoint in the solution space of these problems. In order to obtain an effective search, the method must investigate or accept infeasible solutions. This search of the infeasible region is facilitated through the use of penalty factors.

The ability to explore infeasible solutions represents a major advantage of this method for effectively exploring the solution space. First, instead of being restricted to regions of feasibility, RTS can traverse the regions of infeasibility to include using an infeasible initial solution. Second, the infeasible solutions recorded can be used in real world applications. For instance, an infeasible solution that produces very good results overall may become feasible with the relaxation of a constraint controlled by the decision-maker. These infeasible solutions represent the difficult choices faced by

managers trying to balance competing constraints when developing routes (this occurred in a delivery problem solved by Rochat and Semet in 1994).

From a solution neighborhood, the algorithm chooses the solution that results in the smallest move value. The move value is the difference between the incumbent tour's objective function value and the candidate's objective function value. The objective function value used in these initial tests includes change in travel time, change in waiting time, change in the time window penalty (lateness) and load penalty. With a relatively small amount of coding, the objective function can be expanded to include additional penalties, changed to represent several different weighted objective functions, or combined in a hierarchical objective function.

2.3.4 Tabu Criteria

Tabu search uses short-term memory to determine if a particular tour or attribute has already been visited by examining the attributes that comprise the tour. The examination must efficiently and reliably store and identify solution attributes previously visited during the search. We employ a "Tabulist" matrix of $(n+1)*(n+1)$ dimensions with row numbers corresponding to customer identification number and columns corresponding to the index or position of the customer in the solution tour. The data elements in this array store a value equal to the iteration number that existed when the customer moved into this position, plus the tabu length. Later in the search, this value will be compared to the current iteration to determine if this attribute is tabu.

2.3.5 Algorithm Complexity

The size of the neighborhood considered at each step is $O(nd)$ and the computation of the move value for each neighbor is $O(n)$. If the depth of the insertion moves is restricted to 1, the algorithm achieves a computational complexity of $O(n^2)$. Thus, the worst case complexity is $O(n^2d)$, where d is the depth of the allowable insertion moves. When the insertion depth is expanded, the computational complexity expands with it to $O(n^3)$. However, testing has shown empirically that considerably better times than $O(n^3)$ can be achieved, due to the strong time window infeasibility restriction (Carlton 1995).

1. Initialize starting variables (k max iterations) and structures
2. Compute time matrix
3. Select starting tour
 - a. Compute initial tour cost (Tour cost = Travel time + Penalty term)
 - b. Compute initial hashing values
4. While ($k \leq \text{niters}$)
 - a. Look for incumbent tour in the hashing structure
 - 1) If found, update the iteration when found, increase the tabu length if applicable
 - 2) If not found, add to the hashing structure, decrease the tabu length, if applicable
 - b. Evaluate all later insertions ($d \geq 1$, for customers 1 to $n-1$)
 - c. Evaluate all earlier insertions ($d \leq -2$, for customers 3 to n)
 - d. Move to the non-tabu neighbor. If all tours are tabu, move to the neighbor with the smallest move value, and reduce the tabu length.
 - e. Update the search
 - 1) Incumbent tour schedule
 - 2) Incumbent tour hashing value
 - 3) Retain the best feasible solution found and the tour with the smallest tour cost regardless of feasibility
 - f. $k = k+1$
5. Output results

Figure 4. RTS Pseudocode (Carlton 1995)

2.4 Testing and Validation

Initial testing and validation uses the Solomon VRPTW/mTSPTW problem test set; specifically the 25, 50 and 100 customer problems with random, clustered, and random clustered distribution patterns. Computational results are compared to optimal answers obtained by Desrochers et al. (1992) (Tables 1-6). The first column identifies the problem instance. The second through fifth columns present the results obtained with the Java implemented RTS algorithm, i.e., the objective function value of minimum travel time, number of vehicles required, iteration of best feasible solution and the time (seconds) at which the solution was found, respectively. Similar information is presented in columns six through eight for the optimal solutions obtained by Desrochers et al. (1992). Columns 9 and 10 display the difference in travel time and the percentage difference between the optimal answer (when known) and the result obtained from the RTS algorithm. The last column shows the RTS starting method used to achieve the solution. OST is the ordered starting tour (arranged by time window midpoints). RST is the random arrangement of customers followed by the integer seed used. Listed order (LO) indicates that the initial solution is taken in exact order presented in the problem.

All problems were solved by the RTS algorithm using 2500 iterations, with an overall solution quality better than 99% of optimal in a fraction of the computational time required for the optimal solution. The increase in computational time from the mTSPTW algorithm to the VRPTW algorithm was negligible because most of the structure for the VRPTW was already included in the Java code for the mTSPTW algorithm.

Table 1. Solomon mTSPTW (25 Customers)

Prob Set ¹	Ryer & O'Rourke				Optimal			Difference		Start Method ⁵
	Z _i (T)	Used	Iter ²	Time ³	Z _i (T)	Used	Time ⁴	Δ	Δ%	
R101	867.1	8	317	3	867.1	8	5.8	0.0	0.00%	OST
R102	797.1	7	35	1	797.1	7	20.3	0.0	0.00%	OST
R103	704.6	5	132	1	704.6	5	22.2	0.0	0.00%	OST
R104	666.9	4	86	1	666.9	4	46.0	0.0	0.00%	OST
R105	780.5	6	95	1	780.5	6	22.6	0.0	0.00%	OST
R106	715.4	5	28	0	715.4	5	205.2	0.0	0.00%	RST 0
R107	674.3	4	2080	23	674.3	4	304.1	0.0	0.00%	RST 2
R108	647.3	4	45	0	647.3	4	307.4	0.0	0.00%	OST
R109	691.3	5	21	0	691.3	5	14.4	0.0	0.00%	OST
R110	694.1	5	91	2	679.8	4	64.3	14.3	2.10%	RST 0
R111	678.8	4	178	2	678.8	4	330.3	0.0	0.00%	RST 0
R112	643.0	4	25	0	643.0	4	623.3	0.0	0.00%	LO
C101	2441.3	3	23	0	2441.3	3	18.6	0.0	0.00%	OST
C102	2440.3	3	379	4	2440.3	3	79.9	0.0	0.00%	LO
C103	2440.3	3	72	1	2440.3	3	134.7	0.0	0.00%	OST
C104	2436.9	3	797	8	2436.9	3	223.9	0.0	0.00%	OST
C105	2441.3	3	209	2	2441.3	3	25.6	0.0	0.00%	OST
C106	2441.3	3	26	1	2441.3	3	20.7	0.0	0.00%	OST
C107	2441.3	3	28	1	2441.3	3	31.7	0.0	0.00%	OST
C108	2441.3	3	1421	15	2441.3	3	43.1	0.0	0.00%	OST
C109	2441.3	3	148	1	2441.3	3	585.4	0.0	0.00%	OST
RC101	711.1	4	214	3	711.1	4	225.4	0.0	0.00%	LO
RC102	601.7	3	20	1	596.0	3	18.1	5.7	0.96%	OST
RC103	582.8	3	2193	24	582.8	3	103.0	0.0	0.00%	RST 2
RC104	556.6	3	604	6	556.6	3	177.9	0.0	0.00%	OST
RC105	661.2	4	79	1	661.2	4	37.4	0.0	0.00%	RST 1
RC106	595.5	3	60	1	595.5	3	248.4	0.0	0.00%	RST 1
RC107	548.3	3	69	1	548.3	3	113.9	0.0	0.00%	RST 0
RC108	544.5	3	2203	23	544.5	3	256.0	0.0	0.00%	OST
Average	1218.19	3.93	402.7	4.38	1184.8	3.90	148.6	0.69	0.11%	—

¹ Maximum number of vehicles: $m = 10$. Time window penalty: $p_{TW} = 1.0$.

² Maximum iterations: $k = 2500$.

³ Seconds on a Pentium II 400 MHz system. Total runtime ~ 28 seconds each.

⁴ Seconds on a SUN SPARK 1.

⁵ OST is ordered starting tour. RST # is random starting tour where # is the seed value. LO is listed ordering.

(O'Rourke 1999)

Table 2. Solomon mTSPTW (50 Customers)

Prob Set ¹	Ryer & O'Rourke				Optimal			Difference		Start Method ⁵
	Z _i (T)	Used	Iter ²	Time ³	Z _i (T)	Used	Time ⁴	Δ	Δ%	
R101	1543.8	12	239	9	1535.2	12	66.7	8.6	0.56%	RST 0
R102	1409.0	11	1939	78	1404.6	11	67.8	4.4	0.31%	RST 0
R103	1282.7	9	871	36	1272.5	9	8939.1	10.2	0.80%	OST
R104	1131.9	6	734	31	—	—	—	—	—	RST 0
R105	1401.6	9	402	15	1399.2	9	362.6	2.4	0.17%	LO
R106	1293.0	8	2294	94	1285.2	8	386.4	7.8	0.61%	RST 1
R107	1211.1	7	1786	75	1211.1	7	7362.1	0.0	0.00%	RST 0
R108	1117.7	6	1698	75	—	—	—	—	—	RST 0
R109	1286.7	8	1452	58	—	—	—	—	—	RST 0
R110	1207.8	7	1853	78	1197.0	7	4906.1	10.8	0.90%	RST 1
R111	1216.6	7	1775	72	—	—	—	—	—	RST 2
R112	1140.5	6	1784	78	—	—	—	—	—	RST 2
C101	4862.4	5	119	4	4862.4	5	67.1	0.0	0.00%	LO
C102	4861.4	5	607	19	4861.4	5	330.2	0.0	0.00%	LO
C103	4855.8	5	1699	57	—	—	—	—	—	OST
C104	4884.1	5	1253	43	—	—	—	—	—	LO
C105	4861.2	5	232	7	—	—	—	—	—	OST
C106	4862.4	5	308	9	4862.4	5	91.3	0.0	0.00%	LO
C107	4861.2	5	382	12	—	—	—	—	—	LO
C108	4861.2	5	92	3	—	—	—	—	—	LO
C109	4860.9	5	301	9	—	—	—	—	—	OST
RC101	1444.0	8	1252	38	—	—	—	—	—	RST 1
RC102	1325.1	7	754	23	—	—	—	—	—	RST 1
RC103	1216.2	6	1589	54	—	—	—	—	—	RST 0
RC104	1046.5	5	860	31	—	—	—	—	—	RST 2
RC105	1355.3	8	248	8	—	—	—	—	—	OST
RC106	1223.2	6	1921	61	—	—	—	—	—	RST 2
RC107	1146.0	6	189	7	—	—	—	—	—	LO
RC108	1098.1	6	1821	65	—	—	—	—	—	OST
Average	2374.7	6.66	1050	39.6	—	—	—	—	—	—

¹ Maximum number of vehicles: R sets $m = 15$; C sets $m = 6$; RC sets $m = 8$. Time window penalty: $p_{rw} = 3.0$.

² Maximum iterations: $k = 2500$.

³ Seconds on a Pentium II 400 MHz system. Total runtime ~ 100 seconds each.

⁴ Seconds on a SUN SPARK 1.

⁵ OST is ordered starting tour. RST # is random starting tour where # is the seed value. LO is listed ordering.

(O'Rourke 1999)

Table 3. Solomon mTSPTW (100 Customers)

Prob Set ¹	Ryer & O'Rourke				Optimal			Difference		Start Method ⁵
	Z(T)	Used	Iter ²	Time ³	Z(T)	Used	Time ⁴	Δ	Δ%	
R101	2689.6	20	2167	371	2607.7	18	1064.2	81.9	3.14%	RST 0
R102	2522.9	18	1783	322	2434.0	17	756.9	88.9	3.65%	RST 0
R103	2266.8	15	1797	351	—	—	—	—	—	RST 2
R104	2010.6	11	1401	311	—	—	—	—	—	RST 2
R105	2418.0	16	560	93	—	—	—	—	—	RST 1
R106	2256.9	14	1403	252	—	—	—	—	—	LO
R107	2091.6	12	1462	278	—	—	—	—	—	LO
R108	1980.3	10	2325	491	—	—	—	—	—	RST 0
R109	2191.4	13	2149	398	—	—	—	—	—	RST 1
R110	2121.1	12	1479	291	—	—	—	—	—	RST 2
R111	2082.1	12	1882	370	—	—	—	—	—	RST 2
R112	1986.1	11	2325	507	—	—	—	—	—	RST 1
C101	9827.3	10	285	45	9827.3	10	434.5	0.0	0.00%	OST
C102	9820.3	10	237	42	—	—	—	—	—	OST
C103	9813.7	10	256	49	—	—	—	—	—	OST
C104	9809.0	10	2495	536	—	—	—	—	—	RST 2
C105	9821.2	10	313	50	—	—	—	—	—	OST
C106	9827.3	10	455	75	9827.3	10	724.8	0.0	0.00%	OST
C107	9818.9	10	292	48	—	—	—	—	—	OST
C108	9818.9	10	662	115	—	—	—	—	—	OST
C109	9818.6	10	1381	262	—	—	—	—	—	LO
RC101	2685.7	16	897	144	—	—	—	—	—	OST
RC102	2534.0	15	2410	434	—	—	—	—	—	OST
RC103	2352.3	13	1047	195	—	—	—	—	—	RST 0
RC104	2209.1	11	1311	272	—	—	—	—	—	RST 2
RC105	2538.0	15	2327	412	—	—	—	—	—	RST 1
RC106	2457.8	14	443	74	—	—	—	—	—	RST 0
RC107	2236.9	12	1822	344	—	—	—	—	—	RST 0
RC108	2115.9	11	2206	451	—	—	—	—	—	RST 1
Average	4624.9	12.45	1365	261.48	—	—	—	—	—	—

¹ Maximum number of vehicles: $m = 25$. Time window penalty: $p_{TW} = 8.0$.

² Maximum iterations: $k = 2500$.

³ Seconds on a Pentium II 400 MHz system. Total runtime ~ 550 seconds each.

⁴ Seconds on a SUN SPARK 1.

⁵ OST is ordered starting tour. RST # is random starting tour where # is the seed value. LO is listed ordering.

(O'Rourke 1999)

Table 4. Solomon VRPTW (25 Customers)

Prob Set ¹	Ryer & O'Rourke				Optimal			Difference		Start Method ⁵
	Z _c (T)	Used	Iter ²	Time ³	Z _c (T)	Used	Time ⁴	Δ	Δ%	
R101	867.1	8	317	4	867.1	8	5.8	0.0	0.00%	OST
R102	797.1	7	35	1	797.1	7	20.3	0.0	0.00%	OST
R103	704.6	5	132	1	704.6	5	22.2	0.0	0.00%	OST
R104	666.9	4	86	2	666.9	4	46.0	0.0	0.00%	OST
R105	780.5	6	95	1	780.5	6	22.6	0.0	0.00%	OST
R106	715.4	5	1149	12	715.4	5	205.2	0.0	0.00%	RST 0
R107	674.3	4	2080	24	674.3	4	304.1	0.0	0.00%	RST 2
R108	647.3	4	58	1	647.3	4	307.4	0.0	0.00%	OST
R109	691.3	5	32	1	691.3	5	14.4	0.0	0.00%	OST
R110	694.1	5	91	1	679.8	4	64.3	14.3	2.10%	RST 0
R111	678.8	4	178	3	678.8	4	330	0.0	0.00%	RST 0
R112	643.0	4	25	1	643.0	4	623.3	0.0	0.00%	LO
C101	2441.3	3	23	0	2441.3	3	18.6	0.0	0.00%	OST
C102	2440.3	3	106	1	2440.3	3	79.9	0.0	0.00%	LO
C103	2440.3	3	72	1	2440.3	3	134.7	0.0	0.00%	OST
C104	2436.9	3	741	8	2436.9	3	223.9	0.0	0.00%	OST
C105	2441.3	3	170	1	2441.3	3	25.6	0.0	0.00%	OST
C106	2441.3	3	35	1	2441.3	3	20.7	0.0	0.00%	OST
C107	2441.3	3	51	0	2441.3	3	31.7	0.0	0.00%	OST
C108	2441.3	3	455	4	2441.3	3	43.1	0.0	0.00%	OST
C109	2441.3	3	197	2	2441.3	3	585.4	0.0	0.00%	OST
RC101	711.1	4	214	2	711.1	4	225.4	0.0	0.00%	LO
RC102	601.7	3	149	1	596.0	3	18.1	5.7	0.96%	OST
RC103	582.8	3	134	2	582.8	3	103.0	0.0	0.00%	RST 2
RC104	556.6	3	29	1	556.6	3	177.9	0.0	0.00%	LO
RC105	661.2	4	24	1	661.2	4	37.4	0.0	0.00%	RST 1
RC106	595.5	3	60	1	595.5	3	248.4	0.0	0.00%	RST 1
RC107	548.3	3	179	2	548.3	3	113.9	0.0	0.00%	RST 1
RC108	544.5	3	353	3	544.5	3	256.0	0.0	0.00%	LO
Average	1218.2	3.93	250.7	2.86	1184.8	3.90	148.6	0.69	0.11%	LO

¹ Maximum number of vehicles: $m = 10$. Time window penalty: $\rho_{TW} = 8.0$; load penalty $\rho_{LD} = 10.0$.

² Maximum iterations: $k = 2500$.

³ Seconds on a Pentium II 400 MHz system. Total runtime ~ 28 seconds each.

⁴ Seconds on a SUN SPARK 1.

⁵ OST is ordered starting tour. RST # is random starting tour where # is the seed value. LO is listed ordering.

(O'Rourke 1999)

Table 5. Solomon VRPTW (50 Customers)

Prob Set ¹	Ryer & O'Rourke				Optimal			Difference		Start Method ⁵
	Z _c (T)	Used	Iter ²	Time ³	Z _c (T)	Used	Time ⁴	Δ	Δ%	
R101	1543.8	12	239	9	1535.2	12	66.7	8.6	0.56%	RST 0
R102	1409.0	11	1939	82	1404.6	11	67.8	4.4	0.31%	RST 0
R103	1278.7	9	1935	87	1272.5	9	8939.1	6.2	0.49%	OST
R104	1137.4	6	1533	69	—	—	—	—	—	RST 2
R105	1401.6	9	402	16	1399.2	9	362.6	2.4	0.17%	LO
R106	1293.0	8	2294	99	1285.2	8	386.4	7.8	0.61%	RST 1
R107	1211.1	7	1786	79	1211.1	7	7362.1	0.0	0.00%	RST 0
R108	1117.7	6	1698	78	—	—	—	—	—	RST 0
R109	1286.7	8	1451	61	—	—	—	—	—	RST 0
R110	1207.8	7	1853	84	1197.0	7	4906.1	10.8	0.90%	RST 1
R111	1216.6	7	1775	76	—	—	—	—	—	RST 2
R112	1135.0	6	1456	68	—	—	—	—	—	RST 2
C101	4862.4	5	74	3	4862.4	5	67.1	0.0	0.00%	LO
C102	4861.4	5	232	9	4861.4	5	330.2	0.0	0.00%	LO
C103	4861.4	5	2035	87	4861.4	5	896.0	0.0	0.00%	RST 0
C104	4882.8	5	1727	79	—	—	—	—	—	RST 0
C105	4862.4	5	494	19	4862.4	5	99.1	0.0	0.00%	OST
C106	4862.4	5	91	4	4862.4	5	91.3	0.0	0.00%	LO
C107	4862.4	5	154	6	4862.4	5	170.6	0.0	0.00%	LO
C108	4862.4	5	95	4	4862.4	5	245.6	0.0	0.00%	LO
C109	4862.4	5	643	26	—	—	—	—	—	OST
RC101	1446.8	8	1613	60	—	—	—	—	—	OST
RC102	1331.8	7	1508	60	—	—	—	—	—	RST 2
RC103	1210.9	6	2194	94	—	—	—	—	—	OST
RC104	1046.5	5	412	18	—	—	—	—	—	LO
RC105	1355.3	8	104	4	—	—	—	—	—	OST
RC106	1223.2	6	1454	58	—	—	—	—	—	RST 2
RC107	1144.4	6	898	36	—	—	—	—	—	RST 1
RC108	1098.1	6	1361	58	—	—	—	—	—	OST
Average	2375.01	6.66	1153	49.4	—	—	—	—	—	—

¹ Maximum number of vehicles: $m = 15$. Time window penalty: $\rho_{TW} = 1.0$; load penalty $\rho_{LD} = 10.0$.

² Maximum iterations $k = 2500$.

³ Seconds on a Pentium II 400 MHz system. Total runtime ~ 100 seconds each.

⁴ Seconds on a SUN SPARK 1.

⁵ OST is ordered starting tour. RST # is random starting tour where # is the seed value. LO is listed ordering.

(O'Rourke 1999)

Table 6. Solomon VRPTW (100 Customers)

Prob Set ¹	Ryer & O'Rourke				Optimal			Difference		Start Method ⁵
	Z _i (T)	Used	Iter ²	Time ³	Z _i (T)	Used	Time ⁴	Δ	Δ%	
R101	2676.2	20	2271	414	2607.7	18	1064.2	68.5	2.63%	RST 2
R102	2502.4	19	492	96	2434.0	17	756.9	68.4	2.81%	RST 0
R103	2265.0	15	1091	228	—	—	—	—	—	RST 2
R104	2039.6	12	1488	338	—	—	—	—	—	OST
R105	2399.4	16	1974	378	—	—	—	—	—	RST 0
R106	2268.4	14	2431	491	—	—	—	—	—	LO
R107	2129.0	13	1905	406	—	—	—	—	—	RST 1
R108	1956.8	10	2415	565	—	—	—	—	—	RST 0
R109	2181.0	14	1587	311	—	—	—	—	—	RST 1
R110	2133.2	13	1548	328	—	—	—	—	—	RST 2
R111	2077.3	12	2248	491	—	—	—	—	—	RST 2
R112	1971.6	11	1898	460	—	—	—	—	—	RST 2
C101	9827.3	10	263	43	9827.3	10	434.5	0.0	0.00%	OST
C102	9827.3	10	1317	253	9827.3	10	1990.8	0.0	0.00%	OST
C103	9828.9	10	2500	535	—	—	—	—	—	RST 0
C104	9949.6	10	2194	509	—	—	—	—	—	RST 2
C105	9827.3	10	378	65	—	—	—	—	—	OST
C106	9827.3	10	309	55	9827.3	10	724.8	0.0	0.00%	OST
C107	9827.3	10	1144	210	9827.3	10	1010.4	0.0	0.00%	OST
C108	9827.3	10	1638	321	9827.3	10	1613.6	0.0	0.00%	OST
C109	9853.3	10	2202	463	—	—	—	—	—	RST 0
RC101	2669.9	16	2110	381	—	—	—	—	—	OST
RC102	2498.4	15	2136	419	—	—	—	—	—	LO
RC103	2363.6	13	1333	270	—	—	—	—	—	RST 1
RC104	2179.2	11	1365	308	—	—	—	—	—	LO
RC105	2557.4	15	2482	473	—	—	—	—	—	OST
RC106	2432.8	13	2222	434	—	—	—	—	—	RST 2
RC107	2266.1	12	2024	417	—	—	—	—	—	RST 2
RC108	2175.1	12	2122	475	—	—	—	—	—	RST 1
Average	4632.3	12.62	1693	349.6	—	—	—	—	—	—

¹ Maximum number of vehicles: $m = 25$. Time window penalty: $\rho_{TW} = 8.0$; load penalty $\rho_{LD} = 10.0$.

² Maximum iterations $k = 2500$.

³ Seconds on a Pentium II 400 MHz system. Total runtime ~ 550 seconds each.

⁴ Seconds on a SUN SPARK 1.

⁵ OST is ordered starting tour. RST # is random starting tour where # is the seed value. LO is listed ordering.

(O'Rourke 1999)

2.5 Extensions for Solving Mobility Routing Problems

The first step in transforming this algorithm from solving academic test problems to tackling global routing problems is transitioning from the x-y plane to geographic coordinates. This is accomplished in conjunction with the ability to determine an aircraft's groundspeed based on its associated true airspeed, the prevalent wind direction and speed.

To incorporate the effect of winds on the RTS algorithm, the distance and bearing is first calculated as shown in Departments of the Air Force and Navy's AFR 51-40. Given the departure latitude (L_1) and longitude (λ_1) and destination latitude (L_2) and longitude (λ_2), the great circle distance in nautical miles (D) can be found using the following formulation.

$$D = 60 * \cos^{-1} [\sin L_1 * \sin L_2 + \cos L_1 * \cos L_2 * \cos (\lambda_2 - \lambda_1)]$$

Using this distance, the heading angle (H) in degrees is

$$H = \cos^{-1} \left[\frac{\sin L_2 - \sin L_1 * \cos(D/60)}{\sin(D/60) * \cos L_1} \right].$$

Correcting this angle to the proper quadrant the initial true heading (Θ_{XY}) is

$$\Theta_{XY} = H \text{ if } \sin (\lambda_2 - \lambda_1) < 0$$

or

$$\Theta_{XY} = 360 - H \text{ if } \sin (\lambda_2 - \lambda_1) \geq 0.$$

Finally, using the bearing from the departure point to the destination point, current airspeed, wind speed and direction, a ground speed can be calculated. The true heading of the wind is represented by Θ_{WS} and the course offset from true heading from X to Y is

denoted by γ , thus adjusting heading for the wind drift. When the wind direction results in a headwind component, the angle between Θ_{XY} and Θ_{WS} (δ) is less than 90 degrees, The wind component of the groundspeed (A) becomes negative and thus reduces the overall groundspeed. Conversely, when winds result in a tailwind component, δ is greater than 90 degrees (Figure 5), A becomes positive and increases the overall groundspeed.

$$\cos(180 - \delta) = A/WS$$

$$A = WS \cdot \cos(180 - \delta)$$

$$\sin(180 - \delta) = C/WS$$

$$C = WS \cdot \sin(180 - \delta)$$

$$B^2 + C^2 = AS^2$$

$$B = \sqrt{AS^2 - C^2}$$

$$GS = A + B$$

$$GS = WS \cdot \cos(180 - \delta) + \sqrt{AS^2 - WS^2 \cdot \sin^2(180 - \delta)}$$

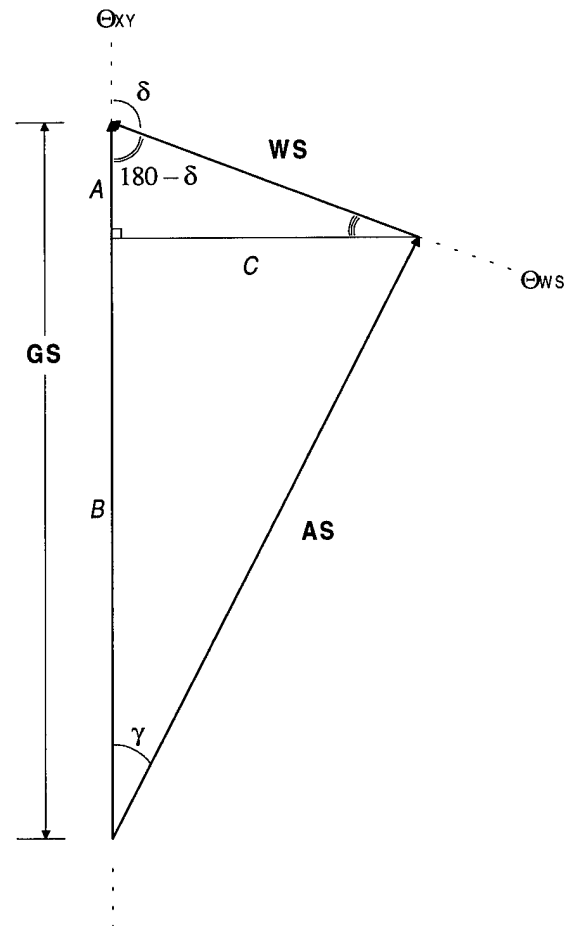


Figure 5. Calculation of Groundspeed to Account for Winds

With the translation to a real-world geographical coordinate representation complete, the time matrix used by the RTS can be updated to tackle realistic routing problems.

The second algorithm extension adds a restriction on possible routes based on the maximum leg distance for a vehicle. A simple search of those time matrix values that exceed the maximum leg distance, with the subsequent substitution of a very large value for such elements of the time matrix, precludes the RTS from selecting those routes in its final solution (unless no other feasible solution exists). In a similar manner we can restrict prohibited international flight routes by accessing the time matrix directly and assigning the same large value.

The next critical dimension of handling a global routing problem is an extension to handle multi-depot problems. This required additional logic to ensure vehicles assigned to different depots return to their respective starting depot while accounting for the change in travel time based on their respective depot location. Each vehicle node can be considered an aggregation of a return node for the previous vehicle and a start node for the next vehicle with zero cost between the two. Cost calculation "into" the node is assigned the distance from the customer back to its appropriate depot. This is allowed since multi-depot position integrity is maintained due the fact that vehicle ordering is strictly enforced by the algorithm. As implemented in this algorithm, multiple depots are modeled with the restriction that available vehicles be assigned to desired depots at the onset. Regardless of depot location, only those vehicles resulting in the best solution will be chosen.

2.6 Dimensions of the Mobility Routing Problem

When MASS flight plans a route, it evaluates the feasibility of fuel requirements, allowable cabin load (ACL), maximum on ground (MOG) feasibility, crew duty day

(CDD), and then updates the crew plan. This Aircraft Flight Plan Algorithm (AFPA) is capable of incorporating many of these considerations when selecting the routes during its search. Vehicle fuel requirement is implemented by the maximum leg restriction discussed earlier. Capacity constraints that represent the VRPTW can be extended in the future to include precedence for a pickup and delivery problem (PDP) version if required. Currently, MOG is captured by service and wait times. Crew duty day (not currently implemented) can be tracked by individual aircraft (since crews are modeled in MASS as a single entity), with a CDD clock refreshed either through mandatory waiting times or at bases that have rested crews available.

Time windows become necessary for two reasons. First, every AMC airlift scenario uses a document known as the Time-Phased Force Deployment Data (TPFDD) document, which specifies origins, destinations, cargo types, and their required delivery times (Cox 1998). Although these delivery times define the “not-earlier-than-time” (NET) and the “not-later-than-time” (NLT) for each individual piece of cargo, the NET and NLT can be used to derive the time window boundaries for origins and destinations. Time windows can also take into account normal operating hours of bases that are subject to the constraint of quiet hours.

Finally, the apparent problem of applying a VRP format (all destinations must be visited once – no more, no less) to an aircraft routing problem can be overcome with the inclusion of multiple customers at the same location. These customers share the total demand between them and may or may not have similar time windows. The algorithm determines the number of aircraft needed to service these destinations based on the capacity requirements and time window restrictions. Air refueling points are

incorporated as customers, with zero demand and service time, at strategic locations in the scenario, or at established air refueling tracks.

All these considerations are important and have a direct impact on route selection. Ignoring them and determining routes based on distance alone can not accurately represent the best routes needed for MASS. By starting with a simple scenario and adding these constraints, the effect on route selection becomes readily apparent. Deterministic approaches often reach their limit in ability to solve very basic VRPTW's when their size exceeds 50 customers.

The computational advantages of solving a real world problem, as well as the effect of additional constraints on route selection are shown using a notional problem involving the 50 United States capitals. A good feasible solution was obtained in less than 30 seconds on a Dell 266 Pentium II lap top computer (Figure 6). With the additional considerations of time windows, servicing, capacity and the possible use of multiple depots, the solution to the 50 U. S. capitals problem is altered dramatically (Figure 7).

The algorithm presented thus far uses a reactive tabu length to intensify and diversify the search. With the expansion of the algorithm to include additional constraints, the need for reactive penalty functions becomes essential. Reactive penalty functions presented by Gendreau and Laporte (1996) offer the benefit of incorporating reactive penalty parameters in their RTS algorithm. The penalty coefficients are set at an initial value ρ and then multiplied every ten iterations by $2^{[(t/5)-1]}$, where t is the number of feasible solutions among the last ten solutions. Based on the number of feasible solutions ρ is either increased or decreased accordingly. The resulting mix of feasible and

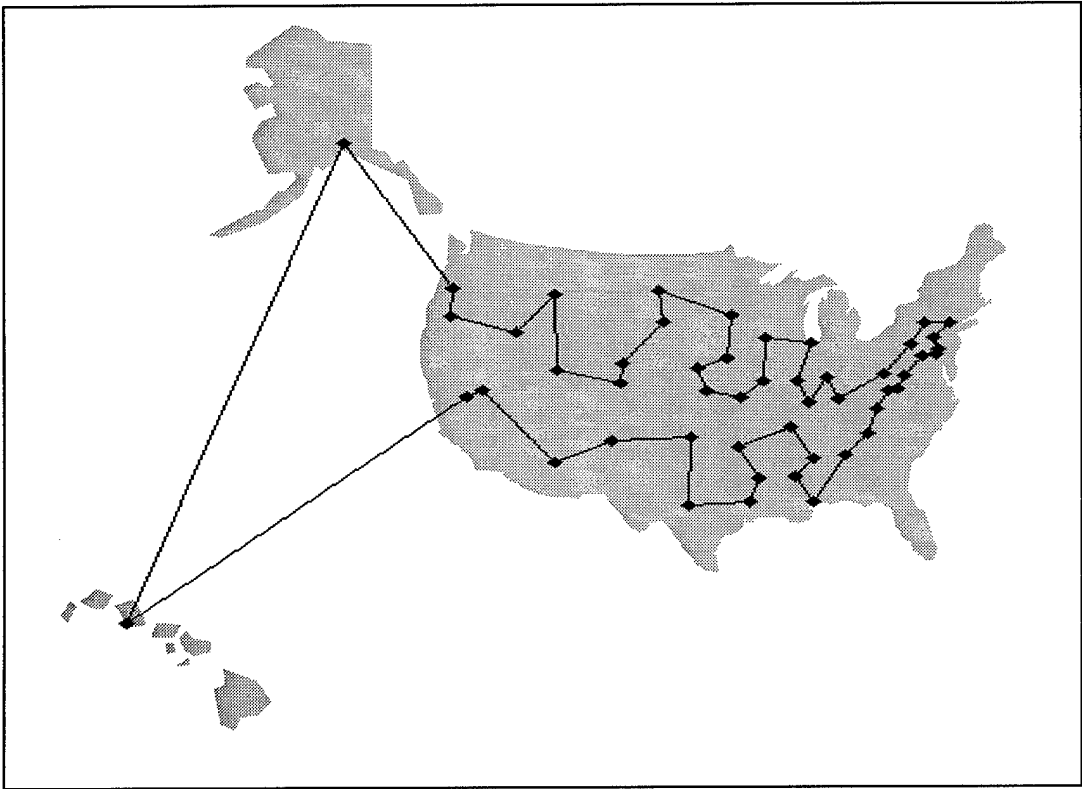
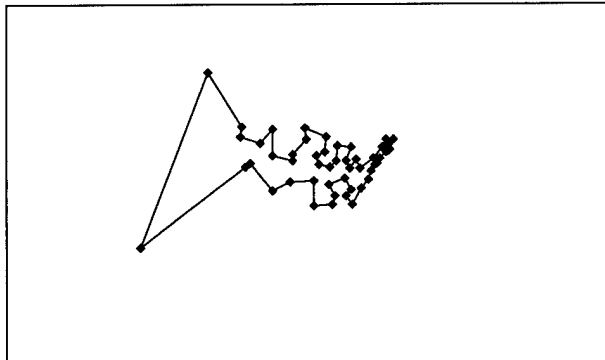
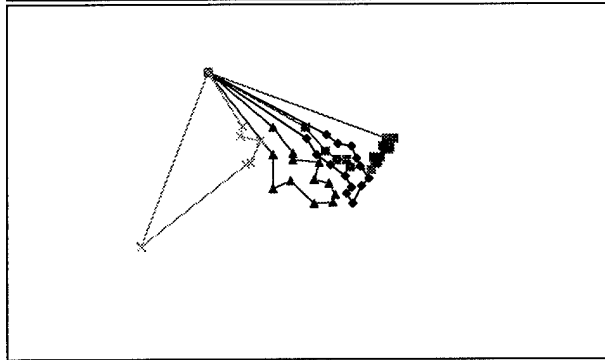


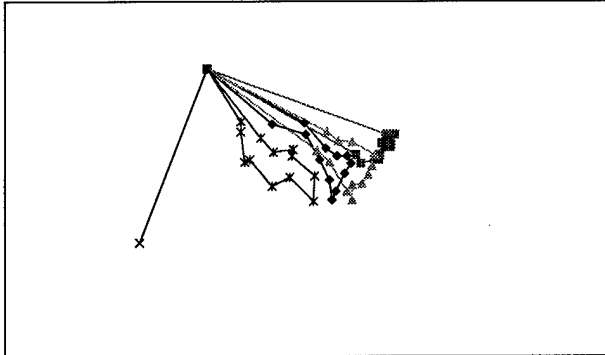
Figure 6. Solution of Simple TSP comprised of the 50 U. S. Capitals



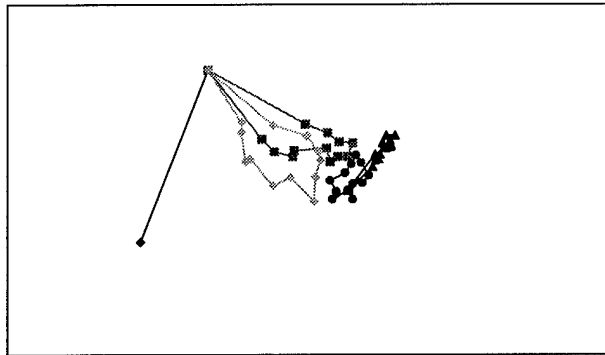
**Relaxed Scenario
(1 vehicle required)**



**Time Window and
Service Time Constraints
(4 vehicles required)**



**Capacity Constraints
(5 vehicles required)**



**Multiple Depots
(2 Depots – 5 vehicles required)**

Figure 7. Mobility Problem Constraints and their Effect on Route Selection

infeasible solutions improves the overall quality of the search (Gendreau and Laporte 1996).

The penalty terms used in the initial testing were previously determined to be effective by Carlton (1995). Usually, the process of determining these parameters is a difficult and tedious process. Reactive penalties update the penalty parameters associated with vehicle capacity, route duration, and time windows automatically during the execution of the algorithm. All of these penalty factors are relevant to the mobility problem and a reactive search based exploring these penalties is essential to exploring the solution space of these complex problems.

Two notional MASS scenarios are presented and solved in Figures 8 and 9. The first solution to a scenario was solved in 18 seconds but is too small to display the advantages of determining routes with a heuristic approach. The larger scenario (Figure 9) provided a solution in 36 seconds and was obtained after implementing the reactive penalties in addition to previous extensions of the initial algorithm. This scenario is taken from the hub and spoke mixed integer programming model presented by Cox (1998). The scope of this multi depot problem starts to display the enhanced capabilities of a heuristic approach. We note that integer-programming approach for this scenario required 18 to 94 hours to solve using version 3.0 CPLEX solver on a Sun Sparc station 10.

Maximum Number of Vehicles: 10
 Iterations: 2500
 Capacity: 112
 Time Window Penalty Factor: 8.0
 Load Overage Penalty Factor: 10.0

Best Feasible Cost/Travel Time $Z_1(t)$: 4773.0
 Best Tour Distance (travel time - serv. time): 4663.0
 Best Feasible total wait 830.1
 Best Feasible vehicle count: 4
 Best Feasible Time of Search: 9
 Best feasible iteration: 1271

Total Time of Search: 18

IB Customers	Latitude	Longitude	D
0 McGuire AFB	40 0.9 N	74 35.6 W	0
1 Ramstein AB	49 26.2 N	7 36 E	34
2 Barajas	40 29.5 N	3 34.1 W	10
3 Moron AB	37 10.5 N	5 37 W	23
4 Rota NS	36 38.8 N	6 20.8 W	20
5 Rhein Main AB	50 1.6 N	8 32.6 E	17
6 Heathrow	51 28.3 N	0 27.3 W	25
7 Charleston AFB	32 53.9 N	80 2.4 W	20
8 JFK Intl	40 38.4 N	73 46.7 W	24
9 Bahrain Intl	26 16.3 N	50 38 E	42
10 Dhahran Intl	26 15.9 N	50 9.1 E	45
11 King Aziz Intl	21 41.1 N	39 9.4 E	40
12 AR 13	36 20 N	20 0 E	0
13 AR 14	40 25 N	21 36 W	0

10 Vehicles Available @ McGuire AFB (Capacity 112)

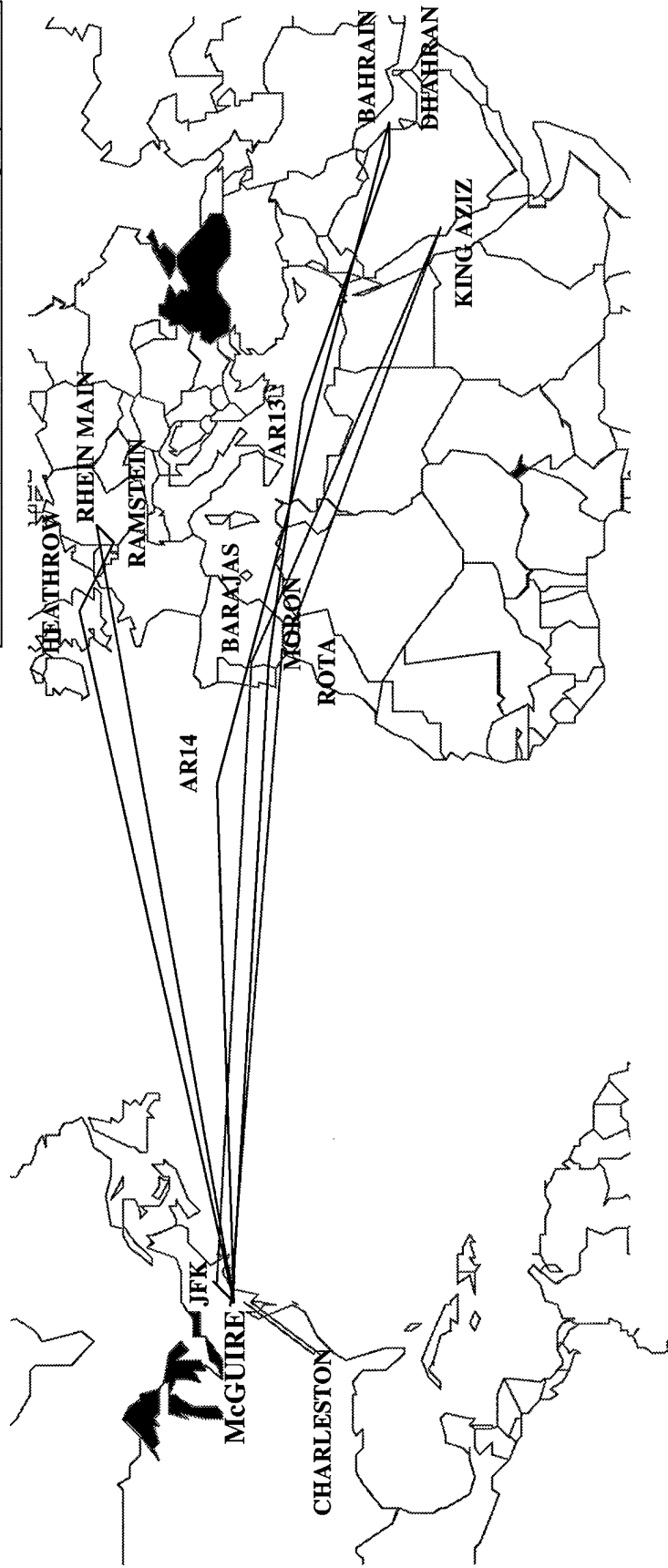


Figure 8: SOUTHWEST ASIA SCENARIO

Maximum Number of Vehicles: 10
 Iterations: 4000
 Capacity: 112
 Time Window Penalty Factor: 1000.0
 Load Overage Penalty Factor: 1000.0
 Best Feasible Cost/Travel Time Zt(0): 5173.3
 Best Feasible vehicle count: 4
 Best Feasible Time of Search: 23
 Best feasible iteration: 2655
 Total Time of Search: 36

16 Customers	Latitude	Longitude	D
1 YokotaAB	35	139	0
2 KadenaAB	26	127	0
3 OsanAB	37	127	57
4 OsanAB	37	127	49
5 KunsanAB	35	126	49
6 KunsanAB	35	126	69
7 TaeguAB	35	128	66
8 TaeguAB	35	128	54
9 N_AR_Point	55	176	0
10 S_AR_Point	53	178	0
11 N_AR_Point	55	176	0
12 S_AR_Point	55	178	0
13 N_AR_Point	55	176	0
14 S_AR_Point	53	178	0
15 N_AR_Point	55	176	0
16 S_AR_Point	53	178	0

10 Vehicles : Capacity 112
 5 @ McChord AFB, 5 @ Travis AFB

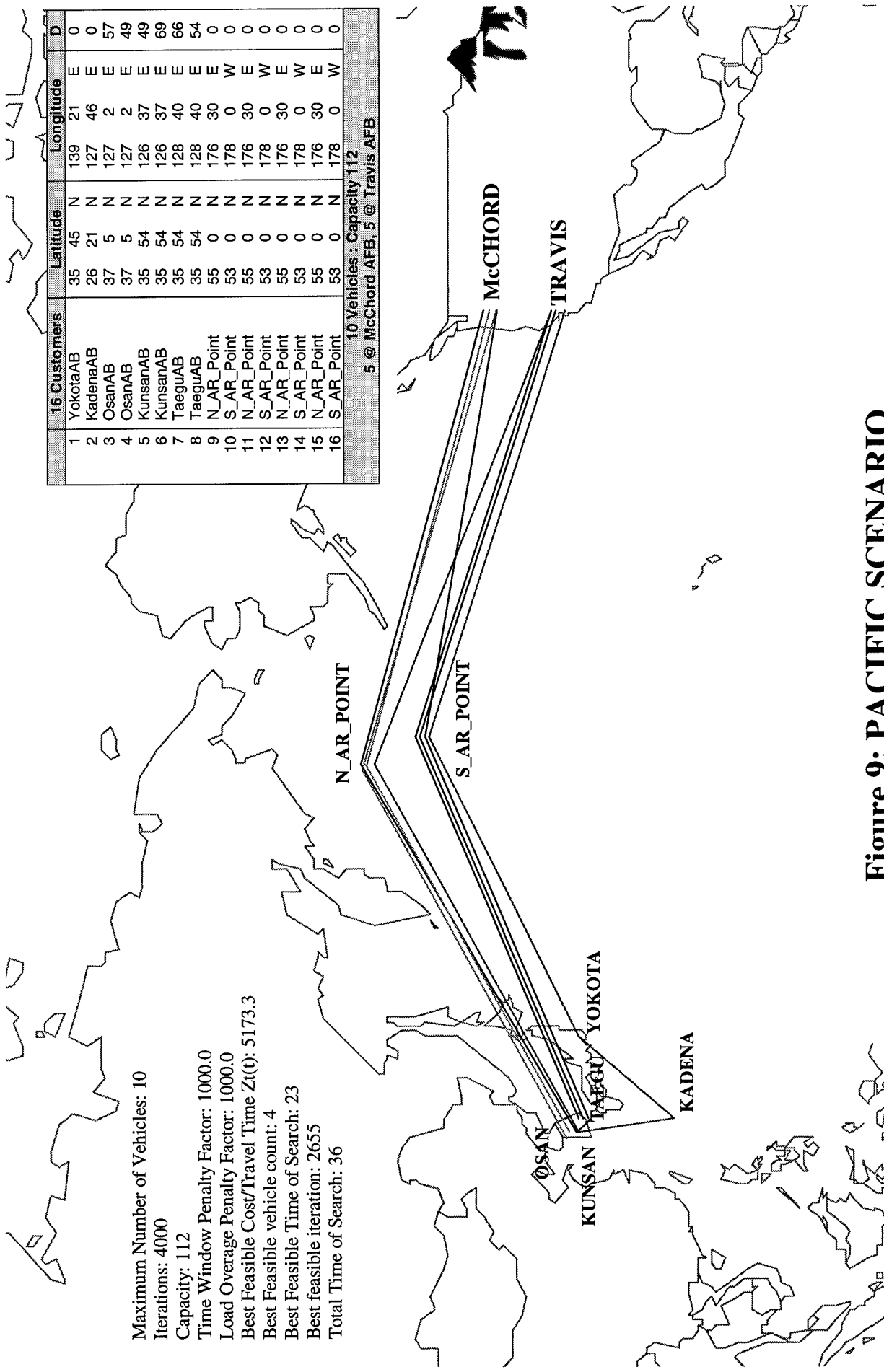


Figure 9: PACIFIC SCENARIO

2.7 Future Research

As heuristic research advances, it is more common to see two heuristic methods combined in a composite algorithm to achieve a better overall performance, as first observed by Ball and Magazine (1981). The benefits of randomness enjoyed by SA approaches can be employed in this RTS by an automatic restart capability. This extension would employ a random starting tour when a fixed number of iterations fails to find an improving solution. Based on testing, this addition appears to be more useful in solving smaller problems (25 customer). In larger problems, the best RTS solutions were obtained with a greater number of iterations; consequently, a reset feature would only be useful for searches involving large number of iterations. An approach similar to this using several constructive algorithms as starting points for solving TSP problems is presented by the Jump Search algorithm (Tsubakitani and Evans 1998). Using several good starting points and a simple local search, this algorithm shows improved results compared to a pure TS algorithm. The development of these composite approaches show promise in solving today's applied combinatorial problems.

One important extension of this project that can be employed is the explicit consideration of non-homogeneous vehicles. Modeling nonhomogenous vehicles is straightforward since the defining attributes are capacity and airspeed. Specifically, capacity can be based on a vehicle type, while airspeed requires another time matrix to be calculated for each vehicle.

The multiple depot problems presented are intended only to show the promise of the RTS algorithm. Extending the algorithm to an approach similar to that of Renaud et al. (1996) should be accomplished to efficiently solve larger multiple depot vehicle

routing problems. In this Fast improvement Intensification and Diversification algorithm (FIND) each customer is initially assigned to its nearest depot, and then a heuristic is applied to each depot's customer set. The fast improvement is accomplished by repeatedly applying three different types of exchanges, inter-depot (2-route exchanges between routes of different depots), intra-depot (2-route exchange between routes of the same depot) and 3-route (exchange vertices between three routes). The intensification step works on one depot at a time employing the intra-depot step to each depot in turn until no improvement is accomplished for 300 consecutive iterations. Finally, the diversification is accomplished through the repeated steps of best reinsertion between depots and inter-depot and intra depot steps while preventing moves that are tabu using a random tabulength.

2.8 Conclusion

Currently no optimization efforts are employed in MASS simulations. Earlier approaches tackled this same problem by considering only distance and route length constraints using two separate programs with run times exceeding half an hour. By contrast, our RTS algorithm can efficiently pick routes while explicitly incorporating distance, time windows, winds, vehicle capacity, vehicle range, service time, multiple depots, and -- with minor alterations -- heterogeneous vehicles. Written in the object-oriented Java programming language, it is a metaheuristic algorithm capable of running on any computer and solving large problems on a standard laptop PC in a fraction of the time required by deterministic approaches.

Previous route selection efforts outside of stochastic simulation, has centered deterministic efforts with the k-shortest path (Rink 1997), math programming (Cox 1998) and NRMO with a direct delivery deterministic linear programming model. Although useful for the purpose for which they were designed, all efforts are limited by the excessive computational time and effort required to solve complex routing problem in a mobility scenario.

The final goal of this research effort was to provide a software application that will provide a set of prioritized routes that will be used as a direct input into MASS. This automated and efficient route selection tool will provide quick and near optimum route selection without the need for an experienced analyst and numerous simulation replications needed in a trial and error approach. Although further development and calibration is necessary to accurately model the mobility system, many of the characteristics and considerations that comprise this complicated system can effectively be employed in this efficient yet powerful heuristic.

The benefits of optimizing tools are currently being realized throughout various transportation networks from snowplows to garbage trucks and from Delta Airlines to the United Parcel Service. In today's world of increasing technology and shrinking route infrastructure, the United States Air Force and Air Mobility Command can hardly afford not to implement available, proven, and smart algorithms in its modeling and airlift operations to increase efficiency, capability and Global Reach.

Appendix A: Extended Problem Formulation

Throughout my research I have encountered many good articles that are in turn used as reference sources for other published journals. But there is one particular reference that is used time and time again, in almost every article, journal or book written on the vehicle routing problem. This is the special issue "Routing and Scheduling of Vehicles and Crews, The State of the Art", *Computers & Operations Research* written by Lawrence Bodin, Bruce Golden, Arjang Assad, and Michael Ball (1983).

This 146-page special edition makes up the entire journal issue and covers a range of related problems such as the traveling salesman problem, vehicle routing problem, crew scheduling problem and combined routing and scheduling problems. The topics included in each section include a review of the problem background, formulation, and algorithms used to solve the problem. Although the content of this article is extensive and thorough, some sections such as current heuristic approaches suffer from the fact that it was published 16 years ago. Fortunately, the underlying basic formulation is unaffected and as relevant as ever.

Bodin et al. continues the discussion of routing problems into combining crew scheduling problems and vehicle routing problems. Unfortunately, the problem I want to formulate involves an expansion of the multiple depot VRP with multiple non-homogeneous vehicles. With minor changes in notation, I am able to pick up the formulation of this problem with the aid of Carlton's dissertation "A Tabu Search Approach to the General Vehicle Routing Problem" (1995).

A.1 Traveling Salesman Problem

The basic building block for studying the VRP is the traveling salesman problem (TSP). Without fully understanding the TSP, you can not hope to formulate and solve the more complex problem of the VRP. For this reason it is important to review the basic formulation of this problem. The first step is defining the TSP. Let G be our network with the set of nodes (N) and a set of branches (A) where and the associated costs of these branches is $C = c_{ij}$. Let's also assume that the costs are symmetric ($c_{ij} = c_{ji}$). The objective of this problem is to form a tour over all the nodes beginning and ending at the origin (node 1), which gives the minimum total tour length or cost.

The first half of this problem is the formulation of an assignment problem with only one arc (x_{ij}) starting at node i , and only one arc (x_{ij}) terminating at node j . for every node in N .

$$x_{ij} = \begin{cases} 1 & \text{if arc } i-j \text{ is in the tour} \\ 0 & \text{otherwise} \end{cases}$$

$$\text{Minimize } \sum_{i=1}^n \sum_{j=1}^n c_{ij} x_{ij}$$

$$\sum_{i=1}^n x_{ij} = b_j = 1 \quad (j = 1, \dots, n)$$

$$\sum_{j=1}^n x_{ij} = a_i = 1 \quad (i = 1, \dots, n)$$

$$X = (x_{ij}) \in S \quad x_{ij} = 0 \text{ or } 1 \quad (i, j = 1, \dots, n)$$

This is not the complete problem however, because subtours are not eliminated by this formulation. This is accomplished by the inclusion of subtour breaking constraints.

These constraints along with the assignment formulation prevent subtours from being formed. There are basically three different ways to represent the subtour breaking constraint (Bodin et al. 1983).

$$S = \{(x_{ij}): \sum_{i \in Q} \sum_{j \notin Q} x_{ij} \geq 1 \text{ for every nonempty proper subset } Q \text{ of } N\};$$

$$S = \{(x_{ij}): \sum_{i \in R} \sum_{j \in R} x_{ij} \leq |R| - 1 \text{ for every nonempty subset } R \text{ of } \{2, 3, \dots, n\}\};$$

$$S = \{(x_{ij}): y_i - y_j + nx_{ij} \leq n - 1 \text{ for } 2 \leq i \neq j \leq n \text{ for some real numbers } y_i\}.$$

The first representation states that every node subset (Q) of the set of nodes N must be connected to the other nodes in the solution. The second representation states that the arcs selected in our solution contain no cycles because if a cycle is present on R nodes, the solution must contain at least $|R|$ arcs. The third constraint is not so straightforward and needs a little more explanation. For this constraint let's define y_i as:

$$y_i = \begin{cases} t & \text{if node } i \text{ is visited on the } t^{\text{th}} \text{ step in a tour} \\ 0 & \text{otherwise.} \end{cases}$$

If an arc in the solution tour ($x_{ij} = 1$), this constraint becomes

$$t - (t + 1) + n \leq n - 1.$$

Conversely, everything outside the solution ($x_{ij} = 0$) simply reduces to

$$y_i - y_j \leq n - 1.$$

This third representation does have an advantage over the other two, adding only $n^2 - 3n + 2$ constraints, whereas the previous two add 2^n subtour breaking constraints to the problem's formulation (Bodin et al. 1983).

A.2 Multiple Traveling Salesman Problem

The next level of complexity in building up to the VRP is the addition of more salesman to the problem, creating the multiple traveling salesman problem (MTSP). Let M be the number of salesman or vehicles that make up our fleet. Our objective, once again, is to minimize the total distance traveled. We will assume that M salesman depart from the same depot and that each customer must be visited only once, and by only one salesman. Even with these changes the formulation is only an extension of the basic TSP presented earlier and is displayed below.

$$\begin{aligned}
 & \text{Minimize } \sum_{i=1}^n \sum_{j=1}^n c_{ij} x_{ij} \\
 & \sum_{i=1}^n x_{ij} = b_j = \begin{cases} M & \text{if } j = 1 \\ 1 & \text{if } j = 2, 3, \dots, n \end{cases} \\
 & \sum_{j=1}^n x_{ij} = a_i = \begin{cases} M & \text{if } i = 1 \\ 1 & \text{if } i = 2, 3, \dots, n \end{cases} \\
 & X = (x_{ij}) \in S \\
 & x_{ij} = 0 \text{ or } 1 \quad (i, j = 1, \dots, n)
 \end{aligned}$$

The first constraint in the formulation requires that all salesmen be used by forcing them to leave the depot. Likewise the second constraint requires all salesman to return to the depot. Any one of the subtour breaking constraints used earlier in the TSP can be used for the MTSP.

The apparent complexity of this new problem can be solved by simply reducing the MTSP to M copies of the TSP. This is accomplished by creating dummy depots (D_1, \dots, D_M) all connected to the original network. These M copies are either not connected, or are connected by cost prohibitive arcs. By transforming these single TSP

copies back to one common depot, the problem is now a series of M subtours, which is the MTSP. This relatively straightforward transformation of the MTSP helps us understand why an algorithm used to solve a TSP, can be used to solve a MTSP (Bodin et al. 1983).

A.3 Vehicle Routing Problem

The VRP can be viewed as an extension of the TSP, obtained by adding a capacity constraint to the salesman or vehicles. The VRP involves a number of vehicles (w) leaving a depot and servicing a number of customers (n), each with a unique demand (d_i). Each vehicle (v) has a limited capacity (K_v) and maximum time length for a route (T_v) that constrains their closed delivery routes. This particular instance of the VRP is commonly known as the general vehicle routing problem (GVRP). If the route length or range constraints are removed, then we refer to this problem as the standard vehicle routing problem (SVRP) (Bodin et. al, 1983). In addition to the cost (c_{ij}) or travel time of using an arc, consider the time required to for a vehicle v to deliver or service at node i is s_i^v , travel time for vehicle v from node i to node j as t_{ij}^v , and finally $x_{ij}^v = 1$ if arc i - j is used by vehicle v . From this, the formulation of the GVRP follows:

$$\text{Minimize } \sum_{i=1}^n \sum_{j=1}^n \sum_{v=1}^w c_{ij} x_{ij}^v \quad (3.1)$$

$$\text{Subject to } \sum_{i=1}^n \sum_{v=1}^w x_{ij}^v = 1 \quad (j = 2, \dots, n) \quad (3.2)$$

$$\sum_{j=1}^n \sum_{v=1}^w x_{ij}^v = 1 \quad (i = 2, \dots, n) \quad (3.3)$$

$$\sum_{i=1}^n x_{ip}^v - \sum_{j=1}^n x_{pj}^v = 0 \quad (v = 1, \dots, w; p = 1, \dots, n) \quad (3.4)$$

$$\sum_{i=1}^n d_i \left(\sum_{j=1}^n x_{ij}^v \right) \leq K_v \quad (v = 1, \dots, w) \quad (3.5)$$

$$\sum_{i=1}^n s_i^v \sum_{j=1}^n x_{ij}^v + \sum_{i=1}^n \sum_{j=1}^n t_{ij}^v x_{ij}^v \leq T_v \quad (v = 1, \dots, w) \quad (3.6)$$

$$\sum_{j=2}^n x_{1j}^v \leq 1 \quad (v = 1, \dots, w) \quad (3.7)$$

$$\sum_{i=2}^n x_{i1}^v \leq 1 \quad (v = 1, \dots, w) \quad (3.8)$$

$$X \in S \quad x_{ij}^v = 0 \text{ or } 1 \quad \text{for all } i, j, v$$

The objective function (3.1), minimizing the overall distance, remains the same but is formulated by summing over all the vehicles. Equations (3.2) and (3.3) make sure every customer is visited by one and only one vehicle. It is important to note that we are assuming that a customer's demand does not exceed vehicle capacity and each customer is fully serviced by the one vehicle that visits it. Equation (3.4) checks the continuity of our routes while (3.5) maintains the capacity constraint on all of the vehicles. Since we are representing route length restrictions by time, we use Equation (3.6) to insure maximum route time is not exceeded. Finally, Equations (3.7) and (3.8) insure that we do not use more vehicles than we have.

In addition to these equations we must once again include our subtour breaking constraints that will entail a slight modification to those used earlier in the TSP. Since the third subtour representation is the most efficient, we will use that formulation and expand it.

$$S = \{(x_{ij}^v): y_i^v - y_j^v + nx_{ij}^v \leq n-1 \text{ for } 2 \leq i \neq j \leq n \text{ for some real numbers } y_i^v\}$$

This simply applies the original subtour breaking constraint to each vehicle in turn. We can also eliminate some redundant constraints from the formulation above. Using (3.2) and (3.4) enforces (3.3) automatically and makes it unnecessary (Bodin et al. 1983). Likewise (3.4) and (3.7) imply (3.8) so this too can be eliminated from the formulation (Bodin et al. 1983).

Finally, one common restriction added to the VRP is time windows. Let a_j be the arrival time to node j , e_j be the earliest delivery time allowable and l_j be the no later than time for delivery. Using a nonlinear representation we get:

$$a_j = \sum_{v=1}^w \sum_{i=1}^n (a_i + s_i^v + t_{ij}^v) x_{ij}^v \quad (j = 1, \dots, n)$$

$$a_1 = 0$$

$$e_j \leq a_j \leq l_j \quad (j = 2, \dots, n)$$

For each j , one of the x_{ij}^v variables equals 1, so a_j is the sum of the previous arrival time (a_i), the service time at node i (s_i^v), and the travel time from i to j (t_{ij}^v). Alternatively we can use the linear representation of time windows constraint in the formulation (Bodin et al. 1983).

$$\left. \begin{aligned} a_j &\geq (a_i + s_i^v + t_{ij}^v) - (1 - x_{ij}^v) T_{max}^v \\ a_j &\leq (a_i + s_i^v + t_{ij}^v) + (1 - x_{ij}^v) T_{max}^v \end{aligned} \right\} \text{ for all } i, j, v$$

When $x_{ij}^v = 1$, the second half of the equation is eliminated and a_j is simply determined from the previous arrival time, previous service time and the travel time between the nodes. On the other hand, when $x_{ij}^v = 0$, the constraints are redundant.

A.4 Multiple Depot VRP

Expanding the previous GVRP to account for multiple bases of operation or depots gives us the multiple depot VRP. This problem can be formulated with only minor changes. Let M be the number of depots in our problem. First the original VRP formulation indexes are changed for equation (3.2), ($j = M + 1, \dots, n$), and equation (3.3), ($i = M + 1, \dots, n$). Next the constraints (3.7) and (3.8) must be changed to sum over all the depots individually in order to check that the number of vehicles being used does not exceed the number of vehicles on hand.

$$\sum_{i=1}^M \sum_{j=M+1}^n x_{ij}^v \leq 1 \quad (v = 1, \dots, w)$$

$$\sum_{p=1}^M \sum_{i=M+1}^n x_{ip}^v \leq 1 \quad (v = 1, \dots, w)$$

Of course, this change also includes an adjustment of the subtour breaking constraint. Although only one is used, we will show the changes for all three (Bodin et al. 1983).

$$S = \{(x_{ij}): \sum_{i \in Q} \sum_{j \notin Q} x_{ij} \geq 1 \text{ for every non empty proper subset } Q \text{ of } \{1, 2, \dots, n\} \text{ containing nodes } 1, 2, \dots, M\};$$

$$S = \{(x_{ij}): \sum_{i \in R} \sum_{j \in R} x_{ij} \leq |R| - 1 \text{ for every nonempty subset } R \text{ of } \{M + 1, M + 2, \dots, n\}\};$$

$$S = \{(x_{ij}): y_i - y_j + nx_{ij} \leq n - 1 \text{ for } M + 1 \leq i \neq j \leq n \text{ for some real numbers } y_i\}.$$

At this point the article, Bodin et al. continues into the discussion of combining crew scheduling problems and vehicle routing problems. Unfortunately, the problem I want to formulate involves an expansion of the multiple depot VRP to a multiple non-

homogeneous vehicle pick up and delivery problem. With minor changes in notation, I am able to pick up the formulation of this problem with the aid of Carlton (1995).

A.5 Pickup and Delivery Problem

The pickup and delivery problem (PDP) is a VRP that adds the precedence constraint. Precedence means that a package must be picked up at node i before it can be delivered to node j . With this added constraint, and some minor changes in notation, we finally arrive at the one of the most general routing problems studied. Simpler problems that must be formulated are simply a relaxation of this problem.

In this formulation, a superscript of (v, r) will be used corresponding to the specific vehicle v assigned to depot r . The customers are still indexed by i or j , each requiring a load d_i , to be picked up and delivered from node i to location $n + i$. The set of all depots is defined as D and the set of all vehicles as V .

The set of pickup locations are P^+ , where $|P^+| = n$, and the pickup locations will be numbered from 1 to n . The set of delivery locations are P^- , where $|P^-| = n$, and these delivery locations will be numbered from $n + 1$ to $2n$. The set of all pickup and delivery locations, $(P^+ \cup P^-)$, will be P and the set of all modeled pickup and delivery locations, customers and depots, will be referred to as N . Customer subscripts referring to a depot at the beginning of a tour are annotated as 0 and those at the end of a tour are labeled $2n+1$.

We also introduce a load variable Y_i indicating the total vehicle load at customer i . With these changes, the formulation of the multiple depot, multiple non-homogeneous vehicle, route length constrained, PDP with time windows is:

Objective Function

$$\text{Minimize } \sum_{r \in D} \sum_{v \in V} \sum_{i \in N} \sum_{j \in N} c_{ij}^{vr} x_{ij}^{vr}$$

Subject to:

Tour constraints:

$$\sum_{r \in D} \sum_{v \in V} \sum_{j \in N} x_{ij}^{vr} = 1 \quad \forall i \in P^+ \quad (4.1)$$

$$\sum_{j \in N} x_{ij}^{vr} - \sum_{j \in N} x_{ij}^{vr} = 0 \quad \forall i \in P, v \in V, r \in D \quad (4.2)$$

$$\sum_{j \in P^+} x_{0,j}^{vr} = 1 \quad \forall v \in V, r \in D \quad (4.3)$$

$$\sum_{i \in P^+} x_{i,2n+1}^{vr} = 1 \quad \forall v \in V, r \in D \quad (4.4)$$

$$\sum_{j \in N} x_{ij}^{vr} - \sum_{j \in N} x_{j,n+i}^{vr} = 0 \quad \forall i \in P^+, v \in V, r \in D \quad (4.5)$$

Precedence constraints:

$$a_i + s_i + t_{i,n+i}^{vr} \leq a_{n+i} \quad \forall i \in P^+ \quad (4.6)$$

$$\text{If } x_{ij}^{vr} = 1 \text{ then: } a_i + s_i + t_{ij}^{vr} \leq a_j \quad \forall i \in P, v \in V, r \in D \quad (4.7)$$

$$\text{If } x_{0,j}^{vr} = 1 \text{ then: } a_0^{vr} + t_{0,j}^{vr} \leq a_j \quad \forall i \in P^+, v \in V, r \in D \quad (4.8)$$

$$\text{If } x_{i,2n+1}^{vr} = 1 \text{ then: } a_i + s_i + t_{i,2n+1}^{vr} \leq a_{2n+1}^{vr} \quad \forall i \in P, v \in V, r \in D \quad (4.9)$$

Capacity constraints:

$$\text{If } x_{ij}^{vr} = 1 \text{ then: } Y_i^{vr} + d_j = Y_j^{vr} \quad \forall i \in P, j \in P^+, v \in V, r \in D \quad (4.10)$$

$$\text{If } x_{ij}^{vr} = 1 \text{ then: } Y_i^{vr} + d_{j-n} = Y_j^{vr} \quad \forall i \in P, j \in P^-, v \in V, r \in D \quad (4.11)$$

$$\text{If } x_{0,j}^{vr} = 1 \text{ then: } Y_0^{vr} + d_j = Y_j^{vr} \quad \forall j \in P^+, v \in V, r \in D \quad (4.12)$$

$$Y_0^{vr} = 0 \quad \forall v \in V, r \in D \quad (4.13)$$

$$0 \leq Y_i^{vr} \leq K^{vr} \quad \forall i \in P^+, v \in V, r \in D \quad (4.14)$$

Time Window Constraints:

$$e_i \leq a_i \leq l_i \quad \forall i \in P \quad (4.15)$$

$$e_0^{vr} \leq a_0^{vr} \leq l_0^{vr} \quad \forall v \in V, r \in D \quad (4.16)$$

$$e_{2n+1}^{vr} \leq a_{2n+1}^{vr} \leq l_{2n+1}^{vr} \quad \forall v \in V, r \in D \quad (4.17)$$

Binary Constraints:

$$x_{ij}^{vr} \in \{0,1\} \quad \forall i, j \in N, v \in V, r \in D$$

With the exception of the expanded notation, many of the constraints remain the same as those presented in earlier problems. The first group of constraints (4.1) - (4.5) are responsible for building the tours. Constraints (4.3) and (4.4) are responsible for making sure all vehicles are used by making them leave and return to the depot. If it is not necessary to use all vehicles in the problem then we can change the equality to a less than or equal to sign (Carlton, 1995). Finally constraint (4.5) requires the same vehicle that picks up a package to deliver it.

The precedence constraints (4.6) - (4.9) are the next group of constraints. When presented this way, the subtour breaking constraint used before, is essentially included in this formulation (Carlton, 1995). The use of service time and travel time insures a time order sequence of routes. The capacity constraints (4.10) - (4.14) are now tracked at every node as well as by vehicle. Finally, the representation of time windows (4.15) -

(4.17) is expanded to include hard time windows leaving and returning to the depots which enforces a limit on the possible route length.

Appendix B: Java Documentation

Class Hierarchy

- class `java.lang.Object`
- class `Convert`
- class `CoordType`
- class `CycleOut`
- class `HashMod`
- class `InFromKeybd`
- class `KeyObj`
- class `KeyToString`
- class `MTSPTW`
- class `BestSolnMod`
- class `TsptwPen`
- class `NoCycleOut`
- class `NodeType`
- class `PrintCalls`
- class `PrintFlag`
- class `ReacTabuObj`
- class `ReadFile`
- class `SearchOut`
- class `StartPenBestOut`
- class `StartTourObj`
- class `TabuMod`
- class `TimeMatrixObj`
- class `Timer`
- class `TsptwPenOut`
- class `TwBestTTOut`
- class `ValueObj`
- class `VrpPenType`

Index of all Fields and Methods

A

assignInputFile(String). Static method in class `ReadFile`
assignInputFile sets up the `FileInputStream`.

B

bearingXY(CoordType, CoordType, double). Static method in class `Convert`
bearingXY calculates the true bearing (in degrees) from one coordinate point to the second coordinate point and returns the value as a double precision number.

bestCost. Variable in class `SearchOut`

bestCost. Variable in class `StartPenBestOut`

Penalty related value.

bestCost. Variable in class TwBestTTOut
best tour related value.

bestiter. Variable in class SearchOut

bestiter. Variable in class StartPenBestOut
Penalty related value.

bestiter. Variable in class TwBestTTOut
best tour related value.

bestnv. Variable in class SearchOut

bestnv. Variable in class StartPenBestOut
Penalty related value.

bestnv. Variable in class TwBestTTOut
best tour related value.

BestSolnMod(). Constructor for class BestSolnMod

bestTime. Variable in class SearchOut

bestTime. Variable in class StartPenBestOut
Penalty related value.

bestTime. Variable in class TwBestTTOut
best tour related value.

bestTour. Variable in class SearchOut

bestTour. Variable in class StartPenBestOut
Saved tour.

bestTour. Variable in class TwBestTTOut
best tour related value.

bestTT. Variable in class SearchOut

bestTT. Variable in class StartPenBestOut
Penalty related value.

bestTT. Variable in class TwBestTTOut
best tour related value.

bfCost. Variable in class SearchOut

bfCost. Variable in class StartPenBestOut
Penalty related value.

bfCost. Variable in class TwBestTTOut
best tour related value.

bfiter. Variable in class SearchOut

bfiter. Variable in class StartPenBestOut
Penalty related value.

bfiter. Variable in class TwBestTTOut
best tour related value.

bfny. Variable in class SearchOut

bfny. Variable in class StartPenBestOut
Penalty related value.

bfny. Variable in class TwBestTTOut
best tour related value.

bfTime. Variable in class SearchOut

bfTime. Variable in class StartPenBestOut
Penalty related value.

bfTime. Variable in class TwBestTTOut
best tour related value.

bfTour. Variable in class SearchOut

bfTour. Variable in class StartPenBestOut
Saved tour.

bfTour. Variable in class TwBestTTOut
best tour related value.

bfTT. Variable in class SearchOut

bfTT. Variable in class StartPenBestOut

Penalty related value.

bfTT. Variable in class TwBestTTOut
best tour related value.

C

compPens(NodeType[], int). Static method in class NodeType
compPens computes the vehicle capacity overload and time window penalties.

compPens(NodeType[], int). Method in class VrpPenType
compPens computes the vehicle capacity overload and time window penalties.

Convert(()). Constructor for class Convert

CoordType(()). Constructor for class CoordType
Default constructor.

CoordType(String, double, double). Constructor for class CoordType
Lat/long constructor.

copy(()). Method in class NodeType

countVeh(NodeType[]). Static method in class NodeType
Method countVeh finds the number of vehicles being used in the current tour by counting the vehicle to demand transitions.

countVehicles(NodeType[]). Static method in class TabuMod
countVeh method calculates the number of vehicles used in the current tour by counting the number of vehicle (type 2) to demand (type 1) transitions.

cycle(ValueObj, double, int, int, int, double, int, int, PrintFlag). Static method in class TabuMod
cycle method updates the search parameters if the incumbent tour is found in the hashing structure.

CycleOut(()). Constructor for class CycleOut
Default constructor.

CycleOut(int, int, double, ValueObj). Constructor for class CycleOut
Specified constructor.

cyclePrint. Variable in class PrintFlag
print flag.

D

distanceXY(CoordType, CoordType). Static method in class Convert
distanceXY calculates the great circle distance (in nautical miles) between two coordinate points and returns the value as a double precision number.

DMMmtoDd(int, double). Static method in class Convert
DMMmtoDd converts a number in "Degrees Minutes Decimal Minutes" (D.MMm) format to "Degrees Decimal Degrees" (D.d) format.

DMMmtoDd(int, double, String). Static method in class Convert
DMMmtoDd converts a number in "Degrees Minutes Decimal Minutes" (D.MMm) format to "Degrees Decimal Degrees" (D.d) format.

DMMSSstoDd(int, int, double). Static method in class Convert
DMMSSstoDd converts a number in "Degrees Minutes Seconds Decimal Seconds" (D.MMSSs) format to "Degrees Decimal Degrees" (D.d) format.

DMMSSstoDd(int, int, double, String). Static method in class Convert
DMMSSstoDd converts a number in "Degrees Minutes Seconds Decimal Seconds" (D.MMSSs) format to "Degrees Decimal Degrees" (D.d) format.

E

endTime. Variable in class Timer
end time.

endTime(()). Method in class Timer
endTime assigns end time.

equals(KeyObj). Method in class KeyObj
Overloaded equals(), check only attribute fields.

equals(ValueObj). Method in class ValueObj
Overloaded equals(), check only attribute fields.

F

firstHashVal(int). Static method in class HashMod
firstHashVal method assigns the primary hashing value.

G

getEa(()). Method in class NodeType

getId(()). Method in class NodeType

getLa(()). Method in class NodeType

getLoad(()). Method in class NodeType

getM(()). Method in class NodeType

getQty(()). Method in class NodeType

getType(()). Method in class NodeType

getWait(()). Method in class NodeType

groundSpeed(double, double, double, double). Static method in class WindAdjust
groundSpeed method returns the ground speed given the heading between points, the wind heading, the wind speed, and the aircraft's airspeed.

H

hashCode(()). Method in class KeyObj
Overloaded hashCode method.

hashCode(()). Method in class ValueObj
Overloaded hashCode method.

HashMod(()). Constructor for class HashMod

HHMMtoMM(int). Static method in class Convert
HHMMtoMM converts a military time to the equivalent number of minutes (i.e., 0630 hours to 390 minutes) for use in time window and service time calculations.

HMMtoHh(int). Static method in class Convert
HMMtoHh converts a military specified time to the equivalent decimal hour equivalent (i.e., 0630 hours to 6.5 hours) for use in time window and service time calculations.

I

InFromKeybd(()). Constructor for class InFromKeybd

insert(NodeType[], int, int). Static method in class NodeType
Method insert allows the element designated by "chI" to be shifted by "chD" elements.

iterPrint. Variable in class PrintFlag
print flag.

K

keyDouble(String). Static method in class InFromKeybd
keyDouble allows user to enter a double from the keyboard.

keyFloat(String). Static method in class InFromKeybd
keyFloat allows user to enter a float from the keyboard.

keyInt(String). Static method in class InFromKeybd
keyInt allows user to enter an integer from the keyboard.

KeyObj(int, int, int, int, int, int). Constructor for class KeyObj
Specified constructor.

keyString(String). Static method in class InFromKeybd
keySting allows user to enter a string from the keyboard.

KeyToString(()). Constructor for class KeyToString

keyToString(int, int, int, int, int, int). Static method in class KeyToString
KeyToString Class converts the attributes of tour to a concatenated string used as a key to the hashtable of tours.

L

loadPrint. Variable in class PrintFlag
print flag.

lookFor(Hashtable, int, int, int, int, int, int, int). Static method in class HashMod
lookFor method searches for the current tour in the hashing structure, if the tour is found a true value for the boolean "found" is returned, if not found, the tour is added to the hashtable.

M

main(String[]). Static method in class MTSPTW
main executes MTSPTW problem.

mavg. Variable in class CycleOut
moving average.

MMtoHHMM(int). Static method in class Convert
MMtoHHMM converts a given number of minutes to a military time hour format (i.e., 390 minutes to 0630 hours) for human friendly output.

movePrint. Variable in class PrintFlag
print flag.

moveValTT(int, int, NodeType[], NodeType[], int[][]). Static method in class NodeType
Method moveValTT computes the incremental change in the value of the travel time from the incumbent tour to the proposed neighbor tour, and computes the neighbor schedule parameters preparing for computation of penalty terms.

moveValTT(int, int, NodeType[], NodeType[], int[][]). Static method in class TabuMod
Method moveValTT computes the incremental change in the value of the travel time from the incumbent tour to the proposed neighbor tour, and computes the neighbor schedule parameters preparing for computation of penalty terms.

MTSPTW(()). Constructor for class MTSPTW

N

noCycle(double, int, double, int, int, PrintFlag). Static method in class TabuMod
noCycle method updates the search parameters if the incumbent tour is not found in the hashing structure.

NoCycleOut(()). Constructor for class NoCycleOut
Default constructor.

NoCycleOut(int, int). Constructor for class NoCycleOut
Specified constructor.

NodeType(()). Constructor for class NodeType
Default constructor.

NodeType(int, int, int, int, int, int, int). Constructor for class NodeType
Specified constructor.

numfeas. Variable in class SearchOut

P

penTrav. Variable in class SearchOut

penTrav. Variable in class StartPenBestOut
Penalty related value.

penTrav. Variable in class TsptwPenOut
Penalty related value.

print(()). Method in class NodeType

PrintCalls(()). Constructor for class PrintCalls

PrintFlag(()). Constructor for class PrintFlag
Default PrintFlag constructor sets all to "true".

PrintFlag(boolean). Constructor for class PrintFlag
Additional PrintFlag constructor allows specification of either "true" or "false".

printInitVals(int, int, int, double, String). Static method in class PrintCalls

printTour(NodeType[]). Static method in class NodeType

R

randWtWZ(int, int, int). Static method in class HashMod
randWtWZ method computes Woodruff & Zemel random weights between 1 & range for all

nodes.

ReactTabuObj(). Constructor for class ReactTabuObj

ReadFile(). Constructor for class ReadFile

readNC(String). Static method in class TimeMatrixObj

readNC is used to read from the first token from the input file (the number of customers (nc)).

readNextDouble(StreamTokenizer). Static method in class ReadFile

readNextString method gets the next token and returns it as a double.

readNextInt(StreamTokenizer). Static method in class ReadFile

readNextString method gets the next token and returns it as an integer.

readNextString(StreamTokenizer). Static method in class ReadFile

readNextString method gets the next token and returns it as a string.

readNV(String). Static method in class TimeMatrixObj

readNV is used to read from the second token from the input file (the number of vehicles (nv)).

readTSPTW(double, int, int, String, CoordType[], int[]). Static method in class TimeMatrixObj

readTSPTW reads in the geographical coordinates and time window file and calculates the time between each node

readTSPTWdepot(double, int, int, String, CoordType[], int[]). Static method in class TimeMatrixObj

readTSPTWdepot reads in the geographical coordinates, load quantity, service time, and time window information associated with depot and customer locations from the input file.

rtsStepPrint(int, int, int, int, int, int, int, int). Static method in class PrintCalls

S

search(double, double, double, double, int, int, int, int, int, int, int, int, int, int, VrpPenType, int[][]), PrintFlag, int, int, int, int, int, int, int, int, int, int, int, int, int, int, int, int, NodeTypes[], NodeTypes[], NodeTypes[]). Static method in class ReactTabuObj

ReactTabuObj steps through iterations of the reactive tabu search.

SearchOut(). Constructor for class SearchOut

Default constructor.

SearchOut(int, int, int, int, int, int, int, int, int, int, int, int, int, int, VrpPenType, NodeTypes[], NodeTypes[], NodeTypes[]). Constructor for class SearchOut

Specified constructor.

secondHashVal(int, int, int, NodeTypes[], int[]). Static method in class HashMod

secondHashVal updates the Woodruff & Zemel second hashing value based on the tour insertion move.

setId(int). Method in class NodeTypes

setLoad(int). Method in class NodeTypes

setQty(int). Method in class NodeTypes

setType(int). Method in class NodeTypes

setWait(int). Method in class NodeTypes

ssltc. Variable in class CycleOut

ssltc. Variable in class NoCycleOut

cycle related variable.

startPenBest(int, int, int, NodeTypes[], double, double, int, int, int, int, VrpPenType, int, int, int, int, int, int, int, int, int, NodeTypes[], NodeTypes[]). Static method in class StartTourObj

startPenBest initializes "best" values and their times.

StartPenBestOut(). Constructor for class StartPenBestOut

Default constructor.

StartPenBestOut(int, int, int, int, int, int, int, int, int, int, int, int, int, VrpPenType, NodeTypes[], NodeTypes[]). Constructor for class StartPenBestOut

Specified constructor.

startPrint. Variable in class PrintFlag

print flag.

startTime. Variable in class Timer

begin time.

startTime(). Method in class Timer

startTime assigns start time.

startTour(NodeType[], int[[]], int, int). Static method in class NodeType
 Method startTour will bubble sort the initial tour based on the average time window time.

StartTourObj(()). Constructor for class StartTourObj

stepLoopPrint. Variable in class PrintFlag
 print flag.

stepPrint. Variable in class PrintFlag
 print flag.

sumWait(NodeType[]). Static method in class NodeType
 Method sumWait calculates the total "waiting" time in a particular tour by summing the wait values for each individual node.

swap(int, int). Static method in class MTSPTW
 Swap allows generic swap of integers.

swapInt(int, int). Static method in class NodeType
 Method swapInt switches two integers

swapNode(NodeType[], int, int). Static method in class NodeType
 Method swapNode allows the node array elements "a" and "b" to be swapped in the Node Array "z".

T

tabuLen. Variable in class CycleOut

tabuLen. Variable in class NoCycleOut
 cycle related variable.

TabuMod(()). Constructor for class TabuMod

timeMatrix(int, int, double, int, CoordType[], int[]). Static method in class TimeMatrixObj
 timeMatrix computes simple two-dimensional time/distance matrix.

timeMatrixDepot(int, int, double, int, CoordType[], int[]). Static method in class TimeMatrixObj
 timeMatrixDepot computes the two-dimensional array used as the "time" matrix.

TimeMatrixObj(()). Constructor for class TimeMatrixObj

timePrint. Variable in class PrintFlag
 print flag.

Timer(()). Constructor for class Timer
 Default constructor.

toString(()). Method in class KeyObj
 toString changes a KeyObj to a string for use in the hashTable.

toString(()). Method in class ValueObj
 toString changes a ValueObj to a string for use in the hashTable.

totalSeconds. Variable in class Timer
 duration of run.

totalSeconds(()). Method in class Timer
 totalSeconds returns duration.

totPenalty. Variable in class SearchOut

totPenalty. Variable in class StartPenBestOut
 Penalty related value.

totPenalty. Variable in class TsptwPenOut
 Penalty related value.

tour. Variable in class SearchOut

tourCost. Variable in class SearchOut

tourCost. Variable in class StartPenBestOut
 Penalty related value.

tourCost. Variable in class TsptwPenOut
 Penalty related value.

tourHVwz(NodeType[], int[]). Static method in class HashMod
 tourHVwz method computes the Woodruff & Zemel hashing value from the sum of adjacent node id multiplication.

tourPen. Variable in class SearchOut

tourPen. Variable in class StartPenBestOut

Tour penalty values.

tourSched(int, NodeType[], int[][]). Static method in class NodeType

Method tourSched should be called with the syntax tourLen = tourSched(nodeArray, time) from the orderStartingTour method.

TsptwPen(). Constructor for class TsptwPen

tsptwPen(int, NodeType[], VrpPenType, double, double, int, int, int, int). Static method in class TsptwPen

tsptwPen method uses the TW and load penalties to computes tourCost of tour as tour length + scaled penalty for infeasibilities.

tsptwPenNormalized(int, NodeType[], VrpPenType, double, double, int, int, int, int). Static method in class TsptwPen

tsptwPenNormalized method uses the TW and load penalties to computes tourCost of tour as tour length + scaled penalty for infeasibilities.

TsptwPenOut(). Constructor for class TsptwPenOut

Default constructor.

TsptwPenOut(int, int, int, int). Constructor for class TsptwPenOut

Specified constructor.

tv1. Variable in class SearchOut

tv1. Variable in class TsptwPenOut

Penalty related value.

twBestTT(int, int, int, int, int, int, NodeType[], int, int, int, int, int, int, int, int, NodeType[], NodeType[], int, int). Static method in class BestSolnMod

twBestTT compares current tour with previous best and best feasible tours and updates records accordingly.

TwBestTTOut(). Constructor for class TwBestTTOut

Default constructor.

TwBestTTOut(int, int, int, int, int, int, int, int, int, int, int, NodeType[], NodeType[]). Constructor for class TwBestTTOut

Specified constructor.

twrdPrint. Variable in class PrintFlag

print flag.

V

ValueObj(int, int, int, int, int, int, int). Constructor for class ValueObj

Specified constructor.

VrpPenType(). Constructor for class VrpPenType

Default constructor.

VrpPenType(int, int). Constructor for class VrpPenType

Specified constructor.

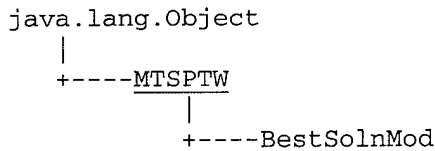
VrpPenType(int, int, int). Constructor for class VrpPenType

Specified constructor.

W

WindAdjust(). Constructor for class WindAdjust

Class BestSolnMod



public class **BestSolnMod**
extends MTSPTW BestSolnMod class retains the tours with the best travel times and tour costs.

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

Constructor Index

BestSolnMod()

Method Index

twBestTT(int, int, int, int, int, int, NodeType[], int, int, int, int, int, int, int, int, NodeType[], NodeType[], int, int)

twBestTT compares current tour with previous best and best feasible tours and updates records accordingly.

Constructors

BestSolnMod

```
public BestSolnMod()
```

Methods

twBestTT

```
public static TwBestTTOut twBestTT(int numnodes,
                                     int totPenalty,
                                     int penTrav,
                                     int tvl,
                                     int nvu,
                                     int iter,
                                     NodeType tour[],
                                     int bfCost,
                                     int bfTT,
                                     int bfnv,
                                     int bfiter,
                                     int bestCost,
                                     int bestTT,
                                     int bestnv,
                                     int bestiter,
                                     NodeType bfTour[],
                                     NodeType bestTour[],
                                     int bfTime,
                                     int bestTime)
```

twBestTT compares current tour with previous best and best feasible tours and updates records accordingly.

Returns:

returns packages output object.

Class Convert

```
java.lang.Object
|
+----Convert
```

public class **Convert**

extends Object Convert contains general conversion formulas applicable to location and distance calculations. Included are conversions between decimal format and hours-minutes-seconds format, great circle distance between two specified coordinates, and bearing from one point to another.

Version:

v1.1 Feb 99

Author:

Kevin P. O'Rourke, David M. Ryer

Constructor Index

Convert()

Method Index

bearingXY(CoordType, CoordType, double)

bearingXY calculates the true bearing (in degrees) from one coordinate point to the second coordinate point and returns the value as a double precision number.

distanceXY(CoordType, CoordType)

distanceXY calculates the great circle distance (in nautical miles) between two coordinate points and returns the value as a double precision number.

DMMmtoDd(int, double)

DMMmtoDd converts a number in "Degrees Minutes Decimal Minutes" (D.MMm) format to "Degrees Decimal Degrees" (D.d) format.

DMMmtoDd(int, double, String)

DMMmtoDd converts a number in "Degrees Minutes Decimal Minutes" (D.MMm) format to "Degrees Decimal Degrees" (D.d) format.

DMMSSstoDd(int, int, double)

DMMSSstoDd converts a number in "Degrees Minutes Seconds Decimal Seconds" (D.MMSSs) format to "Degrees Decimal Degrees" (D.d) format.

DMMSSstoDd(int, int, double, String)

DMMSSstoDd converts a number in "Degrees Minutes Seconds Decimal Seconds" (D.MMSSs) format to "Degrees Decimal Degrees" (D.d) format.

HHMMtoMM(int)

HHMMtoMM converts a military time to the equivalent number of minutes (i.e., 0630 hours to 390 minutes) for use in time window and service time calculations.

HMMtoHh(int)

HMMtoHh converts a military specified time to the equivalent decimal hour equivalent (i.e., 0630 hours to 6.5 hours) for use in time window and service time calculations.

MMtoHHMM(int)

MMtoHHMM converts a given number of minutes to a military time hour format (i.e., 390 minutes to 0630 hours) for human friendly output.

Constructors

Convert

```
public Convert()
```

Methods

DMMmtoDd

```
public static double DMMmtoDd(int degrees,  
                               double minutes)
```

DMMmtoDd converts a number in "Degrees Minutes Decimal Minutes" (D.MMm) format to "Degrees Decimal Degrees" (D.d) format. The D.MMm is the "human friendly" form of the data. The D.d format is required to readily perform distance calculations.

Parameters:

degrees - integer degree value of coordinate.
minutes - double minute value of coordinate.

Returns:

returns double Dd coordinate in the "degrees decimal degrees" format.

DMMmtoDd

```
public static double DMMmtoDd(int degrees,  
                               double minutes,  
                               String name)
```

DMMmtoDd converts a number in "Degrees Minutes Decimal Minutes" (D.MMm) format to "Degrees Decimal Degrees" (D.d) format. The D.MMm is the "human friendly" form of the data. The D.d format is required to readily perform distance calculations. This version of the method considers hemisphere and assigns a negative value if appropriate to south and east coordinates.

Parameters:

degrees - integer degree value of coordinate.
minutes - double minute value of coordinate.
name - string hemisphere value of coordinate (either "E", "W", "N", or "S").

Returns:

returns Dd coordinate in the "degrees decimal degrees" format.

DMMSSstoDd

```
public static double DMMSSstoDd(int degrees,  
                                 int minutes,  
                                 double seconds)
```

DMMSSstoDd converts a number in "Degrees Minutes Seconds Decimal Seconds" (D.MMSSs) format to "Degrees Decimal Degrees" (D.d) format. The D.MMSSs is the "human friendly" form of the data. The D.d format is required to readily perform distance calculations.

Parameters:

degrees - integer degree value of coordinate.
minutes - integer minute value of coordinate.
seconds - double second value of coordinate.

Returns:

returns Dd coordinate in the "degrees decimal degrees" format.

DMMSSstoDd

```
public static double DMMSSstoDd(int degrees,  
                                 int minutes,  
                                 double seconds,  
                                 String name)
```

DMMSSstoDd converts a number in "Degrees Minutes Seconds Decimal Seconds" (D.MMSSs) format to "Degrees Decimal Degrees" (D.d) format. The D.MMSSs is the "human friendly" form

of the data. The D.d format is required to readily perform distance calculations. This version of the method considers hemisphere and assigns a negative value if appropriate to south and east coordinates.

Parameters:

degrees - integer degree value of coordinate.
minutes - integer minute value of coordinate.
seconds - double second value of coordinate.
name - string hemisphere value of coordinate (either "E", "W", "N", or "S").

Returns:

returns Dd coordinate in the "degrees decimal degrees" format.

HMMtoHh

```
public static double HMMtoHh(int time)
```

HMMtoHh converts a military specified time to the equivalent decimal hour equivalent (i.e., 0630 hours to 6.5 hours) for use in time window and service time calculations.

Parameters:

time - integer whole minute "military format" (0630 hours) time value.

Returns:

returns Hh double fractional hour (6.5 hours) time value.

HHMMtoMM

```
public static int HHMMtoMM(int time)
```

HHMMtoMM converts a military time to the equivalent number of minutes (i.e., 0630 hours to 390 minutes) for use in time window and service time calculations.

Parameters:

time - integer whole minute "military format" (0630 hours) time value.

Returns:

returns MM integer number of minutes (390 minutes) time value.

MMtoHHMM

```
public static int MMtoHHMM(int time)
```

MMtoHHMM converts a given number of minutes to a military time hour format (i.e., 390 minutes to 0630 hours) for human friendly output.

Parameters:

time - integer number of minutes (390 minutes) time value.

Returns:

returns HHMM integer whole minute "military format" (0630 hours) time value.

distanceXY

```
public static double distanceXY(CoordType x,  
                                CoordType y)
```

distanceXY calculates the great circle distance (in nautical miles) between two coordinate points and returns the value as a double precision number.

Parameters:

x - CoordType coordinate of first position.
y - CoordType coordinate of second position.

Returns:

returns distanceXY double distance between the two points in nautical miles.

bearingXY

```
public static double bearingXY(CoordType x,  
                               CoordType y,  
                               double dXY)
```

bearingXY calculates the true bearing (in degrees) from one coordinate point to the second coordinate point and returns the value as a double precision number.

Parameters:

x - CoordType coordinate of first position.
y - CoordType coordinate of second position.
dXY - double distance between the first and second position, in nautical miles.

Returns:

returns thetaXY double initial true heading from the first point to the second point measured from true north in degrees.

Class CoordType

```
java.lang.Object
|
+----CoordType
```

public class **CoordType**

extends Object CoordType is used to hold coordinate location for customer/vehicle nodes. It contains fields for both x, y integer data and lat/long data, although only one set will be used.

Version:

v1.1 Feb 99

Author:

Kevin P. O'Rourke, David M. Ryer

Constructor Index

CoordType()

Default constructor.

CoordType(String, double, double)

Lat/long constructor.

Constructors

CoordType

```
public CoordType()
```

Default constructor. Assigns name to null and all values to zero.

CoordType

```
public CoordType(String nameLabel,
                  double lat,
                  double lon)
```

Lat/long constructor. Assigns name, latitude, and longitude as specified.

Class CycleOut

```
java.lang.Object
|
+----CycleOut
```

public class **CycleOut**

extends Object CycleOut is used as a package to output multiple fields from the class Cycle.

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

Variable Index

mavg

moving average.

ssltlc

tabuLen

Constructor Index

CycleOut()

Default constructor.

CycleOut(int, int, double, ValueObj)

Specified constructor.

ssltlc

```
public int ssltlc
```

tabuLen

```
public int tabuLen
```

mavg

```
public double mavg  
    moving average.
```

Constructors

CycleOut

```
public CycleOut()
```

Default constructor. Assigns all values to zero.

CycleOut

```
public CycleOut(int ssltlc,  
                int tabuLen,  
                double mavg,  
                ValueObj matchPtr)
```

Specified constructor. Values set as passed.

Class HashMod

```
java.lang.Object
```

```
|
```

```
+----HashMod
```

```
public class HashMod
```

extends Object HashMod Class contains methods to assign first and second hashing values (used in the hashtable) and the search method to search the hashtable.

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

Constructor Index

HashMod()

Method Index

firstHashVal(int)

firstHashVal method assigns the primary hashing value.

lookFor(Hashtable, int, int, int, int, int, int, int)

lookFor method searches for the current tour in the hashing structure, if the tour is found a true value for the boolean "found" is returned, if not found, the tour is added to the hashtable.

randWtWZ(int, int, int)

randWtWZ method computes Woodruff & Zemel random weights between 1 & range for all nodes.

secondHashVal(int, int, int, NodeType[], int[])

secondHashVal updates the Woodruff & Zemel second hashing value based on the tour insertion move.

tourHVwz(NodeType[], int[])

tourHVwz method computes the Woodruff & Zemel hashing value from the sum of adjacent node id multiplication.

Constructors

HashMod

```
public HashMod()
```

Methods

lookFor

```
public static boolean lookFor(Hashtable daHashTab,  
                             int fhv,  
                             int shv,  
                             int cost,  
                             int tvl,  
                             int twPen,  
                             int loadPen,  
                             int lastIter)
```

lookFor method searches for the current tour in the hashing structure, if the tour is found a true value for the boolean "found" is returned, if not found, the tour is added to the hashtable.

Parameters:

- daHashTab - hashtable object.
- fhv - First hashing value (objective function).
- shv - Second hashing value (Woodruff & Zemel).
- tourCost - Tour cost.
- tvl - Travel time.
- twPen - Time window penalty.
- loadPen - Load overage penalty.
- lastIter - Iteration on which the tour was previously found.

Returns:

returns true boolean value if the tour was previously found.

randWtWZ

```
public static final int[] randWtWZ(int ZRANGE,  
                                   int nc,  
                                   int numnodes)
```

randWtWZ method computes Woodruff & Zemel random weights between 1 & range for all nodes.

Parameters:

ZRANGE - maximum weight value.
nc - number of customers (targets).
numnodes - total number of nodes.

Returns:

returns integer array of "z" weights.

tourHVwz

```
public static final int tourHVwz(NodeType tour[],
                                int zArr[])
```

tourHVwz method computes the Woodruff & Zemel hashing value from the sum of adjacent node id multiplication.

Parameters:

tour - tour node array to be processed.
zArr - "z" array of random weights.

Returns:

returns secondary hashing value function (thv).

firstHashVal

```
public static final int firstHashVal(int zT)
```

firstHashVal method assigns the primary hashing value. Currently, it assigns the objective function as the first hashing value (fhv). Method can be updated as desired.

Parameters:

zT - objective function value.

Returns:

returns first hashing value (fhv).

secondHashVal

```
public static final int secondHashVal(int shv,
                                       int chI,
                                       int chD,
                                       NodeType tour[],
                                       int zArr[])
```

secondHashVal updates the Woodruff & Zemel second hashing value based on the tour insertion move.

Parameters:

shv - current tour hashing value.
chI - node insertion position.
chD - node insertion depth.
tour - tour node array for processing.
zArr - "z" array of random weights.

Returns:

returns updated hashing value to reflect insertion.

Class InFromKeybd

```
java.lang.Object
```

```
|
```

```
+----InFromKeybd
```

```
public class InFromKeybd
```

extends Object InFromKeybd class allows us to enter strings, integers, doubles and floats from the keyboard with a specified prompt.

Version:

v1.1 Feb 99

Author:

Kevin P. O'Rourke, David M. Ryer

Constructor Index

InFromKeybd()

Method Index

keyDouble(String)

keyDouble allows user to enter a double from the keyboard.

keyFloat(String)

keyFloat allows user to enter a float from the keyboard.

keyInt(String)

keyInt allows user to enter an integer from the keyboard.

keyString(String)

keyString allows user to enter a string from the keyboard.

Constructors

InFromKeybd

```
public InFromKeybd()
```

Methods

keyString

```
public static final String keyString(String prompt)
    keyString allows user to enter a string from the keyboard.
```

Parameters:

prompt - Text prompt printed on screen.

Returns:

returns user entered string.

keyInt

```
public static final int keyInt(String prompt)
    keyInt allows user to enter an integer from the keyboard.
```

Parameters:

prompt - Text prompt printed on screen.

Returns:

returns user entered integer.

keyDouble

```
public static final double keyDouble(String prompt)
    keyDouble allows user to enter a double from the keyboard.
```

Parameters:

prompt - Text prompt printed on screen.

Returns:

returns user entered double.

keyFloat

```
public static final float keyFloat(String prompt)
    keyFloat allows user to enter a float from the keyboard.
```

Parameters:

prompt - Text prompt printed on screen.

Returns:

returns user entered float.

Class KeyObj

```
java.lang.Object
|
+-----KeyObj
```

public final class **KeyObj**

extends Object KeyObj Class is used to access tour attributes in the hashtable for comparison.

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

Constructor Index

KeyObj(int, int, int, int, int, int)
Specified constructor.

Method Index

equals(KeyObj)
Overloaded equals(), check only attribute fields.

hashCode()
Overloaded hashCode method.

toString()
toString changes a KeyObj to a string for use in the hashTable.

Constructors

KeyObj

```
public KeyObj(int fhv,
              int shv,
              int cost,
              int tvl,
              int twPen,
              int loadPen)
```

Specified constructor. Values set as passed.

Methods

equals

```
public final boolean equals(KeyObj a)
    Overloaded equals(), check only attribute fields. Do not check first two data elements to keep
    inline with hashCode overload.
```

Parameters:

a - element compared calling object.

Returns:

returns true if objects are equal, false otherwise.

toString

```
public final String toString()
    toString changes a KeyObj to a string for use in the hashTable.
```

Returns:

returns concatenated String.

Overrides:

toString in class Object

hashCode

```
public final int hashCode()
```

Overloaded hashCode method. Note: if two objects are equal according to the equals method, then calling the hashCode method on each of the two objects must produce the same integer result. Only check first two data elements because of size limitations of Integer.

Returns:

returns integer hashcode value.

Overrides:

hashCode in class Object

Class KeyToString

```
java.lang.Object
|
+----KeyToString
```

public class **KeyToString**

extends Object **KeyToString** Class converts the attributes of tour to a concatenated string used as a key to the hashtable of tours.

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

Constructor Index

KeyToString()

Method Index

keyToString(int, int, int, int, int)

KeyToString Class converts the attributes of tour to a concatenated string used as a key to the hashtable of tours.

Constructors

KeyToString

```
public KeyToString()
```

Methods

keyToString

```
public static String keyToString(int fhv,
                                int shv,
                                int tourCost,
                                int tvl,
                                int twPen,
                                int loadPen)
```

KeyToString Class converts the attributes of tour to a concatenated string used as a key to the hashtable of tours.

Parameters:

fhv - First hashing value (objective function).

shv - Second hashing value (Woodruff & Zemel).

tourCost - Tour cost.

tv1 - Travel time.
twPen - Time window penalty.
loadPen - Load overage penalty.

Class **MTSPTW**

```
java.lang.Object
|
+----MTSPTW
```

public class **MTSPTW**
extends Object **MTSPTW** is the main part that implements the multiple traveling salesperson problem with time windows solve algorithm. This version calls the specific methods to read file input and generate the appropriate time matrix.

Version:
v1.1 Mar 99

Author:
Kevin P. O'Rourke, David M. Ryer

Constructor Index

MTSPTW()

Method Index

main(String[])
main executes **MTSPTW** problem.

swap(int, int)
Swap allows generic swap of integers.

Constructors

MTSPTW

```
public MTSPTW()
```

Methods

swap

```
public static void swap(int a,
                        int b)
    Swap allows generic swap of integers.
```

Parameters:

a - integer
b - integer

Returns:

returns void

main

```
public static void main(String argv[])
    main executes MTSPTW problem. Initializes global variables, calls methods to read data and wind files, calls method to compute time matrix, calls tabu search method, writes output to file.
```

Parameters:

nv - number of vehicles, overridden by file information
iters - number of iterations

integer - precision scaling factor
file - data file name, without extension (actual filename must end with .dat).
wind - file name, without extension (actual filename must end with .dat).
reroute - identifier. Use 111 (one one one) to specify reroute.

Class NoCycleOut

```
java.lang.Object
|
+----NoCycleOut
```

public class NoCycleOut
extends Object NoCycleOut is used as a package to output multiple fields from the method NoCycle.

Version:
v1.1 Mar 99

Author:
Kevin P. O'Rourke, David M. Ryer

Variable Index

ssltlc
cycle related variable.

tabuLen
cycle related variable.

Constructor Index

NoCycleOut()
Default constructor.

NoCycleOut(int, int)
Specified constructor.

Variables

ssltlc

```
public int ssltlc
cycle related variable.
```

tabuLen

```
public int tabuLen
cycle related variable.
```

Constructors

NoCycleOut

```
public NoCycleOut()
Default constructor. Assigns all values to zero.
```

NoCycleOut

```
public NoCycleOut(int ssltlc,
                  int tabuLen)
Specified constructor. Values set as passed.
```

Class NodeType

```
java.lang.Object
|
+----NodeType
```

public class **NodeType**

extends Object **NodeType** defines the relevant information of each particular node.

Version:

v1.1 Feb 99

Author:

Kevin P. O'Rourke, David M. Ryer

Constructor Index

NodeType()

Default constructor.

NodeType(int, int, int, int, int, int, int)

Specified constructor.

Method Index

compPens(NodeType[], int)

compPens computes the vehicle capacity overload and time window penalties.

copy()

countVeh(NodeType[])

Method countVeh finds the number of vehicles being used in the current tour by counting the vehicle to demand transitions.

getEa()

getId()

getLa()

getLoad()

getM()

getQty()

getType()

getWait()

insert(NodeType[], int, int)

Method insert allows the element designated by "chI" to be shifted by "chD" elements.

moveValTT(int, int, NodeType[], NodeType[], int[][])

Method moveValTT computes the incremental change in the value of the travel time from the incumbent tour to the proposed neighbor tour, and computes the neighbor schedule parameters preparing for computation of penalty terms.

print()

printTour(NodeType[])

setId(int)

setLoad(int)

setQty(int)

setType(int)

setWait(int)

startTour(NodeType[], int[][] , int, int)

Method startTour will bubble sort the initial tour based on the average time window time.

sumWait(NodeType[])

Method sumWait calculates the total "waiting" time in a particular tour by summing the wait values for each individual node.

swapInt(int, int)

Method swapInt switches two integers

swapNode(NodeType[], int, int)

Method swapNode allows the node array elements "a" and "b" to be swapped in the Node Array "z".

tourSched(int, NodeType[], int[][])

Method tourSched should be called with the syntax tourLen = tourSched(nodeArray, time) from the orderStartingTour method.

Constructors

NodeType

```
public NodeType()  
    Default constructor. Assigns all values to zero.
```

NodeType

```
public NodeType(int id,  
                int ea,  
                int la,  
                int qty,  
                int type,  
                int wait,  
                int load)  
    Specified constructor. Values set as passed.
```

Methods

copy

```
public final NodeType copy()
```

swapInt

```
public static final void swapInt(int a,  
                                 int b)
```

Method swapInt switches two integers

swapNode

```
public static final NodeType[] swapNode(NodeType z[],  
                                         int a,  
                                         int b)
```

Method swapNode allows the node array elements "a" and "b" to be swapped in the Node Array "z".

Parameters:

z - node array to be updated.
a - element to be swapped.
b - element to be swapped.

Returns:

returns updated node array.

insert

```
public static final NodeType[] insert(NodeType z[],  
                                       int chI,  
                                       int chD)
```

Method insert allows the element designated by "chI" to be shifted by "chD" elements. chD may be positive or negative.

Parameters:

z - node array to be updated.
chI - location of node to be moved.
chD - depth of move.

Returns:

returns updated node array.

countVeh

```
public static final int countVeh(NodeType tour[])
```

Method countVeh finds the number of vehicles being used in the current tour by counting the vehicle to demand transitions.

Parameters:

tour - node array to be processed.

Returns:

returns integer number of vehicles used in the tour.

sumWait

```
public static final int sumWait(NodeType tour[])
```

Method sumWait calculates the total "waiting" time in a particular tour by summing the wait values for each individual node.

Parameters:

tour - node array to be processed.

Returns:

returns integer value of total wait time in the tour.

compPens

```
public static final VrpPenType compPens(NodeType tour[],  
                                         int capacity)
```

compPens computes the vehicle capacity overload and time window penalties.

Parameters:

tour[] - current tour used to calculate penalties.

capacity - maximum vehicle load.

Returns:

returns the VrpPenType object which the method was called on with updated values.

tourSched

```
public static final int tourSched(int is,  
                                   NodeType tour[],  
                                   int time[][])
```

Method tourSched should be called with the syntax `tourLen = tourSched(nodeArray, time)` from the `orderStartingTour` method. This will use the listing of nodes to return the new `tourLen` value (tour duration). Additionally, the `nodeArray` will be updated to reflect the new arrival and departure times.

Parameters:

is - insertion/starting location for computation of schedule.

tour - node array to be processed.

time - time matrix used to determine schedule.

Returns:

returns integer total tour duration. Updates tour node array as appropriate.

startTour

```
public static final int startTour(NodeType tour[],  
                                   int time[][],  
                                   int nc,  
                                   int nv)
```

Method startTour will bubble sort the initial tour based on the average time window time. No swap is made if the move would violate strong time window infeasibility.

Parameters:

tour - node array to be processed.

time - time matrix used to determine schedule.

nc - number of customers.

nv - number of vehicles.

Returns:

returns integer total tour duration. Updates tour node array as appropriate.

getId

```
public final int getId()
```

getEa

```
public final int getEa()
```

getLa

```
public final int getLa()
```

getQty

```
public final int getQty()
```

getType

```
public final int getType()
```

getWait

```
public final int getWait()
```

getLoad

```
public final int getLoad()
```

getM

```
public final double getM()
```

setId

```
public final void setId(int id)
```

setWait

```
public final void setWait(int wait)
```

setType

```
public final void setType(int type)
```

setQty

```
public final void setQty(int qty)
```

setLoad

```
public final void setLoad(int load)
```

print

```
public final void print()
```

printTour

```
public static final void printTour(NodeType tour[])
```

moveValTT

```
public static int moveValTT(int i,  
                             int d,  
                             NodeType tour[],
```

```
NodeType nbrtour[],  
int time[][])
```

Method `moveValTT` computes the incremental change in the value of the travel time from the incumbent tour to the proposed neighbor tour, and computes the neighbor schedule parameters preparing for computation of penalty terms.

Parameters:

i - node position.
d - move depth.
tour - incumbent tour node array to be processed.
nbrtour - neighbor tour node array to be processed.
time - time matrix used to determine schedule.

Returns:

returns integer move value which is the resultant change in the objective function resulting from the proposed move.

See Also:

[compPens](#)

Class PrintCalls

```
java.lang.Object  
|  
+----PrintCalls
```

public class **PrintCalls**

extends Object **PrintCalls** is to display on the screen initial values and rts steps as required.

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

Constructor Index

PrintCalls()

Method Index

printInitVals(int, int, int, double, String)

rtsStepPrint(int, int, int, int, int, int, int, int)

Constructors

PrintCalls

```
public PrintCalls()
```

Methods

printInitVals

```
public static void printInitVals(int nv,  
                                int iters,  
                                int numcycles,  
                                double factor,  
                                String file)
```

rtsStepPrint

```
public static void rtsStepPrint(int id,  
                                int i,
```

```
int d,  
int k,  
int moveVal,  
int totNbrPen,  
int tabu,  
int numnodes)
```

Class PrintFlag

```
java.lang.Object  
|  
+----PrintFlag
```

public class **PrintFlag**
extends Object PrintFlag contains all print out flags as boolean attributes.

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

Variable Index

cyclePrint
print flag.

iterPrint
print flag.

loadPrint
print flag.

movePrint
print flag.

startPrint
print flag.

stepLoopPrint
print flag.

stepPrint
print flag.

timePrint
print flag.

twrdPrint
print flag.

Constructor Index

PrintFlag()
Default PrintFlag constructor sets all to "true".

PrintFlag(boolean)
Additional PrintFlag constructor allows specification of either "true" or "false".

Variables

movePrint

```
public boolean movePrint  
print flag.
```

startPrint

```
public boolean startPrint  
print flag.
```

timePrint

```
public boolean timePrint
    print flag.
```

stepPrint

```
public boolean stepPrint
    print flag.
```

stepLoopPrint

```
public boolean stepLoopPrint
    print flag.
```

twrdPrint

```
public boolean twrdPrint
    print flag.
```

cyclePrint

```
public boolean cyclePrint
    print flag.
```

iterPrint

```
public boolean iterPrint
    print flag.
```

loadPrint

```
public boolean loadPrint
    print flag.
```

Constructors

PrintFlag

```
public PrintFlag()
    Default PrintFlag constructor sets all to "true".
```

PrintFlag

```
public PrintFlag(boolean set)
    Additional PrintFlag constructor allows specification of either "true" or "false".
```

Class ReactTabuObj

```
java.lang.Object
|
+----ReactTabuObj
```

public class **ReactTabuObj**
extends Object ReactTabuObj class contains the method to perform the reactive tabu search.

Version:
v1.1 Mar 99

Author:
Kevin P. O'Rourke, David M. Ryer

Constructor Index

ReacTabuObj()

Method Index

search(double, double, double, double, int, int, int, int, int, int, int, int, int, int, VrpPenType, int[][],
PrintFlag, int, int, int, int, int, int, int, int, int, int, int, int, int, int, int, int, int, int, NodeType[], NodeType[],
NodeType[])

ReacTabuObj steps through iterations of the reactive tabu search.

Constructors

ReacTabuObj

```
public ReacTabuObj()
```

Methods

search

```
public static SearchOut search(double TWPEN,  
                                double LDPEN,  
                                double INCREASE,  
                                double DECREASE,  
                                int HTSIZE,  
                                int CYMAX,  
                                int ZRANGE,  
                                int DEPTH,  
                                int capacity,  
                                int minTL,  
                                int maxTL,  
                                int tabuLen,  
                                int iters,  
                                int nc,  
                                int numnodes,  
                                VrpPenType tourPen,  
                                int time[][],  
                                PrintFlag printFlag,  
                                int tourCost,  
                                int penTrav,  
                                int totPenalty,  
                                int tvl,  
                                int bfTourCost,  
                                int bfTT,  
                                int bfnv,  
                                int bfiter,  
                                int bestCost,  
                                int bestTT,  
                                int bestnv,  
                                int bestTime,  
                                int bestTimeF,  
                                int bestiter,  
                                int numfeas,  
                                NodeType tour[],  
                                NodeType bestTour[],  
                                NodeType bestTourF[])
```

ReacTabuObj steps through iterations of the reactive tabu search. This method will perform tabu search for VRP with capacity as well as TSP without capacity.

Returns:

returns packaged output object.

Class ReadFile

```
java.lang.Object
|
+----ReadFile
```

public class **ReadFile**

extends Object **ReadFile** Class reads appropriate data from a text file. Methods exist to read specific data types (file format must be known in advance).

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

Constructor Index

ReadFile()

Method Index

assignInputFile(String)

assignInputFile sets up the FileInputStream.

readNextDouble(StreamTokenizer)

readNextString method gets the next token and returns it as a double.

readNextInt(StreamTokenizer)

readNextString method gets the next token and returns it as a integer.

readNextString(StreamTokenizer)

readNextString method gets the next token and returns it as a string.

Constructors

ReadFile

```
public ReadFile()
```

Methods

assignInputFile

```
public static final FileInputStream assignInputFile(String filename)
assignInputFile sets up the FileInputStream.
```

readNextString

```
public static final String readNextString(StreamTokenizer st)
readNextString method gets the next token and returns it as a string.
```

Parameters:

st - string tokenizer.

Returns:

returns next string from file.

readNextDouble

```
public static final double readNextDouble(StreamTokenizer st)
readNextString method gets the next token and returns it as a double.
```

Parameters:

st - string tokenizer.

Returns:

returns next double from file.

readNextInt

```
public static final int readNextInt(StreamTokenizer st)
    readNextString method gets the next token and returns it as a integer.
```

Parameters:

st - string tokenizer.

Returns:

returns next integer from file.

Class SearchOut

```
java.lang.Object
|
+----SearchOut
```

public class **SearchOut**

extends Object SearchOut is used as a package to output multiple information from the Search method in ReacTabuObj.

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

See Also:

[Search](#)

Variable Index

[bestCost](#)

[bestiter](#)

[bestnv](#)

[bestTime](#)

[bestTour](#)

[bestTT](#)

[bfCost](#)

[bfiter](#)

[bfnv](#)

[bfTime](#)

[bfTour](#)

[bfTT](#)

[numfeas](#)

[penTrav](#)

[totPenalty](#)

[tour](#)

[tourCost](#)

[tourPen](#)

[tvI](#)

Constructor Index

[SearchOut\(\)](#)

Default constructor.

[SearchOut](#)(int, int, int, int, int, int, int, int, int, int, int, int, int, int, int, VrpPenType, NodeType[], NodeType[], NodeType[])

Specified constructor.

Variables

totPenalty

public int totPenalty

penTrav

public int penTrav

tourCost

public int tourCost

bfiter

public int bfiter

bfCost

public int bfCost

bfTT

public int bfTT

bestnv

public int bestnv

bestiter

public int bestiter

bestCost

public int bestCost

bestTT

public int bestTT

bfnv

public int bfnv

bfTime

public int bfTime

bestTime

public int bestTime

tvI

public int tvI

numfeas

public int numfeas

tourPen

public VrpPenType tourPen

tour

public NodeType tour[]

bfTour

```
public NodeType bfTour[]
```

bestTour

```
public NodeType bestTour[]
```

Constructors

SearchOut

```
public SearchOut()
```

Default constructor. Assigns all values to zero.

SearchOut

```
public SearchOut(int totPenalty,  
                int penTrav,  
                int tourCost,  
                int bfiter,  
                int bfCost,  
                int bfTT,  
                int bestnv,  
                int bestiter,  
                int bestCost,  
                int bestTT,  
                int bfnv,  
                int bfTime,  
                int bestTime,  
                int tvl,  
                int numfeas,  
                VrpPenType tourPen,  
                NodeType tour[],  
                NodeType bfTour[],  
                NodeType bestTour[])
```

Specified constructor. Values set as passed.

Class StartPenBestOut

```
java.lang.Object
```

```
|  
+----StartPenBestOut
```

```
public class StartPenBestOut
```

extends Object StartPenBestOut is used as a package to output multiple penalty information from method startPenBest.

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

Variable Index

bestCost

Penalty related value.

bestiter

Penalty related value.

bestnv Penalty related value.

bestTime Penalty related value.

bestTour Saved tour.

bestTT Penalty related value.

bfCost Penalty related value.

bfilter Penalty related value.

bfnv Penalty related value.

bfTime Penalty related value.

bfTour Saved tour.

bfTT Penalty related value.

penTrav Penalty related value.

totPenalty Penalty related value.

tourCost Penalty related value.

tourPen Tour penalty values.

Constructor Index

StartPenBestOut() Default constructor.

StartPenBestOut(int, int, int, int, int, int, int, int, int, int, int, VrpPenType, NodeType[], NodeType[]) Specified constructor.

Variables

totPenalty

```
public int totPenalty
    Penalty related value.
```

penTrav

```
public int penTrav
    Penalty related value.
```

tourCost

```
public int tourCost
    Penalty related value.
```

bfilter

```
public int bfilter
    Penalty related value.
```

bfCost

```
public int bfCost  
    Penalty related value.
```

bfTT

```
public int bfTT  
    Penalty related value.
```

bestnv

```
public int bestnv  
    Penalty related value.
```

bestiter

```
public int bestiter  
    Penalty related value.
```

bestCost

```
public int bestCost  
    Penalty related value.
```

bestTT

```
public int bestTT  
    Penalty related value.
```

bfnv

```
public int bfnv  
    Penalty related value.
```

bfTime

```
public int bfTime  
    Penalty related value.
```

bestTime

```
public int bestTime  
    Penalty related value.
```

tourPen

```
public VrpPenType tourPen  
    Tour penalty values.
```

bfTour

```
public NodeType bfTour[]  
    Saved tour.
```

bestTour

```
public NodeType bestTour[]  
    Saved tour.
```

Constructors

StartPenBestOut

```
public StartPenBestOut()  
    Default constructor. Assigns all values to zero.
```

StartPenBestOut

```

public StartPenBestOut(int totPenalty,
                      int penTrav,
                      int tourCost,
                      int bfiter,
                      int bfCost,
                      int bfTT,
                      int bestnv,
                      int bestiter,
                      int bestCost,
                      int bestTT,
                      int bfnv,
                      int bfTime,
                      int bestTime,
                      VrpPenType tourPen,
                      NodeType bfTour[],
                      NodeType bestTour[])

```

Specified constructor. Values set as passed.

Class StartTourObj

```

java.lang.Object
|
+----StartTourObj

```

public class StartTourObj

extends Object StartTourObj class begins timing, computes an initial schedule and initial tour cost (Tour Cost = Travel time + Waiting Time + Penalty Term), computes the initial hashing values: $Z(t)$ and $thv(t)$, and produces a tour based on a sort of increasing avg time windows at each node. The customers are ordered by increasing avg time window value, and the nv vehicle nodes are appended to the end of the tour.

Constructor Index

StartTourObj()

Method Index

startPenBest(int, int, int, NodeType[], double, double, int, int, int, int, VrpPenType, int, int, int, int, int, int, int, int, int, NodeType[], NodeType[])

startPenBest initializes "best" values and their times.

Constructors

StartTourObj

```

public StartTourObj()

```

Methods

startPenBest

```

public static StartPenBestOut startPenBest(int numnodes,
                                             int tvl,
                                             int tourLen,
                                             NodeType tour[],
                                             double TWPEN,
                                             double LDPEN,
                                             int capacity,
                                             int totPenalty,
                                             int penTrav,

```

```

int tourCost,
VrpPenType tourPen,
int bfilter,
int bfTourCost,
int bfTT,
int bfnv,
int bestiter,
int bestCost,
int bestTT,
int bestnv,
int bestTimeF,
int bestTime,
NodeType bestTour[],
NodeType bestTourF[])

```

startPenBest initializes "best" values and their times. Computes cost of initial tour as tour length with added penalty for infeasibilities.

Returns:

returns StartPenBestOut wrapper object for multiple values.

Class TabuMod

```

java.lang.Object
|
+----TabuMod

```

public class **TabuMod**

extends Object TabuMod Class contains methods used in the TabuSearch. countVeh calculates the number of vehicles used in the current tour. noCycle updates the search parameters if tour is not found in the hashtable. cycle updates the search parameters if tour is found in the hashtable. moveValTT computes the incremental change in the value of the travel time.

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

Constructor Index

TabuMod()

Method Index

countVehicles(NodeType[])

countVeh method calculates the number of vehicles used in the current tour by counting the number of vehicle (type 2) to demand (type 1) transitions.

cycle(ValueObj, double, int, int, int, double, int, int, PrintFlag)

cycle method updates the search parameters if the incumbent tour is found in the hashing structure.

moveValTT(int, int, NodeType[], NodeType[], int[][])

Method moveValTT computes the incremental change in the value of the travel time from the incumbent tour to the proposed neighbor tour, and computes the neighbor schedule parameters preparing for computation of penalty terms.

noCycle(double, int, double, int, int, PrintFlag)

noCycle method updates the search parameters if the incumbent tour is not found in the hashing structure.

Constructors

TabuMod

```
public TabuMod()
```

Methods

countVehicles

```
public static final int countVehicles(NodeType tour[])  
    countVeh method calculates the number of vehicles used in the current tour by counting the  
    number of vehicle (type 2) to demand (type 1) transitions.
```

Parameters:

tour - node array to be processed.

Returns:

returns integer number of vehicles used in the tour.

noCycle

```
public static NoCycleOut noCycle(double DECREASE,  
    int minTL,  
    double mavg,  
    int ssltfc,  
    int tabuLen,  
    PrintFlag printFlag)
```

noCycle method updates the search parameters if the incumbent tour is not found in the hashing structure.

Parameters:

DECREASE - adjustive scaling factor to reduce tabu length.

minTL - minimum tabu length.

mavg - moving average between cycles.

ssltfc - steps since last tabu length change.

tabuLen - current tabu length.

printFlag - option to print cycle information.

Returns:

returns noCycleOut wrapped object.

cycle

```
public static CycleOut cycle(ValueObj matchPtr,  
    double INCREASE,  
    int maxTL,  
    int CYMAX,  
    int k,  
    double mavg,  
    int ssltfc,  
    int tabuLen,  
    PrintFlag printFlag)
```

cycle method updates the search parameters if the incumbent tour is found in the hashing structure.

Parameters:

matchPtr - matched information for previously found identical tour

INCREASE - adjustive scaling factor to increase tabu length

maxTL - maximum tabu length

CYMAX - maximum allowable cycle frequency

k - current iteration

mavg - moving average between cycles.

ssltfc - steps since last tabu length change.

tabuLen - current tabu length.

printFlag - option to print cycle information.

Returns:

returns cycleOut wrapped object.

moveValTT

```
public static int moveValTT(int i,  
                             int d,  
                             NodeType tour[],  
                             NodeType nbrtour[],  
                             int time[][])
```

Method moveValTT computes the incremental change in the value of the travel time from the incumbent tour to the proposed neighbor tour, and computes the neighbor schedule parameters preparing for computation of penalty terms.

Parameters:

i - node position.
d - move depth.
tour - incumbent tour node array to be processed.
nbrtour - neighbor tour node array to be processed.
time - time matrix used to determine schedule.

Returns:

returns integer move value which is the resultant change in the objective function resulting from the proposed move.

See Also:

[compPens](#)

Class TimeMatrixObj

```
java.lang.Object  
|  
+----TimeMatrixObj
```

public class **TimeMatrixObj**

extends Object TimeMatrixObj contains methods to calculate the distance/time matrix based on the problem parameters.

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

Constructor Index

TimeMatrixObj()

Method Index

readNC(String)

readNC is used to read from the first token from the input file (the number of customers (nc)).

readNV(String)

readNV is used to read from the second token from the input file (the number of vehicles (nv)).

readTSPTW(double, int, int, String, CoordType[], int[])

readTSPTW reads in the geographical coordinates and time window file and calculates the time between each node

readTSPTWdepot(double, int, int, String, CoordType[], int[])

readTSPTWdepot reads in the geographical coordinates, load quantity, service time, and time window information associated with depot and customer locations from the input file.

timeMatrix(int, int, double, int, CoordType[], int[])

timeMatrix computes simple two-dimensional time/distance matrix.

timeMatrixDepot(int, int, double, int, CoordType[], int[])

timeMatrixDepot computes the two-dimensional array used as the "time" matrix.

Constructors

TimeMatrixObj

```
public TimeMatrixObj()
```

Methods

readNC

```
public static int readNC(String filein)
```

readNC is used to read from the first token from the input file (the number of customers (nc)).

Parameters:

filein - - name of input file

Returns:

returns nc number of customers

readNV

```
public static int readNV(String filein)
```

readNV is used to read from the second token from the input file (the number of vehicles (nv)).

Parameters:

filein - - name of input file

Returns:

returns nv number of vehicles

readTSPTW

```
public static NodeType[] readTSPTW(double factor,  
                                   int nv,  
                                   int nc,  
                                   String filein,  
                                   CoordType coord[],  
                                   int s[])
```

readTSPTW reads in the geographical coordinates and time window file and calculates the time between each node

Parameters:

factor - - integer scaling factor used to increase precision.

nv - - number of aircraft available (vehicles).

nc - - number of targets/route points (customers).

filein - - name of input file.

coord - - blank array where coordinates will be stored upon method completion.

s - - blank array where service times will be stored upon method completion.

Returns:

returns the tour array reflecting file data.

readTSPTWdepot

```
public static NodeType[] readTSPTWdepot(double factor,  
                                         int nv,  
                                         int nc,  
                                         String filein,  
                                         CoordType coord[],  
                                         int s[])
```

readTSPTWdepot reads in the geographical coordinates, load quantity, service time, and time window information associated with depot and customer locations from the input file. This information is returned as a tour array.

Parameters:

factor - - integer scaling factor used to increase precision.

nv - - number of aircraft available (vehicles).

nc - - number of targets/route points (customers).
filein - - name of input file.
coord - - blank array where coordinates will be stored upon method completion.
s - - blank array where service times will be stored upon method completion.

Returns:

returns the tour array reflecting file data.

timeMatrix

```
public static int[][] timeMatrix(int nc,
                                int gamma,
                                double factor,
                                int numnodes,
                                CoordType coord[],
                                int s[])
```

timeMatrix computes simple two-dimensional time/distance matrix.

Parameters:

nc - - number of targets/route points (customers).
gamma - - additional vehicle usage penalty (set to ZERO only).
factor - - integer scaling factor used to increase precision.
coord - - blank array where coordinates will be stored upon method completion.
s - - blank array where service times will be stored upon method completion.

Returns:

returns the time matrix specific to the problem.

timeMatrixDepot

```
public static int[][] timeMatrixDepot(int nc,
                                       int gamma,
                                       double factor,
                                       int numnodes,
                                       CoordType coord[],
                                       int s[])
```

timeMatrixDepot computes the two-dimensional array used as the "time" matrix. This time matrix contains the travel times between respective nodes, general setup for multiple depot problem.

Parameters:

nc - - number of targets/route points (customers).
gamma - - additional vehicle usage penalty (set to ZERO only).
factor - - integer scaling factor used to increase precision.
coord - - blank array where coordinates will be stored upon method completion.
s - - blank array where service times will be stored upon method completion.

Returns:

returns the time matrix specific to the problem.

Class Timer

```
java.lang.Object
|
+----Timer
```

public class **Timer**

extends Object Class is used to time overall computation time.

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

Variable Index

endTime

end time.

startTime

begin time.

totalSeconds

duration of run.

Constructor Index

Timer()

Default constructor.

Method Index

endTime()

endTime assigns end time.

startTime()

startTime assigns start time.

totalSeconds()

totalSeconds returns duration.

Variables

startTime

```
public long startTime
    begin time.
```

endTime

```
public long endTime
    end time.
```

totalSeconds

```
public long totalSeconds
    duration of run.
```

Constructors

Timer

```
public Timer()
    Default constructor. Assigns all values to zero.
```

Methods

startTime

```
public long startTime()
    startTime assigns start time.
```

Returns:

returns start time.

endTime

```
public long endTime()
    endTime assigns end time.
```

Returns:

returns end time.

totalSeconds

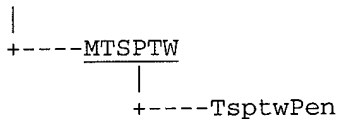
```
public long totalSeconds()
    totalSeconds returns duration.
```

Returns:

returns duration.

Class TsptwPen

```
java.lang.Object
```



```
public class TsptwPen
```

extends MTSPTW tsptwPen class: Given the TW and load penalties, this procedure personalizes the penalties to the mTSPTW; Computes tourCost of tour as tour length + scaled penalty for infeasibilities.

Constructor Index

TsptwPen()

Method Index

tsptwPen(int, NodeType[], VrpPenType, double, double, int, int, int, int)

tsptwPen method uses the TW and load penalties to computes tourCost of tour as tour length + scaled penalty for infeasibilities.

tsptwPenNormalized(int, NodeType[], VrpPenType, double, double, int, int, int, int)

tsptwPenNormalized method uses the TW and load penalties to computes tourCost of tour as tour length + scaled penalty for infeasibilities.

Constructors

TsptwPen

```
public TsptwPen()
```

Methods

tsptwPen

```
public static final TsptwPenOut tsptwPen(int tourLen,
                                           NodeType tour[],
                                           VrpPenType tourPen,
                                           double TWPEN,
                                           double LDPEN,
                                           int totPenalty,
                                           int tourCost,
                                           int penTrav,
                                           int tvl)
```

tsptwPen method uses the TW and load penalties to computes tourCost of tour as tour length + scaled penalty for infeasibilities. This method is used with the absolute penalty factors.

Parameters:

tourLen - tour duration.

tour - node array to be processed.

tourPen - current tour penalty value.

TWPEN - time window penalty factor.

LDPEN - load overage penalty factor.

totPenalty - sum total penalties.

tourCost - total tour cost.
penTrav - travel time penalty.
tv1 - travel duration.

Returns:

returns wrapped multiple objects.

tsptwPenNormalized

```
public static final TsptwPenOut tsptwPenNormalized(int tourLen,  
                                                    NodeType tour[],  
                                                    VrpPenType tourPen,  
                                                    double TWPEN,  
                                                    double LDPEN,  
                                                    int totPenalty,  
                                                    int tourCost,  
                                                    int penTrav,  
                                                    int tv1)
```

tsptwPenNormalized method uses the TW and load penalties to computes tourCost of tour as tour length + scaled penalty for infeasibilities. This method is uses penalty factors of one and is called when the insertion move is made. Penalty values are then comparable from iteration to iteration.

Parameters:

tourLen - tour duration.
tour - node array to be processed.
tourPen - current tour penalty value.
TWPEN - time window penalty factor (IGNORED, set to 1).
LDPEN - load overage penalty factor (IGNORED, set to 1).
totPenalty - sum total penalties.
tourCost - total tour cost.
penTrav - travel time penalty.
tv1 - travel duration.

Returns:

returns wrapped multiple objects.

Class TsptwPenOut

```
java.lang.Object  
|  
+----TsptwPenOut
```

public class **TsptwPenOut**

extends Object TsptwPenOut is used as a package to output multiple penalty information from class TsptwPen.

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

Variable Index

penTrav

Penalty related value.

totPenalty

Penalty related value.

tourCost

Penalty related value.

tv1

Penalty related value.

Constructor Index

TsptwPenOut()

Default constructor.

TsptwPenOut(int, int, int, int)

Specified constructor.

Variables

totPenalty

```
public int totPenalty
    Penalty related value.
```

tourCost

```
public int tourCost
    Penalty related value.
```

penTrav

```
public int penTrav
    Penalty related value.
```

tv1

```
public int tv1
    Penalty related value.
```

Constructors

TsptwPenOut

```
public TsptwPenOut()
    Default constructor. Assigns all values to zero.
```

TsptwPenOut

```
public TsptwPenOut(int totPenalty,
                    int tourCost,
                    int penTrav,
                    int tv1)
    Specified constructor. Values set as passed.
```

Class TwBestTTOut

```
java.lang.Object
|
+----TwBestTTOut
```

public class TwBestTTOut

extends Object TwBestTTOut is used as a package to output multiple information from the TWBestTTOut method.

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

Variable Index

bestCost

bestiter best tour related value.
bestnv best tour related value.
bestTime best tour related value.
bestTour best tour related value.
bestTT best tour related value.
bfCost best tour related value.
bfiter best tour related value.
bfnv best tour related value.
bfTime best tour related value.
bfTour best tour related value.
bfTT best tour related value.

Constructor Index

TwBestTTOut()

Default constructor.

TwBestTTOut(int, int, int, int, int, int, int, int, int, int, int, NodeType[], NodeType[])

Specified constructor.

Variables

bfCost

```
public int bfCost
    best tour related value.
```

bfTT

```
public int bfTT
    best tour related value.
```

bfnv

```
public int bfnv
    best tour related value.
```

bfiter

```
public int bfiter
    best tour related value.
```

bestCost

```
public int bestCost
    best tour related value.
```

bestTT

```
public int bestTT
    best tour related value.
```


bestnv

```
public int bestnv  
    best tour related value.
```

bestiter

```
public int bestiter  
    best tour related value.
```

bfTime

```
public int bfTime  
    best tour related value.
```

bestTime

```
public int bestTime  
    best tour related value.
```

bfTour

```
public NodeType bfTour[]  
    best tour related value.
```

bestTour

```
public NodeType bestTour[]  
    best tour related value.
```

Constructors

TwBestTTOut

```
public TwBestTTOut()  
    Default constructor. Assigns all values to zero.
```

TwBestTTOut

```
public TwBestTTOut(int bfCost,  
                   int bfTT,  
                   int bfnv,  
                   int bfiter,  
                   int bestCost,  
                   int bestTT,  
                   int bestnv,  
                   int bestiter,  
                   int bfTime,  
                   int bestTime,  
                   NodeType bfTour[],  
                   NodeType bestTour[])
```

Specified constructor. Values set as passed.

Class ValueObj

```
java.lang.Object  
|  
+----ValueObj
```

```
public final class ValueObj
```

extends Object ValueObj Class is used to store tour attributes in the hashtable for comparison.

Version:

v1.1 Mar 99

Author:

Kevin P. O'Rourke, David M. Ryer

Constructor Index

ValueObj(int, int, int, int, int, int, int)
Specified constructor.

Method Index

equals(ValueObj)
Overloaded equals(), check only attribute fields.

hashCode()
Overloaded hashCode method.

toString()
toString changes a ValueObj to a string for use in the hashTable.

Constructors

ValueObj

```
public ValueObj(int fhv,  
                int shv,  
                int tourCost,  
                int tvl,  
                int twPen,  
                int loadPen,  
                int lastIter)  
    Specified constructor. Values set as passed.
```

Methods

equals

```
public final boolean equals(ValueObj a)  
    Overloaded equals(), check only attribute fields. Do not check first two data elements to keep  
    inline with hashCode overload.
```

Parameters:

a - element compared calling object.

Returns:

returns true if objects are equal, false otherwise.

toString

```
public final String toString()  
    toString changes a ValueObj to a string for use in the hashTable.
```

Returns:

returns concatenated String.

Overrides:

toString in class Object

hashCode

```
public final int hashCode()  
    Overloaded hashCode method. Note: if two objects are equal according to the equals method, then  
    calling the hashCode method on each of the two objects must produce the same integer result. Do  
    not checking first two data elements because of size limitations of Integer.
```

Returns:

returns integer hashcode value.

Overrides:

hashCode in class Object

Class VrpPenType

```
java.lang.Object
|
+-----VrpPenType
```

public class **VrpPenType**

extends Object VrpPenType class provides the object structure for load and time window penalties.

Version:

v1.1 Feb 99

Author:

Kevin P. O'Rourke, David M. Ryer

Constructor Index

VrpPenType()

Default constructor.

VrpPenType(int, int)

Specified constructor.

VrpPenType(int, int, int)

Specified constructor.

Method Index

compPens(NodeType[], int)

compPens computes the vehicle capacity overload and time window penalties.

Constructors

VrpPenType

```
public VrpPenType()
```

Default constructor. Assigns all values to zero.

VrpPenType

```
public VrpPenType(int tw,
                  int ld)
```

Specified constructor. Values set as passed.

VrpPenType

```
public VrpPenType(int tw,
                  int ld,
                  int nvu)
```

Specified constructor. Values set as passed.

Methods

compPens

```
public final VrpPenType compPens(NodeType tour[],
                                int capacity)
```

compPens computes the vehicle capacity overload and time window penalties.

Parameters:

tour[] - current tour used to calculate penalties.

capacity - maximum vehicle load.

Returns:

returns the VrpPenType object which the method was called on with updated values.

Class WindAdjust

```
java.lang.Object
|
+----WindAdjust
```

public class **WindAdjust**

extends Object WindAdjust will provides the adjusted ground speed given the desired heading from location A to location B, and the wind heading.

Version:

v1.1 Feb 99

Author:

Kevin P. O'Rourke, David M. Ryer

Constructor Index

WindAdjust()

Method Index

groundSpeed(double, double, double, double)

groundSpeed method returns the ground speed given the heading between points, the wind heading, the wind speed, and the aircraft's airspeed.

groundSpeedAF(double, double, double, double)

groundSpeedAF is an experimental method that uses a different formula.

Constructors

WindAdjust

```
public WindAdjust()
```

Methods

groundSpeed

```
public static final double groundSpeed(double headingAtoB,
                                       double windDir,
                                       double airSpeed,
                                       double windSpeed)
```

groundSpeed method returns the ground speed given the heading between points, the wind heading, the wind speed, and the aircraft's airspeed.

Parameters:

headingAtoB - heading between points in degrees.

windDir - wind heading in degrees.

airSpeed - aircraft air speed in knots.

windSpeed - wind speed in knots.

Returns:

returns ground speed in knots.

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13. ABSTRACT (Maximum 200 words) This thesis employs a reactive tabu search heuristic implemented in the Java programming language to solve a real world variation of the vehicle routing problem with the objective of providing quality routes to Mobility Analysis Support System (MASS). MASS is a stochastic simulation model used extensively by Air Mobility Command (AMC) to analyze strategic airlift capabilities and future procurement decisions. This dynamic real world problem of strategic and tactical airlift possesses a number of side constraints such as vehicle capacities, route length and time windows in a sizeable network with multiple depots and a large fleet of heterogeneous vehicles. Finding optimal solutions to this problem is currently not practical. Currently, MASS requires all possible routes used in its simulation to be manually selected. As a result, the route selection process is a tedious and time consuming process that relies on experience and past performance of the model to obtain quality routes for the mobility system.				
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