ABSTRACT

Title of Thesis:	THE ROBUST VEHICLE ROUTING PROBLEM: AN APPLICATION OF THE TRAVELING SALESMAN PROBLEM WITH CENTER
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The objective of the vehicle routing problem (VRP) is to determine minimum distance routes for one or more vehicles, operating from one or more depots, serving a set of customers with non-zero demand, subject to constraints including but the number of vehicles, vehicle capacity, and distance per route. A large research literature exists for the VRP due to the difficulty of the problem and its wide applicability to real-world business operations, such as package delivery.

The objective of the robust vehicle routing problem (RVRP) is to find the shortest possible nominal routes for a set of vehicles operating from a single depot over a number of days. The number of customers assigned to each route is subject to increase or decrease via the exchange of customers between the routes. We describe this variant of the traditional VRP and provide test instances. We give a general solution procedure for the problem based on generating sets of candidate solutions, from which we select the best. We describe and evaluate several candidate solution generation approaches and identify one that consistently yields high quality solutions with reasonable solution times.

THE ROBUST VEHICLE ROUTING PROBLEM:
AN APPLICATION OF THE TRAVELING SALESMAN PROBLEM WITH CENTER

By

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Chapter 1: Introduction

1.1 The Traveling Salesman Problem and the Vehicle Routing Problem:

The vehicle routing problem (VRP) is an extension of the well-known traveling salesman problem (TSP), wherein the objective is to find a Hamiltonian Path on a graph $G = (V, E)$ with the set of nodes V representing the $n = |V|$ cities the salesman must visit and the set of edges E representing the various connections between those cities. If the graph is undirected and complete (every node is directly linked to every other node by an edge on which the direction of travel is not limited), then the number of edges $|E| = n(n-1)/2$. The TSP is known to be NP-hard [1]. The VRP, which adds constraints onto the existing TSP framework, is also NP-hard. The computational difficulty of the TSP is that for a salesman starting in one of the n cities, any of $(n-1)$ cities may be visited next, and so forth, yielding $(n-1)!/2$ possible orderings of for the n cities.

The goal of the traditional VRP is to find the optimal routes for $k \geq 1$ vehicles operating from one or more depots, where optimality is typically defined in terms of minimizing the total distance traveled by all vehicles subject to a set of constraints. Again, we have a graph $G = (V, E)$ where the nodes are now taken to be the set of n customers to be served, where each customer is assumed to have some non-zero demand $d_i,\ i = 1, 2, \ldots n$. The route for each vehicle has some exclusive subset of all edges such that the capacity of the vehicle is not exceeded by the total demand of the customers assigned to that route. The route for each vehicle must be a Hamiltonian path. Additional constraints may also be placed on the vehicles, such as maximum distance, maximum time of travel, and maximum or minimum number of customers served.

Though both the TSP and VRP are well defined in non-Euclidean space, we introduce the Robust Vehicle Routing Problem (RVRP) exclusively in terms of Euclidean 2-D type problems. We study only the single depot case and denote the depot as node 0. Additionally, we make a simplifying assumption that allows examination only of the case where all nodes have a unit demand.

1.2 Motivation for the Robust Vehicle Routing Problem

Consider a package pickup and delivery service which operates a fleet of vehicles from a single depot serving a fixed set of customers. Each day the company's vehicles depart the depot and service the customers on their route. For business efficiency, we desire the most economical routes for the vehicles; typically economy is defined in terms of distance traveled, as is the case here, though travel time or some other measure could be used.

If we also consider the labor implications of the delivery service, then we would likely require that the routes be equivalent from the perspective of the vehicle drivers, that is, that the routes are balanced. In fact, in a real-world application, we would expect that various labor contracts require a balance among the driver workloads on a daily basis. This balance can be specified in a number of ways, the most intuitive perhaps is the number of customers served on each route. Then a rational approach to routing the company's vehicles is that the routes are the shortest known routes such that each has an equal number of customers. If we make the assumption that the vehicles are sufficiently large such that capacity to hold the packages is not a constraint, which often holds in practice, then this routing problem is the VRP with unit demands $(d_i = 1 \; \forall \, i, \; i = 1,2, \dots n)$. A solution to this problem would yield the routes for the company's vehicles.

If the business environment for this company is the same each day, we expect that the company would operate day after day by repeatedly sending its vehicles out to service customers on the routes above. However, in a real-world environment, conditions vary from day to day and may affect the execution of the routes resulting in a labor imbalance. As a very specific example, which we use to frame our problem, if each customer node represents an office building, the driver may have deliveries for several offices within the building on a given day and the total service required at the office building is clearly a non-trivial component of the driver's total workload. To restore the balance of labor, one option would be to re-optimize the routes each day, taking into account the amount of service time required for each customer.

As an alternative, we may prefer to simply shift a few customers between the routes each day to restore balance. To proceed along the lines of this alternative, assume that the company has a set of least cost routes from solving the VRP, that present an equivalent workload for the drivers when the service time at the customers is equal between routes (we refer to these routes throughout as the nominal routes). On days where the service requirements at individual customers result in an unbalanced workload, a manager simply moves some customers from one route to another to restore the balance. We expect these moves would occur only between adjacent routes to minimize the increase in total distance.

This approach may not yield the shortest possible routes. However, using this approach should produce several positive benefits for a small increase in total distance. For example, from the perspective of the driver, notwithstanding the shifting of customers, the driver's route is basically the same every day, which is clearly preferable to learning and traversing a new route each day. From the perspective of the customers, they generally see the same driver every day, which provides for a positive customer service relationship.

To complete our definition of the RVRP, we assume that when customers are moved from one route to another they are moved on to the new route as a continuous segment, as in the route from which they originated. In real-world applications, the cost of travel on a particular edge of the transit network may have a composite definition that includes factors such as safety or fuel efficiency that are important to the company [2]. Alternately, the company may prefer to maximize the number of edges repeated in the routes of alternate days as utilization of those edges is well known and predicable from a planning and management perspective. With costs identified in this manner it may be preferable to exchange nodes between routes in segments (having length that we refer to as the segment length) so that the utilization of preferred edges of the transit network is maximized.

If the benefits of this alternative approach to balancing the routes are significant, then the solution to routing the vehicles is to determine a set of nominal routes that have a structure favorable to the exchange of segments between the routes such that these exchanges do not significantly increase total distance. From these nominal routes, a manager can make small exchanges between the routes based on the daily deliveries, which are known at the start of a day and which give the workload at each customer. Determining the nominal routes is the problem we refer to as the RVRP.

Our description of the RVRP suggests a routing problem with limited applicability. However, the RVRP has applicability in the package delivery service industry [3]. In fact, at least one of the major vehicle routing software companies has devoted development resources toward solving this problem [4].

1.3 Definition of the Robust Vehicle Routing Problem

The RVRP, motivated in the previous section, is a variant of the traditional VRP with additional restrictions. This is a new problem area (we were unable to find any research on or reference to this variant of the traditional VRP in the literature).

We seek to identify a set of nominal routes, which serve as the basis for the vehicles' routes each day and which result in the shortest possible distance over all days and vehicles. The nominal route for each vehicle includes the customer nodes nominally assigned to each vehicle and the edges traveled by that vehicle when servicing that set of customer nodes. Specifically, the number of nodes nominally assigned to each route is $N = n/k$, where n is the size of the problem, i.e., number of nodes not including the depot, and k is the number of vehicles in the problem. For example, if three vehicles operate from the single depot and serve a total of 360 customers, then the number of customers assigned to each nominal route is defined to be $360/3 = 120$. A solution to this 360 node problem is three routes, each having 120 nodes.

We assume that the k vehicles make deliveries daily over s days and that service times at each customer node may vary such that, on one or more days, the drivers' workload for that day would be unequal if each completed their nominal routes. For any such day, we assume the existence of an alternative allocation of the customers among the k routes that gives an equal workload distribution, and that the alternative allocation is given by exchanging a continuous segment of customer nodes between two adjacent routes. We further assume that the inter-route shifts of route segments must occur with a given length; that is, we move customer nodes between routes in blocks of a specified size, which we refer to as the segment length. For example, if the segment length is 10, when nodes are moved to balance driver workload, a route segment 10 customers long is removed from one route and inserted into an adjacent route. In the new route, this segment of 10 customers is serviced sequentially, either in the same or reverse order as in the nominal route using the same edges as in the nominal route.

To further illustrate, consider two nominal routes that have a workload imbalance on a given day due to the variable customer service times at the nodes. To balance the workload of the two drivers, a single sequential string of 10 customers will be moved from the route having the greater workload to the route having the lesser workload. After the move, the route taking the customers will have its nominal route, with a new segment of 10 customers inserted between two of its customers. The route that released the customers will follow its nominal route exactly by skipping over the segment of that route that was removed. In the case where there are more than two routes, balancing the driver workload may require transferring a segment of customers to both of its adjacent routes, or may require that a single route accepts segments from both of its adjacent routes.

We now describe the scenario matrix of the RVRP. To make the RVRP more tractable, we use a scenario matrix to capture an assumption about a specific instance of the RVRP. The scenario matrix for a specific instance of the RVRP is the customer allocations over the s days described by the matrix that defines routes with a balanced workload.

A very complete specification of the RVRP might include, beyond the nodes, vehicles, and other parameters, varying demand information for each node, each day, to specify how the service fluctuates among the various customers. Given this data, we can then compute which specific customer redistribution restores workload balance among the drivers. Subsequent enforcement of segment length restrictions specifies the required inter-route exchanges. Instead of this complete specification, we assume that there exist some values, given in a matrix format (conforming to a fixed segment length restriction) that specifies the allocation of customers over the T days such that the driver workloads each day are equal.

By specifying a scenario matrix for an instance of the RVRP problem, we assume that the typical workload imbalances of the routes can be described. The expected customer shifts necessary for workload balance over a multi-day period has been computed and is available for comparing different solution approaches. For example, using $n = 360$ nodes and $k = 3$ vehicles, we might assume that in any three day period ($s = 3$), the expected customer allocation that will balance the workload of the routes can be described by a matrix as follows:

Day	Route 1	Route 2	Route 3
1	120	120	120
2	120	110	130
3	130	100	130

Table 1.3.1: Sample Scenario Matrix for the RVRP

Given the scenario matrix, we can evaluate and compare different solution approaches for the problem.

Note that the sample scenario matrix given above includes the nominal routes exactly once (as day 1). This is not necessary. In the case where the need to adjust driver workload was infrequent, an alternative scenario matrix could include the nominal routes on more than one day. In the case where rebalancing is so frequent that drivers never all server their nominal set of customers on the same day, an alternative scenario matrix would include no row where all vehicles travel their nominal routes. The RVRP is well defined in both alternative cases. In the later case, an equally suitable scenario matrix for evaluation would be:

Day	Route 1	Route 2	Route 3
1	110	130	120
2	120	110	130
3	130	120	110

Table 1.3.2: An Alternate Sample Scenario Matrix for the RVRP

Obviously there is no day within this scenario matrix when all vehicles travel their nominal route. This case would likely be most relevant when the number of vehicles, k, is large. As the number of scenario matrices that could be defined is large, we restrict our research to a single specific scenario matrix in Section 2.1.

Note that since inter-route moves are defined in terms of single segment exchanges between adjacent routes, the segment length is unique and immediately apparent given the scenario matrix (as is the number of days s). For the two scenario matrices presented above, the segment length is 10.

Finally, we discuss assumptions related to the objective function. Consider an RVRP instance with v vehicles and a fixed scenario matrix. We have a set of nominal solution routes with a total distance traveled by the k vehicles over the s days. In order to compute the objective function we require one additional assumption. We define the objective function to be the total distance over all days and vehicles when the best possible inter-route exchanges are made. It may seem strange to highlight this assumption since selecting least cost seems natural. However, for the RVRP it may in fact be of great interest to define the objective function differently.

For example, an alternate specification of the objective function may be to assume that some strategy is employed when the segments are exchanged. To illustrate, consider an exchange of m customer nodes from route X onto route Y. We could specify that the move occurs according to the strategy that the first m nodes of X adjacent to the depot are attached onto Y. This is a different problem than looking at the best possible exchange. Having a strategy for exchanging the nodes will change how the nominal routes should be formed in a nontrivial manner.

1.4 Mathematical Formulation of the Robust Vehicle Routing Problem

Given our assumptions and definition of the RVRP, we provide a mathematical formulation for the RVRP. We proceed by first describing a mixed integer linear program (MILP) formulation for the traditional VRP that is common in the literature, the Vehicle Flow Model of Bodin et al., 1983 [5]. We then present a model for the RVRP by highlighting the modifications and additions to this model.

The Vehicle Flow Model (VFM) for a single depot VRP with $n + 1$ nodes and k vehicles, where node 0 is defined the depot node, is as follows:

Parameters and decision variables:

n: customers.

k: vehicles.

d_i: demand of customer i $(i = 1,2,3, \ldots, n)$.

N_v: capacity of vehicle v $(v = 1,2,3, \ldots, k)$.

c_{ij}: distance between node i and j $(i, j = 0,1,2, \ldots, n)$.

$x_{ij}^{(v)}$: if vehicle v travels on edge (i, j), then $x_{ij}^{(v)} = 1$, otherwise, $x_{ij}^{(v)} = 0$ $(i, j = 0,1,2, \dots, \mathrm{n})$.

y_{ij} : if any vehicle travels on edge (i, j), then $\mathrm{y}_{\mathrm{ij}} = 1$, otherwise, $y_{ij} = 0$ $(i, j = 0,1,2, \dots, \mathrm{n})$.

u_i: An intermediate variable taking on non-negative integer values $(i = 1,2,3, \dots, n)$.

Minimize:

$$\sum_{v=1}^{k} \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} c_{ij} \, x_{ij}^{(v)} \tag{0}$$

Subject to:

$$\sum_{i=1}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} d_i x_{ij}^{(v)} \leq N_v \quad (v = 1,2,3, \dots, k) \tag{1}$$

$$\sum_{v=1}^{k} x_{ij}^{(v)} = y_{ij} \quad (0 \leq i \neq j \leq n) \tag{2}$$

$$\sum_{\substack{j=0 \\ j \neq i}}^{n} y_{ij} = 1 \quad (i = 1,2,3, \dots, n) \tag{3}$$

$$\sum_{\substack{i=0 \\ i \neq j}}^{n} y_{ij} = 1 \quad (j = 1,2,3, \dots, n) \tag{4}$$

$$\sum_{j=1}^{n} y_{0j} \leq k \tag{5}$$

$$\sum_{i=1}^{n} y_{i0} \leq k \tag{6}$$

$$u_i - u_j + (n+1) y_{ij} \leq n \quad (1 \leq i \neq j \leq n) \tag{7}$$

$$\sum_{\substack{j=0 \\ j \neq i}}^{n} x_{ij}^{(v)} = \sum_{\substack{j=0 \\ j \neq i}}^{n} x_{ij}^{(v)} \quad (i = 1,2,3, \dots, n; v = 1,2,3, \dots, k) \tag{8}$$

$$u_i \in \mathbb{Z} \quad (i = 1,2,3, \dots, n) \tag{9}$$

$$x_{ij}^{(v)} \in \{0,1\} \quad (0 \le i \ne j \le n; v = 1,2,3,\dots,k) \tag{10}$$

$$y_{ij} \in \{0,1\} \quad (0 \le i \ne j \le n) \tag{11}$$

Constraints of the form (1) ensure that the total demand served by any vehicle does not exceed the capacity of the associated vehicle. Constraints of the form (2) require that any edge (i,j) is traversed by no more than one vehicle. Constraints of the form (3) and (4) together require that each customer is visited exactly once by ensuring that the each node in a route has degree two. In a similar sense, constraints (5) and (6) ensure that the degree of the depot node is proportional to the number of vehicles, while allowing that not all available vehicles need be used. Constraints of the form (7) are the sub-tour elimination constraints. Constraints of the form (8) ensure that if a given vehicle, v, reaches a customer node, that a vehicle must depart that node. Finally, the constraints (9) require that u_i be in the set of integers; (10) and (11) specify $x_{ij}^{(v)}$ and y_{ij} to be binary variables.

We now give a MILP formulation for the RVRP with $n+1$ nodes and k vehicles, where node 0 is defined the depot node. Recall that the objective of the RVRP is to determine a set of routes, each serving exactly n/k customers, for exactly k vehicles operating from a single depot. We refer to these routes as the nominal routes and refer to the quantity $N = n/k$ as the nominal route length. Recall that the quality of the nominal routes is measured not by the total distance of the nominal routes but by the total distance traveled by the k vehicles, over T days, where the number of customers served by each vehicle on each day is given by the scenario matrix $[t_{sv}]$. The routes traveled by the vehicles on a given day must conform to the type of move allowed in the RVRP. The routes of the k vehicles on a given day, s, have a specific similarity to the nominal routes for the k vehicles.

For the RVRP model, we reuse the following parameters and decision variables of the VFM:

n: customers.

k: vehicles.

c_{ij} : distance between node i and j $(i, j = 0,1,2, \dots, n)$.

We introduce the following new definitions:

T: the number of scenarios given, i.e., the number of service days included in the problem

$t = [t_{sv}]$: t is a matrix of size $(T \times k)$ that specifies the number of customers served by vehicle v on day s. We refer to this matrix as the scenario matrix.

$r = [r_{sv}]$: r is a matrix of size $(T \times k)$ that specifies the number of routes from which vehicle v has taken customers from on day s. As customers are shifted only from neighboring routes, $r_{sv} \in \{0,1,2\} \; \forall \; s, v$.

P: a suitably large positive number; P is used as a penalty factor in the objective function of the model.

The following parameters and decision variables are modified from the VFM as follows

N: In the RVRP we seek exactly k routes, each serving an equal number of customers N. The quantity N is the nominal route length. The variable N_v of the VFM is therefore constant in the RVRP: $N = \frac{n}{k}, \forall \; v$.

$x_{ij}^{(s,v)}$: To account for the model's multiple days of service, rather than $x_{ij}^{(v)}$, as in the VFM, we have $x_{ij}^{(s,v)}$. If vehicle v travels on edge (i, j) on day s, then $x_{ij}^{(s,v)} = 1$, otherwise $x_{ij}^{(s,v)} = 0$ $(i, j = 0,1.2, \dots, n; v = 1,2,3, \dots, k; s = 0,1,2, \dots, T)$. Note that for $s = 0$, i.e. $x_{ij}^{(0,v)}$, we mean those edges that are included on the nominal route of vehicle v. These are the routes that the RVRP seeks to identify. Explicit inclusion of the $s = 0$ case is necessary as the scenario matrix may not include a day where all vehicles travel their nominal route. Note that $\sum_{i=0}^{n} \sum_{j=0}^{Nn} x_{ij}^{(0,v)} = N \; \forall \; v$. Also note that, though $x_{ij}^{(0,v)}$ are the nominal routes we solve the model to obtain, they are not included in the objective function of the model $(0^{'})$.

$y_{ij}^{(s)}$: Analogous to the y_{ij} of the VFM but with the added superscript s giving a unique set of $y_{ij}^{(s)}$ for each service day. If any vehicle travels on edge (i,j), on day s then $y_{ij}^{(s)} = 1$, otherwise $y_{ij}^{(s)} = 0$; $(i,j = 0,1,2,\ldots n; s = 0,1,2,\ldots,T)$.

$u_i^{(s)}$: An intermediate variable taking on non-negative integer values $(i = 0,1,2,\ldots n; s = 0,1,2,\ldots,T)$. These variables are used in the sub-tour elimination constraints in the same manner as the variables u_i of the VFM. The superscript s is needed as distinct set of intermediate variables is required for each service day.

A mixed integer programming formulation of the RVRP is then:

Minimize ($\beta_a, \delta_b, \rho_c$ and φ_d are explained below):

$$\sum_{s=1}^{T}\sum_{v=1}^{k}\sum_{i=0}^{n}\sum_{\substack{j=0\\j\neq i}}^{n} c_{ij}\, x_{ij}^{(s,v)} + P \times \left(\sum\nolimits_{A}\beta_a + \sum\nolimits_{B}\delta_b + \sum\nolimits_{C}\rho_c + \sum\nolimits_{D}\varphi_d\right) \qquad (0a')$$

Subject to:

$$\sum_{i=1}^{n}\sum_{\substack{j=0\\j\neq i}}^{n} x_{ij}^{(0,v)} = N \qquad (v = 1,2,3,\ldots,k) \qquad (1a')$$

$$\sum_{i=1}^{n}\sum_{\substack{j=0\\j\neq i}}^{n} x_{ij}^{(s,v)} = t_{sv} \qquad (v = 1,2,3,\ldots,k;\; s = 1,2,3,\ldots,T) \qquad (1b')$$

$$\sum_{v=1}^{k} x_{ij}^{(s,v)} = y_{ij}^{(s)} \qquad (0 \le i \neq j \le n;\; s = 0,1,2,3,\ldots,T) \qquad (2')$$

$$\sum_{\substack{j=0\\j\neq i}}^{n} y_{ij}^{(s)} = 1 \qquad (i = 1,2,3,\ldots,n;\; s = 0,1,2,\ldots,T) \qquad (3')$$

$$\sum_{\substack{i=0\\i\neq j}}^{n} y_{ij}^{(s)} = 1 \qquad (j = 1,2,3,\ldots,n;\; s = 0,1,2,\ldots,T) \qquad (4')$$

$$\sum_{j=1}^{n} y_{0j}^{(s)} = k \quad (s = 0,1,2,\dots,T) \tag{5'}$$

$$\sum_{i=1}^{n} y_{i0}^{(s)} = k \quad (s = 0,1,2,\dots,T) \tag{6'}$$

$$u_i^{(s)} - u_j^{(s)} + (n+1)y_{ij}^{(s)} \le n \quad (1 \le i \ne j \le n;\ s = 0,1,2,\dots,T) \tag{7'}$$

$$\sum_{\substack{j=0 \\ j \ne i}}^{n} x_{ij}^{(s,v)} = \sum_{\substack{j=0 \\ j \ne i}}^{n} x_{ji}^{(s,v)} \quad (i = 1,2,3,\dots,n;\ v = 1,2,3,\dots,k;\ s = 0,1,2,\dots,T) \tag{8'}$$

$$u_{\ i}^{(s)} \in \mathbb{Z} \quad (i = 1,2,3,\dots,n) \tag{9'}$$

$$x_{ij}^{(s,v)} \in \{0,1\} \quad (0 \le i \ne j \le n; v = 1,2,3,\dots,k; s = 0,1,2,\dots,T) \tag{10'}$$

$$y_{ij}^{(s)} \in \{0,1\} \quad (0 \le i \ne j \le n; s = 0,1,2,\dots,T) \tag{11'}$$

We discuss the constraints $(1^{'}) - (11^{'})$ first. The constraints are numbered to correspond with the constraints of the VFM. The d_i are omitted in $(1')$ since we have assumed a unit demand at all nodes (i.e., $d_i = 1, \forall\, i = 1,2,3,\dots,n$). Constraints of the form $(1a')$ require that the $s = 0$ routes all have the nominal route length ($N = n/k$); constraints of the form $(1b')$ enforce a similar requirement on the routes for $s > 0$ using the scenario matrix, which specifies the customer loads for each vehicle, each day. As is the case in $(1^{'})$, the inequality of the VFM is a strict equality in the RVRP model for constraints of the form $(5^{'})$ and $(6^{'})$ as degree of the depot node must equal $2 \times k$. Constraints $(2^{'}) - (8^{'})$ are identical to like constraints of the VFM, however, the superscript is included to distinguish between the $T + 1$ sets of analogous constraints, one set for each row in the scenario matrix and one more for the nominal routes.

The first term of the objective function is identical to the VFM with the exception of the summation over all T days and inclusion of the terms $\beta_a, \delta_b, \rho_c$, and φ_d. These are detailed below in $(0b^{'})$, $(0c^{'}), (0d^{'})$, and $(0e^{'})$, respectively. They are each viewed as a constraint in that they penalize the objective function when violated. Thought not immediately linear, terms involving absolute values, such as $(0b^{'}), (0c^{'}), (0d^{'})$, and $(0e^{'})$, are easily converted into a suitable form for linear programming via appropriate transformation [6,7]. We present the converted form after first discussing how these terms work.

To begin, consider the case $k = 2, N = 100$ with nominal routes X and Y and the movement of any segment of 10 nodes from route X to route Y. With the subscript arbitrary, let N_1 and N_{10} be the endpoints of the 10 node sequence in X attached by the edges (N_0, N_1) and (N_{10}, N_{11}), and N_B and N_E be adjacent nodes in route Y between which the segment will be inserted. The insertion of the segment of nodes from X into Y must be such that upon insertion into route Y, the edges connecting N_1 and N_{10} are unchanged. This is the type of inter-route move we allow in the RVRP.

Denote the new routes as X' and Y'. We have $|X| = |Y| = 101$ and $|X'| = 91$, $|Y'| = 111$. Let the set XY be the set of edges (i, j) in routes X and Y, and XY' those in X' and Y'. Then comparing XY to XY', exactly three edges in the set XY are not in the set XY': (N_0, N_1), (N_{10}, N_{11}), and (N_B, N_E). Also, exactly three edges not in XY are in XY': (N_0, N_{11}), and either (N_B, N_1) and (N_{10}, N_E), or (N_1, N_E) and (N_B, N_{10}). All other edges in XY and XY' are common. Then the cardinality of $(X \cap X) = 90$, $(Y \cap Y^{'}) = 100$, and $(Y^{'} \cap X) = 9$. Further, assuming that the set XY is known and adherence to minimum cost, all of the edges in XY' are immediately known, for any 10 node segment selected from route X.

In an identical manner, $(0b^{'}), (0c^{'}), (0d^{'})$, and $(0e^{'})$ enforce set cardinality restrictions between the routes (i.e., the edges) of day s and the nominal routes, ensuring a specified level of agreement between the edges of a given route for a vehicle on a given day, and the nominal route (i.e., $x_{ij}^{(0,v)}$) for that or other vehicles. In conjunction with the restrictions imposed by the constraints $(1^{'}) - (11^{'})$, $(0b^{'}), (0c^{'}), (0d^{'})$, and $(0e^{'})$ enforce the move type allowed in the RVRP. We now present and discuss $(0b^{'}), (0c^{'}), (0d^{'})$, and $(0e^{'})$, after which we give a numerical example.

$$\beta_a = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} \left| x_{ij}^{(0,v)} - x_{ij}^{(s,v)} \right| \tag{0b'}$$

$$(v \in \{1,2,3,\ldots,k : \; t_{sv} = N\};\; s = 1,2,3,\ldots,T)$$

For a route v that, on day s, has $N = n/k$ customers (i.e., $t_{sv} = N$), $(0b^{'})$ requires that route v that on day s be identical to nominal route v. Specifically, $(0b^{'})$ requires that the set of edges $X = \left\{ x_{ij}^{(s,v)} \right\}$ is identical to the set of edges $X^0 = \left\{ x_{ij}^{(0,v)} \right\}$. This is easily measured since, when $x_{ij}^{(0,v)} = x_{ij}^{(s,v)}$, the quantity $\left| x_{ij}^{(0,v)} - x_{ij}^{(s,v)} \right| = 0$, but when $x_{ij}^{(0,v)} \neq x_{ij}^{(s,v)}$, the quantity $\left| x_{ij}^{(0,v)} - x_{ij}^{(s,v)} \right| = 1$. Thus, when the two routes are identical, $\beta_a = 0$, otherwise, $\beta_a > 0$, and the objective function is penalized.

$$\delta_b = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} \left| x_{ij}^{(0,v)} - x_{ij}^{(s,v)} \right| - (N - t_{sv} + 2) \tag{0c'}$$

$$(v \in \{1,2,3,\ldots,k : \; t_{sv} < N\};\; s = 1,2,3,\ldots,T)$$

$$\rho_c = \sum_{i=0}^{n}\sum_{\substack{j=0 \\ j\neq i}}^{n}\left|x_{ij}^{(0,v)} - x_{ij}^{(s,v)}\right| - (t_{sv} - N + 2 \times r_{sv}) \qquad (0d')$$

$$(u \in \{1,2,3,\dots,k : \; t_{sv} > N\};\; s = 1,2,3,\dots,T)$$

For a route u that, on day s, has other than N customers (i.e., $t_{sv} \neq N$), $(0c^{'})$ and $(0d^{'})$ require that route v, on day s, has a specified level of agreement with nominal route v. As with $(0b^{'})$, we count the edges in agreement between the two routes using the quantity $\left|x_{ij}^{(0,v)} - x_{ij}^{(s,v)}\right|$.

For route v on day s such that $t_{sv} < N$, $(0c^{'})$ applies. In $(0c^{'})$ we require that the set $X = \left\{(i,j): x_{ij}^{(s,v)} = 1\right\}$ and set $X^0 = \left\{(i,j): x_{ij}^{(0,v)} = 1\right\}$ have exactly $N - t_{sv} + 2$ edges different (also t_{sv} edges are the same). Route v for day s should include all edges from nominal route v except those exchanged to another route ($N - t_{sv} - 1$) and the two edges that attach this segment into nominal route v. Route v also includes one edge not in nominal route v. When route v, on day s, having $t_{sv} < N$, differs from its base route by $N - t_{sv} + 2$ edges then $\delta_b = 0$, otherwise $\delta_b > 0$, and the objective function is penalized ($\delta_b < 0$ cannot occur given all other constraints satisfied simultaneously).

Similarly, $(0d^{'})$ applies for $t_{sv} > N$ and requires that $X = \left\{(i,j): x_{ij}^{(s,v)} = 1\right\}$ and $X^0 = \left\{(i,j): x_{ij}^{(0,v)} = 1\right\}$ have exactly $t_{sv} - N + 2 \times r_{sv}$ edges different, where r_{sv} is the number of routes from which route v has accepted segments (also $N + 1 - r_{sv}$ are the same). For example, if $r_{sv} = 1$ (i.e., route v has taken a segment a single route), then route v should have all but one edge from its nominal route and will have $t_{sv} - N + 1$ edges not in nominal route v. When route, v on day s, having $t_{sv} > N$, differs from its base route by exactly $t_{sv} - N + 2 \times r_{sv}$ edges then $\rho_c = 0$, otherwise $\rho_c > 0$ ($\rho_c < 0$ cannot occur given all other constraints satisfied simultaneously).

$$\varphi_d = \sum_{\substack{u=1 \\ u \neq v}}^{k} \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} \left(\frac{1}{2}\right) \left(x_{ij}^{(0,u)} + x_{ij}^{(s,v)} - \left|x_{ij}^{(0,u)} - x_{ij}^{(s,v)}\right|\right) + \ (N - t_{sv} + r_{sv}) \qquad (0e^{'})$$

$$(v \in \{1,2,3,\dots,k : \ t_{sv} > N\};\ s = 1,2,3,\dots,T)$$

If $t_{sv} > N$, $(0e^{'})$ also applies. For a route v that on day s has greater than N customers, $(0e^{'})$ requires that route v on day s has a specified level of agreement with the nominal routes other than nominal route v. Specifically, $(0e^{'})$ requires that the set $X = \left\{(i,j): x_{ij}^{(s,v)} = 1\right\}$ agrees with the set $X^0 = \left\{(i,j): x_{ij}^{(s,u\neq v)} = 1\right\}$ by $t_{sv} - N - r_{sv}$ edges, where r_{sv} is the number of routes from which route v has taken route segments. To accomplish this, we count the number of edges in route v on day s and the number of edges in the nominal routes other than v, and we count the number of edges not in agreement between route v on day s and all other nominal routes. Half the difference between the two sums is the total number of edges in agreement between the routes which we require to be $t_{sv} - N - r_{sv}$. Assuming all other constraints are satisfied, $\varphi_d < 0$ is impossible and $\varphi_d = 0$ if route v for day s has the correct agreement with the nominal routes other than nominal route v, otherwise $\varphi_d > 0$, penalizing the objective function.

The terms $\beta_a, \delta_b, \rho_c$ and φ_d each have a subscript we have not yet discussed. In terms of our notation $a = 1,2,\dots,A$; b, c and d are similar, with an upper value of B, C and D, respectively. A, B, C and D depend on the scenario matrix t and cannot be given in general. Given a specific scenario matrix A, B, C and D are known and there may be multiple terms of the form $\beta_a, \delta_b, \rho_c$ and φ_d. For example, if the scenario matrix has 5 elements for which $t_{sv} > N$, then $C = D = 5$. For the six node RVRP example we give below $A = B = C = D = 2$.

As a numerical example, consider an RVRP instance in which $T = 1$ and $t = [130 \quad 110 \quad 120]$ (therefore $r = [1 \quad 0 \quad 0]$) and assume the nominal routes $\{x_{ij}^{(0,1)}\}$, $\{x_{ij}^{(0,2)}\}$, and $\{x_{ij}^{(0,3)}\}$. From constraints $(1^{'})$, the nominal routes each have 120 nodes and 121 edges; the $s = 1$ routes have 131, 111, and 121 edges, respectively. For $s = 1$, $v = 3$, $(0b')$ applies; $\beta_1 = 0$ holds if $\sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} \left| x_{ij}^{(0,3)} - x_{ij}^{(1,3)} \right| = 0$, which is true when $\{x_{ij}^{(1,3)}\}$=$\{x_{ij}^{(0,3)}\}$. For $s = 1$ and $v = 2$, $(0c')$ applies; $\delta_1 = 0$ holds if $\sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} \left| x_{ij}^{(0,v)} - x_{ij}^{(1,2)} \right| - (N - t_{12} + 2) = 12 - (120 - 110 + 2) = 0$, which is true when $\left| \left\{ x_{ij}^{(1,2)} \right\} \cap \left\{ x_{ij}^{(0,2)} \right\} \right| = 110$. For $s = 1$ and $v = 1$, both $(0d')$ and $(0e')$ apply. To have $\rho_1 = 0$, we require that $\sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} \left| x_{ij}^{(0,v)} - x_{ij}^{(1,1)} \right| - (t_{11} - N + 2 \times r_{sv}.\ ) = 12 - (120 - 110 + 2 \times 1) = 0$, which is true when $\left| \left\{ x_{ij}^{(1,1)} \right\} \cap \left\{ x_{ij}^{(0,1)} \right\} \right| = 120$. With respect to $(0d')$, to have $\varphi_1 = 0$, we require that:

$$\sum_{\substack{u=1 \\ u \neq v}}^{k} \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} \left(\frac{1}{2}\right) \left(x_{ij}^{(0,u)} + x_{ij}^{(s,v)} - \left| x_{ij}^{(0,u)} - x_{ij}^{(s,v)} \right| \right) + \ (N - t_{sv} + r_{sv}) = 0.$$

Expanding the first term, we have:

$$\sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} \left(\frac{1}{2}\right) \left(x_{ij}^{(0,2)} + x_{ij}^{(1,1)} - \left| x_{ij}^{(0,2)} - x_{ij}^{(1,1)} \right| \right) + \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} \left(\frac{1}{2}\right) \left(x_{ij}^{(0,3)} + x_{ij}^{(1,1)} - \left| x_{ij}^{(0,3)} - x_{ij}^{(1,1)} \right| \right).$$

The second sum will be zero if $\left|\left\{x_{ij}^{(1,1)}\right\} \cap \left\{x_{ij}^{(0,3)}\right\}\right| = 0$. If $\left|\left\{x_{ij}^{(1,1)}\right\} \cap \left\{x_{ij}^{(0,2)}\right\}\right| = 9$, then $\varphi = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} \left(\frac{1}{2}\right)\left(x_{ij}^{(0,2)} + x_{ij}^{(1,1)} - \left|x_{ij}^{(0,2)} - x_{ij}^{(1,1)}\right|\right) + (N - t_{sv} + r_{sv}) = \frac{18}{2} + (120 - 130 + 1) = 0$. Then, given constraints $(1^{'}) - (11^{'})$ are satistfied, the minimum value of the objective function must include $P \times (\sum_A \beta_a + \sum_B \delta_b + \sum_C \rho_c + \sum_D \varphi_d) = 0$, i.e., where the additional restrictions of the RVRP have been satisfied. Therefore, $(0b^{'}), (0c^{'}), (0d^{'})$, and $(0e^{'})$ enforced the type of move allowed in the RVRP.

As noted, the absolute values present in $(0b^{'}), (0c^{'}), (0d^{'})$, and $(0e')$ make the objective function of the RVRP non-linear. However, absolute values can be eliminated by a conversion of variables as follows:

$$\beta_a = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} z_{ij}^{(s,v)} \qquad (0b'')$$

$$(v \in \{1,2,3,\dots,k : t_{sv} = N\};\ s = 1,2,3,\dots,T)$$

$$\delta_b = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} z_{ij}^{(s,v)} - (N - t_{sv} + 2) \qquad (0c'')$$

$$(v \in \{1,2,3,\dots,k : t_{sv} < N\};\ s = 1,2,3,\dots,k)$$

$$\rho_c = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} z_{ij}^{(s,v)} - (t_{sv} - N + 2 \times r_{sv}) \qquad (0d'')$$

$$(v \in \{1,2,3,\dots,k : t_{sv} > N\};\ s = 1,2,3,\dots,T)$$

$$\varphi_d = \sum_{\substack{u=1 \\ u \neq v}}^{k} \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} \left(\frac{1}{2}\right)\left[w_{ij}^{(s,u)} - \left(x_{ij}^{(0,u)} + x_{ij}^{(s,v)}\right)\right] - (N - t_{sv} + r_{sv}) \qquad (0e^{''})$$

$$(v \in \{1,2,3,\dots,k : t_{sv} > N\};\ s = 1,2,3,\dots,T)$$

$$x_{ij}^{(0,v)} - x_{ij}^{(s,v)} \leq z_{ij}^{(s,v)} \quad (0 \leq i \neq j \leq n; v = 1,2,3,\dots,k; s = 1,2,3,\dots,T) \qquad (12a^{''})$$

$$-x_{ij}^{(0,v)} + x_{ij}^{(s,v)} \leq z_{ij}^{(s,v)} \quad (0 \leq i \neq j \leq n; v = 1,2,3,\dots,k; s = 1,2,3,\dots,T) \qquad (12b'')$$

$$x_{ij}^{(s,v)} - x_{ij}^{(s,u)} \leq w_{ij}^{(s,u)} \qquad (13a'')$$

$$(v \in \{1,2,3,\dots k : t_{sv} > N\}; 0 \leq i \neq j \leq n; 1 \leq u \neq v \leq k; s = 1,2,3,\dots,T)$$

$$-x_{ij}^{(s,v)} + x_{ij}^{(s,u)} \leq w_{ij}^{(s,u)} \qquad (13b'')$$

$$(v \in \{1,2,3,\dots k : t_{sv} > N\}; 0 \leq i \neq j \leq n; 1 \leq u \neq v \leq k; s = 1,2,3,\dots,T)$$

Thus, $z_{ij}^{(s,v)}$ is the smallest number that satisfies $x_{ij}^{(0,v)} - x_{ij}^{(s,v)} \leq z_{ij}^{(s,v)}$ and$-x_{ij}^{(0,v)} + x_{ij}^{(s,v)} \leq z_{ij}^{(s,v)}$. Since the $x_{ij}^{(s,v)}$ are restricted to binary values, $z_{ij}^{(s,v)} \in \{0,1\}$, and $z_{ij}^{(s,v)} = \left|x_{ij}^{(0,v)} - x_{ij}^{(s,v)}\right|$. Similarly, $w_{ij}^{(s,u)} = \left|x_{ij}^{(0,u)} - x_{ij}^{(s,v)}\right|, u \neq v$.

Finally, in the case where $x_{ij}^{(0,v)} = x_{ij}^{(h,v)}$, for some $h \in \{1,2,3,\dots T\}$, i.e., $t_{hv} = N \ \forall \ v$, we may optionally include the constraints (to reduce computation time):

$$x_{ij}^{(0,v)} = x_{ij}^{(h,v)} \quad (0 \leq i \neq j \leq N; v = 1,2,3,\dots,k) \qquad (14)$$

Now consider a small RVRP instance with $n = 6, N = \frac{n}{k} = 3, T = 3, \ P = 20$, and the scenario matrix, $[t_{sv}]$, given by:

Day	Route 1	Route 2
1	3	3
2	1	5
3	5	1

Table 1.4.1: A Scenario Matrix for a Six Node RVRP Instance

The nodes are as in Figure 1.4.1 (numbered counterclockwise, with node 0 the depot).

Node	X	Y
0	3	1
1	6	1
2	6	4
3	4	4
4	1	3
5	1	3
6	1	1

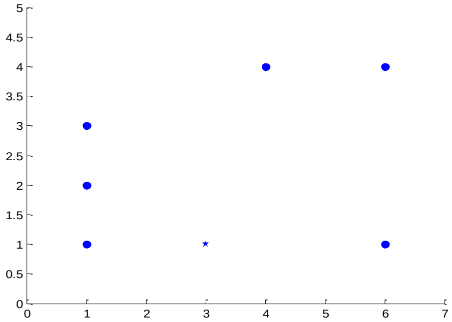


Figure 1.4.1: Six Node RVRP Instance

Including the noted conversions for the absolute value operators where they occur, but not the optional equality constraints of (14), the MILP for this six node problem has 866 variables with 1080 constraints (as well as binary and integer restrictions).

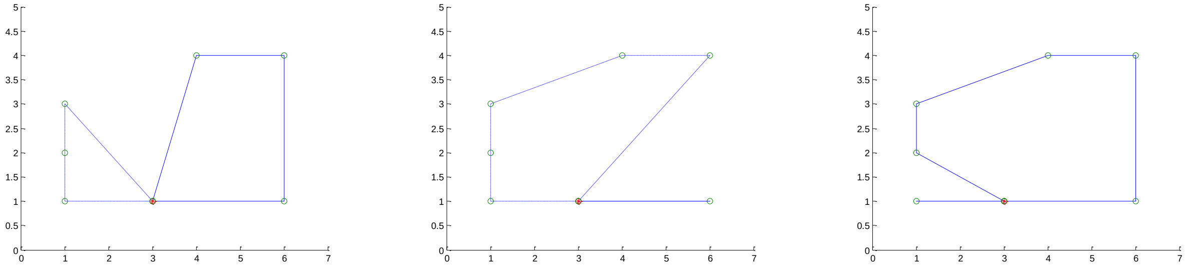
There are eight open source solvers for MILP, that implement a branch-and-bound methodology, available at www.branchandcut.org, which is associated with the Computational Infrastructure for Operations Research project [8]. Several of these solvers include a callable set of routines for specific programming languages, C/C++ being the most common. Some include a black box executable or graphical user interface. A description and comparative analysis of the eight solvers, is available in Linderoth and Ralphs, 2004 [9]. The current release version of lp_solve offers a number of improvements to reduce computation time, such as heuristic selection methods within the traditional branch-and-bound MILP methodology [10]. We selected lp_solve to solve the six node problem presented above.

The model, specified in lp-format [10], is given in an abbreviated from in Appendix A. Abbreviated solver output is given in Appendix B. The test instance is included in Appendix C. The solver took 5.91 hours to generate the optimal solution.

The optimal objective value is 55.79, this is the total distance for two vehicles over the three days. The associated routes are given in Table 1.4.2 and Figure 1.4.2.

Nominal Routes	Route 1: 0→1→2→3→0, Route 2: 0→4→5→6→0
Day 1	(Same as Nominal Routes)
Day 2	Route 1: 0→1→0, Route 2: 0→2→3→4→5→6→0
Day 3	Route 1: 0→1→2→3→4→5, Route 2:0→2→0

Table 1.4.2: Routes for the Three Days of a Six Node RVRP Instance



(a) Day 1 (b) Day 2 (c) Day 3

Figure 1.4.2: Routes for the Three Days of a Six Node RVRP Instance

In the following sections, we introduce a number of heuristic procedures for solving the RVRP. We tested each of the procedures on this six node problem. All returned the optimal solution in less than 0.2 seconds.

Finally, we note that in a non-linear model, $(0b^{'}), (0c^{'}), (0d'),$ and $(0e')$ could be replaced by the somewhat simplified expressions:

$$\beta_a = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} x_{ij}^{(0,v)} x_{ij}^{(s,v)} - (N+1) \qquad (0b''')$$

$$(v \in \{1,2,3,\dots,k : t_{sv} = N\};\ s = 1,2,3,\dots,T)$$

$$\delta_b = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} x_{ij}^{(0,v)} x_{ij}^{(s,v)} - (N+1-t_{sk}) \qquad (0c''')$$

$$(v \in \{1,2,3,\dots k : t_{sk} < N\};\ s = 1,2,3,\dots,T)$$

$$\rho_c = \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} x_{ij}^{(0,v)} x_{ij}^{(s,v)} - N \tag{0c'''}$$

$$(v \in \{1,2,3, \dots k : \ t_{sv} > N\}; s = 1,2,3, \dots, T)$$

$$\varphi_d = \sum_{\substack{u=1 \\ u \neq v}}^{k} \sum_{i=0}^{n} \sum_{\substack{j=0 \\ j \neq i}}^{n} x_{ij}^{(0,u)} x_{ij}^{(s,v)} - (t_{sv} - N - r_{sv}) \tag{0e'''}$$

$$(v \in \{1,2,3, \dots, k : \ t_{sv} > N\}; \ s = 1,2,3, \dots T)$$

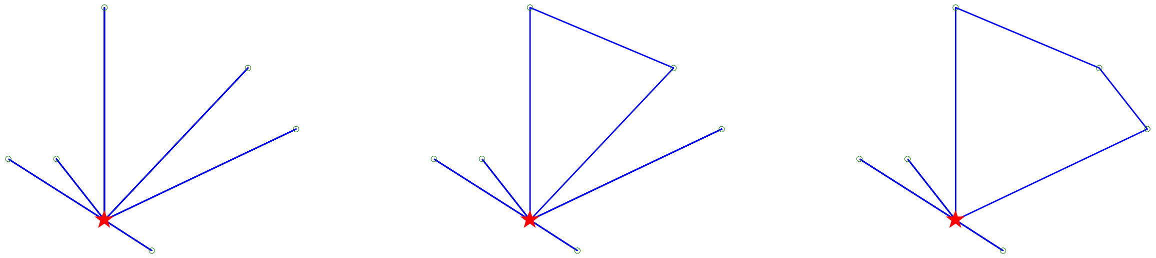
Since $x_{ij}^{(s,v)} \in \{0,1\}$ these constraints simply replace the absolute value functions of $(0b'), (0c'), (0d')$, and $(0e')$ with the product of two binary variable $(x_{ij}^{(s,v)})$. The expressions $(0b''), (0c'''), (0d''')$, and $(0e''')$ work in the same manner as $(0b'), (0c'), (0d')$, and $(0e')$ but use a different function to count the edges that agree between the two routes. The constant terms of $(0b''), (0c'''), (0d''')$, and $(0e''')$ are slightly modified from $(0b'), (0c'), (0d')$, and $(0e')$ to reflect the different counting mechanism.

1.5 Solution Methodologies for the VRP

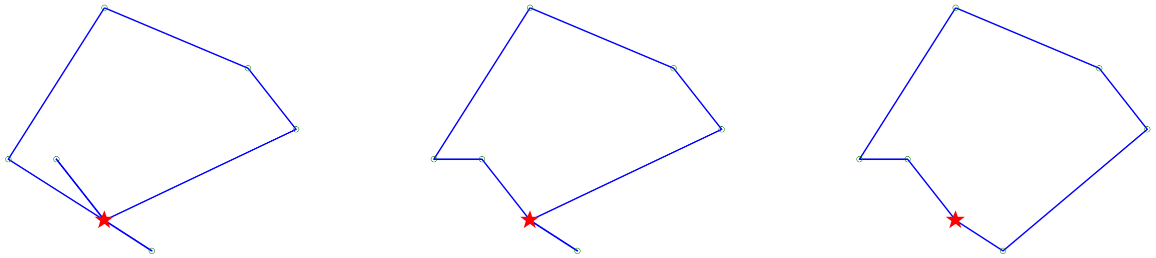
As illustrated above, using the VFM or another formulation, small instances of the VRP can be solved to optimality using MILP. Solving large instances using MILP is unrealistic.

There are extremely efficient heuristic methods that can be used to produce optimal or near-optimal solutions to the VRP. Generally speaking, heuristic methods apply intelligent “rules of thumb,” based on some portion of the problem data, to yield a high-quality solution. Heuristic measures for the VRP fall into two general categories, those for route construction and those for local improvement given a current solution to the problem. We give a basic introduction to some common VRP heuristics below; throughout we assume a graph $G = (V, E)$ with a single depot (node 0) and n other nodes (i.e., $|V| = n + 1$).

Two widely used methods of route construction for the VRP are the Clarke-Wright [11] and sweep heuristics. In the Clarke-Wright procedure we initially form a singleton route between each of the n nodes and the depot. We calculate the savings of joining two routes according to $s_{ij} = d_{0i} + d_{0j} - d_{ij} \quad 1 \le i, j \le n$, then process the savings list in decreasing order of s_{ij}, joining singleton routes into larger routes provided constraints, such as vehicle capacity, are not violated. Figure 1.5.1 gives an illustration of the process where $n = 6$ and assuming vehicle capacity or other constraints are not violated.



(a) Singleton Routes (b) First Two Routes Joined (c) Additional Routes Included



(d) Additional Routes Included (e) Additional Routes Included (f) Initial Route Complete

Figure 1.5.1: The Clarke-Wright Procedure for Initial Route Formation

Initial route formulation construction with the sweep procedure begins by forming a singleton route between the depot node and any of the other n nodes. From this first node, while no constraints are violated, we proceed in a clockwise or counter-clockwise fashion, including additional nodes into the route [12]. We illustrate the procedure in Figure 1.5.2 with $n = 8$ and assuming vehicle capacity or other constraints are not violated.

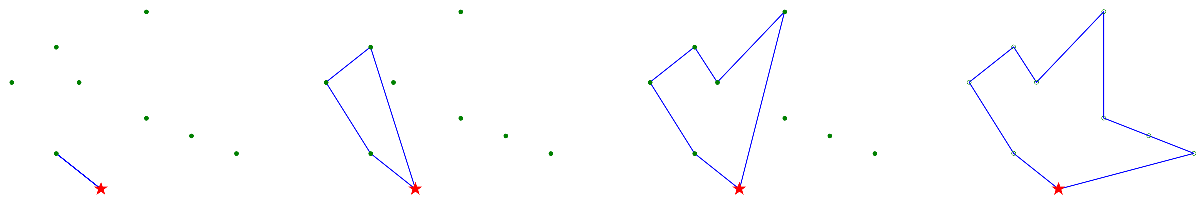

(a) Initial node (b) Clockwise Inclusion (c) Clockwise Inclusion (d) Initial Route

Figure 1.5.2: The Sweep Procedure for Initial Route Formation

Two widely used route improvement heuristics for the VRP are k-opt and the k-point move. Both these heuristics can be applied in an intra-route or an inter-route manner. For a k-point move, select k nodes then search for an alternate set of edges with which to connect the k nodes into the graph such that the alternate edge set yields a lower overall cost [12]. For an inter-route move, we must also verify feasibility with respect to vehicle capacity or other constraints. Figure 1.5.3 illustrates an intra-route two-point move ($n = 7$) and Figure 1.5.4 illustrates an inter-route one-point move ($n = 8$).

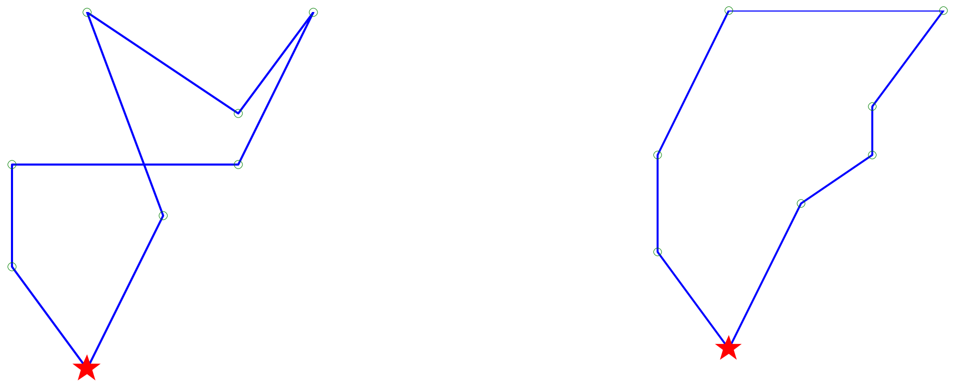
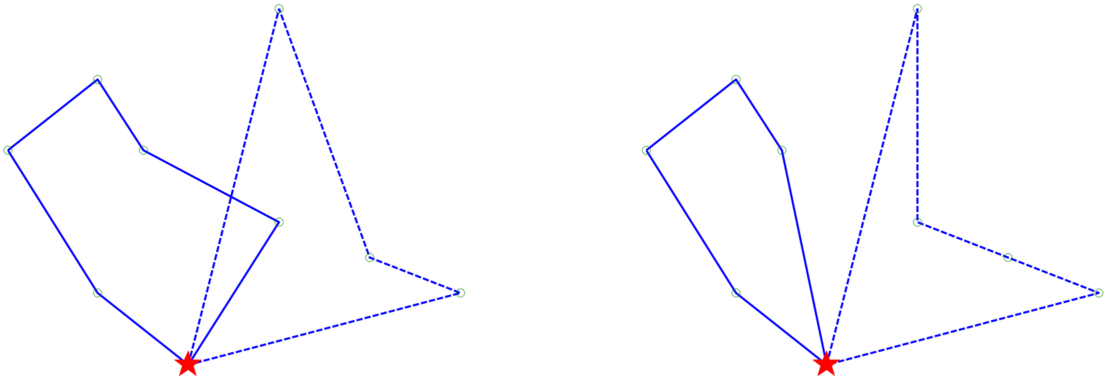

(a) Prior to Exchange (b) After exchange

Figure 1.5.3: An Intra-route Two-Point-Move



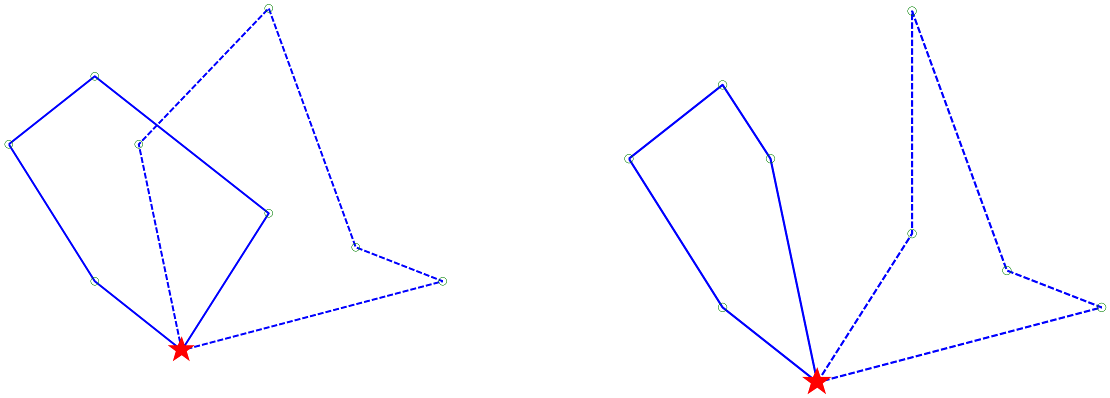
(a) Prior to Exchange (b) After exchange

Figure 1.5.4: An Inter-route One-Point-Move

For a k-opt move, we select and remove k existing edges of the graph and replace them with k alternate edges such that the new set of edges yields a lower overall cost [13]. Figure 1.5.5 illustrates an intra-route two-opt move ($n = 7$) and Figure 1.5.6 illustrates an inter-route two-opt move ($n = 8$). For the inter-route move, note that we remove one edge from each of two different routes and replace the removed edge of each route with an alternate edge; also, we must verify feasibility with respect to vehicle capacity or other constraints.

(a) Prior to Exchange (b) After exchange

Figure 1.5.5: An Intra-route Two-Opt Move



(a) Prior to Exchange (b) After exchange

Figure 1.5.6: An Inter-route Two-Opt Move

In solving a specific VRP instance, we typically proceed by first applying a route construction heuristic to form an initial solution. We then repetitively apply a set of different route improvement heuristics. “VRP solvers” are typically meta-heuristic-based algorithms that utilize route improvement heuristics as basic subroutines of simulated annealing, TABU search, the (modified) Lin-Kernighan algorithm, evolutionary algorithms, or other search methodologies [12,13].

1.6 VRP Solvers and the Default Solver

There are a number of commercial VRP solvers, e.g., RouteSmart [14]. Commercial VRP software includes several layers of additional complexity such as the ability to solve routing problems on real world transit networks, via integration of geographical information systems or other software, or a variety of business specific constraints, such as driver work hour limitations or preferential weighting of right turns over left turns. For non-commercial purposes, and academic problems (e.g., the

Euclidian 2-D graphs studied here) there are at least two, open source codes capable of solving the VRP.

For SYMPHONY, Ralphs, et al. [15,16], have built a number of application solvers for specific operations research problems, such as the VRP. These application solvers are implemented using SYMPHONY as a base subroutine.

The VPRH Library developed by Chris Groër [17] implements a set of heuristic methods for route construction and improvement, coded using efficient data structures in C/C++. This library has been extensively tested against benchmark problems and generally returns a solution within 3% of optimality. The VPRH Library is easy to modify to include additional constraints. Due to this adaptability, we use the VPRH Library in developing our solution methods.

In describing our heuristic procedures for the RVRP, when we refer to improving single routes, we are applying route improvement heuristics to a set of initial routes. Alternately, when we refer to improving routes we apply a series of heuristic methods where we consider moves that shift a node from its initial routes to another route.

To maintain consistency across solution approaches when using the VPRH Library for intra-route or inter-route moves, we fixed a robust set of heuristic operators comprised of the one-point move, two-point move, three-point move, and two-opt exchange.

Chapter 2: Comparison of Approaches

2.1 Test Problems

Test problems for the TSP and VRP are typically given in the TSPLIB file type, which is a standardized file format for detailing the parameters of a specific TSP or VRP instance [18]. Maintaining consistency with this convention, we created test problems for the RVRP by adding onto this existing framework. A test instance for the RVRP requires the following additional TSPLIB file type fields:

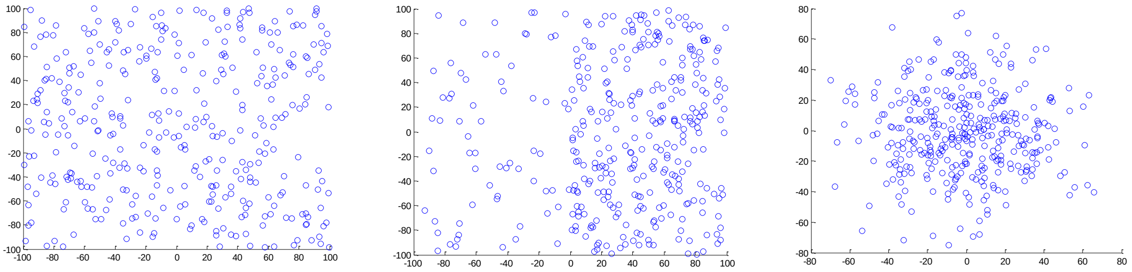
Field Name	Description
SEGMENT_LENGTH	Integer specifying the size of the segment length parameter
SCENARIOS	Integer specifying the number of days included in the scenario matrix (i.e., number of rows)
SCENARIO_DETAIL	Integer valued matrix detailing the specific customer load assigned to each route on a given day.

Table 2.1.1: Additional TSPLIB Field Names for the RVRP

To compare solution approaches for the RVRP, we developed a base set of 15 problems specifying the number and location of the nodes, and the number of vehicles. We selected $n = 360$ service nodes with a single depot and $k = 3$ vehicles. This is a non-trivial problem to solve, both from the perspective of graph size and from the perspective of vehicle count since, for three or more vehicles, each route has two unique adjacent routes.

All graphs are Euclidean 2-D and complete. Since any distribution in the plane can be normalized to the origin, we use $(0,0)$ as the location of the single depot (i.e., node 0) for all problems. We randomly generated the node locations, creating five each of three different node distributions, which we refer to as: random, right-biased, and normally distributed. Each represents a different distribution of the customer nodes.

For the randomly distributed instances, for all nodes, $X_i, Y_i = \mathcal{U}(0,1) * 200 - 100$. For the the right-biased distribution, for 240 nodes, $X_i, Y_i = \mathcal{U}(0,1) * 200 - 100$, and for the other 120 nodes, $X_i = \mathcal{U}(0,1) * 100$. For the normally distributed instances, for all nodes, $X_i, Y_i = (100/3.5) * \mathcal{N}(0,1)$. The node locations were all generated in MATLAB (version R2007b) using the default settings for random variate generation [19]. Graphical examples of the node distributions used are as follows:



(a) Random Distribution (b) Right-biased Distribution (c) Normal Distribution

Figure 2.1.1: Three Node Distributions for RVRP Instances Studied

From the 15 base problems, we generated two test sets of 15 RVRP instances, 15 each using segment length 10 and segment length 15. The number of nodes exchanged between two routes is required to be a multiple of the segment length. Reference to the individual instances is according to the format of the following example: N360_SL10_RAND_1. This instance has 360 service nodes, a segment length of 10, and the node distribution is random. The test instances are included in Appendix D.

In terms of the difference from the nominal route length ($N = n/k$), the general form of the scenario matrix is given below in Table 2.1.2, where the symbol Δ denotes the quantity segment length.

Day	Route 1	Route 2	Route 3
1			
2		-Δ	+Δ
3		+Δ	-Δ
4	-Δ	+ Δ	
5	+Δ	-Δ	
6	-Δ		+Δ
7	+Δ		-Δ
8	+Δ	-2 x Δ	+Δ
9	-2 x Δ	+Δ	+Δ
10	+Δ	+Δ	-2 x Δ

Table 2.1.2: Difference from Nominal Route Length in RVRP Instances Studied

Then the specific scenario matrices within the respective test problem sets are as follows:

Day	Route 1	Route 2	Route 3
1	120	120	120
2	120	110	130
3	120	130	110
4	110	130	120
5	130	110	120
6	110	120	130
7	130	120	110
8	130	100	130
9	100	130	130
10	130	130	100

Table 2.1.3: Scenario Matrix with SL10

Day	Route 1	Route 2	Route 3
1	120	120	120
2	120	105	135
3	120	135	105
4	105	135	120
5	135	105	120
6	105	120	135
7	135	120	105
8	135	90	135
9	90	135	135
10	135	135	90

Table 2.1.4: Scenario Matrix with SL15

The scenario matrices specified above were provided by an industry expert at a major package delivery company in the United States [3]. Though we used the scenario matrix directly from the initial suggestion, we considered whether or not this scenario matrix was a reasonable starting point for initial research regarding the RVRP.

Though the choice of 10 days is arbitrary we felt that it was reasonable from several perspectives. We believe that 10 is a sufficiently large number such that the procedures that yield the best results for a scenario matrix with 10 days will also yield the best results for a scenario matrix of greater size. Ten (or perhaps, at least 10) also seems reasonable as, in practical application of the RVRP. We might expect the scenario matrix to represent a probability distribution of the number and type of inter-route exchanges anticipated over some extended period of time, say a year. Using a 10 row scenario matrix with unique rows says that we expect, in the course of an extended period of time, with equal probability that any of 10 unique scenarios could occur on any given day. Since we are interested in an extended period of time, 10 unique possible configurations seem reasonable. If the possible configurations (represented by rows of the scenario matrix) are distributed with unequal probability, we can increase the size of the scenario matrix, repeating rows as needed to describe the expected distribution.

Note that the scenario matrix across all problems is balanced, that is, the column sums of the scenario matrix are equal. This seemed to be the most logical type of scenario matrix for the RVRP since, if the matrix is not symmetric, it suggests that at least one route should have a number of customers other than n/k. While this may seem to limit the application of the RVRP, here again refer to our conceptual argument for the RVRP: deliveries to customer nodes where a series of several services (deliveries) may be required. In the case where the scenario matrix is not balanced, it may be reasonable to collapse some of the n nodes and redefine the problem (now of size $n^{'} < n$) to have a balanced scenario matrix with nominal route length $N = n'/k$. This argument is also relevant to the case where the initial number of nodes is not divisible by the number of vehicles.

2.2 Lower Bounds

As noted, our work appears to be the first investigation into this particular variant of the VRP. The optimal solutions to our test instances are unknown. We now try to develop a lower bound to the optimal solution of each problem.

The RVRP is a routing problem with more than one vehicle ($k > 1$). Assume an instance of the RVRP and let C_{nom} denote the distance by all vehicles when using the optimal nominal routes subject to the restrictions of the RVRP. Let C_{VRP} denote the total distance by all vehicles when utilizing the optimal VRP routes in a VRP with the same node distribution and number of vehicles as the RVRP instance. Then we have $C_{VRP} \leq C_{nom}$. Let C_{alt} represent the optimal total distance by all vehicles on any single day of the scenario matrix. By the triangle inequality, we have $C_{nom} \leq C_{alt}$. In the case where the routes for a given day are different from the nominal routes, the inequality is strict.

Now consider the VRP with one vehicle ($k = 1$) and unit demand at all nodes. Let C_1 denote the total distance by a single vehicle to each of the nodes in the problem instance. Clearly, the minimum cost for C_1 is given by an optimal solution to the TSP and $C_1 < C_{VRP}$, again by the triangle inequality. The relationship of these four quantities is $C_1 < C_{VRP} \leq C_{nom} \leq C_{alt}$. Given that an instance of the RVRP has T days, clearly $T \times C_1 < \sum_T C_{alt}$. A lower bound for any solution approach to the RVRP instance is given by T times the optimal solution to the TSP based on the instance nodes.

There are at least two open source solvers for the TSP. The LKH solver developed by Keld Helsgaun [20] implements a modified version of the Lin-Kernighan heuristic. The LKH solver currently holds the record for best-known solution to a TSP problem with two million nodes. The Concorde solver developed by Applegate [21], et al., has two implementations, one using the Lin-Kernighan heuristic and another that provides exact solutions (i.e., provably optimal) using a MILP routine. Using the exact algorithm of Concorde, we can determine the optimal solution to a TSP instance derived from the nodes of a particular RVRP instance and provide a definitive lower bound for each RVRP instance we developed.

Our lower bound is not feasible for the RVRP and we do not know how tight the bound is to the optimal solution. Furthermore, given the number of days of the scenario matrix, T, the lower bounds listed below apply to any RVRP based on the node distribution in the specific instance. That is, given a specific node distribution and a fixed T, the lower bound derived in the manner below is the same across any possible segment length and any possible specific scenario matrix (having T rows).

The exact algorithm of Concorde is implemented on the publically available Network Enabled Optimization Server [22,23,24]. The results from solving the related TSP problems for each RVRP instance are given in Table 2.2.1.

Instance	TSP Optimal	Solution Time (sec)	Lower Bound when $T = 10$
N360_SL*_RAND_1	2850.6	44.2	28506
N360_SL*_RAND_2	2822.6	37.9	28226
N360_SL*_RAND_3	2822.8	2.2	28228
N360_SL*_RAND_4	2796.6	1.3	27966
N360_SL*_RAND_5	2857.1	1.5	28571
N360_SL*_RBIAS_1	2695.6	1.8	26956
N360_SL*_RBIAS_2	2652.6	2.8	26526
N360_SL*_RBIAS_3	2613.0	3.9	26130
N360_SL*_RBIAS_4	2636.2	4.6	26362
N360_SL*_RBIAS_5	2602.1	4.6	26021
N360_SL*_NORM_1	1903.2	2.81	19032
N360_SL*_NORM_2	1964.0	1.9	19640
N360_SL*_NORM_3	1841.1	34.9	18411
N360_SL*_NORM_4	1826.7	10.1	18267
N360_SL*_NORM_5	1808.5	48.6	18085

Table 2.2.1: Lower Bounds for 15 Node Sets Used in RVRP Instances

2.3 A Solution Algorithm for the Robust Vehicle Routing Problem

The challenge of the RVRP is that determining what segments should be exchanged between routes is only possible given some routes to consider. However, given any set of nominal routes, determining what customer nodes should be exchanged between routes to meet the requirements of the scenario matrix is a very simple optimization problem for each day of the scenario matrix. To solve the optimization problem we need only examine routes that must exchange nodes and identify the least cost edges with which to make the exchange (see Section 1.4). Thus, our general approach to solving the RVRP is to execute a procedure that outputs several candidate solutions to the RVRP (i.e., each candidate solution specifies one feasible solution for the nominal routes), then choose the best from the candidate solutions.

To proceed, we first select a range of values for one or more parameters and fix the initial values of the parameter(s). Next we generate a candidate solution to the vehicle routing problem using a specific approach that depends on the value of the input parameter. Thus, for each different value of the parameter, we desire a different candidate solution of nominal routes. We repeat this procedure by modifying the value of the parameter until we have generated the desired number of candidate solutions. Once the set of candidate solutions is populated, for each candidate solution we can determine the total cost by solving a small optimization problem for each day of the scenario matrix. Finally, we select as our solution the best candidate solution.

Using this framework, the individual optimization problems that need to be solved to find the exchanged segments is easy. The challenging component is step two, generating the candidate solutions. Clearly our approach to generating candidate solutions must return several unique solutions to evaluate and choose from. However, the number of candidate solutions should be small, otherwise computation time will rapidly grow.

The remainder of this thesis focused on the solution candidate generation step of the general algorithm given above. We consider several approaches to generating the candidates. Our goal is to find some approach that will generate a small number of candidate solutions that produce at least one candidate solution that has a high solution quality in terms of the total distance of the nominal routes but that also has a structure allowing for low cost exchange of customer node segments between the routes.

In Chapter 3 we consider two solution candidate generation approaches that apply traditional VRP solution approaches. We use these two approaches as baselines for comparing alternative candidate solution approaches, which we consider in Chapter 4.

2.4 Evaluation of Alternative Candidate Generation Approaches

We evaluate each candidate solution generation approach with three measures: total distance, flexibility test result, and computation time growth rate (in solution time with *N*, the number of service nodes). Total distance and flexibility can be computed directly. We used MATLAB to evaluate the computation time growth rate. Results are presented in Chapter 5.

For a given set of nominal routes, the total distance is defined to be the total distance by all vehicles in making the trips required by the scenario matrix. As noted earlier, we decided to measure total distance assuming the best possible segment exchanges given a set of nominal routes from a solution approach. In the case of the test problems we studied, for a given set of nominal routes, the total distance is the smallest possible total distance by the three vehicles over 10 days where the routes the vehicles travel is modified according to the requirements of the scenario matrix.

Our second performance measure is the flexibility of the routes to a change in the segment length, a measure of sensitivity to the segment length. Specifically, a flexible solution to a RVRP instance would perform equally well if the segment length was slightly smaller or larger than the segment length used to calculate the total cost measure. To evaluate the flexibility of the solution, we recompute the total route length, as above, redefining the segment length (SL) to be $SL + \Delta$ where $\Delta \in \{\pm 3, \pm 2, \pm 1\}$. The flexibility test score is the average of these six total length values.

To determine the growth rates, we generated five RVRP instances each of size $n \in \{90, 120, 180, 240, 300\}$ using a random node distribution. We used a segment length of 10 for each instance and defined the scenario matrices for each instance as in Table 2.1.2. We also used the results from the $n = 360$ instance giving 30 instances total. To determine the computation time growth rate for each solution approach, we solve each of the 30 instances using each of the solution approaches described in Chapters 3 and 4 and record the computation time. Thus, for each solution approach we generate a set 30 data points total, to which we added the data point (0,0) under the assumption that if $n = 0$, the solution time is zero. For each solution approach, we analyze the data set using MATLAB to determine the relationship: computation time as a function of n.

Chapter 3: Baseline Candidate Solution Generation Approaches

We describe two candidate solution generation procedures for the RVRP, which we refer to as the Traditional VRP and the All Sweeps approaches. We note that the first procedure has excellent performance in terms of solution time and the second procedure has excellent performance in terms of solution quality. As discussed in Section 2.2, the optimal solutions to the RVRP instances we developed are unknown and we have only lower bounds for the problems. Since both procedures are easily derived from quick adaptation of existing VRP research, and they each yield good performance in one of the principle performance measures, we use these approaches as performance baselines in assessing the performance of the approaches we develop in later sections. To give a complete visual illustration of the RVRP, we plot the best solution to the N360_SL10_RAND_1 test instance for both solution approaches (Figure 3.1.4 and Figure 3.2.1, respectively).

3.1 Traditional VRP

One of the most popular ways to solve the VRP is to construct an initial solution using the Clarke-Wright procedure, then improve that solution using route improvement heuristics (e.g., two-opt). We can apply that same approach to develop the nominal routes for the RVRP.

The Traditional VRP approach does not attempt to specifically consider the additional restrictions of the RVRP. We might expect that this would result in low-quality solutions. However, this turns out not to be the case.

To see why this is so, recall the discussion of Section 1.4 where we develop a MILP for the RVRP. Consider day *s* of the scenario matrix for which a segment exchange occurs. The edges included in the routes of day s are identical to the nominal routes, except those edges involved in exchanges. From our definition of the RVRP, the maximum number of segment exchanges on any day can be no more than k. When n is large relative to k, the total distance of the edges involved in exchanges on day s is small compared to the edges of the nominal routes that persist in the routes of day s. As result, the quality of the nominal routes, is important to overall solution quality.

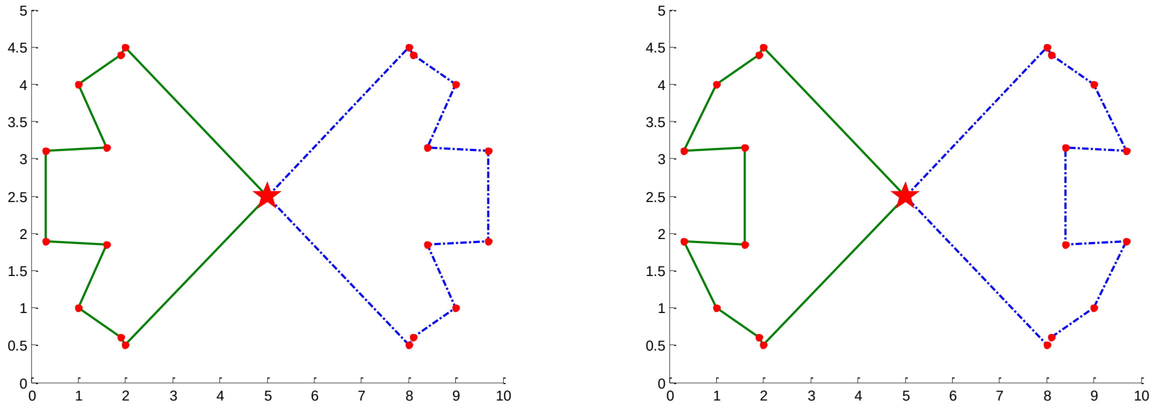
A solution approach that yields low quality nominal routes generally cannot outperform a solution approach with high quality nominal routes, regardless of how well the first approach minimizes the length of edges involved in segment exchanges. Given two solution approaches that yield nominal routes of equal quality, the distinction between them in terms of RVRP solution quality is how well they minimize the distance of edges added and removed (compared to the nominal routes) during segment exchanges. Any solution approach that yields high quality nominal routes will typically perform well in terms of the RVRP (depending on the specific details of the RVRP instance). Thus, even though the Traditional VRP solution approach for the RVRP is formulated without specifically considering the segment exchanges, the method applied is highly effective in solving VRPs. As result the nominal routes generated by the Traditional VRP approach are generally of high quality, and, as result, the solution quality in terms of the RVRP is generally good.

Extrapolating this line of thought seems to suggest that the solution to the RVRP should be identical to solution of a regular VRP problem and that the optimal solution to the VRP will be an optimal solution to the RVRP. However, consider the following simple counter-example (Appendix E provides full detail for the problem). Let $N = \frac{n}{k} = \frac{20}{2} = 10$, and the scenario matrix $[t_{sv}]$ be:

Day	Route 1	Route 2
1	10	10
2	5	15
3	15	5

Table 3.1.1: Scenario Matrix for a 20 Node RVRP Instance

Figure 3.1.1 plots two possible sets of nominal routes. Throughout, we refer to the route drawn in the solid line as route one, the dashed line as route two. The routes of Figure 3.1.1(a) are optimal for the VRP defined by the first row of the scenario matrix of this RVRP instance; the total distance of the nominal routes is 30.7. The routes of Figure 3.1.1(b) are suboptimal; the total distance is 31.3 (2.0% above optimal).

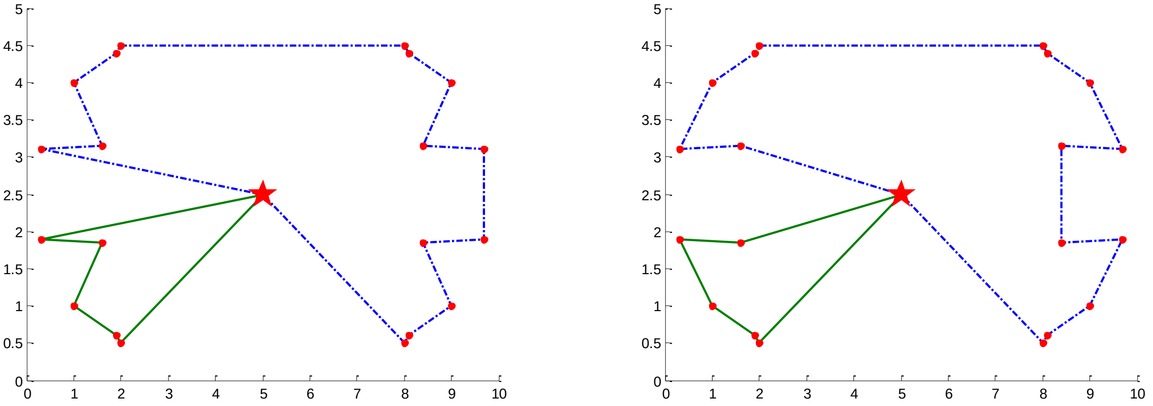


(a) Nominal Routes that are VRP Optimal

(b) Nominal Routes that are not VRP-Optimal

Figure 3.1.1: Two Alternative Sets of Nominal Routes for a 20 Node RVRP Instance

The best possible routes for day two (by making the best possible segment exchange) are plotted in Figure 3.1.2. The routes for day three are given by reflection of the day two routes over the line $x = 5$. With respect to the two possible sets of nominal routes defined above, day two and day three of the scenario matrix each have a total distance of 37.8 and 35.7, respectively. The total distance by the two vehicles over three days is 106.2 and 102.7, respectively. The RVRP solution using the non-VRP-optimal nominal routes is 3.3% better than the solution derived from the VRP-optimal nominal routes.



(a) Day Two Routes for VRP-Optimal Routes (b) Day Two Routes for Non-Optimal Routes

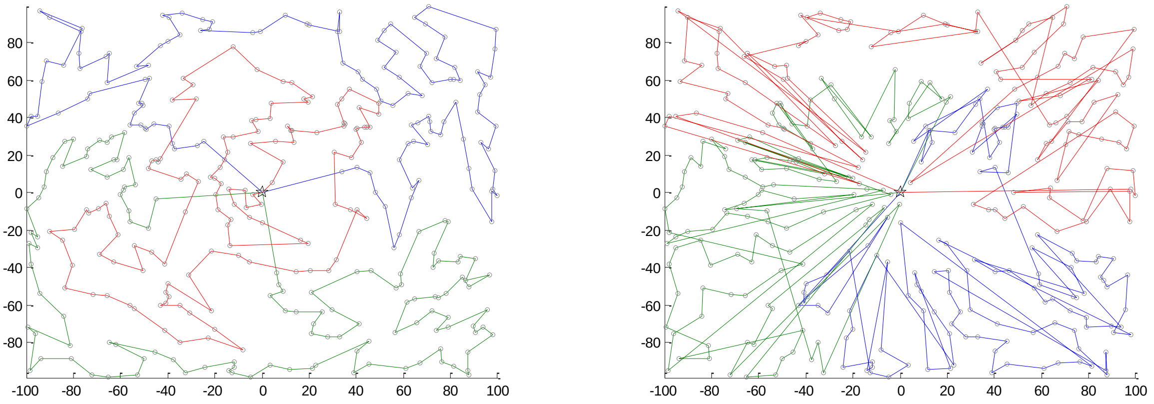
Figure 3.1.2: Day Two Routes for Two Alternative Sets of Nominal Routes for a 20 Node RVRP Instance

We can improve the overall performance of the Traditional VRP approach by using a parameterized Clarke-Wright procedure to develop a set of solutions for the RVRP increasing the likelihood that one of the solutions will be favorable for segment exchange. The input to the route improvement stage of traditional VRP solution is the output from the Clarke-Wright procedure. By using a parameterized procedure, we generate different inputs to the route improvement stage, which typically results in convergence to different local minima of the search space. The parameterized Clarke-Wright procedure suggested by Yellow [25] incorporates a weighting parameter, γ, into the savings calculation according to:

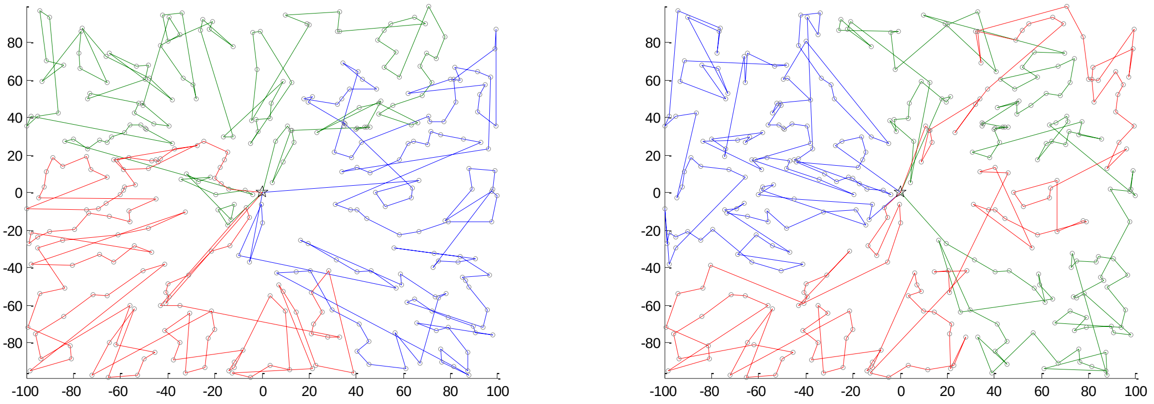
$$s_{ij} = d_{0i} + d_{0j} - \gamma \times d_{ij} \quad (0 \leq i, j \leq n)$$

Note that when γ=1 we have the traditional Clarke-Wright algorithm discussed in Section 1.5. We used $\gamma \in \{0.6, 1.0, 1.2, 1.6\}$, thus the Traditional VRP approach generates four candidate solutions.

To illustrate the impact of the value of the parameter γ, Figure 3.1.3 displays the initial routes generated by the algorithm for the N360_SL10_RAND_1 instance. The value of γ and the total distance of all routes is indicated with each plot.



(a) $\gamma = 0.6$, Total Distance: 3463.1 (b) $\gamma = 1.0$, Total Distance: 7471.5

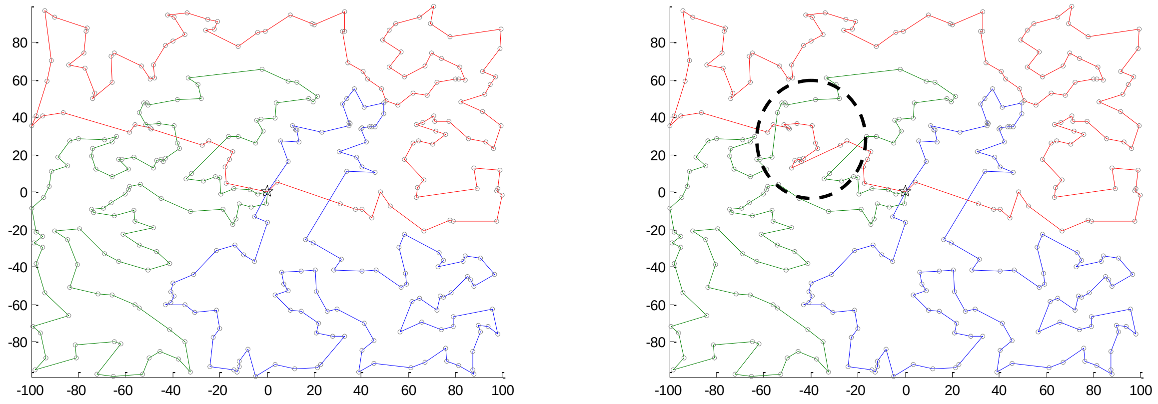


(c) $\gamma = 1.2$, Total Distance: 5773.9 (d) $\gamma = 1.6$, Total Distance: 5599.2

Figure 3.1.3: Initial Route Formation Using a Parameterized Clarke-Wright Procedure

The graphs generated by the procedure are clearly very different start vectors in the solution space. Each initial set of routes generally converges to a different RVRP solution, thus giving four unique candidate solutions for the nominal routes, from which we select the best as our result.

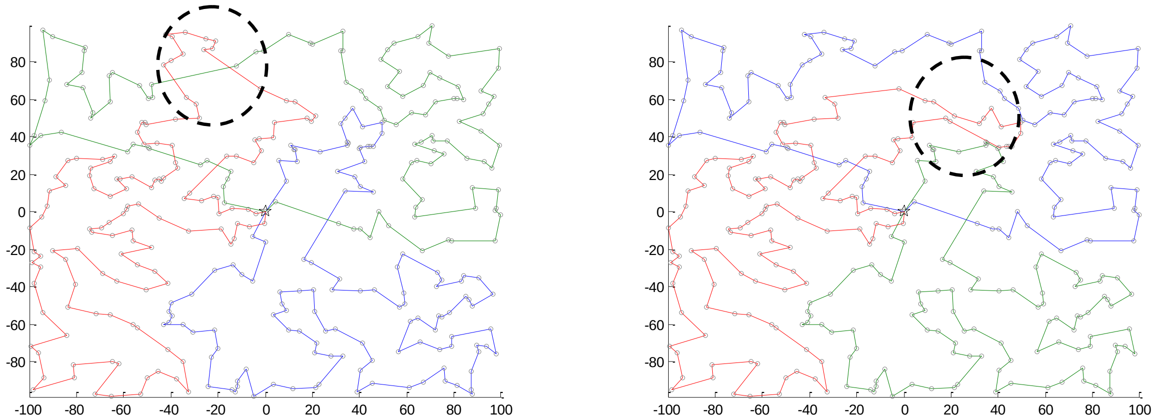
The sequence of plots given in Figure 3.1.4 illustrate the segment exchanges that occur during the 10 days of the scenario matrix for the best nominal routes found using the Traditional VRP approach for the N360_SL10_RAND_1 instance. Each plot corresponds to one day of the scenario matrix (Table 2.1.3). For each plot, we list give the detail of the scenario matrix row to which the plot corresponds (i.e., s: R1-R2-R3, where R1, R2, and R3 are the number of nodes assigned to the three routes, respectively, on day (row) s of the scenario matrix). For the purposes of corresponding with the scenario matrix detail, in all plots, route one is in the lower right of the plot, route two the lower left, and route three the topmost route. As the first row of Table 2.1.3 has all routes with $N = \frac{n}{k} = \frac{360}{3} = 120$ customers, Figure 3.1.4(a) gives the nominal routes. In each plots we highlight the region(s) of inter-route segment exchange using a dashed circle.



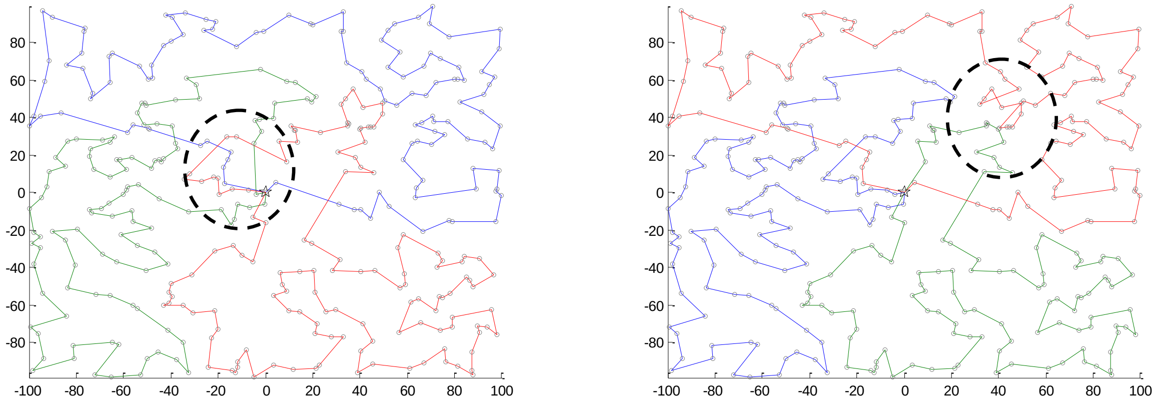
(a) 1: 120-120-120

(b) 2: 120-110-130

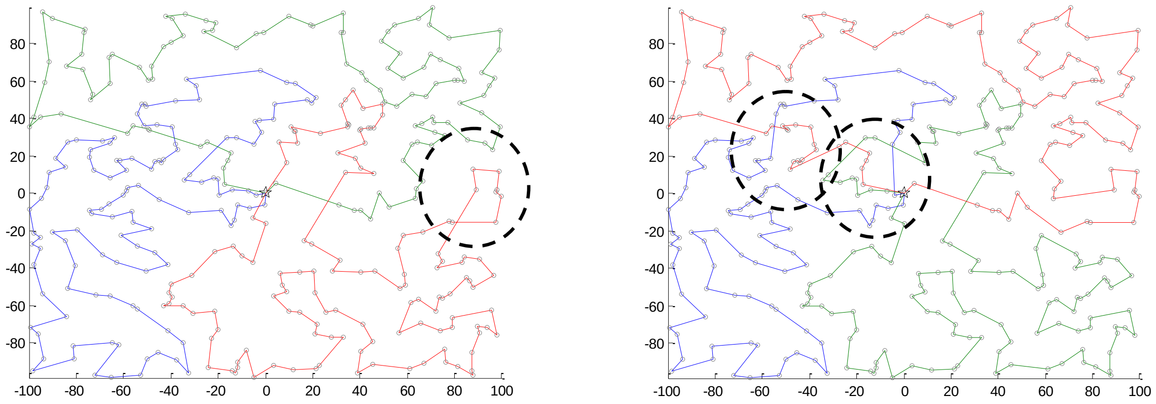
Figure 3.1.4: Routes for the 10 Days of RVRP Instance N360_SL10_RAND_1, Best Result from the Traditional VRP Approach



(c) 3: 120-130-110 (d) 4: 110-130-120

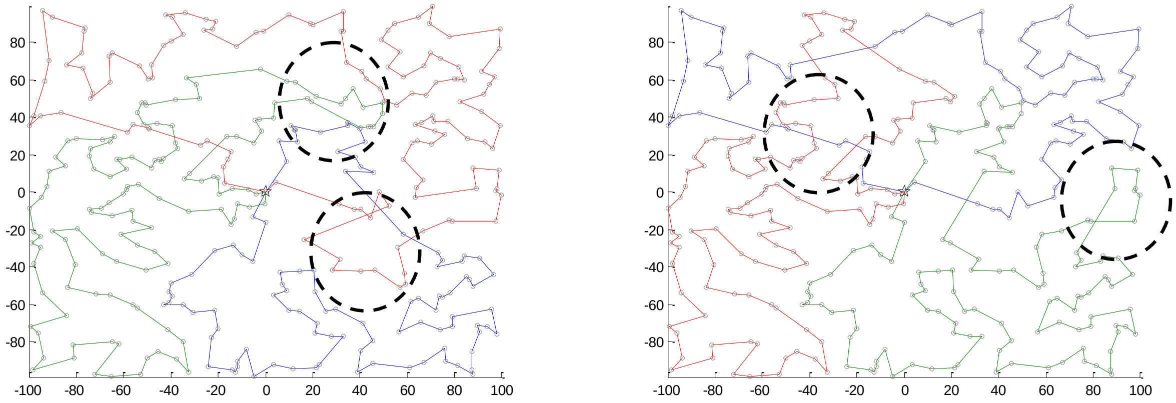


(e) 5: 130-110-120 (f) 6: 110-120-130



(g) 7: 130-120-110 (h) 8: 130-100-130

Figure 3.1.4: Routes for the 10 Days of RVRP Instance N360_SL10_RAND_1, Best Result from the Traditional VRP Approach (continued)



(i) 9: 100-130-130

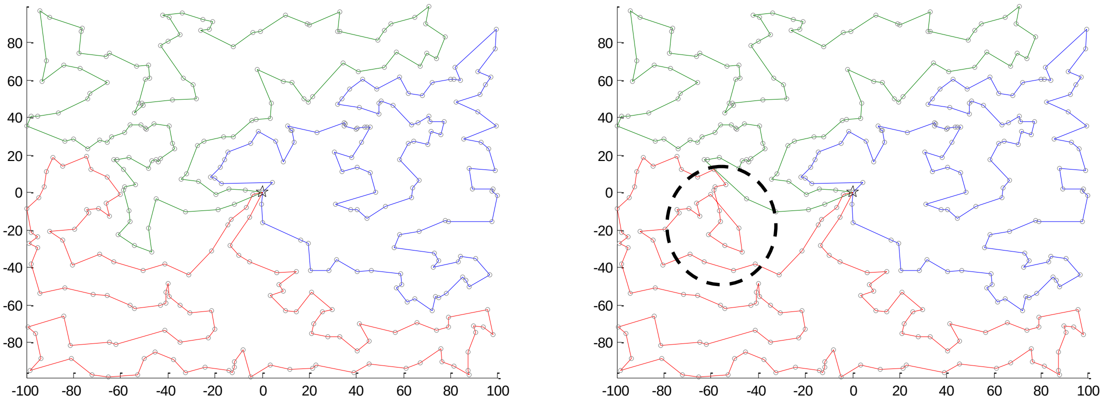
(j) 10: 130-130-100

Figure 3.1.4: Routes for the 10 Days of RVRP Instance N360_SL10_RAND_1, Best Result from the Traditional VRP Approach (continued)

3.2 All Sweeps

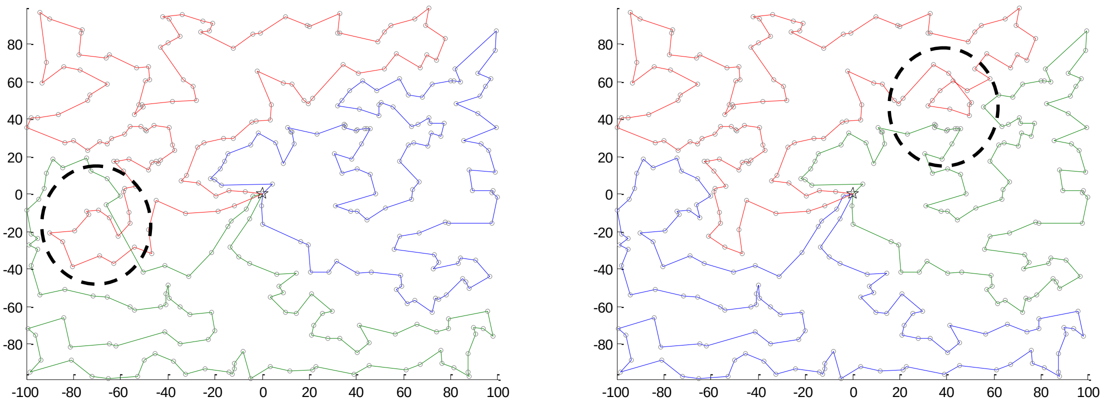
In the second approach to the RVRP, we apply the sweep procedure with subsequent route improvement, to all possible sweep starts. We begin by calculating the radial order of the nodes, then process the first $1/k$ of the list, by using each subsequent node as the start of the sweep procedure for initial route formation. From each set of initial routes generated, we then improve the routes using route improvement heuristics. There are n/k iterations total; we only process the first $1/k$ of the list since any node in the remainder of the list will yield an identical result to one of the nodes already tested (only the route numbers will be different). The All Sweeps approach generates n/k candidate solutions from which we select the best.

Figure 3.2.1 illustrates the segment exchanges that occur during the 10 days of the scenario matrix using the best nominal routes found using the All Sweeps approach. The format of Figure 3.2.1 is identical to that of Figure 3.1.4 except, for the purpose of corresponding with scenario matrix detail, route one is now on the right, route two is in the upper left, and route three is in the lower left. Again, dashed circles indicate the region(s) of inter-route segment exchange.



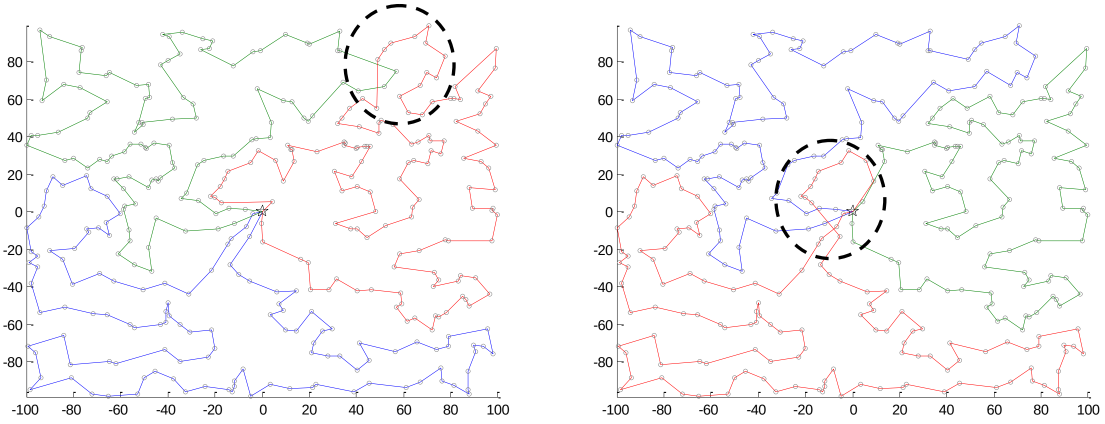
(a) 1: 120-120-120

(b) 2: 120-110-130



(c) 3: 120-130-110

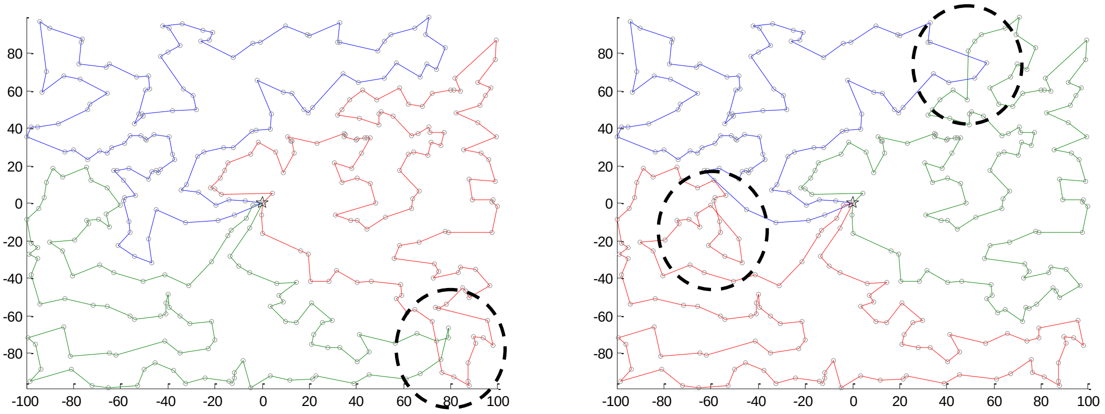
(d) 4: 110-130-120



(e) 5: 130-120-110

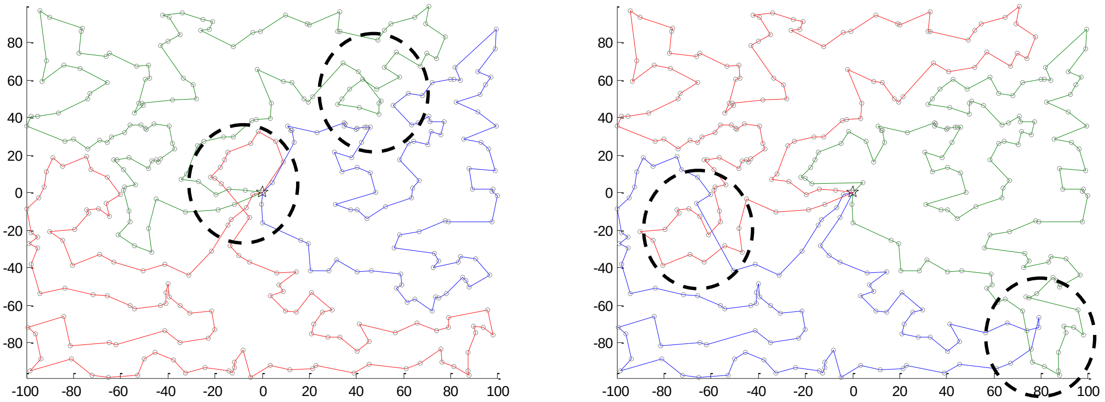
(f) 6: 110-120-130

Figure 3.2.1: Routes for the 10 Days of RVRP Instance N360_SL10_RAND_1, Best Result from the All Sweeps Approach



(g) 7: 130-120-110

(h) 8: 130-100-130



(i) 9: 100-130-130

(j) 10: 130-130-100

Figure 3.2.1: Routes for the 10 Days of RVRP Instance N360_SL10_RAND_1, Best Result from the All Sweeps Approach (continued)

The routes developed by this procedure generally are of high quality. As suggested in Figure 3.2.1, the strong performance of the All Sweeps approach results from locating the best possible division points for the nodes of the graph into individual routes (akin to slicing the graph into pie pieces). Good division points occur where the density of nodes is high. The All Sweeps approach identifies these regions by generating a candidate solution for every possible segmentation point (via $N = n/k$ iterations). By segmenting the graph where the node density is high, the nominal routes that are generated have a high density of nodes at their boundary with adjacent routes, making the routes well suited to low cost inter-route exchanges.

Chapter 4: Alternative Candidate Solution Generation Approaches

4.1 Forced-Cross Approaches

Observations from the Traditional VRP approach (e.g., Figure 3.1.4) suggested that high-quality solutions to the RVRP may include nominal routes that intersect each other. These intersection points could provide high-quality exchange sites among the routes. For example, a route that intersects another route at two points such that the two intersection points are close, and the length of the overlap (in terms of customer nodes) is close to the segment length, yields a high quality site for segment exchange. To implement this idea, we considered a number of approaches using parameters to force specific intersecting structures in the generated nominal routes.

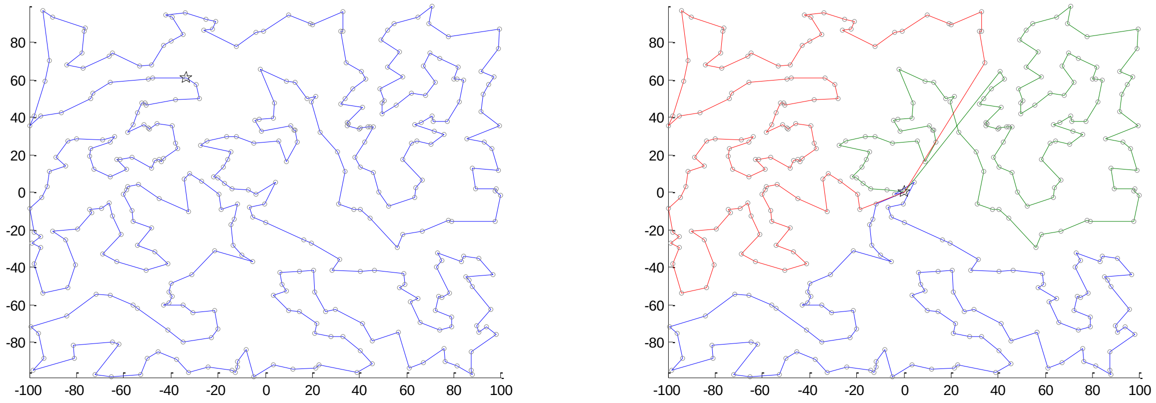
Ultimately, all of these approaches yielded poor results for the following two reasons. In general, multiple intersections of the routes degrade route quality. Even in the cases where the lengths of edges involved in segment exchanges was small, this reduction objective cost failed to overcome the cost increase resulting from the loss of efficiency of multiple vehicles visiting the same points of the graph. Second, as noted, we assume a no information state in our solution approaches. If the segment length were known, creating nominal routes with intersection points that yielded low cost segment exchanges may be possible. In the absence of this specific information, the search for intersection points requires a number of parameters. As result, these procedures were generally slow and, when good solutions were generated, they tended to fail in terms of the second quality measure, robustness. We provide numerical results for the Forced Cross solution approaches in Appendix F, rather than Chapter 5.

4.2 Great Circle Approach

In terms of an instance with a small number of nodes, a route-first-divide-later approach might provide a high-quality solution. In the Great Circle approach, we first route all of the nodes in a single Hamiltonian path. Then, starting from the Great Circle, we subdivide the single route according to capacity constraints of the vehicles. On a small graph where the nodes might all fall into some circular shape, such as the six node RVRP of Section 1.4, this approach is likely to perform well. However, as the size of the graph increases, as the in the case of our RVRP test instances, the quality of this approach quickly breaks down.

The Great Circle approach has two steps. First, we include all n customer nodes of the graph into a single route by applying an initial route formation heuristic and subsequent route improvement heuristics (temporarily ignoring the depot node). Due to the use of heuristics, the single route created in the first step converges to a local minimum. To create multiple candidate solutions, we use a parameterized Clarke-Wright algorithm for initial route construction. In step two, we select the Great Circle having least cost and identify the best possible points at which to break up the single route such that k routes are created.

When n is large, a high-quality route formed during step one of the procedure has an increasingly non-circular shape, and includes a number of small sub-tours off the general path of the route. As result, step two is typically unable to identify low cost points at which the single route can be subdivided. Figure 4.2.1 gives the best result generated for the N360_SL10_RAND_1 instance using the Great Circle approach.



(a) The Great Circle Route, Before Insertions

(b) Nominal Routes: 120-120-120

Figure 4.2.1: Difficulties with the Great Circle Approach on N360_SL10_RAND_1

The great circle route, prior to insertions is given in Figure 4.2.1(a). The inability of step two of the procedure to find high-quality points to subdivide the great circle route is evident in Figure 4.2.1(b). As these plots illustrate, complexity of large problem sizes makes the Great Circle Approach ineffective for the RVRP.

The failure of the Great Circle approach provides an additional example of how ignoring the cost of the edges involved in exchanges, despite their low number, can lead to a poor quality solution. Numerical results for the Great Circle approach are given in Appendix F. We briefly revisit the Great Circle approach in Section 4.5.

4.3 Percentage Approach

A third solution approach to the RVRP tries to develop the nominal routes of the candidate solutions in two (or more) stages. In the first stage we identify some subset X of the n nodes and construct k routes (skeleton routes), each having less than n/k nodes (but not necessarily the same number of nodes). We then consider the set of nodes Y not in X and sequentially insert the nodes of Y into the routes formed on X until each route consists of exactly $N = n/k$ and Y is empty. We refer to this approach as the Percentage approach and tested two variants on the general framework.

Note that regardless of how X is determined, since the nodes of Y are individually inserted into the routes formed on X, there are $|Y|!$ possible orderings in which the nodes of Y may be inserted. Each ordering may result in a different final result. Accordingly, any Percentage approach for the RVRP requires at least two critical decisions. The first decision is how to allocate the n nodes between X and Y. The second decision is the order of insertion of Y onto the routes formed on X.

For the first variant of the Percentage approach we determined X and Y using the distance of the customer nodes from the depot. We considered several alternative allocations. For example, in an outer-inner approach, X is defined to be the $P\%$ of nodes furthest from the depot. To generate multiple candidate solutions, we vary P. After forming routes on the nodes of X, we insert Y using least cost insertion, considering the nodes of Y in decreasing order of their distance from the depot. With each allocation strategy for determining X and Y, we tested a number alternative of ordering strategies for inserting Y (e.g, reverse order of their distance from the nearest center of mass of the routes formed on X).

Our second variant of the Percentage approach allocated nodes between X and Y based on their nearness to other nodes. We tested several definitions for nearness with the basic operation the same under each definition (e.g, nearest neighbor distance, average neighbor distance, etc.). Nodes that were labeled as distant from other nodes were placed into X and used for generation of the skeleton routes. Nodes determined to be near other nodes were assigned to Y and inserted onto the skeleton routes. As in our first variant of the Percentage approach, we tested several strategies for inserting Y onto X. In this second variant, we also tested using more than two sets, subdividing the node population into as many as five levels of closeness.

For both variants, results from the Percentage approach were competitive for some instances. However, solution quality from these procedures was inconsistent and suggested that the procedures may only perform well on instances well suited for the technique. Additionally, several of the procedures performed poorly in terms of computation time. Numerical results are given in Appendix F.

4.4 Efficient Sweep Approaches

The All Sweeps solution approach of Section 3.2 generates high-quality solutions but computation time is slow. Clearly a method that could obtain results similar to the All-Sweeps approach with shorter overall computation time would be desirable. We considered three such approaches, which attempt to intelligently choose a start node for the sweep procedure, reducing the generated candidate pool and computation time. We refer to these candidate solution generation approaches, respectively, as Sweep Neighbor, Sweep MST (minimum spanning tree), and Sweep Sectors.

The basic operation for all three methods is the same. We discuss this first. Details of the initialization algorithms, unique for each method, are described after.

Using the initialization algorithm, select a single start node for the sweep procedure (Section 1.5). Execute the sweep procedure for initial route formation, then improve single routes. Each procedure has a single parameter. The value of the parameter is varied and each new parameter value requires another iteration of the procedure, generating another candidate solution.

The basic operation of the initialization algorithms is the same: each attempt to locate a set of k nodes that are n/k nodes distant from each other (using the polar coordinates of each of the n nodes relative to the depot) and that are each in area of the graph where the node density is high. The start node determined by the initialization algorithm is then used in the sweep procedure for initial route formation. Since the initialization algorithm identifies nodes in the densest portions of the graph, the initial routes generated by the sweep procedure yields k routes whose boundaries are located in the densest portion of the graph.

For the Sweep Neighbor approach, we compute the polar coordinates of the n nodes then divide the set of nodes into n/k k-tuples. This gives n/k sets of k nodes each, with the nodes in each set being n/k apart from each other (radially). For each node in each set we compute the sum of the distance to its ω-closest neighbors, where ω is a parameter whose value we specify. The set having the smallest total distance is selected and one of the nodes from the set is selected as the start node of the sweep procedure by which the initial routes are formed. For the Sweep Neighbor approach we can select any of the k nodes in the minimum distance k-tuple since all k of the nodes will give the same result for the sweep procedure (since they are radially n/k nodes apart). From the set of solutions generated over ω, the least cost solution is returned as our result from the approach. The parameter $\omega \in [5,65]$. We increment ω using a step size of 5 generating 11 candidate solutions to consider and select from.

For the Sweep MST approach, we proceed identically as with the Sweep Neighbor approach. However, rather than compute the total distance to the ω closest neighbors, we compute the MST of size ω for each node, a different measure closeness between the nodes. The parameter $\omega \in [5,45]$; we increment ω using a step size of 5. In this way, the Sweep MST approach generates a set of nine candidate solutions.

For the Sweep Sector approach, we again begin by computing the polar coordinates of the nodes. Rather than compute node specific information in the next step, we count the number of nodes found in an angle of ω degrees with the depot. That is, we directly measure the node density in each sector of the graph by slicing the graph into identical "pie pieces" and count the nodes found in each "slice." For a given angle ω, we have 360/ ω sectors. We group the sectors into equidistant k-tuples and select the k-tuple having the greatest total number of nodes.

In contrast to the Neighbor or MST approach, the choice of start node in the Sweep Sector approach is not arbitrary. The k-tuple with the highest node density clearly has a non-trivial number of nodes that could equally be selected as the start node of a sweep procedure: in each k-tuple, we have k individual sectors, each expected to have more than one node. We return the most central node in any sector of the k-tuple as the start node for the sweep procedure. The parameter $\omega \in \{6, 9, 12, 15, 18, 21, 24, 27, 30\}$. Thus, this procedure generates nine candidate solutions.

Figures 4.4.1, 4.4.2, and 4.4.3, respectively, plot the best nominal routes for each of the three solution approaches of this section. Numerical results are presented in Chapter 5.

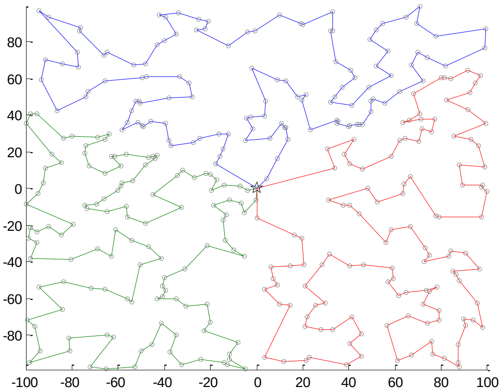


Figure 4.4.1: Best Nominal Routes for RVRP Instance N360_SL10_RAND_1 Using Sweep Neighbor Solution Approach ($\omega = 3.0$)

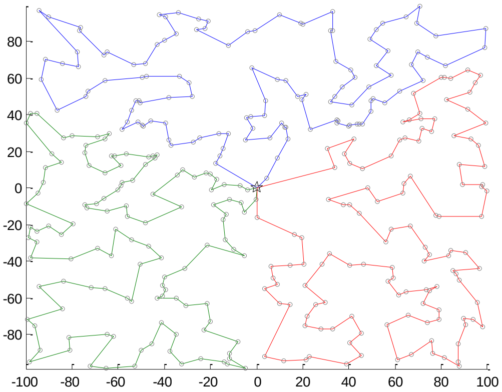


Figure 4.4.2: Best Nominal Routes for RVRP Instance N360_SL10_RAND_1 Using Sweep MST Solution Approach ($\omega = 3.0$)

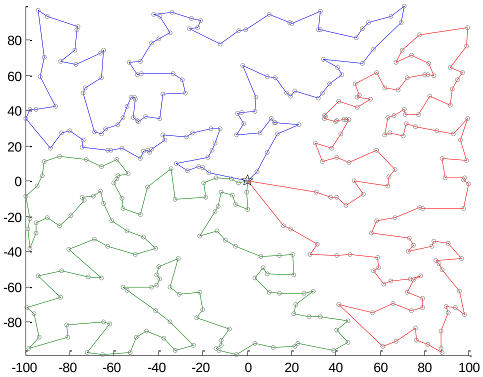


Figure 4.4.3: Best Nominal Routes for RVRP Instance N360_SL10_RAND_1 Using Sweep Sector Solution Approach ($\omega = 3.0$)

4.5 Approaches Based on the Traveling Salesman Problem with Center

The solution approaches described in this section are generally the best of those we tested. Typically, they delivered a high-quality solution with a reasonable computation time.

As noted, the TSP and its variants have been studied extensively. Lipowski and Lipowska [26] define a TSP variant where the objective is to minimize the total distance of the route and includes an additional objective: minimize the distance of the route from a single node defined to be the center of the graph. Liposki and Lipowska give the example of military patrols in the vicinity of a war time operating base with the expectation that the patrol may need to quickly return to the base from any point of the patrol. Price [27] examines routing a blood donation collection vehicle around a centrally located hospital, where there may be an urgent need for the vehicle to return to the hospital to replenish supply.

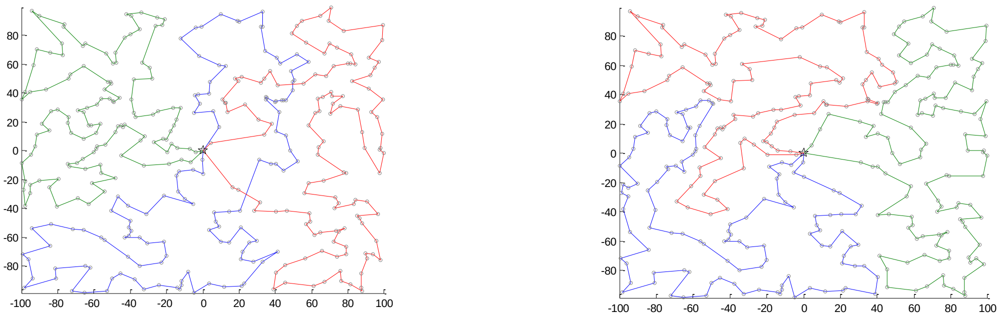
The traveling salesman problem with a center (TSPwC) is characterized by a two component objective function. The first component is the total cost of Hamiltonian cycle, as in the traditional TSP. The second component is a penalty function that increases with distance from the center of the graph. In Euclidean 2-D space, the resulting objective function for the TSPwC is given by min $\mathrm{C} = \sum_{i=0}^{n} \sum_{j=0, j \neq i}^{n} c_{ij} x_{ij}$, with edge costs, c_{ij}, computed according to $c_{ij} = (1 - w) \times d_{ij} + w \times d_{ij}^{c}$. Here, d_{ij} is the Euclidean distance (norm) between the nodes i and j, d_{ij}^{c} is a measure of the distance from center for the edge (i, j), and w is a weight.

In applying the TSPwC methodology to the RVRP, we begin by defining a single depot node to be the center graph. This is analogous to the usage given in the two examples above.

With respect to distance from center (d_{ij}^{c}), the distance from center of an edge (i, j) is measured three ways: the average distance, the minimum distance, and the maximum distance. In Euclidean 2-D, the average distance of an edge from the depot node is the midpoint of the edge; the minimum distance of an edge is the distance between the central node and the nearer of the two nodes that define the edge, i.e., the endpoint of the edge nearer to the depot; the maximum distance is defined analogously to the minimum, but using the more distant of the two endpoint nodes. We conducted tests with all three distance definitions. However, results from defining the distance from center in terms of the maximum were consistently inferior to the other two definitions and the maximum distance definition was subsequently dropped from consideration. In the following discussion, the abbreviation EP or EP distance refers to the distance between an edge (i, j) and the central node based on the minimum distance of the edge from the center (i.e., in terms of the nearer endpoint). Similarly, the abbreviation MP or MP distance refers to the distance from center measure defined in terms of the midpoint of an edge. Note that for any edge, the MP distance is usually greater than the EP distance.

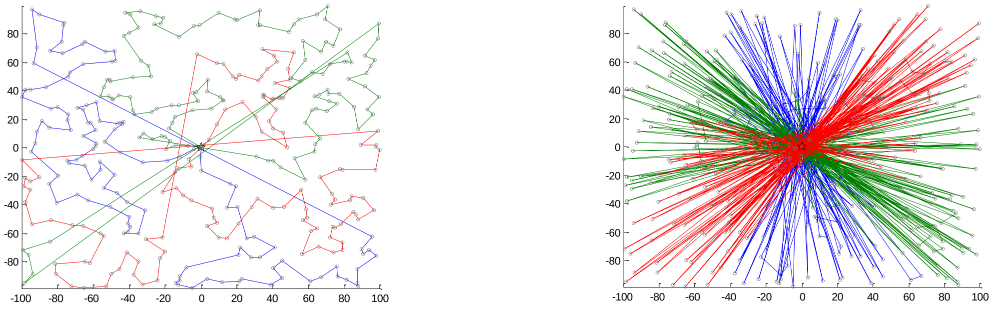
The weight w has a value in the range [0.0, 1.0], where $w = 0$ corresponds to the traditional, single objective, TSP. Note that, for a high value of the weight w, the emphasis placed on minimizing the distance of the route from the center node will cause the route to repeatedly pass through or near the central node. A small value for the weight *w* emphasizes minimizing total distance, in which case passing near the central node generally is inferior to some alternative routing and typically would not be found in a high-quality solution. We illustrate this in Figure 4.5.1 using the test instance N360_SL10_RAND_1 and solution approach w/Center (MP,CW), which we describe in greater detail below. Although our analysis of the weight *w* focuses on one instance and one solution approach, the same general observations hold for all approaches involving the TSPwC methodology.

In Figure 4.5.1 we present four plots that illustrate the effect of increasing the value of the weight *w* over the values 0.05, 0.25, 0.65, and 0.70. The value of *w* and the total distance (under the best possible exchanges rule) over the 10 days of the scenario matrix of instance N360_SL10_RAND_1 are listed with each plot.



(a) Weight *w*=0.05, Total Distance: 30454.8

(b): Weight *w*=0.25, Total Distance: 30215.4



(c): Weight *w*=0.65, Total Distance: 39536.2

(d): Weight *w*=0.7, Total Distance: 473163.1

Figure 4.5.1: Nominal Routes from w/Center (MP,CW) for four Values of Weight *w*

These plots illustrate the conflicting nature of the two objectives of the TSPwC. When *w* is small, the emphasis on minimizing total distance results in high-quality routes that infrequently pass near the depot. When *w* is large, total distance grows rapidly as the routes pass through or near the depot with increasing frequency. In terms of solutions to the RVRP, solution quality significantly degrades for $w \geq 0.65$. This is further illustrated in Figure 4.5.2 which plots the best solution found in each of the 15 SL10 instances using the w/Center (MP,CW) procedure. Also evident in Figure 4.5.3, and consistent with his results, is the inflection point discussed in detail by Price [27].

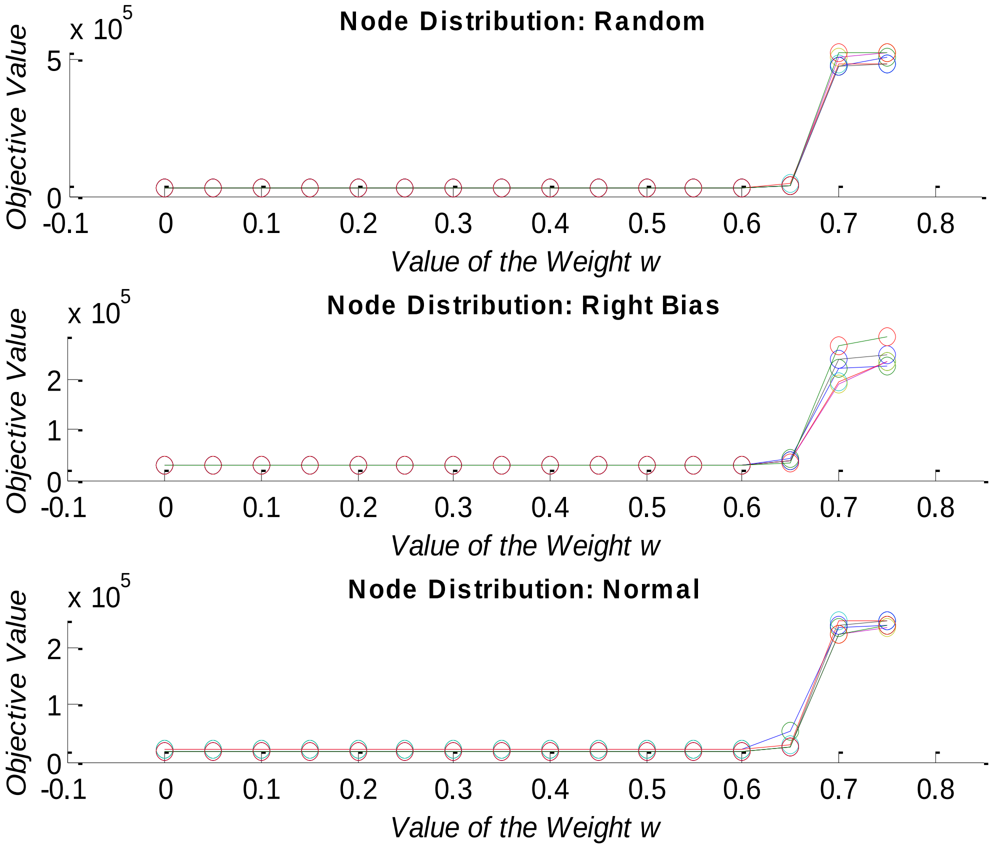


Figure 4.5.2: Lowest Cost Solution Found Using w/Center (MP,CW) Procedure at Different Values for the Weight *w* in 15 Test Instances with Segment Length 10.

Due to the rapid and significant increase of cost associated with the inflection point, Figure 4.5.2 is of little value in discerning the presence of any pattern for smaller values of w. In Figure 4.5.3, we present identical data to Figure 4.5.2 but plot each node distribution independently (five instances each) and disregard values of $w > 0.6$. As seen in Figure 4.5.3, though minimum values tend to occur in the range $w \in [0.2, 0.5]$, this is a relatively large range. Furthermore, several minimum values fall outside of this the range. As a result, in our TSPwC approaches, we discretize the range [0.05, 0.55] using an interval with of 0.05 and selected the best result from the 11 candidate solutions. Finally, in Figure 4.5.2(c), we see that the results of the w/Center (MP,CW) approach are consistently good for $w \in [0.0, 0.6]$.

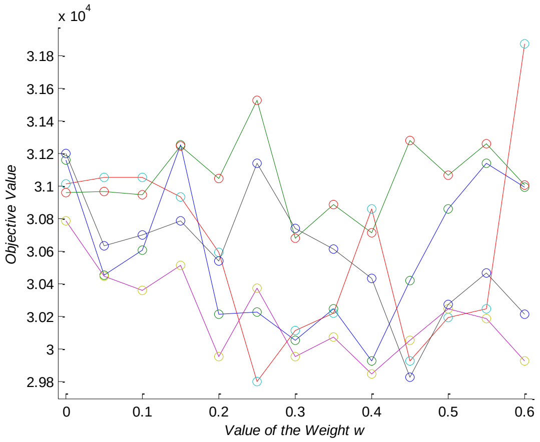


Figure 4.5.3: Best Total Distance for 13 Values of the TSPwC Weight Parameter *w* when Applied to 5 RVRP With Randomly Distributed Nodes Using the w/Center (MP,CW) Approach.

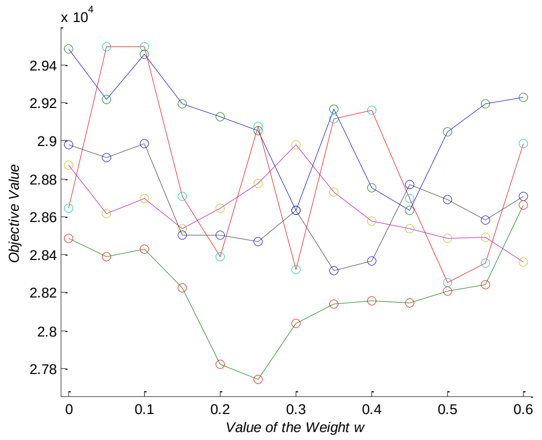


Figure 4.5.4: Best Total Distance for 13 Values of the TSPwC Weight Parameter *w* when Applied to 5 RVRP With Right-Biased Distributed Nodes Using the w/Center (MP,CW) Approach.

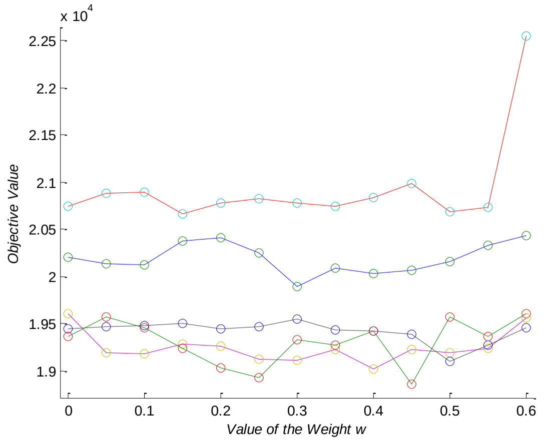


Figure 4.5.5: Best Total Distance for 13 Values of the TSPwC Weight Parameter *w* when Applied to 5 RVRP With Normally Distributed Nodes Using the w/Center (MP,CW) Approach

Finally, before discussing specific implementations, we give an example to demonstrate why the TSPwC methodology tends to yield better results than other procedures. The nominal routes returned by these approaches are generally similar to those returned by sweep-based approaches. However, the nominal routes derived using the TSPwC methodology exhibit additional structure favorable for inter-route segment exchanges. We illustrate this with Figure 4.5.6, which plots the best nominal routes for the test instance N360_SL10_RAND_1 found using the w/Center (MP,CW) approach.

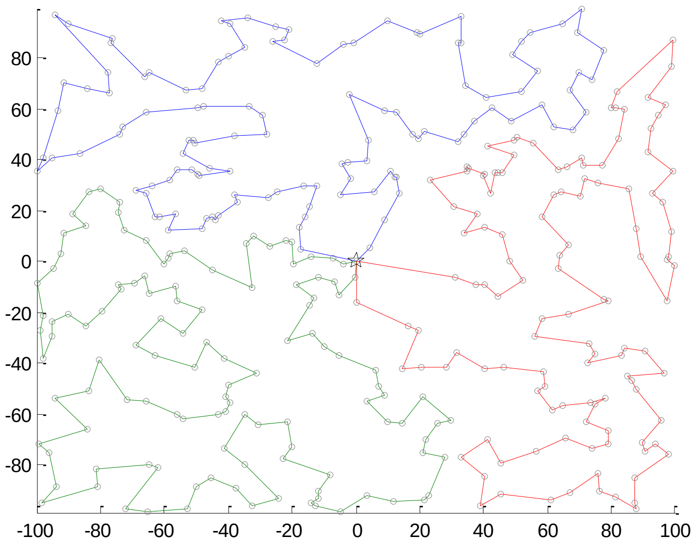


Figure 4.5.6: Best Nominal Routes for Instance N360_SL10_RAND_1

As mentioned, the general form of the three routes is similar to the results obtained from the sweep-based approaches. Each route has a wedge shape that includes all of the nodes within an angle having the depot as its vertex. The nominal routes generated by both approaches tend to have favorable structures for a route taking a segment from an adjacent route (typically along the boundaries of the two routes).

The w/Center approaches tend to have additional structure as suggested by the Figure 4.5.6. Including the second objective function produces an additional benefit. Routes which release segments of nodes on a given day tend to have a low cost edge with which to span the gap created by the removed segment.

The improvement over sweep approaches is not dramatic, but the cumulative effect over the multiple days of the scenario matrix clearly differentiates the procedures for most instances. Also, in the w/Center approaches, there tend to be more sites that yield favorable exchanges, resulting in better overall performance in terms of the quality measure for robustness (the average performance in the case where the segment length is slightly larger or smaller than given in the test instance).

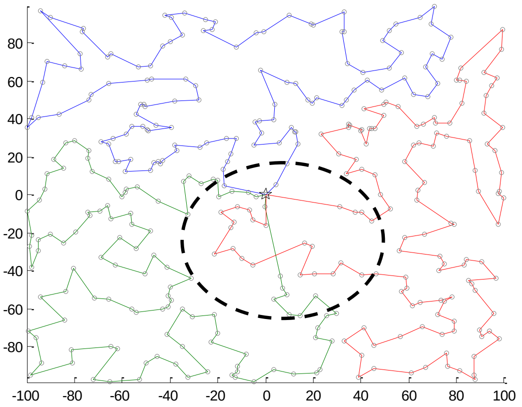


Figure 4.5.7: Best Possible Exchange of Segment in a 110-130-120 Scenario for w/Center (MP,CW) Solution to Instance N360_SL10_RAND_1

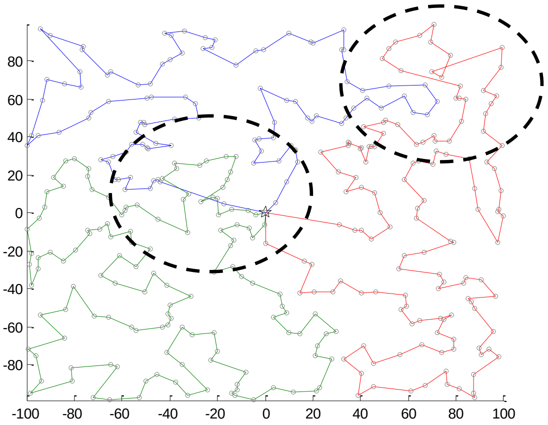


Figure 4.5.8: Best Possible Exchange of Segment in a 130-130-100 Scenario for w/Center (MP,CW) Solution to Instance N360_SL10_RAND_1

Figures 4.5.7 and 4.5.8 illustrate the benefit of this additional route structure. In both plots, route one is in the lower left of the plot, route two the lower right, and route three the topmost. The exchange sites are highlighted with a dashed circle. In Figure 4.5.7, a segment of length 10 is exchanged from route one to route two. In Figure 4.5.8, one segment of length 10 is exchanged from route three to routes one and two.

We tested a number of procedures based on the TSPwC methodology, including some with very intricate algorithms. In the end, the simplest procedures yielded the best results. We discuss these first.

Section 5.1 includes the results from six variants of the following basic algorithm. We begin by defining the distance to center to be either MP or EP distance and select whether or not to weight the edges incident to the depot node. Then we loop the next three steps for each value of w in the interval [0.05, 0.55] using a step size of 0.05. First, compute a weighted distance matrix according to the methodology of the TSPwC, using the selected center distance measure and current value of the weight w. Next, initial routes are formed, using the weighted distance matrix, by either the traditional Clarke-Wright route construction procedure or the sweep procedure, where the start node for the sweep procedure is determined using the Sweep Sector approach of Section 4.4, with a sector width of 15. After the initial routes are formed, we apply traditional route improvement heuristics, again using the weighted distance matrix. The total distance over the T days of the scenario matrix is computed using a distance matrix with the weight $w = 0$ (i.e., an unweighted distance matrix). By varying the weight w we generate 11 candidate solutions and return the least cost candidate as the result. Table 4.5.1 gives the notation used in Section 5.1 for the six w/Center approaches.

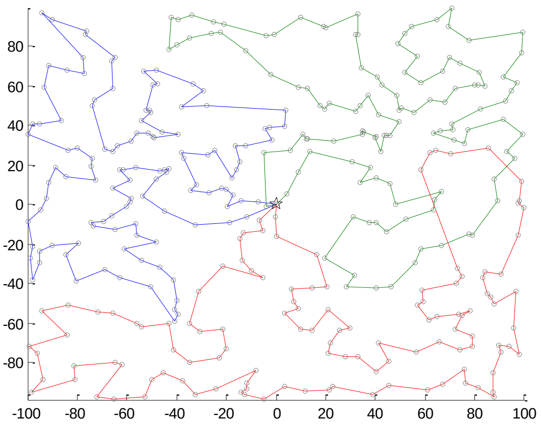
Notation	Definition
w/Center (EP,CW)	Defines edge distance to center in terms of nearest endpoint to the depot node and forms initial routes using the traditional Clarke-Wright procedure. Edges incident to the depot node are weighted in the same manner as the other edges.
w/Center (MP,SW)	Defines edge distance to center in terms of the distance from the midpoint of the edge to the depot node and forms initial routes using the sweep procedure. Edges incident to the depot node are weighted in the same manner as the other edges.
w/Center (MP,CW)	Defines edge distance to center in terms of the distance from the midpoint of the edge to the depot node and forms initial routes according to the traditional Clarke-Wright procedure. Edges incident to the depot node are weighted in the same manner as the other edges.
w/Center (EP,CW)*	Identical to the above except that edges incident to the depot node are not weighted according to the TSPwC methodology. The cost of edges incident to the depot node is calculated in the traditional Euclidean norm (i.e., with the weight $w = 0$).
w/Center (MP,SW)*	
w/Center (MP,CW)*	

Table 4.5.1: Notation Definition for w/Center Approaches

We tested several additional variations of the TSPwC concept, each generally more complex than the approaches detailed above, and each generally yielding lower quality solutions. We briefly describe these approaches in the Table 4.5.2 and give a plot of the W/Center Route Center approach in Figure 4.5.9. As with other noncompetitive solution approaches, numerical results for these procedures are presented in Appendix F, rather than in Section 5.

Name	Description and Comment
w/Center Non-Affine	Rather than defining the weight w to give a convex combination of the Euclidean distance and the MP or EP distance, we compute a weighted distance matrix according to: $c_{ij} = d_{ij} + w \times d_{ij}^{c}$ Though this procedure gave good quality results on some test instances, it was inconsistent.
w/Center Outer Penalty	Applies the TSPwC methodology but includes the weight w in distance calculation only of those nodes a certain distance from the depot node (i.e., in the sense of the Percentage approach of Section 4.3). This procedure gave good results for some test problems but was inconsistent. Also, the procedure included a distance from depot parameter (defined in the manner of the first Percentage approach of Section 4.3) which either increased the parameter space to two dimensions (increasing computation time) or requiring selection of a fixed value. Testing this procedure led to the depot-edges-unweighted approaches, i.e., w/Center(,)* approaches given in Table 4.5.1
w/Center Route Centers	Rather than defining the depot node as the center, this procedure defined v (vehicles) centers, the center of mass of each individual route. A weighted distance matrix that encouraged including nodes into routes to minimize the distance from one of the route centers was updated during route formation, as were the centers of mass of the routes. Ultimately, the procedure was slow and the results were mediocre.

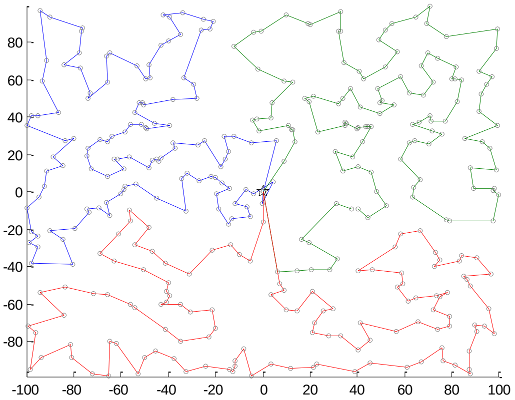
Table 4.5.2: Noncompetitive w/Center Approaches



Total Distance: 30684.2; Solution Time: 167.7 (s)

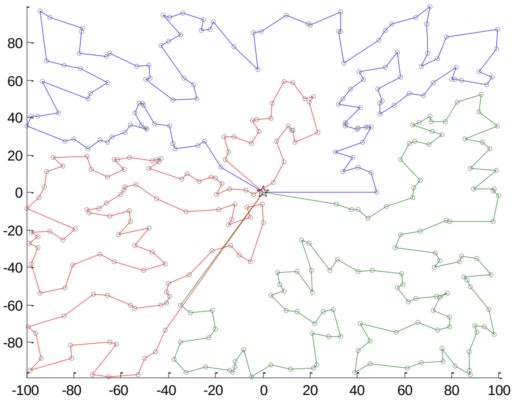
Figure 4.5.9: Best Solution to the N360_SL10_RAND_1 instance using the w/Center Route Centers approach.

Finally, we revisited the Great Circle approach described in Section 4.2 in the context of the TSPwC methodology. In contrast to the naïve Great Circle approach given earlier, a Great Circle approach that combined the route-first-divide-second approach with the two component objective function of the TSPwC might yield high-quality results. By including the second objective the Great Circle route generated in step one may include several good alternatives for dividing the large route into *v* individual routes, overcoming the failure of the naïve approach. We tested the w/Center Great Circle approach and it produced low quality solutions. Plots of the best solutions for the N360_SL10_RAND_1 instance, using the w/Center Great Circle approach under EP and MP distance, are given below.



Total Distance: 30647.6; Solution Time: 140.6 (s)

Figure 4.5.10: Best Solution to the N360_SL10_RAND_1 instance using the w/Center Great Circle approach under MP distance.



Total Distance: 30647.6; Solution Time: 140.6 (s)

Figure 4.5.11: Best Solution to the N360_SL10_RAND_1 instance using the w/Center Great Circle approach under EP distance.

Chapter 5: Computational Results

5.1 Total distance and Flexibility Test Score for 30 RVRP Instances

The following 30 tables detail, by instance, the performance of the 11 best solution approaches (including the baseline approaches). In each table, the first column gives the solution approach. The notation for the w/Center approaches is as given in Section 4.5. The second column, labeled "distance," gives the total distance by all vehicles over the 10 days of the scenario matrix (for the best candidate solution). Each of the solution approaches has an associated parameter; the listed parameter value corresponds to the solution given in the second column. Note that no value is listed in this column for the All Sweeps approach as the "parameter" for this procedure is simply the number of one of the nodes and is, therefore, arbitrary. Column four gives the solution time in seconds (for the entire procedure). Column five gives the flexibility test score for each approach (see Section 2.3). The least cost and second least cost solution and flexibility test score are highlighted.

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	30909.1	0.6	31.9	30958.4
All Sweeps	30190.6	--	998.0	30209.5
Sweep Neighbor	30489.4	3	79.5	30463
Sweep MST	30489.4	10	59.6	30463
Sweep Sectors	30384.6	6	57.7	30417.1
w/Center (EP,CW)	30025	0.15	104.2	30029.5
w/Center (MP,SW)	30326.3	0.55	139.2	30323.2
w/Center (MP,CW)	29928.2	0.4	92.4	29942.3
w/Center (EP,CW)*	30130.9	0.2	84.2	30125.8
w/Center (MP,SW)*	30087.1	0.25	154.4	30056.1
w/Center (MP,CW)*	30147.2	0.4	82.6	30147.4

Table 5.1.1: Results for Instance N360_SL10_RAND_1

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	30333.2	0.6	23.4	30322
All Sweeps	30033.2	--	856.0	30057.7
Sweep Neighbor	30212.1	0.5	67.2	30154.8
Sweep MST	30212.1	15	75.0	30154.8
Sweep Sectors	30253.5	6	60.6	30240
w/Center (EP,CW)	30281.9	0.1	93.0	30302.8
w/Center (MP,SW)	29873.8	0.3	124.3	29848.1
w/Center (MP,CW)	29797.5	0.25	77.8	29809.4
w/Center (EP,CW)*	30108.1	0.1	97.8	30139
w/Center (MP,SW)*	30065	0.5	135.0	30053.4
w/Center (MP,CW)*	30130.7	0.1	102.1	30094.5

Table 5.1.2: Results for Instance N360_SL10_RAND_2

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	30419.3	1	24.4	30433.9
All Sweeps	29734.1	--	882.8	29770
Sweep Neighbor	30145.2	2.5	59.8	30168.1
Sweep MST	30087.4	10	57.8	30126.2
Sweep Sectors	30136.5	18	66.0	30172.8
w/Center (EP,CW)	30181.3	0.25	89.3	30183
w/Center (MP,SW)	29836.7	0.25	194.4	29819.6
w/Center (MP,CW)	29849.4	0.4	89.8	29880.4
w/Center (EP,CW)*	30018.3	0.2	82.2	30026.1
w/Center (MP,SW)*	29576.9	0.55	146.2	29569.6
w/Center (MP,CW)*	29657	0.2	79.0	29692.1

Table 5.1.3: Results for Instance N360_SL10_RAND_3

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	30782.9	0.6	25.1	30772.6
All Sweeps	30085	--	872.1	30086.9
Sweep Neighbor	30111.8	3.5	55.4	30083.6
Sweep MST	30049.2	15	56.3	30017.3
Sweep Sectors	30049.2	18	50.4	30017.3
w/Center (EP,CW)	30499.2	0.35	84.0	30533.2
w/Center (MP,SW)	29995.6	0.3	137.6	29992.4
w/Center (MP,CW)	29829.5	0.45	97.4	29786.9
w/Center (EP,CW)*	29885.3	0.3	96.9	29882.1
w/Center (MP,SW)*	30061.5	0.3	152.1	30028.9
w/Center (MP,CW)*	30141.5	0.5	85.0	30130.7

Table 5.1.4: Results for Instance N360_SL10_RAND_4

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	30951.7	1.4	23.8	30973.9
All Sweeps	30688.6	--	894.1	30726.7
Sweep Neighbor	30778.5	4	80.5	30786.7
Sweep MST	30659	25	56.4	30673.5
Sweep Sectors	30692.7	24	58.8	30684
w/Center (EP,CW)	30816.8	0.2	87.7	30822.7
w/Center (MP,SW)	30593.2	0.5	136.5	30588.4
w/Center (MP,CW)	30676.9	0.3	97.8	30662.4
w/Center (EP,CW)*	30691.1	0.2	98.9	30696.6
w/Center (MP,SW)*	30250.1	0.25	131.0	30301.3
w/Center (MP,CW)*	30582.9	0.3	79.8	30586.1

Table 5.1.5: Results for Instance N360_SL10_RAND_5

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	29367.7	0.6	24.2	29356.7
All Sweeps	28699.2	--	893.4	28751.6
Sweep Neighbor	29006.9	0.5	61.3	28998.3
Sweep MST	29006.9	25	54.5	28998.3
Sweep Sectors	29321.4	9	54.6	29343.8
w/Center (EP,CW)	28557.5	0.2	115.0	28584
w/Center (MP,SW)	28826.8	0.6	135.4	28822.8
w/Center (MP,CW)	28632	0.3	86.1	28615.1
w/Center (EP,CW)*	28930.3	0.15	99.1	28926.2
w/Center (MP,SW)*	28589.5	0.15	136.5	28584.9
w/Center (MP,CW)*	28737.9	0.15	99.3	28714.8

Table 5.1.6: Results for Instance N360_SL10_RBIAS_1

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	28573.5	1.6	26.8	28596.4
All Sweeps	27896.8	--	962.0	27890.5
Sweep Neighbor	28602	0.5	61.1	28613.2
Sweep MST	28331.6	35	60.4	28341.1
Sweep Sectors	28176.6	18	51.9	28169.4
w/Center (EP,CW)	28346.2	0.2	94.7	28375
w/Center (MP,SW)	27735.5	0.6	109.9	27749.6
w/Center (MP,CW)	28255.3	0.5	123.4	28247.5
w/Center (EP,CW)*	28321.2	0.1	105.3	28322.8
w/Center (MP,SW)*	28262.4	0.5	148.4	28251.4
w/Center (MP,CW)*	28026.9	0.25	102.4	28042.4

Table 5.1.7: Results for Instance N360_SL10_RBIAS_2

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	28636.5	0.6	28.1	28594.3
All Sweeps	28004.9	--	926.9	27992.4
Sweep Neighbor	28006.6	4	61.6	28000.7
Sweep MST	28141.6	45	50.9	27998.6
Sweep Sectors	27697	15	56.3	27713
w/Center (EP,CW)	28290	0.3	101.1	28294.2
w/Center (MP,SW)	28136.5	0.5	143.3	28094.9
w/Center (MP,CW)	28360.2	0.6	95.4	28380.4
w/Center (EP,CW)*	28136.5	0.05	105.0	28107.4
w/Center (MP,SW)*	28010.3	0.35	138.1	27979.6
w/Center (MP,CW)*	28076.4	0.45	109.0	28102.8

Table 5.1.8: Results for Instance N360_SL10_RBIAS_3

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	28688.4	0.6	28.9	28707.8
All Sweeps	28041.8	--	940.6	28063
Sweep Neighbor	28491.5	2	84.4	28472.1
Sweep MST	28491.5	15	72.3	28472.1
Sweep Sectors	28430.3	30	57.6	28482.4
w/Center (EP,CW)	28349.2	0.25	96.3	28381.6
w/Center (MP,SW)	28372.7	0.55	151.1	28394.8
w/Center (MP,CW)	28315.9	0.35	116.1	28337.6
w/Center (EP,CW)*	28432.3	0.05	103.2	28430
w/Center (MP,SW)*	28158.6	0.3	133.2	28150
w/Center (MP,CW)*	28216.8	0.25	118.5	28219.8

Table 5.1.9: Results for Instance N360_SL10_RBIAS_4

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	28334.1	1.4	25.2	28307
All Sweeps	28146.8	--	927.0	28178.5
Sweep Neighbor	27975.4	0.5	69.0	27970.1
Sweep MST	27918.6	25	49.1	27906.4
Sweep Sectors	28403.7	1	47.9	28401.6
w/Center (EP,CW)	28104	0.2	80.0	28101.6
w/Center (MP,SW)	28016	0.35	149.4	28018.6
w/Center (MP,CW)	27743	0.25	90.3	27802.2
w/Center (EP,CW)*	27688.3	0.15	94.9	27700.9
w/Center (MP,SW)*	28071.1	0.4	136.6	28078.5
w/Center (MP,CW)*	27814.9	0.45	89.9	27903.6

Table 5.1.10: Results for Instance N360_SL10_RBIAS_5

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	20324.6	0.6	24.1	20319.8
All Sweeps	19860.3	--	1033.6	19856.9
Sweep Neighbor	20238.3	6.5	59.6	20237.7
Sweep MST	20119.7	25	55.3	20137.8
Sweep Sectors	20221.2	9	55.9	20224.5
w/Center (EP,CW)	19828.6	0.2	109.7	19836
w/Center (MP,SW)	20006.4	0.4	206.2	19997.7
w/Center (MP,CW)	19889.7	0.3	104.8	19896.2
w/Center (EP,CW)*	19995.4	0.2	114.5	19975.6
w/Center (MP,SW)*	19914.9	0.3	222.1	19923
w/Center (MP,CW)*	20043.4	0.05	111.9	20038.9

Table 5.1.11: Results for Instance N360_SL10_NORM_1

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	20979.7	1.6	34.0	20966.8
All Sweeps	20645.6	--	1171.2	20645.3
Sweep Neighbor	21024.6	0.5	67.5	20813.4
Sweep MST	20634.3	15	56.1	20680.1
Sweep Sectors	20906	3	53.6	20915.9
w/Center (EP,CW)	20617.6	0.3	101.5	20595.5
w/Center (MP,SW)	20661.2	0.15	162.9	20666.5
w/Center (MP,CW)	20664.2	0.15	75.6	20678.5
w/Center (EP,CW)*	20633	0.25	100.0	20633.7
w/Center (MP,SW)*	20547.8	0.1	178.4	20547.7
w/Center (MP,CW)*	20550.5	0.1	117.2	20613.5

Table 5.1.12: Results for Instance N360_SL10_NORM_2

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	19703.8	1	31.2	19697.3
All Sweeps	19201.2	--	1060.1	19210.3
Sweep Neighbor	19179.5	6	110.1	19195.4
Sweep MST	19441.6	5	89.8	19435.8
Sweep Sectors	19481.7	12	52.3	19493.5
w/Center (EP,CW)	19425.1	0.25	92.7	19435.8
w/Center (MP,SW)	19327.1	0.3	155.7	19329.7
w/Center (MP,CW)	19015.9	0.4	96.0	18998
w/Center (EP,CW)*	19263.8	0.1	107.3	19247.3
w/Center (MP,SW)*	19141.8	0.15	163.0	19157.5
w/Center (MP,CW)*	19154.5	0.05	99.5	19141.9

Table 5.1.13: Results for Instance N360_SL10_NORM_3

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	19537.6	1	27.6	19540.8
All Sweeps	19108.2	--	1004.6	19099.1
Sweep Neighbor	19673.7	0.5	72.3	19642.6
Sweep MST	19673.7	10	56.6	19642.6
Sweep Sectors	19566.9	9	56.5	19586
w/Center (EP,CW)	19134.8	0.1	82.5	19149.9
w/Center (MP,SW)	19256.8	0.4	163.6	19240.1
w/Center (MP,CW)	19106.4	0.5	89.8	19114.1
w/Center (EP,CW)*	19151.2	0.3	93.8	19153.9
w/Center (MP,SW)*	19330.9	0.45	146.2	19345
w/Center (MP,CW)*	19072.1	0.35	100.7	19055.3

Table 5.1.14: Results for Instance N360_SL10_NORM_4

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	19336.1	0.6	37.0	19350.4
All Sweeps	18994.8	--	930.1	19001.1
Sweep Neighbor	19253.3	2	91.1	19246.8
Sweep MST	19253.3	10	68.8	19246.8
Sweep Sectors	19032.5	1	60.2	19052.9
w/Center (EP,CW)	19099.3	0.3	87.7	19090.5
w/Center (MP,SW)	19082.8	0.4	157.6	19066.5
w/Center (MP,CW)	18855.3	0.45	107.0	18840.9
w/Center (EP,CW)*	18954.6	0.1	86.8	18941
w/Center (MP,SW)*	19080	0.35	158.1	19075.3
w/Center (MP,CW)*	19139.3	0.35	96.5	19125.2

Table 5.1.15: Results for Instance N360_SL10_NORM_5

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	31000.3	0.6	22.1	31039.1
All Sweeps	30310.1	--	948.4	30307.6
Sweep Neighbor	30543.3	2	57.9	30557.2
Sweep MST	30543.3	10	60.1	30557.2
Sweep Sectors	30529.3	6	58.3	30539.5
w/Center (EP,CW)	30105.5	0.15	104.6	30134.2
w/Center (MP,SW)	30487.5	0.55	140.7	30514.2
w/Center (MP,CW)	30086.9	0.4	92.4	30058.1
w/Center (EP,CW)*	30350.1	0.2	85.4	30326.2
w/Center (MP,SW)*	30193.5	0.25	154.4	30197.6
w/Center (MP,CW)*	30347.9	0.4	83.4	30350.5

Table 5.1.16: Results for Instance N360_SL15_RAND_1

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	30503.7	0.6	23.5	30480.3
All Sweeps	30193.2	--	861.5	30201.5
Sweep Neighbor	30548.2	0.5	43.2	30256.3
Sweep MST	30396.3	10	77.2	30256.3
Sweep Sectors	30420	1	60.5	30435.4
w/Center (EP,CW)	30289.4	0.1	94.3	30314.8
w/Center (MP,SW)	29951.1	0.3	124.9	29994.5
w/Center (MP,CW)	29826.6	0.25	78.0	29866.2
w/Center (EP,CW)*	30319.5	0.1	98.6	30322.4
w/Center (MP,SW)*	30106	0.2	135.5	30162.8
w/Center (MP,CW)*	30173.1	0.1	103.1	30167.4

Table 5.1.17: Results for Instance N360_SL15_RAND_2

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	30511.7	1	24.7	30505.6
All Sweeps	29926.2	--	888.8	29946.1
Sweep Neighbor	30143.1	0.5	41.9	30178.2
Sweep MST	30259.3	10	57.9	30283.3
Sweep Sectors	30298.8	18	66.5	30308.5
w/Center (EP,CW)	30265	0.05	90.1	30281.4
w/Center (MP,SW)	30097.7	0.45	194.9	30066.7
w/Center (MP,CW)	29972.2	0.4	90.1	29958.3
w/Center (EP,CW)*	30099.6	0.2	82.5	30135.1
w/Center (MP,SW)*	29695.7	0.55	147.1	29692.1
w/Center (MP,CW)*	29817.5	0.2	79.6	29817.6

Table 5.1.18: Results for Instance N360_SL15_RAND_3

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	30842.2	0.6	25.5	30859.5
All Sweeps	30170.7	--	882.4	30162.9
Sweep Neighbor	30241.8	2.5	42.9	30236.6
Sweep MST	30142	15	58.0	30167
Sweep Sectors	30142	18	51.4	30167
w/Center (EP,CW)	30657.2	0.35	91.2	30646
w/Center (MP,SW)	30129.7	0.3	145.3	30123
w/Center (MP,CW)	29882.3	0.45	99.8	29889.9
w/Center (EP,CW)*	30023.4	0.3	96.0	30034.1
w/Center (MP,SW)*	30085.8	0.45	154.9	30129.2
w/Center (MP,CW)*	30309.7	0.5	87.2	30270.9

Table 5.1.19: Results for Instance N360_SL15_RAND_4

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	30967.9	1	24.9	30958.8
All Sweeps	30744.5	--	912.5	30756.7
Sweep Neighbor	30898.9	3	53.6	30857.8
Sweep MST	30782.6	25	57.7	30787.3
Sweep Sectors	30859	24	60.8	30823.9
w/Center (EP,CW)	30889.5	0.2	88.3	30890
w/Center (MP,SW)	30712.2	0.2	136.4	30693.5
w/Center (MP,CW)	30821.8	0.4	97.7	30805.1
w/Center (EP,CW)*	30870.9	0.2	98.4	30857.8
w/Center (MP,SW)*	30399.5	0.25	130.3	30465.7
w/Center (MP,CW)*	30741.5	0.3	79.7	30750.4

Table 5.1.20: Results for Instance N360_SL15_RAND_5

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	29494.4	0.6	24.6	29491.1
All Sweeps	28831.8	--	904.5	28866.9
Sweep Neighbor	29159	0.5	45.0	29148.5
Sweep MST	29159	25	55.0	29148.5
Sweep Sectors	29553.3	9	55.4	29500.6
w/Center (EP,CW)	28649.2	0.25	115.8	28635.2
w/Center (MP,SW)	28914	0.45	134.5	28903.1
w/Center (MP,CW)	28735.6	0.3	87.0	28724.5
w/Center (EP,CW)*	29029.9	0.3	100.0	29011
w/Center (MP,SW)*	28706.6	0.15	137.8	28682.2
w/Center (MP,CW)*	28845.7	0.15	100.6	28840.3

Table 5.1.21: Results for Instance N360_SL15_RBIAS_1

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	28733.6	1.6	27.0	28703.7
All Sweeps	27980.5	--	953.0	27963.9
Sweep Neighbor	28420.3	4.5	47.4	28448.4
Sweep MST	28420.3	35	60.7	28448.4
Sweep Sectors	28284.5	18	52.6	28303.2
w/Center (EP,CW)	28427	0.2	96.1	28408.5
w/Center (MP,SW)	27843.3	0.6	110.5	27849.3
w/Center (MP,CW)	28361	0.5	125.0	28349.8
w/Center (EP,CW)*	28440.3	0.1	106.6	28440.5
w/Center (MP,SW)*	28357	0.5	139.2	28334.8
w/Center (MP,CW)*	28172.3	0.25	97.3	28156.3

Table 5.1.22: Results for Instance N360_SL15_RBIAS_2

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	28721.7	0.6	27.1	28751.5
All Sweeps	28082	--	864.4	28071.6
Sweep Neighbor	28105.6	2.5	37.7	28107.6
Sweep MST	28287.5	45	47.8	28170.8
Sweep Sectors	27882.8	15	46.4	27889.7
w/Center (EP,CW)	28397.7	0.3	94.3	28385.1
w/Center (MP,SW)	28227.6	0.5	130.9	28213.4
w/Center (MP,CW)	28526	0.6	89.7	28489.3
w/Center (EP,CW)*	28218.9	0.05	95.4	28222.7
w/Center (MP,SW)*	28004.4	0.35	133.7	28023.4
w/Center (MP,CW)*	28114.1	0.45	105.7	28141.9

Table 5.1.23: Results for Instance N360_SL15_RBIAS_3

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	28791.6	1.6	28.3	28779
All Sweeps	28240.5	--	878.2	28225
Sweep Neighbor	28584.6	1.5	60.2	28582.4
Sweep MST	28584.6	15	67.9	28582.4
Sweep Sectors	28619	30	54.3	28681.2
w/Center (EP,CW)	28498.5	0.35	91.8	28499.3
w/Center (MP,SW)	28428.9	0.1	138.5	28413.4
w/Center (MP,CW)	28522.7	0.35	103.5	28497.4
w/Center (EP,CW)*	28604.7	0.05	98.0	28578.8
w/Center (MP,SW)*	28310.5	0.3	125.9	28301.5
w/Center (MP,CW)*	28395.8	0.25	111.6	28411.6

Table 5.1.24: Results for Instance N360_SL15_RBIAS_4

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	28358.7	1.4	23.3	28367
All Sweeps	28267.3	--	865.2	28286.8
Sweep Neighbor	28114.6	0.5	47.0	28123.7
Sweep MST	28077.2	25	47.5	28085.7
Sweep Sectors	28526.3	1	46.9	28557.7
w/Center (EP,CW)	28131.1	0.2	77.6	28148.8
w/Center (MP,SW)	28084.8	0.35	143.7	28095.8
w/Center (MP,CW)	27894.7	0.25	87.2	27953.3
w/Center (EP,CW)*	27793.4	0.15	91.4	27829.4
w/Center (MP,SW)*	28225.8	0.4	131.9	28234.8
w/Center (MP,CW)*	28068.6	0.35	85.3	28081.4

Table 5.1.25: Results for Instance N360_SL15_RBIAS_5

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	20349.6	0.6	24.2	20342.4
All Sweeps	19918.8	--	1039.7	19921.2
Sweep Neighbor	20326.3	4.5	43.5	20293.3
Sweep MST	20209.3	35	55.7	20209.9
Sweep Sectors	20290.7	9	56.2	20283.7
w/Center (EP,CW)	19905.6	0.2	88.4	19901.8
w/Center (MP,SW)	19999.1	0.4	170.0	20008.2
w/Center (MP,CW)	19930.5	0.3	87.0	19916.1
w/Center (EP,CW)*	20020.9	0.2	98.2	20018.5
w/Center (MP,SW)*	20013.1	0.3	188.4	20011.4
w/Center (MP,CW)*	20110.3	0.05	99.1	20090.7

Table 5.1.26: Results for Instance N360_SL15_NORM_1

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	21022.7	1.6	32.1	21035.4
All Sweeps	20716.1	--	1006.0	20711.5
Sweep Neighbor	21091.6	0.5	40.9	20877.7
Sweep MST	20736.1	15	49.0	20745.8
Sweep Sectors	20990	9	46.7	20979.5
w/Center (EP,CW)	20645.7	0.3	100.9	20654.9
w/Center (MP,SW)	20801.8	0.15	161.3	20780.3
w/Center (MP,CW)	20717	0.15	75.4	20716.1
w/Center (EP,CW)*	20747	0.15	99.3	20756.4
w/Center (MP,SW)*	20578.7	0.1	177.8	20587.1
w/Center (MP,CW)*	20660.8	0.1	117.1	20673.2

Table 5.1.27: Results for Instance N360_SL15_NORM_2

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	19691.2	1	30.5	19722
All Sweeps	19233.9	--	1058.0	19260
Sweep Neighbor	19258	4	76.6	19259.3
Sweep MST	19492.8	5	93.1	19499.6
Sweep Sectors	19579.2	12	52.9	19581.5
w/Center (EP,CW)	19508.9	0.25	96.7	19508.2
w/Center (MP,SW)	19402	0.3	159.4	19400.4
w/Center (MP,CW)	19060.3	0.4	100.6	19052
w/Center (EP,CW)*	19281	0.1	111.9	19274.6
w/Center (MP,SW)*	19219.4	0.15	163.1	19210.6
w/Center (MP,CW)*	19164.5	0.25	99.6	19161.8

Table 5.1.28: Results for Instance N360_SL15_NORM_3

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	19614.9	1	28.0	19616.3
All Sweeps	19180.3	--	1003.7	19167.9
Sweep Neighbor	19804.1	0.5	51.3	19690.5
Sweep MST	19732.3	5	56.9	19690.5
Sweep Sectors	19641.2	9	56.3	19654.1
w/Center (EP,CW)	19226	0.1	82.3	19218.5
w/Center (MP,SW)	19305.8	0.4	166.4	19324.8
w/Center (MP,CW)	19206.6	0.5	104.0	19208.1
w/Center (EP,CW)*	19276.9	0.3	106.6	19270.6
w/Center (MP,SW)*	19450.3	0.45	162.4	19442.4
w/Center (MP,CW)*	19126.4	0.35	121.8	19108.9

Table 5.1.29: Results for Instance N360_SL15_NORM_4

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	19397.3	1	44.9	19420.1
All Sweeps	19077.1	--	1033.2	19068.1
Sweep Neighbor	19333.5	1.5	69.8	19334.7
Sweep MST	19333.5	10	72.2	19334.7
Sweep Sectors	19116.6	1	65.2	19114.2
w/Center (EP,CW)	19145.9	0.3	105.5	19143.7
w/Center (MP,SW)	19153.4	0.2	196.1	19158.9
w/Center (MP,CW)	18922.5	0.25	134.3	18947.6
w/Center (EP,CW)*	18963	0.1	108.4	18970.7
w/Center (MP,SW)*	19115.4	0.35	240.2	19129.1
w/Center (MP,CW)*	19146.1	0.35	104.5	19151.1

Table 5.1.30: Results for Instance N360_SL15_NORM_5

5.2 Average Performance

To give an indication of average performance among the solution approaches, this section presents the 30 tables of Section 5.1 at two levels of aggregation. Tables 5.2.1 – 5.2.6 give an average over five similar instances. For example, Table 5.2.1 is an average of Tables 5.1.1-5.1.5 and gives the average result for the five instances where the segment length was 10 and the node distribution was random. While the types of problems averaged in each of the tables are consistent, each table is an average computed on only five sample problems.

Tables 5.2.7 and 5.2.8 give the average over all 15 instances for which the segment length was 10 and 15, respectively. Unlike the first six tables of this section,

Table 5.2.7 and 5.2.8 average problem instances in which the node distribution is not consistent. While we include them to provide a notion of relative overall performance among the solution approaches, we emphasize that great care should be observed when interpreting these results. The least cost and second least cost solution and flexibility test score are highlighted.

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	30679.2	0.8	25.7	30692.2
All Sweeps	30146.3	--	900.6	30170.2
Sweep Neighbor	30347.4	2.7	68.5	30331.2
Sweep MST	30299.4	15.0	61.0	30287.0
Sweep Sectors	30303.3	14.4	58.7	30306.2
w/Center (EP,CW)	30360.8	0.2	91.6	30374.2
w/Center (MP,SW)	30125.1	0.4	146.4	30114.3
w/Center (MP,CW)	30016.3	0.4	91.0	30016.3
w/Center (EP,CW)*	30166.7	0.2	92.0	30173.9
w/Center (MP,SW)*	30008.1	0.4	143.8	30001.9
w/Center (MP,CW)*	30131.9	0.3	85.7	30130.2

Table 5.2.1: Average Results, Randomly Distributed Instances (Segment Length 10)

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	28720.0	1.0	26.6	28712.4
All Sweeps	28157.9	--	930.0	28175.2
Sweep Neighbor	28416.5	1.5	67.5	28410.9
Sweep MST	28378.0	29.0	57.4	28343.3
Sweep Sectors	28405.8	14.6	53.7	28422.0
w/Center (EP,CW)	28329.4	0.2	97.4	28347.3
w/Center (MP,SW)	28217.5	0.5	137.8	28216.1
w/Center (MP,CW)	28261.3	0.4	102.3	28276.6
w/Center (EP,CW)*	28301.7	0.1	101.5	28297.5
w/Center (MP,SW)*	28218.4	0.3	138.6	28208.9
w/Center (MP,CW)*	28174.6	0.3	103.8	28196.7

Table 5.2.2: Average Results, Right-Biased Instances (Segment Length 10)

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	19976.4	1.0	30.8	19975.0
All Sweeps	19562.0	--	1039.9	19562.5
Sweep Neighbor	19873.9	3.1	80.1	19827.2
Sweep MST	19824.5	13.0	65.3	19828.6
Sweep Sectors	19841.7	6.8	55.7	19854.6
w/Center (EP,CW)	19621.1	0.2	94.8	19621.5
w/Center (MP,SW)	19666.9	0.3	169.2	19660.1
w/Center (MP,CW)	19506.3	0.4	94.7	19505.5
w/Center (EP,CW)*	19599.6	0.2	100.5	19590.3
w/Center (MP,SW)*	19603.1	0.3	173.6	19609.7
w/Center (MP,CW)*	19592.0	0.2	105.2	19595.0

Table 5.2.3: Average Results, Normally Distributed Instances (Segment Length 10)

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	30765.2	0.8	24.1	30768.7
All Sweeps	30268.9	--	898.7	30275.0
Sweep Neighbor	30475.1	1.7	47.9	30417.2
Sweep MST	30424.7	14.0	62.2	30410.2
Sweep Sectors	30449.8	13.4	59.5	30454.9
w/Center (EP,CW)	30441.3	0.2	93.7	30453.3
w/Center (MP,SW)	30275.6	0.4	148.4	30278.4
w/Center (MP,CW)	30118.0	0.4	91.6	30115.5
w/Center (EP,CW)*	30332.7	0.2	92.2	30335.1
w/Center (MP,SW)*	30096.1	0.3	144.4	30129.5
w/Center (MP,CW)*	30277.9	0.3	86.6	30271.4

Table 5.2.4: Average Results, Randomly Distributed Instances (Segment Length 15)

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	28820.0	1.2	26.1	28818.5
All Sweeps	28280.4	--	893.1	28282.8
Sweep Neighbor	28476.8	1.9	47.5	28482.1
Sweep MST	28505.7	29.0	55.8	28487.2
Sweep Sectors	28573.2	14.6	51.1	28586.5
w/Center (EP,CW)	28420.7	0.3	95.1	28415.4
w/Center (MP,SW)	28299.7	0.4	131.6	28295.0
w/Center (MP,CW)	28408.0	0.4	98.5	28402.9
w/Center (EP,CW)*	28417.4	0.1	98.3	28416.5
w/Center (MP,SW)*	28320.9	0.3	133.7	28315.3
w/Center (MP,CW)*	28319.3	0.3	100.1	28326.3

Table 5.2.5: Average Results, Right-Biased Instances (Segment Length 15)

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	20015.1	1.0	31.9	20027.2
All Sweeps	19625.2	--	1028.1	19625.7
Sweep Neighbor	19962.7	2.2	56.4	19891.1
Sweep MST	19900.8	14.0	65.4	19896.1
Sweep Sectors	19923.5	8.0	55.5	19922.6
w/Center (EP,CW)	19686.4	0.2	94.8	19685.4
w/Center (MP,SW)	19732.4	0.3	170.7	19734.5
w/Center (MP,CW)	19567.4	0.3	100.3	19568.0
w/Center (EP,CW)*	19657.8	0.2	104.9	19658.2
w/Center (MP,SW)*	19675.4	0.3	186.4	19676.1
w/Center (MP,CW)*	19641.6	0.2	108.4	19637.1

Table 5.2.6: Average Results, Normally Distributed Instances (Segment Length 15)

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	26458.5	0.9	27.7	26459.9
All Sweeps	25955.4	--	956.8	25969.3
Sweep Neighbor	26212.6	2.4	72.0	26189.8
Sweep MST	26167.3	19.0	61.3	26153.0
Sweep Sectors	26183.6	11.9	56.0	26194.3
w/Center (EP,CW)	26103.8	0.2	94.6	26114.4
w/Center (MP,SW)	26003.2	0.4	151.1	25996.9
w/Center (MP,CW)	25928.0	0.4	96.0	25932.8
w/Center (EP,CW)*	26022.7	0.2	98.0	26020.6
w/Center (MP,SW)*	25943.2	0.3	152.0	25940.1
w/Center (MP,CW)*	25966.1	0.3	98.2	25973.9

Table 5.2.7: Average Results, for All Instances (Segment Length 10)

Solution Approach	Distance	Parameter Value	Time	Flexibility Test
Traditional VRP	26533.4	1.0	27.4	26538.1
All Sweeps	26058.2	--	940.0	26061.2
Sweep Neighbor	26304.9	1.9	50.6	26263.5
Sweep MST	26277.1	19.0	61.1	26264.5
Sweep Sectors	26315.5	12.0	55.4	26321.3
w/Center (EP,CW)	26182.8	0.2	94.5	26184.7
w/Center (MP,SW)	26102.6	0.4	150.2	26102.6
w/Center (MP,CW)	26031.1	0.4	96.8	26028.8
w/Center (EP,CW)*	26136.0	0.2	98.4	26136.6
w/Center (MP,SW)*	26030.8	0.3	154.8	26040.3
w/Center (MP,CW)*	26079.6	0.3	98.4	26078.3

Table 5.2.8: Average Results for All Instances (Segment Length 15)

5.3 Computation Time Growth Rates

We calculated the computation time growth rates for each of the solution approaches displayed in the tables of Section 5.1 and 5.2. Initial plots of the growth rate data for all 11 approaches suggested that a polynomial fit was appropriate. For each approach, we initially assumed a straight-line relationship, then successively tested the null hypothesis that the polynomial was of higher order until the null hypothesis was rejected at the .01 significance level. The results are presented in the series of figures below, but can be quickly summarized. With exception of the All Sweeps approach, which grows $O(n^3)$, the computation time for all approaches grows $O(n^2)$.

Polynomial model: Degree 2:
f(x) = p1*x^2 + p2*x + p3
Coefficients (.01 significance level):
p1 = 0.0001064 (6.244e-005, 0.0001504)
p2 = 0.03286 (0.01975, 0.04598)
p3 = 0 (fixed at bound)

SSE: 81.95
Adjusted R-square: 0.9672
RMSE: 1.576

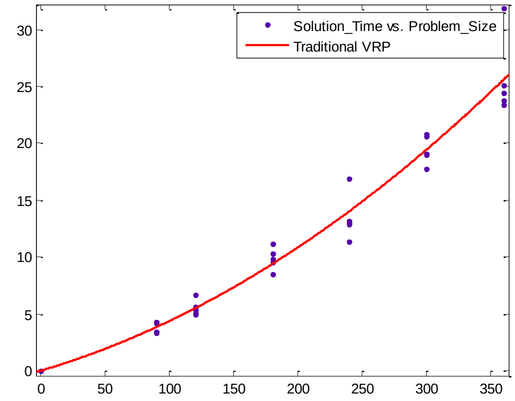


Figure 5.3.1: Computation Time Growth Rate for the Traditional VRP Approach

Polynomial model: Degree 3:
f(x) = p1*x^3 + p2*x^2 + p3*x + p4
Coefficients (.01 significance level):
p1 = 1.525e-005 (6.985e-006, 2.351e-005)
p2 = 0.001094 (-0.003154, 0.005343)
p3 = 0.1216 (-0.3928, 0.636)
p4 = 0 (fixed at bound)

SSE: 1.77e+004
Adjusted R-square: 0.9943
RMSE: 23.52

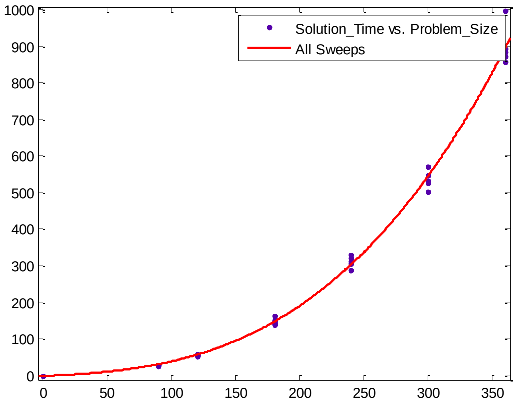


Figure 5.3.2: Computation Time Growth Rate for the All Sweeps Approach

Polynomial model: Degree 2:
f(x) = p1*x^2 + p2*x + p3
Coefficients (.01 significance level):
p1 = 0.0003743 (0.0002201, 0.0005286)
p2 = 0.0523 (0.006297, 0.09831)
p3 = 0 (fixed at bound)

SSE: 1009
Adjusted R-square: 0.9438
RMSE: 5.529

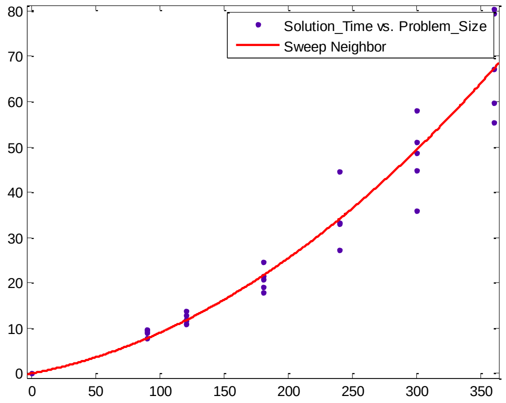


Figure 5.3.3: Computation Time Growth Rate for the Sweep Neighbor Approach

Polynomial model: Degree 2:
f(x) = p1*x^2 + p2*x + p3
Coefficients (.01 significance level):
p1 = 0.0003544 (0.0001952, 0.0005136)
p2 = 0.02788 (-0.0196, 0.07536)
p3 = 0 (fixed at bound)

SSE: 1074
Adjusted R-square: 0.9176
RMSE: 5.706

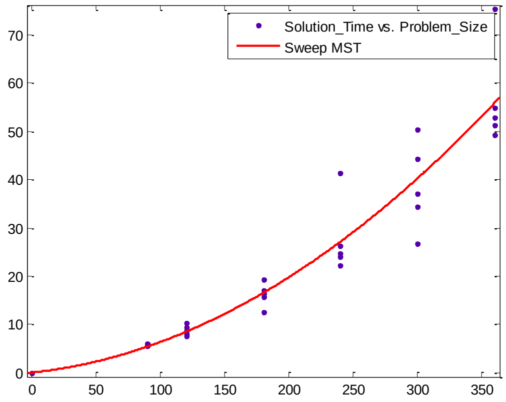


Figure 5.3.4: Computation Time Growth Rate for the Sweep MST Approach

Polynomial model: Degree 2:
f(x) = p1*x^2 + p2*x + p3
Coefficients (.01 significance level):
p1 = 0.0003628 (0.0002693, 0.0004563)
p2 = 0.02904 (0.001154, 0.05692)
p3 = 0 (fixed at bound)

SSE: 370.5
Adjusted R-square: 0.9712
RMSE: 3.351

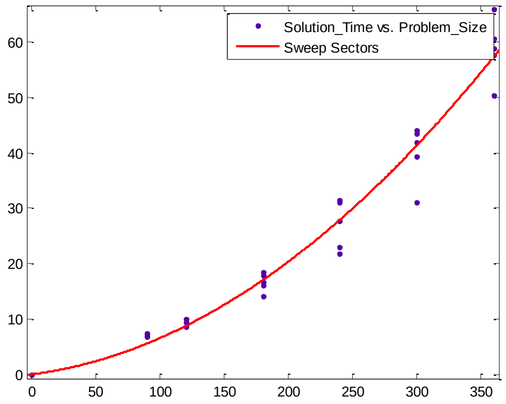


Figure 5.3.5: Computation Time Growth Rate for the Sweep Sector Approach

```
Polynomial model: Degree 2:
      f(x) = p1*x^2 + p2*x + p3
Coefficients (.01 significance level):
      p1 =   0.0004581  (0.000345, 0.0005711)
      p2 =     0.09153  (0.05782, 0.1252)
      p3 =           0  (fixed at bound)

  SSE: 541.7
  Adjusted R-square: 0.9835
  RMSE: 4.051
```

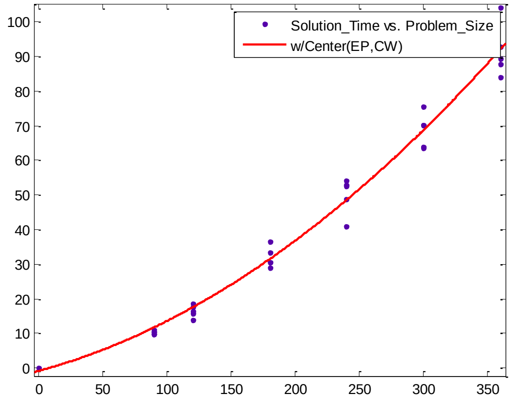


Figure 5.3.6: Computation Time Growth Rate for the w/Center(EP,CW) Approach

```
Polynomial model: Degree 2:
      f(x) = p1*x^2 + p2*x + p3
Coefficients (.01 significance level):
      p1 =   0.0008311  (0.0005188, 0.001143)
      p2 =      0.1166  (0.02342, 0.2097)
      p3 =           0  (fixed at bound)

  SSE: 4135
  Adjusted R-square: 0.9543
  RMSE: 11.19
```

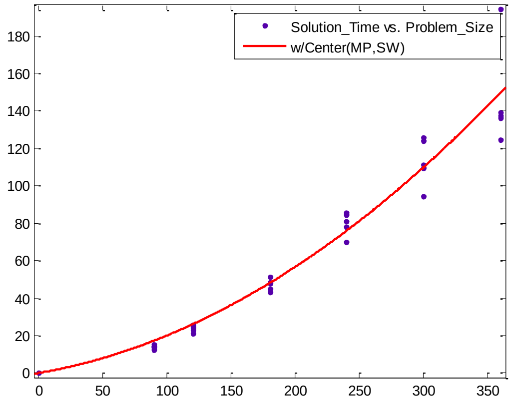


Figure 5.3.7: Computation Time Growth Rate for the w/Center(MP,SW) Approach

```
Polynomial model: Degree 2:
      f(x) = p1*x^2 + p2*x + p3
Coefficients (.01 significance level):
      p1 =   0.0004739  (0.0003453, 0.0006025)
      p2 =     0.08011  (0.04176, 0.1185)
      p3 =           0  (fixed at bound)

  SSE: 701
  Adjusted R-square: 0.9776
  RMSE: 4.609
```

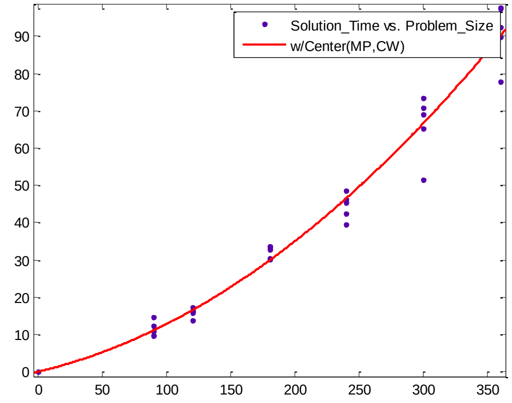


Figure 5.3.8: Computation Time Growth Rate for the w/Center(MP,CW) Approach

Polynomial model: Degree 2:
f(x) = p1*x^2 + p2*x + p3
Coefficients (.01 significance level):
p1 = 0.0003938 (0.0002553, 0.0005323)
p2 = 0.1233 (0.08194, 0.1646)
p3 = 0 (fixed at bound)

SSE: 813.5
Adjusted R-square: 0.9769
RMSE: 4.965

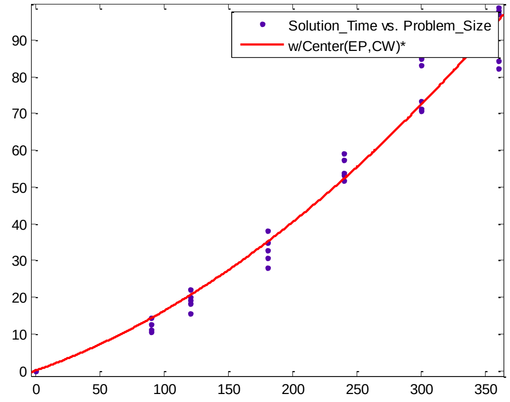


Figure 5.3.9: Computation Time Growth Rate for the w/Center(EP,CW)* Approach

Polynomial model: Degree 2:
f(x) = p1*x^2 + p2*x + p3
Coefficients (.01 significance level):
p1 = 0.0008304 (0.0006047, 0.001056)
p2 = 0.1112 (0.0439, 0.1785)
p3 = 0 (fixed at bound)

SSE: 2158
Adjusted R-square: 0.975
RMSE: 8.087

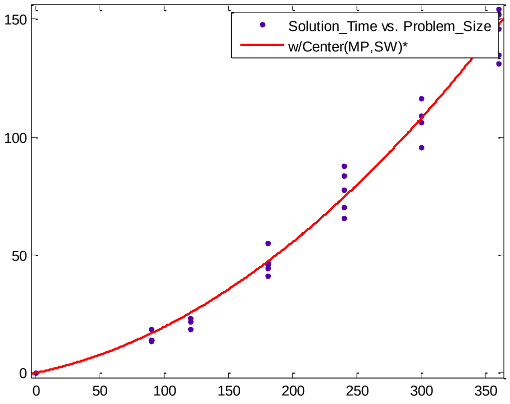


Figure 5.3.10: Computation Time Growth Rate for the w/Center(MP,SW)* Approach

Polynomial model: Degree 2:
f(x) = p1*x^2 + p2*x + p3
Coefficients (.01 significance level):
p1 = 0.0003328 (0.0001324, 0.0005332)
p2 = 0.1362 (0.07647, 0.196)
p3 = 0 (fixed at bound)

SSE: 1703
Adjusted R-square: 0.9498
RMSE: 7.183

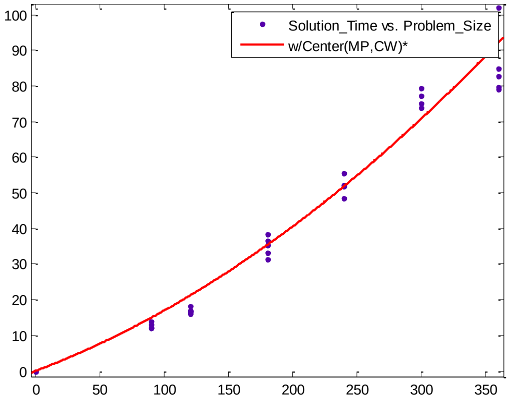


Figure 5.3.11: Computation Time Growth Rate for the w/Center(MP,CW)* Approach

5.4. Discussion

In Section 2.2, we established lower bounds for the optimal solution to 30 RVRP instances. Comparing the results of the RVRP solution approaches presented above to the lower bounds is of little use since we don't know how tight the bounds are. In the absence of known optimal values for the RVRP instances, proposed solution approaches can only be compared in a relative sense (i.e., to each other). The objective of this comparison is to identify which candidate solution generation approaches we should use in the generic solution algorithm given in Section 2.3.

In Sections 3.1 and 3.2 we described the Traditional VRP and All Sweeps baseline approaches. The Traditional VRP approach yields solutions that are of reasonable quality and computation time is fast. The All Sweeps approach is costly computationally and the solutions are generally of high quality.

The efficient sweep approaches described in Section 4.4 represent a compromise between the two baseline approaches. Computation time is roughly twice that of the Traditional VRP approach but the quality gap between the Traditional VRP approach and All Sweeps approach is reduced by more than 50%. Of the three procedures, the Sweep MST approach generally performs the best.

Altogether, the six w/Center approaches yielded the best result for 28 of the 30 instances and included the best or second best result for every instance. However, among the six approaches, the w/Center (MP,CW) and w/Center (MP,SW)* approaches consistently standout from the other four w/Center approaches.

Compared to the All Sweeps approach, the solution quality of the w/Center(MP,CW) and w/Center (MP,SW)* approaches is better in 16 and 18 of the 30 instances, respectively. Both approaches offer a significant computational savings when compared to the All Sweeps approach. Computation time for the w/Center (MP,CW) approach is less than $\frac{1}{9}$ the time required for the All Sweeps approach. Computation time for the w/Center (MP,SW)* approach is less that $\frac{1}{6}$ the time required by the All Sweeps approach. Furthermore, the growth rate for both w/Center approaches is $O(n^2)$, while the All Sweeps approach grows $O(n^3)$.

Between the two, the solution quality of the w/Center (MP,CW) approach was better than the w/Center (MP,SW)* approach on 17 of 30 instances, and its computation time is 59.5% less. However, the two procedures tended to perform well on different problems suggesting that they may best be used in combination.

We include the results of the test files generated and solved to establish computation time growth rates as Appendix G. The results for these smaller problems are consistent with our results above.

Finally, the candidate solution generation approach that resulted in the least total distance generally also had the best flexibility test score. Candidate solution generation approaches that gave high quality solutions were also insensitive to small changes in the segment length.

Chapter 6: Conclusions and Future Work

We formulated a new variant of the VRP, called the RVRP. Our solution approach was to generate a set of candidate solutions, from which we selected the best. We explored several approaches to forming candidate solutions and identified two good approaches, one based on the sweep procedure and one based on the TSPwC. Implementing our general algorithm with the TSPwC candidate generation approach consistently returned high quality solutions for all the test problems with reasonable computation times.

There are four areas of future research into the RVRP.

1. Improved solution methodologies to refine the best-known solutions our procedures generated. Our RVRP test instances are given in Appendix D.
2. Alternative solution approaches. Though the solution approaches we propose are deterministic, the complexity of the problem and the inability to define a heuristic operator (in the sense of a two opt) suggests that a genetic algorithm or meta-heuristic approach may produce high quality results.
3. Examination and characterization of the sensitivity of the RVRP to the parameters of individual instances. Our research focused exclusively on a single scenario matrix. However, we could consider different matrices and parameter values.
4. Examine the RVRP under modified assumptions such as allowing segment exchanges between non-adjacent routes or allowing multiple segment exchanges. We could also make alternative assumptions regarding how the objective function of the RVRP is computed. For example, we could replace

the minimum possible cost assumption we used in our scoring function and instead evaluate proposed solution quality under the assumption that that a simple decision rule is used for the movement of segments (e.g., always exchange, from a route, the first 10 customers adjacent to the depot).

Research along the lines of the last point may broaden the applicability of the RVRP beyond its current niche, package pickup and delivery. For example, our definition of least cost may make our proposed solution approaches difficult to implement in a number of practical settings. Studying alternate definitions of least cost may result in solution strategies that guide managers in making real-time moves of customers between routes as the workday unfolds and conditions change.

Appendix A: Mixed Integer Linear Program for the Six Node Problem

The MILP (in lp-format) for the six node RVRP Instance of Section 1.4 is given below. The model is given in an abbreviated form. Constraints are grouped and labeled according to the formulation given in Section 1.4 with the absolute conversions given first.

Min:

3.00 X000111 + 4.24 X000211 + ... + 3.00 X010011 + 3.00 X010211 + ...+ 1.00 X060511 + 3.00 X000112 + 4.24 X000212 + ... + 3.00 X010012 + 3.00 X010212 + ... + 1.00 X060512 + 3.00 X000121 + 4.24 X000221 + ... + 3.00 X010021 + 3.00 X010221 + ... + 1.00 X060521 + 3.00 X000122 + 4.24 X000222 + ... + 3.00 X010022 + 3.00 X010222 + ... + 1.00 X060522 + 3.00 X000131 + 4.24 X000231 + ... + 3.00 X010031 + 3.00 X010231 + ... + 1.00 X060531 + 3.00 X000132 + 4.24 X000232 + ... + 3.00 X010032 + 3.00 X010232 + ... + 1.000 X060532 + TRM1 + TRM2 + TRM3 + TRM4 + TRM5 + TRM6 + TRM7 + TRM8;

$(0b''), (0c''), (0d'')$, and $(0e'')$

20 Z000111 + 20 Z000211 + ... + 20 Z010011 + 20 Z010211 + ... + 20 Z060511 - TRM1 = 0;
20 Z000112 + 20 Z000212 + ... + 20 Z010012 + 20 Z010212 + ... + 20 Z060512 - TRM2 = 0;
20 Z000121 + 20 Z000221 + ... + 20 Z010021 + 20 Z010221 + ... + 20 Z060521 - 40 - 40 - TRM3 = 0;
20 Z000122 + 20 Z000222 + ... + 20 Z010022 + 20 Z010222 + ... + 20 Z060522 - 80 - TRM4 = 0;
20 Z000131 + 20 Z000231 + ... + 20 Z010031 + 20 Z010231 + ... + 20 Z060531 - 80 - TRM5 = 0;
20 Z000132 + 20 Z000232 + ... + 20 Z010032 + 20 Z010232 + ... + 20 Z060532 - 40 - 40 - TRM6 = 0;
10 W000121 - 10 X000101 - 10 X000122 + 10 W000221 - 10 X000201 - 10 X000222 + ... + 10 W010021 - 10 X010001 - 10 X010022 + 10 W010221 - 10 X010201 - 10 X010222 + ... + 10 W060521 - 10 X060501 - 10 X060522 + 20 - TRM7 = 0;
10 W000132 - 10 X000102 - 10 X000131 + 10 W000232 - 10 X000202 - 10 X000231 + ... + 10 W010032 - 10 X010002 - 10 X010031 + 10 W010232 - 10 X010202 - 10 X010231 + ... + 10 W060532 - 10 X060502 - 10 X060531 + 20 - TRM8 = 0;

Subject To:

$(12a'')$ & $(12b'')$

X000101 - X000111 - Z000111 <= 0;
- X000101 + X000111 - Z000111 <= 0;
X000201 - X000211 - Z000211 <= 0;
- X000201 + X000211 - Z000211 <= 0;
...
X010001 - X010011 - Z010011 <= 0;
- X010001 + X010011 - Z010011 <= 0;
X010201 - X010211 - Z010211 <= 0;
- X010201 + X010211 - Z010211 <= 0;
...
X060501 - X060511 - Z060511 <= 0;
- X060501 + X060511 - Z060511 <= 0;
X000102 - X000112 - Z000112 <= 0;
- X000102 + X000112 - Z000112 <= 0;
X000202 - X000212 - Z000212 <= 0;
- X000202 + X000212 - Z000212 <= 0;
...
X010002 - X010012 - Z010012 <= 0;
- X010002 + X010012 - Z010012 <= 0;
X010202 - X010212 - Z010212 <= 0;

```
- X010202 + X010212 - Z010212 <= 0;
...
X060502 - X060512 - Z060512 <= 0;
- X060502 + X060512 - Z060512 <= 0;
X000101 - X000121 - Z000121 <= 0;
- X000101 + X000121 - Z000121 <= 0;
X000201 - X000221 - Z000221 <= 0;
- X000201 + X000221 - Z000221 <= 0;
...
X010001 - X010021 - Z010021 <= 0;
- X010001 + X010021 - Z010021 <= 0;
X010201 - X010221 - Z010221 <= 0;
- X010201 + X010221 - Z010221 <= 0;
...
X060501 - X060521 - Z060521 <= 0;
- X060501 + X060521 - Z060521 <= 0;
X000102 - X000122 - Z000122 <= 0;
- X000102 + X000122 - Z000122 <= 0;
X000202 - X000222 - Z000222 <= 0;
- X000202 + X000222 - Z000222 <= 0;
...
X010002 - X010022 - Z010022 <= 0;
- X010002 + X010022 - Z010022 <= 0;
X010202 - X010222 - Z010222 <= 0;
- X010202 + X010222 - Z010222 <= 0;
...
X060502 - X060522 - Z060522 <= 0;
- X060502 + X060522 - Z060522 <= 0;
X000101 - X000131 - Z000131 <= 0;
- X000101 + X000131 - Z000131 <= 0;
X000201 - X000231 - Z000231 <= 0;
...
X010001 - X010031 - Z010031 <= 0;
- X010001 + X010031 - Z010031 <= 0;
X010201 - X010231 - Z010231 <= 0;
- X010201 + X010231 - Z010231 <= 0;
...
X060501 - X060531 - Z060531 <= 0;
- X060501 + X060531 - Z060531 <= 0;
X000102 - X000132 - Z000132 <= 0;
- X000102 + X000132 - Z000132 <= 0;
X000202 - X000232 - Z000232 <= 0;
- X000202 + X000232 - Z000232 <= 0;
...
X010002 - X010032 - Z010032 <= 0;
- X010002 + X010032 - Z010032 <= 0;
X010202 - X010232 - Z010232 <= 0;
- X010202 + X010232 - Z010232 <= 0;
...
X060502 - X060532 - Z060532 <= 0;
- X060502 + X060532 - Z060532 <= 0;
```

$(13a'')$ & $(13b'')$

```
X000101 - X000122 - W000121 <= 0;
- X000101 + X000122 - W000121 <= 0;
X000201 - X000222 - W000221 <= 0;
```

```
- X000201 + X000222 - W000221 <= 0;
...
X010001 - X010022 - W010021 <= 0;
- X010001 + X010022 - W010021 <= 0;
X010201 - X010222 - W010221 <= 0;
- X010201 + X010222 - W010221 <= 0;
...
X060501 - X060522 - W060521 <= 0;
- X060501 + X060522 - W060521 <= 0;
X000102 - X000131 - W000132 <= 0;
- X000102 + X000131 - W000132 <= 0;
X000202 - X000231 - W000232 <= 0;
- X000202 + X000231 - W000232 <= 0;
...
X010002 - X010031 - W010032 <= 0;
- X010002 + X010031 - W010032 <= 0;
X010202 - X010231 - W010232 <= 0;
- X010202 + X010231 - W010232 <= 0;
...
X060502 - X060531 - W060532 <= 0;
- X060502 + X060531 - W060532 <= 0;
```

$(1a')$:

```
X010001 + X010201 + ... + X060501 - 3 = 0;
X010002 + X010202 + ... + X060502 - 3 = 0;
X010011 + X010211 + ... + X060511 - 3 = 0;
```

$(1b')$:

```
X010012 + X010212 + ... + X060512 - 3 = 0;
X010021 + X010221 + ... + X060521 - 1 = 0;
X010022 + X010222 + ... + X060522 - 5 = 0;
X010031 + X010231 + ... + X060531 - 5 = 0;
X010032 + X010232 + ... + X060532 - 1 = 0;
```

$(2^{'})$:

```
X000101 + X000102 - Y00010 = 0;
X000201 + X000202 - Y00020 = 0;
...
X010001 + X010002 - Y01000 = 0;
X010201 + X010202 - Y01020 = 0;
...
X060501 + X060502 - Y06050 = 0;
X000111 + X000112 - Y00011 = 0;
X000211 + X000212 - Y00021 = 0;
...
X010011 + X010012 - Y01001 = 0;
X010211 + X010212 - Y01021 = 0;
...
X060511 + X060512 - Y06051 = 0;
X000121 + X000122 - Y00012 = 0;
X000221 + X000222 - Y00022 = 0;
...
X010021 + X010022 - Y01002 = 0;
X010221 + X010222 - Y01022 = 0;
..
X060521 + X060522 - Y06052 = 0;
```

```
X000131 + X000132 - Y00013 = 0;
X000231 + X000232 - Y00023 = 0;
..
X010031 + X010032 - Y01003 = 0;
X010231 + X010232 - Y01023 = 0;
...
X060531 + X060532 - Y06053 = 0;
```

$(3')$ & $(4')$

```
Y01000 + Y01020 + ... + Y01060 - 1 = 0;
...
Y06000 + Y06010 + ... + Y06050 - 1 = 0;
Y00010 + Y02010 + ... + Y06010 -1 = 0;
...
Y00060 + Y01060 + ... + Y05060 -1 = 0;
Y01001 + Y01021 + ... + Y01061 - 1 = 0;
...
Y06001 + Y06011 + ... + Y06051 - 1 = 0;
Y00011 + Y02011 + ... + Y06011 -1 = 0;
...
Y00061 + Y01061 + ... + Y05061 -1 = 0;
Y01002 + Y01022 + ... + Y01062 - 1 = 0;
...
Y06002 + Y06012 + ... + Y06052 - 1 = 0;
Y00012 + Y02012 + ... + Y06012 -1 = 0;
...
Y00062 + Y01062 + ... + Y05062 -1 = 0;
Y01003 + Y01023 + ... + Y01063 - 1 = 0;
...
Y06003 + Y06013 + ... + Y06053 - 1 = 0;
Y00013 + Y02013 + ... + Y06013 -1 = 0;
...
Y00063 + Y01063 + ... + Y05063 -1 = 0;
```

$(5')$ & $(6')$

```
Y00010 + Y00020 + ... + Y00060 - 2 = 0;
Y01000 + Y02000 + ... + Y06000 - 2 = 0;
...
Y00013 + Y00023 + ... + Y00063 - 2 = 0;
Y01003 + Y02003 + ... + Y06003 - 2 = 0;
```

$(7')$

```
U010 - U020 + 7 Y01020 - 6 <= 0;
U010 - U030 + 7 Y01030 - 6 <= 0;
...
U060 - U050 + 7 Y06050 - 6 <= 0;
U011 - U021 + 7 Y01021 - 6 <= 0;
U011 - U031 + 7 Y01031 - 6 <= 0;
...
U061 - U051 + 7 Y06051 - 6 <= 0;
U012 - U022 + 7 Y01022 - 6 <= 0;
U012 - U032 + 7 Y01032 - 6 <= 0;
...
U062 - U052 + 7 Y06052 - 6 <= 0;
U013 - U023 + 7 Y01023 - 6 <= 0;
```

U013 - U033 + 7 Y01033 - 6 <= 0;
...
U063 - U053 + 7 Y06053 - 6 <= 0;

$(8')$
X010001 - X000101 + X010201 - X020101 + ... + X010601 - X060101 = 0;
X020001 - X000201 + X020101 - X010201 + ... + X020601 - X060201 = 0;
...
X060001 - X000601 + X060101 - X010601 + ... + X060501 - X050601 = 0;
X010002 - X000102 + X010202 - X020102 + ... + X010602 - X060102 = 0;
X020002 - X000202 + X020102 - X010202 + ... + X020602 - X060202 = 0;
..
X060002 - X000602 + X060102 - X010602 + ... + X060502 - X050602 = 0;
X010011 - X000111 + X010211 - X020111 + ... + X010611 - X060111 = 0;
X020011 - X000211 + X020111 - X010211 + ... + X020611 - X060211 = 0;
..
X060011 - X000611 + X060111 - X010611 + ... + X060511 - X050611 = 0;
X010012 - X000112 + X010212 - X020112 + ... + X010612 - X060112 = 0;
X020012 - X000212 + X020112 - X010212 + ... + X020612 - X060212 = 0;
..
X060012 - X000612 + X060112 - X010612 + ... + X060512 - X050612 = 0;
X010021 - X000121 + X010221 - X020121 + ... + X010621 - X060121 = 0;
X020021 - X000221 + X020121 - X010221 + ... + X020621 - X060221 = 0;
..
X060021 - X000621 + X060121 - X010621 + ... + X060521 - X050621 = 0;
X010022 - X000122 + X010222 - X020122 + ... + X010622 - X060122 = 0;
X020022 - X000222 + X020122 - X010222 + ... + X020622 - X060222 = 0;
..
X060022 - X000622 + X060122 - X010622 + ... + X060522 - X050622 = 0;
X010031 - X000131 + X010231 - X020131 + ... + X010631 - X060131 = 0;
X020031 - X000231 + X020131 - X010231 + ... + X020631 - X060231 = 0;
..
X060031 - X000631 + X060131 - X010631 + ... + X060531 - X050631 = 0;
X010032 - X000132 + X010232 - X020132 + ... + X010632 - X060132 = 0;
..
X060032 - X000632 + X060132 - X010632 + ... + X060532 - X050632 = 0;

$(9')$
Integer: U010, U020, ..., U060; U011, U021, ..., U061; U012, U022, ..., U062; U013, U023, ..., U063;

$(10')$& $(11')$
Binary: Y00010, Y00020, ..., Y06050; Y00011, Y00021, ..., Y06051; Y00012, Y00022, ..., Y06052; Y00013, Y00023, ..., Y06053; X000101, X000201, ..., X060502; X000111, X000211, ..., X060512; X000121, X000221, ..., X060522; X000131, X000231, ..., X060532; Z000111, Z000211, ..., Z060512; Z000121, Z000221, ..., Z060522; Z000131, Z000231, ..., Z060532; W000121, W000221, ..., W060521; W000132, W000232, ..., W060532;

Appendix B: Optimal Solution to a Six Node Problem, Solver Output

The abbreviated lp_solve output for the six node problem of Section 1.4 is given below. Under the heading Primal Variables, only the non-zero variables are listed.

```
Model name:  'LPSolver' - run #1
Objective:   Minimize(R0)

Model size:     1080 constraints,     866 variables,        4756 non-zeros.
Sets:                             0 GUB,                0 SOS.
Row-types:       800 LE,               0 GE,                280 EQ.

CONSTRAINT CLASSES
General REAL     120
General MIP        4
General BIN      892
Knapsack BIN      14
GUB               50

Using DUAL simplex for phase 1 and PRIMAL simplex for phase 2.
The primal and dual simplex pricing strategy set to 'Devex'.

Found dual solution with 37 fixed slack variables left basic.
Optimal solution with dual simplex at iter          987.
Relaxed solution       49.7057142857 after        987 iter is B&B base.

Feasible solution              76.26 after      65089 iter,        66 nodes (gap 52.4%)
Improved solution              71.95 after      66205 iter,        88 nodes (gap 43.9%)
Improved solution              71.26 after      68391 iter,       115 nodes (gap 42.5%)
Improved solution              70.79 after      73103 iter,       172 nodes (gap 41.6%)
Improved solution              70.11 after      73742 iter,       182 nodes (gap 40.2%)
Improved solution              68.54 after      76747 iter,       217 nodes (gap 37.1%)
Improved solution              67.96 after      79034 iter,       252 nodes (gap 36.0%)
Improved solution              65.25 after      81922 iter,       282 nodes (gap 30.7%)
Improved solution              64.57 after      82564 iter,       293 nodes (gap 29.3%)
Improved solution              61.91 after     115518 iter,       449 nodes (gap 24.1%)
Improved solution              61.72 after     128536 iter,       593 nodes (gap 23.7%)
Improved solution              61.04 after     128560 iter,       594 nodes (gap 22.4%)
Improved solution              59.03 after     132278 iter,       648 nodes (gap 18.4%)
Improved solution              58.35 after     132325 iter,       649 nodes (gap 17.0%)
Improved solution              57.69 after     426415 iter,      1211 nodes (gap 15.7%)
Improved solution              55.79 after     446453 iter,      1496 nodes (gap 12.0%)

Primal variables:

 Column Name       Value    Slack                Min               Max
 ---------------------------------------------------------------------------------
 X000611               1         0.289756     -1.00E+30      1.00E+30
 X040011               1           7.8425     -1.00E+30      1.00E+30
```

X050411	1	0	-1.00E+30	1.00E+30
X060511	1	0	0	0
X000312	1	0	-1.00E+30	1.00E+30
X010012	1	-0.0756707	-1.00E+30	1.00E+30
X020112	1	0	-1.00E+30	1.00E+30
X030212	1	0	-1.00E+30	1.00E+30
X000621	1	4.32683	-1.00E+30	1.00E+30
X060021	1	0	-1.00E+30	1.00E+30
X000522	1	0	-1.00E+30	1.00E+30
X010022	1	0	-1.00E+30	1.00E+30
X020122	1	0	-1.00E+30	1.00E+30
X030222	1	0	-1.00E+30	1.00E+30
X040322	1	0	0	0
X050422	1	0	-1.00E+30	1.00E+30
X000631	1	-0.710427	-1.00E+30	1.00E+30
X020031	1	2.985	-1.00E+30	1.00E+30
X030231	1	0	-1.00E+30	1.00E+30
X040331	1	0	0	0
X050431	1	0	-1.00E+30	1.00E+30
X060531	1	0	-1.00E+30	1.00E+30
X000132	1	0	0	0
X010032	1	0	-1.00E+30	1.00E+30
Z040021	1	-3.1989	-1.00E+30	1.00E+30
Z050421	1	0	0	0.428571
Z060521	1	0	0	0.428571
Z000322	1	0	0	0
Z000522	1	0	-1.00E+30	1.00E+30
Z040322	1	0	0	0.25
Z050422	1	0	-1.00E+30	1.00E+30
Z20031	1	0	-1.00E+30	1.00E+30
Z030231	1	-2.20363	-1.00E+30	1.00E+30
Z040031	1	0	-1.00E+30	1.00E+30
Z040331	1	0	0	0
Z000132	1	-0.0376829	0	2
Z000332	1	-0.223689	1	1
Z020132	1	0	-1.00E+30	1.00E+30
Z030232	1	0	-1.00E+30	1.00E+30
W000521	1	0	-1.00E+30	1.00E+30
W000621	1	0	-1.00E+30	1.00E+30
X000601	1	0	0	0
W010021	1	0	-1.00E+30	1.00E+30
W020121	1	0	-1.00E+30	1.00E+30
W030221	1	0	-1.00E+30	1.00E+30

W040021	1	0	-1.00E+30	1.00E+30
X040001	1	0	-1.00E+30	1.00E+30
W040321	1	0	0	2
X050401	1	0	0	0
W060521	1	0	-1.00E+30	1.00E+30
X060501	1	0	0	0
W000332	1	0	-1.00E+30	1.00E+30
X000302	1	0	0	0
W000632	1	0	-1.00E+30	1.00E+30
W010032	1	0	-1.00E+30	1.00E+30
X010002	1	0	-1.00E+30	1.00E+30
W020032	1	0	-1.00E+30	1.00E+30
W020132	1	0	0.712054	2.15848
X020102	1	0	-1.00E+30	1.00E+30
X030202	1	0	-1.00E+30	1.00E+30
W040332	1	0	-1.00E+30	1.00E+30
W050432	1	0	-1.00E+30	1.00E+30
W060532	1	0	-1.00E+30	1.00E+30
Y00030	1	0	-1.00E+30	1.00E+30
Y00060	1	0	0	0
Y01000	1	0	-1.00E+30	1.00E+30
Y02010	1	0	-1.00E+30	1.00E+30
Y03020	1	0	-1.00E+30	1.00E+30
Y04000	1	-0.361707	-1.00E+30	1.00E+30
Y05040	1	0	0	0
Y06050	1	0	-1.00E+30	1.00E+30
Y00031	1	0	-1.00E+30	1.00E+30
Y00061	1	0	-1.00E+30	1.00E+30
Y01001	1	0	-1.00E+30	1.00E+30
Y02011	1	0	-1.00E+30	1.00E+30
Y03021	1	0	-1.00E+30	1.00E+30
Y04001	1	0	-1.00E+30	1.00E+30
Y05041	1	0	-1.00E+30	1.00E+30
Y06051	1	0	-1.00E+30	1.00E+30
Y00052	1	0	0	0.0357143
Y00062	1	-0.83	-1.00E+30	1.00E+30
Y01002	1	0	-1.00E+30	1.00E+30
Y02012	1	0	-1.00E+30	1.00E+30
Y03022	1	0	-1.00E+30	1.00E+30
Y04032	1	0	-1.00E+30	1.00E+30
Y05042	1	0	-1.00E+30	1.00E+30
Y06002	1	0	-1.00E+30	1.00E+30
Y00013	1	0	-1.00E+30	1.00E+30

```
Y00063           1    -3.05762   -1.00E+30   1.00E+30
Y01003           1           0   -1.00E+30   1.00E+30
Y02003           1           0   -1.00E+30   1.00E+30
Y03023           1           0   -1.00E+30   1.00E+30
Y04033           1           0   -1.00E+30   1.00E+30
Y05043           1           0   -1.00E+30   1.00E+30
Y06053           1           0   -1.00E+30   1.00E+30
U010             2           0      -5.125          0
U020             1           0           0      5.125
U040             6           0      -5.125       4.25
U050             5           0   -1.00E+30   1.00E+30
U011             2           0          -1          0
U021             1           0           0          1
U041             2           0          -1          6
U051             1           0   -1.00E+30   1.00E+30
U012             4           0        -1.5      4.125
U022             3           0      -0.875      4.125
U032             2           0   -1.00E+30   1.00E+30
U042             1           0      -5.125          6
U023             4           0     -3.0625     5.9375
U033             3           0   -1.00E+30   1.00E+30
U043             2           0     -5.0625          4
U053             1           0     -0.9375     3.0625

Optimal solution          55.79 after   79223340 iter,      2992 nodes (gap 11.9%).
Excellent numeric accuracy ||*|| = 1.98952e-013

MEMO: lp_solve version 5.5.0.15 for 32 bit OS, with 64 bit REAL variables.  In the total
iteration count 79223340, 35891128 (45.3%) were bound flips.  There were 452438
refactorizations, 0 triggered by time and 450017 by density.  On average 95.8 major pivots per
refactorization.  The largest [LUSOL v2.2.1.0] fact(B) had 4630 NZ entries, 1.2x largest basis.
The maximum B&B level was 39, 0.0x MIP order, 26 at the optimal solution.  The constraint
matrix inf-norm is 20, with a dynamic range of 20.  Time to load data was 0.084 seconds,
presolve used 0.140 seconds, ... 21290.605 seconds in simplex solver, in total 21290.829 seconds.
```

Appendix C: Six Node Robust Vehicle Routing Problem Instance

The TSPLIB file for the six node RVRP instance presented in Section 1.4 and solved using the MILP formulation is given below.

```
NAME: N6_smprob
TYPE: CVRP
COMMENT: 1000000
DIMENSION: 7
CAPACITY: 3
VEHICLES: 2
EDGE_WEIGHT_TYPE: FUNCTION
EDGE_WEIGHT_FORMAT: EUC_2D
NODE_COORD_TYPE: TWOD_COORDS
NODE_COORD_SECTION
1     3     0
2     3     3
3     1     3
4     -2    2
5     -2    1
6     -2    0
DEMAND_SECTION
1     1
2     1
3     1
4     1
5     1
6     1
DEPOT_SECTION
0.00000      0.00000
-1
SEGMENT_LENGTH: 2
SCENARIOS: 3
SCENARIO_DETAIL:
1     3     3
2     1     5
3     5     1
EOF
```

Appendix D: 30 Test Instances for the Robust Vehicle Routing Problem

The TSPLIB files for the 30 test instances we developed for the RVRP are presented below. The development of these test instances is discussed in Chapter 2. Note that for the sake of brevity, only the test instances with segment length 10 are presented in full (both sets of test instances utilize a common node distribution, see Chapter 2). Also for the sake of brevity, the DEMAND_SECTION has been abbreviated in all but the first instance listed: N360_SL10_rand_1. The complete DEMAND_SECTION for the other 14 instances is identical to that of the N360_SL10_rand_1 instance. The corresponding instances for segment length 15 are given by the substitution of the fields as follows:

Segment Length 10 Instance (replace)	Segment Length 15 Instance (by)
`SEGMENT_LENGTH: 10`	`SEGMENT_LENGTH: 15`
`SCENARIOS: 10`	`SCENARIOS: 10`
`SCENARIO_DETAIL:`	`SCENARIO_DETAIL:`
`1     120   120   120`	`1     120   120   120`
`2     120   110   130`	`2     120   105   135`
`3     120   130   110`	`3     120   135   105`
`4     110   130   120`	`4     105   135   120`
`5     130   110   120`	`5     135   105   120`
`6     110   120   130`	`6     105   120   135`
`7     130   120   110`	`7     135   120   105`
`8     130   100   130`	`8     135   90    135`
`9     100   130   130`	`9     90    135   135`
`10    130   130   100`	`10    135   135   90`

```
NAME: N360_SL10_rand_1
TYPE: CVRP
COMMENT: 1000000
DIMENSION: 361
CAPACITY: 120
VEHICLES: 3
EDGE_WEIGHT_TYPE: FUNCTION
EDGE_WEIGHT_FORMAT: EUC_2D
NODE_COORD_TYPE: TWOD_COORDS
NODE_COORD_SECTION
1      -33.52421   60.97794
2      97.65758    0.5570091
3      -5.256619   -13.19406
4      49.37219    41.80672
5      33.99176    11.05280
6      59.11840    -48.99924
7      -45.49131   -84.95988
8      -43.21697   17.82048
9      43.45115    34.84842
10     -63.07257   17.60268
11     66.74067    6.740451
12     -66.06699   -5.476726
13     90.65314    -35.23776
14     44.50961    -13.80278
15     -73.15032   52.97956
16     70.61850    99.29253
17     86.33855    -46.99634
18     12.83693    58.41340
19     -20.23533   -73.07815
20     -11.67950   -92.89277
21     40.33615    -9.210702
22     -47.99140   12.59541
23     -94.29411   -53.82344
24     89.59305    -71.04752
25     99.23380    35.41917
26     55.89666    -29.18590
27     97.88028    2.094461
28     -2.489408   38.94133
29     -74.40347   19.05859
30     -7.126544   1.222151
31     48.51810    55.27985
32     34.67833    37.04055
33     74.79590    -36.10127
34     51.65008    66.42857
35     23.43505    32.16431
36     -45.03656   17.41364
37     -32.72433   -96.18431
38     67.14471    67.39001
39     -22.82273   -77.20042
40     -83.93069   68.08409
41     73.11687    -32.50066
42     -12.92519   -14.11287
43     -65.58382   58.75573
44     -99.14072   -71.68650
45     30.49937    21.62037
46     -26.06207   86.12576
47     -24.78016   27.28875
```

48	-11.73151	-90.44587
49	3.224770	39.66922
50	-39.97708	-48.57809
51	-4.335639	38.18030
52	-98.75063	-27.36405
53	-65.71282	8.376845
54	-39.28851	-55.57162
55	48.89291	81.09747
56	16.17867	-25.29177
57	40.24144	-84.23670
58	60.93288	-93.81401
59	70.39705	25.38016
60	-76.45581	87.39933
61	31.45273	-36.01294
62	50.59029	49.03495
63	40.42576	-42.21432
64	21.02369	-75.12919
65	-92.34667	2.816199
66	-60.96998	-22.49763
67	-33.86366	95.72195
68	28.56668	-41.63645
69	-56.51921	18.46851
70	-84.61804	14.27129
71	96.11787	23.17120
72	-58.64821	12.18285
73	96.65067	-44.02812
74	22.07420	-69.63007
75	-50.40429	46.60250
76	3.591586	-92.06030
77	42.56621	60.32446
78	-48.02620	-18.71662
79	-77.06280	66.00229
80	9.933899	94.20710
81	-56.21965	-15.50339
82	-37.56488	-89.21903
83	94.62662	57.40736
84	-38.16190	26.01540
85	89.24950	1.763877
86	-17.88763	13.53723
87	-97.93328	-38.16183
88	-37.98620	49.42719
89	-68.95863	-32.66783
90	98.81651	76.67088
91	-9.952159	-33.26882
92	9.043657	59.20292
93	-47.53365	60.95676
94	76.50825	-89.95226
95	-79.38779	-19.49897
96	64.71254	93.03833
97	-14.56485	-17.12481
98	84.06894	-33.89529
99	5.602432	27.27447
100	74.16693	71.60507
101	-29.43784	57.65680
102	-19.96952	7.681949
103	19.58458	48.33409
104	82.30359	47.94412

105	-73.40260	-11.04108
106	-91.56651	70.08197
107	-19.79221	-1.093028
108	19.14154	89.63151
109	83.93586	59.55764
110	-41.24484	-73.39108
111	9.007869	-52.44605
112	56.33636	-74.45531
113	-34.52009	6.824080
114	-80.94745	-88.66066
115	-11.66348	-6.285000
116	-94.18464	96.53756
117	35.07808	36.44423
118	-77.68192	74.18015
119	-60.07195	-0.7578869
120	6.032308	-42.46756
121	25.47137	-63.39614
122	-25.28067	92.24380
123	21.29073	51.25230
124	69.27774	90.07070
125	40.38914	34.25333
126	-21.42522	-62.78908
127	14.37373	-42.03161
128	-50.04525	-88.35844
129	45.46935	-91.18675
130	-31.33417	-44.08823
131	-84.27306	-65.90607
132	-39.55381	35.42011
133	-39.91950	80.48359
134	-95.35576	-29.60254
135	-64.77715	-79.96830
136	72.18376	58.60045
137	31.18963	-6.313514
138	71.30752	37.46824
139	-45.81191	36.61571
140	79.18955	-15.71282
141	-58.24192	31.86851
142	92.83363	26.68543
143	-17.12798	5.029202
144	-54.08696	-61.74371
145	63.67404	2.381202
146	-27.91130	49.66605
147	0.3048136	-16.03462
148	49.53482	47.49588
149	66.36998	37.29355
150	-21.10580	91.14520
151	-80.67273	-38.41871
152	-46.92168	-31.53983
153	58.38900	-22.59329
154	87.37215	-94.76482
155	13.65172	26.70928
156	87.60431	13.05021
157	19.44968	-26.89772
158	97.59039	-15.70826
159	52.46970	-7.559946
160	-62.87683	-37.11224
161	3.354001	-54.86766

162	28.03042	-76.81262
163	73.79018	-73.20678
164	20.02367	89.30469
165	99.93388	-1.513406
166	-74.16474	49.64273
167	-41.32587	-37.81297
168	-4.624125	-98.45895
169	-74.08351	23.12433
170	-54.37531	-28.48533
171	-63.78559	29.76581
172	34.40311	69.19544
173	-34.84303	-79.72935
174	58.11750	17.66037
175	9.202781	16.47644
176	-53.88869	4.360752
177	37.35249	-9.080034
178	-90.18348	93.34040
179	14.51971	-63.53861
180	98.75246	11.87843
181	-27.40619	25.29490
182	11.74413	-93.97400
183	85.45607	28.45461
184	-48.02470	67.63223
185	66.49500	-20.97280
186	-64.97482	-12.53156
187	75.96844	-83.02345
188	-44.07345	16.27550
189	69.89520	74.33640
190	61.34320	-58.61858
191	-62.17497	-81.07800
192	95.71179	-62.40956
193	-49.25447	33.56731
194	55.70922	46.48418
195	62.15691	26.20209
196	-0.4094104	-6.358769
197	83.14463	-37.12753
198	-79.80329	28.29333
199	-72.83508	12.40538
200	71.66336	32.74533
201	-96.27071	-75.02459
202	45.66560	34.80544
203	63.33157	36.06226
204	-76.75591	86.02403
205	-2.288724	65.76394
206	-30.51032	-64.37993
207	54.77820	89.84812
208	-42.94265	-60.07543
209	64.87934	-56.46387
210	-65.38779	-98.29562
211	72.72869	-39.87468
212	85.21095	-45.10583
213	-61.77925	17.28969
214	-89.92950	-20.68943
215	9.689895	-62.71944
216	-98.09642	-21.43672
217	65.67274	-69.08123
218	81.70888	66.46089

219	41.05935	-70.04958
220	-51.33394	35.90919
221	17.84632	50.01800
222	87.77999	-97.02200
223	79.10040	-71.55070
224	21.24524	-93.86888
225	58.47567	61.73910
226	67.23351	-90.57081
227	12.02822	33.23629
228	-99.86098	-8.793513
229	-49.74497	60.59928
230	-13.61028	-28.31222
231	-13.86943	-94.93319
232	75.04661	-56.28237
233	-86.47181	42.18298
234	-32.01864	9.784157
235	-64.58759	73.93861
236	-50.79296	47.76713
237	45.56390	-79.35397
238	-42.35902	94.28664
239	-52.53167	47.74252
240	-72.06820	-97.22849
241	-55.85394	35.82433
242	63.50934	-2.899454
243	-24.35419	-93.05633
244	33.10304	-77.11208
245	87.16266	-84.67498
246	-14.70378	21.56494
247	21.03201	-53.30683
248	93.91689	-71.59771
249	-27.06981	6.034640
250	32.88951	86.06026
251	-37.04898	23.38055
252	77.14317	37.97838
253	-40.89105	-53.11483
254	-40.92678	-58.63123
255	81.41641	-92.52675
256	-1.423082	32.67299
257	-58.57207	1.450914
258	-94.83615	-2.839910
259	-65.95821	72.33900
260	-39.53189	93.10298
261	92.28793	51.93759
262	56.73149	-50.66411
263	34.65129	35.25349
264	68.14445	51.86109
265	-15.82914	17.23796
266	40.74747	64.48785
267	-3.742676	85.36703
268	64.11520	27.51338
269	-12.52196	-96.21243
270	71.99477	-63.13187
271	-98.22055	-94.65186
272	99.20622	86.99973
273	-44.95979	-3.106528
274	-93.29671	58.95711
275	-69.58001	-8.632932

276	-4.080769	-1.158148
277	77.76847	-14.85721
278	-43.31618	78.35443
279	56.82541	74.85703
280	-65.92150	26.63007
281	46.25871	-41.54414
282	-50.67563	-41.66433
283	-83.63181	-50.89999
284	70.58175	40.86958
285	37.31043	54.92237
286	91.62212	64.53072
287	97.01112	61.23793
288	6.944524	-49.24581
289	81.19609	60.09997
290	-4.670276	25.94174
291	77.93425	-53.69969
292	-95.23005	-23.78465
293	-74.25504	-9.359672
294	48.12804	0.1119116
295	-21.79596	8.114309
296	-21.27431	-30.97097
297	20.36967	-41.71399
298	-95.22291	40.70572
299	-22.46580	86.81568
300	-88.65077	18.83495
301	37.91411	18.61815
302	4.078181	47.74621
303	-84.78271	-25.47136
304	-18.74805	-9.345925
305	-13.95743	1.875113
306	31.86246	85.74216
307	-56.32177	-9.842439
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309	-6.465665	-8.127229
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311	22.79677	-91.75347
312	80.11955	60.44044
313	-49.44413	34.30233
314	-55.98094	-59.93448
315	-52.83900	-97.08273
316	62.02590	52.63321
317	40.48181	13.50235
318	75.70097	30.84276
319	42.20225	26.94808
320	32.21605	46.86604
321	-12.08451	77.46532
322	12.55872	33.18180
323	98.06226	-75.86508
324	91.46308	42.74712
325	-32.63634	-10.55456
326	-68.90884	28.19647
327	-16.58418	29.77923
328	10.89540	35.67508
329	-94.04958	-88.23447
330	73.34126	-55.20935
331	78.88285	-66.40369
332	-0.5619231	85.70588

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333   -58.14260   3.046198
334   44.31943    34.67270
335   39.94322    33.56004
336   -7.850554   -83.70772
337   -65.88139   -54.98531
338   58.87429    -43.16216
339   77.69993    82.75275
340   -71.49709   -54.17969
341   87.93432    -50.27592
342   -99.94783   35.25815
343   -12.23900   29.69813
344   -97.76645   40.73537
345   -53.09690   67.42065
346   41.39684    45.45914
347   38.83287    -96.11312
348   -46.97583   16.74930
349   -34.68528   84.17536
350   -81.35321   -81.66440
351   -91.68013   10.91212
352   51.85603    86.16056
353   -35.02510   -60.10941
354   4.364362    5.063917
355   90.37758    -74.65218
356   33.79568    49.74546
357   -5.375676   -37.06626
358   29.87443    -62.56517
359   33.12718    96.07903
360   -53.97051   42.56543
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8     1
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344   1
345   1
346   1
347   1
348   1
349   1
350   1
351   1
352   1
353   1
354   1
355   1
356   1
357   1
358   1
359   1
360   1
DEPOT_SECTION
0.00000      0.00000
-1
SEGMENT_LENGTH: 10
SCENARIOS: 10
SCENARIO_DETAIL:
1     120   120   120
2     120   110   130
3     120   130 110
4     110   130   120
```

```
5     130   110   120
6     110   120   130
7     130   120   110
8     130   100   130
9     100   130   130
10    130   130   100
EOF
```

```
NAME: N360_SL10_rand_2
TYPE: CVRP
COMMENT: 1000000
DIMENSION: 361
CAPACITY: 120
VEHICLES: 3
EDGE_WEIGHT_TYPE: FUNCTION
EDGE_WEIGHT_FORMAT: EUC_2D
NODE_COORD_TYPE: TWOD_COORDS
NODE_COORD_SECTION
1      33.80852    -60.35564
2      0.04226486  -60.98569
3      -56.40124   -34.63207
4      14.32314    76.06757
5      -75.56217   -5.779627
6      34.23325    -19.20613
7      19.91711    -64.15370
8      -88.80477   93.78500
9      -88.73140   -18.50885
10     -69.49987   68.89748
11     -96.07579   23.06502
12     -12.96489   -24.67778
13     66.44430    75.43635
14     23.47803    56.97049
15     4.025883    -7.009143
16     72.77364    62.79539
17     -80.46042   79.68883
18     81.61044    -14.15229
19     -78.39666   -33.13412
20     3.399352    19.32942
21     -71.36880   80.39816
22     11.87411    40.41329
23     -99.08408   -24.50898
24     53.33640    46.99118
25     69.74184    90.82056
26     83.36426    8.562623
27     97.39365    8.021167
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30     -79.84990   -63.60390
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38     87.71157    -58.30595
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219	-72.53927	-32.20017
220	0.9464635	-19.75603
221	-19.00830	5.395950
222	-65.28557	78.84715
223	15.03672	55.67213
224	21.24359	-86.12648
225	-57.11085	-44.24310
226	3.986451	-24.12603
227	97.83716	72.93451
228	-2.016968	-16.00793
229	38.97464	-52.02451
230	-17.71564	19.53090
231	-93.04465	-4.119119
232	-41.43369	79.70950
233	60.28835	86.94185
234	-30.69960	63.57737
235	-83.33681	41.78180
236	2.221274	48.64412
237	-26.63332	79.94196
238	47.89590	-86.95204
239	4.948033	-32.81776
240	60.90417	-99.13299
241	63.38224	65.61912
242	-62.10571	1.487075
243	-75.26131	-26.76751
244	64.19930	-54.67206
245	27.57952	6.966342
246	-96.77604	-42.10303
247	79.19093	-86.32582
248	3.075011	-83.00585
249	8.904387	-86.33211
250	21.28844	-18.03670
251	52.08724	-75.32372
252	71.06937	-11.39668
253	-23.42631	79.78795
254	-83.07016	-29.27220
255	46.77466	-75.96438
256	-33.60213	13.82221
257	67.94991	75.00655
258	-25.65534	-30.28500
259	65.64305	-91.61580
260	-64.69627	-71.53206
261	-74.09603	-84.68143
262	75.97672	48.10532
263	-91.18417	-8.694975
264	37.34401	33.64986
265	46.75458	39.84922
266	-12.56551	14.27144
267	-24.03222	25.73867
268	95.93149	75.55279
269	-20.20131	32.47035
270	-11.96262	75.08273
271	-68.63842	-6.496596
272	-34.79314	-71.73280
273	-37.18761	-86.37311
274	78.90013	42.84848
275	-50.59517	-38.40279

276	-37.86420	34.23280
277	-18.22622	30.48417
278	41.60218	6.209768
279	-71.27248	43.02141
280	74.26441	0.9621246
281	-83.36882	-2.400128
282	-7.652432	-0.4323382
283	-93.92220	87.19511
284	50.64011	-22.14366
285	40.00853	-76.57097
286	-57.09755	-51.91529
287	35.98094	36.98170
288	11.45854	67.85072
289	70.13578	94.02892
290	11.71310	-56.96608
291	80.35474	52.06867
292	-16.09646	16.82057
293	-28.37433	-19.40969
294	-2.202497	2.008068
295	-48.80757	-0.8711562
296	85.83385	30.27367
297	-6.648637	48.74123
298	-49.19843	-39.60931
299	-13.75631	-82.07761
300	40.50600	65.19310
301	-19.53403	-22.08260
302	-63.63198	55.06097
303	71.25022	-64.12618
304	16.84024	-78.12776
305	-25.28424	81.03167
306	-55.66109	75.27020
307	-56.20118	99.95851
308	4.446488	72.85094
309	-13.31546	-92.62450
310	48.26080	8.936488
311	-85.91007	99.52324
312	69.46669	2.201631
313	35.97605	74.70244
314	-72.66969	-85.95570
315	71.68044	97.50774
316	-60.03318	84.54269
317	21.46799	12.85218
318	8.608996	-13.70759
319	-67.53506	-32.43109
320	-98.86938	44.14468
321	54.29703	-97.26889
322	52.95751	-25.18796
323	-15.78613	84.53704
324	-88.63737	9.295930
325	17.14940	-5.222626
326	-65.16895	-0.6925363
327	45.72213	-38.20578
328	6.858210	90.16751
329	-49.38714	96.39866
330	83.41135	2.712621
331	51.63890	98.51797
332	77.40614	-8.831260

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333   -86.24036   -14.79182
334   -63.29436   -57.35704
335   47.41453    -61.35011
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337   55.39858    45.32742
338   0.3806838   5.949139
339   -14.90063   65.81615
340   22.24743    2.374886
341   71.15438    10.39237
342   34.15942    -57.34302
343   4.718409    17.56413
344   -40.23692   -71.44736
345   40.79382    -89.55530
346   -23.67782   36.66158
347   13.53700    21.71189
348   77.57219    -56.06881
349   68.58986    -18.74401
350   79.75971    25.98159
351   87.80062    11.06153
352   63.08703    -74.48418
353   -99.72843   -66.16033
354   -99.38186   -99.80012
355   -82.50623   -16.36751
356   -47.85453   -2.302864
357   -95.44027   -68.02623
358   -15.18304   33.36771
359   -31.78701   -96.41592
360   8.270786    -76.06493
DEMAND_SECTION
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2     1
3     1
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DEPOT_SECTION
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SEGMENT_LENGTH: 10
SCENARIOS: 10
SCENARIO_DETAIL:
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2     120   110   130
3     120   130   110
4     110   130   120
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EOF
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NAME: N360_SL10_rand_4
TYPE: CVRP
COMMENT: 1000000
DIMENSION: 361
CAPACITY: 120
VEHICLES: 3
EDGE_WEIGHT_TYPE: FUNCTION
EDGE_WEIGHT_FORMAT: EUC_2D
NODE_COORD_TYPE: TWOD_COORDS
NODE_COORD_SECTION
1      82.33012    86.83396
2      -52.15727   -39.44360
3      53.21651    -20.22375
4      15.82881    -50.42075
5      8.533392    -60.82360
6      6.342222    -87.45405
7      89.96553    22.65797
8      -56.51696   24.30409
9      -25.57942   -32.83683
10     20.77897    -78.77036
11     38.24271    -60.34973
12     18.02277    6.701890
13     -47.73675   -50.42213
14     -14.34984   -14.40906
15     78.26481    -35.00271
16     50.95264    30.33408
17     -23.77292   -54.96307
18     -80.20563   89.22560
19     -73.56139   4.126511
20     27.74030    82.06466
21     84.58786    -82.68006
22     63.42776    27.95036
23     -79.92068   -28.11902
24     -25.83064   95.91910
25     -24.02196   -77.33598
26     80.26842    58.72897
27     -88.32948   -27.24328
28     23.67640    -37.60593
29     14.66101    5.251430
30     31.36291    -72.22377
31     13.53767    89.47775
32     -85.01324   98.24134
33     51.45658    81.81351
34     -4.532377   -42.47750
35     58.31387    -19.62070
36     -33.81674   6.818695
37     35.66482    26.88512
38     -33.28979   37.82373
39     -6.211866   -62.96267
40     -37.54975   -23.44092
41     39.74200    -73.63464
42     8.732584    -96.99836
43     -96.81652   -24.81368
44     -27.57975   79.31394
45     -56.52539   -31.26887
46     18.55879    -43.84802
47     65.48256    75.23100
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50	63.98913	69.61565
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52	-60.06324	-0.6195474
53	2.528720	59.36806
54	22.76477	-85.45943
55	23.25028	-38.98074
56	-93.50606	84.55463
57	-65.53028	15.89042
58	39.63657	64.67044
59	-53.78786	-53.31681
60	-49.03918	-75.75133
61	-18.22136	88.20730
62	74.70502	99.38922
63	83.97810	-41.05572
64	-39.17400	-43.74542
65	-71.18967	44.66211
66	-88.59666	77.17393
67	-26.92030	0.6784729
68	-69.21838	-21.62961
69	-70.57134	78.70443
70	-38.29571	-92.64397
71	0.3505067	-47.85371
72	-80.08463	96.87323
73	-87.94143	-37.48835
74	-39.25071	-53.16630
75	28.13791	15.89316
76	-50.12444	56.81354
77	-40.22968	-92.93311
78	40.26785	18.09039
79	-62.61426	-34.25889
80	83.42759	-53.14837
81	-44.47836	-86.09452
82	3.247312	81.54598
83	-22.78395	4.845648
84	-67.26366	9.827815
85	-23.05476	-71.11330
86	-85.05776	77.81590
87	-34.77367	10.00069
88	4.002659	-66.35914
89	23.45675	98.23693
90	-53.32828	-46.71574
91	-0.5313852	95.22633
92	-34.26227	88.70242
93	67.15811	5.243498
94	-81.00495	-20.53301
95	49.02042	96.25413
96	-69.98455	-67.20431
97	92.94500	19.62734
98	57.59750	45.00598
99	-33.20293	44.04490
100	-87.94959	-30.96815
101	-59.33302	6.547072
102	85.80581	18.71456
103	91.41110	97.23239
104	71.45588	-71.60677

105	47.96404	-42.43977
106	75.63293	2.991889
107	25.04074	-4.800236
108	69.86486	-1.310048
109	3.861557	-20.77006
110	-47.64537	-43.58043
111	-25.36348	-70.21346
112	6.089345	34.71246
113	59.83757	-25.74778
114	-47.02845	-37.44006
115	82.67460	53.93633
116	-41.67496	27.40212
117	-34.09457	16.86770
118	15.00264	83.97359
119	55.07938	0.9634631
120	0.1579204	46.07728
121	85.21925	-80.38105
122	55.91992	-1.266822
123	48.46642	-61.51106
124	83.44996	40.35312
125	-72.39708	-90.15794
126	63.39230	92.60332
127	-51.18825	-17.98028
128	-79.97451	15.91861
129	-23.59191	-8.896727
130	-81.32685	-72.82025
131	-33.49405	-40.66143
132	85.97615	-32.91447
133	17.82102	73.49918
134	32.06879	32.98196
135	68.50439	45.91924
136	6.373319	16.58216
137	-10.01762	56.63755
138	-17.70133	9.348784
139	-64.87341	21.91620
140	92.09223	-62.95635
141	73.35461	-14.35373
142	42.42979	26.79215
143	76.68171	70.80169
144	39.71835	-37.02900
145	89.38387	98.37453
146	93.05111	79.94445
147	-31.51788	-23.86883
148	-66.35084	-14.56361
149	29.33764	-62.27735
150	-24.11523	65.03127
151	-0.1981764	85.14367
152	-64.96088	24.28689
153	-70.35265	-3.404835
154	53.58386	8.043960
155	30.15471	14.50379
156	92.32211	-44.86926
157	-49.99742	-89.42696
158	-90.06380	73.98988
159	91.74607	42.31367
160	12.60600	-39.94253
161	84.11138	92.56448

162	-86.70304	-53.23400
163	-85.97856	8.434690
164	-41.33817	36.81072
165	17.09929	-27.85563
166	12.34519	-47.21033
167	7.488985	10.96826
168	-32.37500	-92.74950
169	-60.95454	67.04987
170	48.25573	-24.41212
171	-90.78663	-10.72169
172	98.59686	18.66405
173	-10.15970	61.60979
174	64.25436	17.01916
175	82.35587	95.34316
176	-31.81723	-91.39290
177	-42.48454	-91.11927
178	89.82289	97.69595
179	51.88569	77.52116
180	77.56353	18.58028
181	-30.27779	-96.74651
182	-84.19831	-20.28553
183	-16.84587	18.01714
184	-80.96613	27.15279
185	-55.51774	-98.14139
186	-11.33073	48.45752
187	-75.11525	50.14763
188	-52.90534	37.96066
189	-72.48392	13.28897
190	37.46142	4.001034
191	-76.06505	24.07045
192	-23.20760	-10.43826
193	9.433523	79.95885
194	-47.47448	66.79623
195	-23.37425	-53.38947
196	-80.45424	-82.22874
197	17.56927	35.22942
198	-79.73206	-17.93806
199	-68.73298	-25.12269
200	-61.15471	-5.102358
201	-51.18183	-13.39740
202	92.23962	-47.75650
203	43.82804	-27.49528
204	2.153697	-29.98992
205	-52.40417	-81.72638
206	26.29721	48.95831
207	-12.17272	-67.67731
208	47.55111	-35.76992
209	-27.89612	-66.14599
210	44.70148	36.89864
211	92.45618	2.068285
212	-93.43907	61.34296
213	-72.35013	0.2276335
214	-31.47207	83.42844
215	-89.80786	-90.34339
216	-61.19734	94.99088
217	-88.28315	2.031107
218	-99.71101	28.60721

219	-63.62655	7.005361
220	57.04184	63.56851
221	83.56161	-47.77819
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225	-48.99481	79.15227
226	27.06001	57.45941
227	-79.54398	-57.41576
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230	-47.27848	-17.63113
231	24.51188	-24.94162
232	-37.19671	-25.38174
233	85.98952	-24.25583
234	-42.50192	-41.38750
235	39.45436	52.41736
236	-84.92107	-44.05388
237	-41.80114	-3.824295
238	-98.08675	8.289326
239	-74.41536	-89.42150
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241	-22.27962	-51.81377
242	-93.81091	60.43696
243	67.37876	-58.66962
244	-29.85046	82.24099
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252	-7.316922	18.88985
253	40.49543	-79.95694
254	-45.51737	-37.33664
255	47.06851	71.19533
256	98.52452	-10.18654
257	90.32093	32.04577
258	-57.88418	-2.625196
259	98.19171	-94.57751
260	89.11060	24.81782
261	68.70069	-83.72851
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268	-27.19459	-28.60824
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270	76.72252	-47.24354
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273	-18.44407	12.14433
274	-33.36578	29.27078
275	-20.63842	20.54648

276	-46.79876	6.201913
277	40.26979	-8.814388
278	95.93179	92.83168
279	-8.038137	-96.73111
280	74.94247	89.21883
281	-48.61114	82.14065
282	93.82946	92.76021
283	23.14598	-31.24311
284	83.97359	70.58659
285	41.39723	48.51902
286	-49.83131	8.403664
287	-14.14610	-89.91658
288	-59.46608	22.56811
289	-59.00639	61.65930
290	30.81827	55.41672
291	-20.72381	74.43893
292	38.06455	-82.14548
293	-71.41331	-21.30872
294	53.18509	47.98082
295	-76.21886	5.554016
296	98.12064	77.33080
297	-23.87900	-49.76169
298	-7.130575	-7.236246
299	72.71832	-54.11558
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301	-32.96255	-2.879984
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303	-43.09771	55.38588
304	64.93967	18.39270
305	32.14375	97.45801
306	-26.81299	-75.59420
307	36.06702	34.53379
308	53.58987	93.74258
309	-34.28328	13.23314
310	-6.251002	12.97319
311	30.38112	-48.07068
312	-33.57539	3.950316
313	69.95295	-16.28298
314	40.83173	-53.18718
315	-25.69859	92.91637
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317	-55.09395	40.49751
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321	-74.54642	-23.88004
322	-75.90996	-5.364175
323	-34.99920	-50.49581
324	-68.14790	-8.700546
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326	85.73227	-63.39453
327	29.91543	10.52465
328	83.11297	19.43169
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330	9.588634	-78.07074
331	34.75977	-66.12986
332	36.34688	95.47268

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335   -87.58012   -25.53018
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337   -93.48734   31.72903
338   -59.92440   61.64181
339   48.05783    -11.71047
340   -66.94113   76.43507
341   6.558805    11.91090
342   -22.87281   -89.80691
343   46.81190    92.90484
344   -20.87385   -57.55829
345   87.19856    51.17615
346   64.03612    20.55710
347   -11.74319   -46.70214
348   25.72164    -80.25230
349   -42.15350   66.39581
350   -56.31641   14.00872
351   -15.39655   -49.66162
352   76.66413    -98.97729
353   -24.24827   95.45547
354   56.98751    -12.65170
355   -85.25562   -68.58602
356   62.15446    21.91638
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DEMAND_SECTION
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DEPOT_SECTION
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SEGMENT_LENGTH: 10
SCENARIOS: 10
SCENARIO_DETAIL:
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NAME: N360_SL10_rand_5
TYPE: CVRP
COMMENT: 1000000
DIMENSION: 361
CAPACITY: 120
VEHICLES: 3
EDGE_WEIGHT_TYPE: FUNCTION
EDGE_WEIGHT_FORMAT: EUC_2D
NODE_COORD_TYPE: TWOD_COORDS
NODE_COORD_SECTION
1      -28.94414   59.24018
2      -76.91595   79.60729
3      -44.54351   51.57206
4      5.143857    -97.63683
5      30.90898    -86.49055
6      -31.52719   -56.10341
7      67.65268    98.98907
8      0.6137124   87.84351
9      -94.36753   66.52258
10     22.15058    -27.54118
11     -96.21717   -27.70430
12     25.07709    69.59238
13     -58.30869   -60.01229
14     -73.93854   -5.574842
15     -5.772204   -43.88609
16     94.79893    -26.60571
17     28.57155    -89.27337
18     -44.53510   -3.108998
19     59.92169    18.98377
20     70.34251    -5.373818
21     41.39436    30.36210
22     -39.73560   -86.12353
23     50.65531    12.05071
24     -70.46206   70.48311
25     -46.93352   -3.299844
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27     -17.05157   68.79354
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228	48.99152	-17.77941
229	69.48732	-70.61076
230	41.14218	-83.13598
231	3.477674	-3.483382
232	29.28316	-75.78387
233	80.14417	-95.71122
234	34.65020	-34.28705
235	8.331594	-63.82437
236	51.11064	-34.30058
237	36.68334	-21.64714
238	73.94795	-78.62006
239	52.47402	-72.30900
240	80.45209	-27.88389
241	16.48629	65.61912
242	-15.79884	1.487075
243	-81.58626	-26.76751
244	-95.19453	-54.67206
245	-1.770839	6.966342
246	-44.34660	-42.10303
247	-32.04857	-86.32582
248	-42.53008	-83.00585
249	-65.81935	-86.33211
250	-20.14734	-18.03670
251	39.52991	-75.32372
252	-59.26471	-11.39668
253	33.26530	79.78795
254	-11.38678	-29.27220
255	-13.34095	-75.96438
256	-64.95211	13.82221
257	-61.35954	75.00655
258	23.28427	-30.28500
259	-46.19788	-91.61580
260	11.93559	-71.53206
261	88.95679	-84.68143
262	42.89433	48.10532
263	35.84393	-8.694975
264	91.87611	33.64986
265	55.06686	39.84922
266	21.54539	14.27144
267	89.60047	25.73867
268	-88.07168	75.55279
269	-46.25753	32.47035
270	97.33601	75.08273
271	54.44135	-6.496596
272	-4.929140	-71.73280
273	36.17991	-86.37311
274	-16.61305	42.84848
275	-23.97016	-38.40279

276	-57.34592	34.23280
277	-23.41240	30.48417
278	-94.06645	6.209768
279	-5.535787	43.02141
280	-33.32546	0.9621246
281	95.16896	-2.400128
282	11.08871	-0.4323382
283	69.26073	87.19511
284	-18.38730	-22.14366
285	-7.596367	-76.57097
286	65.26134	-51.91529
287	98.24064	36.98170
288	4.789530	67.85072
289	85.08738	94.02892
290	47.80437	-56.96608
291	13.48601	52.06867
292	93.75553	16.82057
293	64.89989	-19.40969
294	91.92185	2.008068
295	29.26921	-0.8711562
296	-24.08530	30.27367
297	-4.685064	48.74123
298	82.37796	-39.60931
299	-97.02923	-82.07761
300	-68.66123	65.19310
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303	-88.06179	-64.12618
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305	77.92706	81.03167
306	-78.07348	75.27020
307	-12.44538	99.95851
308	-43.95398	72.85094
309	97.04926	-92.62450
310	21.75174	8.936488
311	-49.25016	99.52324
312	-73.47706	2.201631
313	9.000978	74.70244
314	65.56078	-85.95570
315	67.40125	97.50774
316	66.66973	84.54269
317	-59.25691	12.85218
318	8.883540	-13.70759
319	74.98854	-32.43109
320	-75.79998	44.14468
321	71.27016	-97.26889
322	79.95520	-25.18796
323	-56.42698	84.53704
324	-84.60418	9.295930
325	-5.156968	-5.222626
326	67.00549	-0.6925363
327	-6.121300	-38.20578
328	-17.24601	90.16751
329	0.5492527	96.39866
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331	-73.54294	98.51797
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338   44.44193    5.949139
339   -32.20017   65.81615
340   -19.75603   2.374886
341   5.395950    10.39237
342   78.84715    -57.34302
343   55.67213    17.56413
344   -86.12648   -71.44736
345   -44.24310   -89.55530
346   -24.12603   36.66158
347   72.93451    21.71189
348   -16.00793   -56.06881
349   -52.02451   -18.74401
350   19.53090    25.98159
351   -4.119119   11.06153
352   79.70950    -74.48418
353   86.94185    -66.16033
354   63.57737    -99.80012
355   41.78180    -16.36751
356   48.64412    -2.302864
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359   -32.81776   -96.41592
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2     1
3     1
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DEPOT_SECTION
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SEGMENT_LENGTH: 10
SCENARIOS: 10
SCENARIO_DETAIL:
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2     120   110   130
3     120   130   110
4     110   130   120
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6     110   120   130
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EOF
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NAME: N360_SL10_Rbias_2
TYPE: CVRP
COMMENT: 1000000
DIMENSION: 361
CAPACITY: 120
VEHICLES: 3
EDGE_WEIGHT_TYPE: FUNCTION
EDGE_WEIGHT_FORMAT: EUC_2D
NODE_COORD_TYPE: TWOD_COORDS
NODE_COORD_SECTION
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2      97.58540    20.26161
3      3.091454    21.62762
4      49.38818    97.63345
5      86.27221    59.32358
6      24.28762    30.44036
7      83.42702    96.77029
8      81.35912    89.59698
9      62.89731    19.00255
10     0.2238199   0.1799324
11     37.97239    71.17638
12     90.44057    86.77268
13     68.03516    11.83079
14     37.88231    3.902298
15     63.19547    59.81945
16     24.32695    60.43135
17     57.14131    51.64324
18     98.17287    0.7507404
19     84.96820    68.89333
20     28.34442    94.60204
21     68.24577    87.35365
22     35.81245    11.32765
23     98.69268    35.45694
24     8.398629    24.19368
25     25.03059    56.03333
26     81.13466    61.27271
27     8.442310    30.08091
28     53.12540    79.81417
29     80.06230    79.56416
30     73.88232    78.10923
31     14.16630    35.10984
32     43.78942    5.429735
33     35.03804    70.87046
34     47.84975    99.29285
35     58.74034    16.24765
36     14.58057    11.35663
37     90.53306    91.28754
38     64.01942    48.16570
39     16.29396    85.18060
40     56.59106    80.99138
41     93.16161    18.67595
42     78.31019    24.71999
43     68.56871    5.418884
44     46.62193    60.89614
45     26.03181    77.72324
46     56.92682    51.10641
47     24.87707    2.775009
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52	92.58098	62.56364
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54	51.75412	75.09854
55	62.70053	15.35188
56	91.31824	35.67872
57	66.39683	14.39508
58	38.91928	85.06077
59	74.00076	33.78698
60	81.76349	27.51965
61	60.03448	0.6010973
62	8.499706	80.19120
63	92.23580	49.74083
64	5.359782	53.78428
65	52.70250	87.09126
66	11.88533	72.28436
67	38.01430	66.80859
68	81.28326	17.88278
69	24.40959	55.04953
70	88.44227	95.98751
71	71.26468	59.60217
72	37.81484	80.85707
73	24.89196	98.45323
74	25.28537	88.59245
75	76.72436	21.38370
76	4.986188	3.463006
77	68.52885	45.11238
78	62.02781	1.379456
79	74.66846	47.37107
80	97.72556	95.11971
81	38.39135	24.89523
82	26.02056	38.64228
83	87.74696	43.14334
84	80.60960	83.08865
85	46.11211	82.46468
86	9.096169	45.29986
87	56.42688	38.05602
88	18.73829	92.58685
89	53.16896	74.08437
90	35.50333	73.76331
91	31.47835	94.69160
92	72.67415	51.00997
93	51.57729	79.18792
94	79.06449	45.21735
95	20.44926	84.91987
96	67.81061	39.04308
97	5.248554	73.83765
98	80.11723	97.64385
99	67.85686	52.32991
100	94.60089	42.99153
101	9.155814	20.71581
102	90.84383	32.34014
103	50.99530	11.08702
104	61.49036	37.52100

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106	7.748748	34.21052
107	85.06141	81.71188
108	14.45269	53.16853
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110	62.23914	77.43097
111	99.75519	12.02628
112	51.73441	62.54501
113	99.05112	34.66487
114	22.65345	33.46194
115	39.80052	57.46165
116	69.65687	86.39376
117	6.464076	19.85631
118	74.76616	67.24509
119	42.04004	90.18314
120	81.13174	19.91572
121	37.96053	-29.82841
122	31.90678	-49.65203
123	98.60511	-88.99043
124	71.81809	-50.14146
125	41.31834	-27.69952
126	9.863024	-53.39582
127	73.45591	-57.42496
128	63.73063	-41.28044
129	7.384188	-1.476366
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131	98.15962	-50.67472
132	49.67994	-38.12661
133	2.241365	-6.493154
134	5.383155	-35.85800
135	14.08738	-23.42513
136	89.34743	-20.35040
137	46.58201	-81.37796
138	56.08567	-39.34346
139	49.44563	-5.357517
140	6.778549	-37.50516
141	89.76466	-77.49942
142	28.85653	-16.52976
143	26.90468	-91.22189
144	59.41942	-31.92058
145	47.58790	-32.97797
146	36.83110	-20.42357
147	65.56111	-76.72147
148	93.82004	-6.997315
149	62.04252	-95.00340
150	28.28401	-15.82098
151	20.51813	-28.64459
152	43.91341	-68.71291
153	2.725022	-14.11498
154	87.61843	-51.20866
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156	20.35924	-92.88451
157	51.99168	-73.21039
158	5.382430	-74.98480
159	86.21874	-40.73196
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161	54.80091	-52.08505

162	56.68608	-21.90774
163	68.03950	-84.23879
164	37.13786	-66.29329
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166	45.63507	-79.38776
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169	3.800153	-68.75793
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173	51.33640	-70.60847
174	24.09048	-59.53364
175	25.99653	-75.28741
176	75.89742	-49.67222
177	99.33427	-86.51327
178	35.67057	-6.802769
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180	11.00485	-9.875631
181	59.70452	-54.69771
182	43.05952	-40.29699
183	73.07180	-10.70402
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185	9.480768	-61.36824
186	45.09635	-78.29682
187	64.00745	-56.66206
188	13.20388	-81.13191
189	45.28224	-57.67759
190	65.21996	-94.40292
191	82.69984	-87.14522
192	30.80769	-50.76022
193	40.23636	-78.88232
194	88.42313	-47.30306
195	70.05795	-82.88017
196	24.18723	-32.24816
197	75.98318	-97.61465
198	29.09257	-27.82110
199	27.74387	-7.283081
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203	30.42985	-32.70243
204	29.08603	-80.40693
205	24.25163	-53.82504
206	93.66836	-46.32949
207	86.01903	-82.07503
208	39.72283	-95.19065
209	47.94191	-7.627289
210	56.49961	-70.86710
211	48.96194	-23.49265
212	26.98116	-39.88956
213	98.97401	-26.81244
214	18.36757	-83.25134
215	86.16567	-99.53738
216	3.263257	-64.97510
217	33.19580	-70.39529
218	74.87470	-93.23032

219	64.43665	-68.76525
220	16.92380	-56.83539
221	95.22051	-38.08475
222	54.32702	-63.45795
223	25.14135	-36.32286
224	57.85723	-40.76194
225	91.54766	-36.86997
226	89.55965	-46.83987
227	48.25066	-50.34138
228	44.27400	-91.05358
229	31.17550	-20.64310
230	5.531377	-33.86037
231	75.37918	-57.41256
232	13.19475	-48.69324
233	35.59221	-26.22190
234	39.58710	-57.95935
235	88.55212	-87.83277
236	2.123955	-6.095022
237	84.40807	-44.08765
238	28.80706	-8.425800
239	25.03429	-56.32376
240	48.83796	-53.93106
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242	-53.38195	29.13173
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266	96.23514	16.55624
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269	-32.45760	15.01565
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271	-36.43892	61.87546
272	96.88968	21.76167
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286	71.94341	41.62268
287	35.54498	71.87557
288	61.16765	56.21690
289	6.248574	-59.24063
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293	-43.66793	-56.96469
294	-3.819933	-51.22538
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296	-58.34832	-60.42753
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304	-69.49239	71.73820
305	-68.88948	84.09700
306	-82.08612	50.16778
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310	58.04703	0.9100381
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312	-5.480499	40.75935
313	41.71763	-23.33201
314	91.61189	45.73669
315	1.155113	77.45694
316	-38.98938	-88.83034
317	57.96224	-72.35674
318	-52.72261	72.61300
319	-53.13943	-15.65070
320	-7.060120	-17.73717
321	23.87736	91.82827
322	23.06588	50.04906
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324	-75.24129	-53.29684
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332	14.23722	98.99805

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DEPOT_SECTION
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SEGMENT_LENGTH: 10
SCENARIOS: 10
SCENARIO_DETAIL:
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3     120   130   110
4     110   130   120
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9     100   130   130
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EOF
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NAME: N360_SL10_Rbias_3
TYPE: CVRP
COMMENT: 1000000
DIMENSION: 361
CAPACITY: 120
VEHICLES: 3
EDGE_WEIGHT_TYPE: FUNCTION
EDGE_WEIGHT_FORMAT: EUC_2D
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NODE_COORD_SECTION
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4      74.36749    16.53922
5      38.51023    18.16035
6      25.15038    69.14365
7      3.675974    21.37635
8      47.21229    29.81049
9      64.50723    76.83351
10     27.89699    50.11501
11     51.78609    90.94648
12     24.56666    5.785290
13     29.75082    43.67519
14     65.04741    57.22548
15     89.13933    56.50672
16     86.11065    82.38166
17     20.99151    12.60988
18     39.90939    30.01168
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21     96.68016    76.62994
22     61.91574    75.13042
23     16.53458    13.88648
24     82.61990    34.93195
25     65.56931    15.13406
26     54.64526    49.67207
27     25.13293    80.86523
28     4.015638    63.28688
29     23.33754    68.84015
30     36.11129    63.95702
31     63.34550    72.93217
32     98.60981    85.98457
33     20.71566    62.69554
34     75.70840    18.05914
35     88.63281    57.33065
36     47.22298    16.35662
37     15.89135    90.60517
38     81.09208    7.734279
39     47.65078    33.85347
40     11.62875    58.06176
41     87.57206    47.52352
42     63.51864    80.53205
43     9.728135    53.07781
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47     98.85679    65.81161
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254	32.32375	-44.40395
255	-39.81212	-17.74204
256	92.59781	-1.853678
257	-59.86602	-72.64223
258	80.32657	-96.41964
259	-66.62382	-39.49199
260	-74.06832	-69.65680
261	4.903010	-98.03584
262	-85.64982	-95.92858
263	25.16872	-41.38806
264	9.672654	35.31710
265	50.34702	70.73442
266	48.15259	90.34589
267	-4.169149	73.60027
268	-89.74461	76.84475
269	-29.95955	-34.58693
270	67.13505	-38.67697
271	-25.52180	-82.04284
272	-87.18800	28.25416
273	-64.15380	-66.00247
274	-13.14088	60.80354
275	53.25395	83.98496

276	29.82331	37.97807
277	95.94556	45.65219
278	27.34927	31.11902
279	20.36537	-3.443671
280	-69.21987	19.99442
281	4.044821	-23.90123
282	-16.13300	-87.85163
283	68.08015	91.83066
284	29.20776	84.68954
285	-36.86697	-17.21496
286	-78.72730	92.79886
287	-1.458043	-71.96941
288	13.77064	0.1210627
289	42.14722	-98.38152
290	-74.05289	-22.73652
291	-94.91434	-55.04839
292	76.30041	14.78299
293	70.46526	92.44978
294	27.62994	25.19372
295	-73.51602	98.04559
296	-34.90769	-55.21437
297	19.37841	-93.90636
298	-45.92237	-22.04467
299	42.75388	86.84311
300	-8.814700	75.08199
301	-16.52480	54.56045
302	-70.48303	30.92588
303	78.50707	85.98432
304	-93.54767	-99.52640
305	39.53084	-27.20989
306	-25.87799	15.03019
307	-25.82977	-27.45586
308	62.93642	-42.64463
309	80.63953	-47.93845
310	-15.72494	47.62862
311	-26.39213	39.99115
312	-60.80080	1.410097
313	-14.32224	-40.21723
314	-59.59547	93.99319
315	-65.82615	27.44009
316	57.76899	18.17952
317	-60.42128	-86.23915
318	-5.855146	-82.19633
319	61.38641	-78.36155
320	43.29557	71.87838
321	29.88747	54.18061
322	22.74945	-11.43659
323	-88.54335	5.109086
324	-9.871246	85.14777
325	23.91768	22.29067
326	67.40070	36.54687
327	-68.10927	33.47865
328	94.01624	-89.92242
329	13.28659	81.38765
330	-34.14351	-38.35073
331	57.07685	69.57608
332	30.81582	46.88505

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333   9.310188    25.40160
334   -16.86540   -84.29690
335   93.38103    -44.67984
336   -42.20572   -51.26245
337   -94.25414   9.428828
338   49.03510    -95.93565
339   -81.30550   -75.79099
340   37.81099    86.34944
341   -42.01480   -66.14139
342   -27.52801   61.03160
343   -79.95563   -83.13159
344   -71.41220   81.80798
345   19.31124    -27.02903
346   -9.192468   -94.09098
347   -93.38138   84.08418
348   -69.55608   -8.506663
349   93.51727    -89.03838
350   46.39545    57.31430
351   63.32570    60.15489
352   38.80495    -40.61201
353   -80.40082   -65.81897
354   -55.39678   1.098704
355   95.30092    53.95842
356   -55.94289   -50.38184
357   1.958076    -13.80750
358   45.52288    -29.75595
359   36.33612    20.70955
360   83.60043    -36.37356
DEMAND_SECTION
1     1
2     1
3     1
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358   1
359   1
360   1
DEPOT_SECTION
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-1
SEGMENT_LENGTH: 10
SCENARIOS: 10
SCENARIO_DETAIL:
1     120   120   120
2     120   110   130
3     120   130   110
4     110   130   120
5     130   110   120
6     110   120   130
7     130   120   110
8     130   100   130
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EOF
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NAME: N360_SL10_Rbias_5
TYPE: CVRP
COMMENT: 1000000
DIMENSION: 361
CAPACITY: 120
VEHICLES: 3
EDGE_WEIGHT_TYPE: FUNCTION
EDGE_WEIGHT_FORMAT: EUC_2D
NODE_COORD_TYPE: TWOD_COORDS
NODE_COORD_SECTION
1      3.693174    65.22102
2      12.53068    83.46672
3      19.72295    42.36541
4      93.88319    88.61168
5      80.11951    36.81492
6      48.24640    49.58979
7      79.82236    16.57441
8      8.441772    65.35954
9      37.10465    28.22268
10     93.38249    22.04766
11     46.58433    57.72728
12     10.66552    71.66782
13     49.62490    29.80020
14     87.16277    84.79850
15     72.87608    79.53344
16     45.04095    50.75349
17     29.69020    92.85162
18     55.26372    86.22250
19     96.52164    36.66213
20     25.66827    77.78872
21     45.92260    40.24149
22     25.29367    94.00990
23     30.31590    62.41499
24     2.077050    16.65434
25     76.61926    92.34446
26     57.63497    47.89514
27     96.60646    74.31355
28     69.47844    54.13540
29     67.16713    55.22782
30     1.365187    58.32777
31     26.00654    6.261882
32     47.45825    46.93204
33     50.37335    47.52756
34     18.64256    55.56093
35     14.36747    31.35035
36     30.86059    30.87671
37     81.52583    38.25440
38     24.84219    85.51016
39     0.1321818   85.45761
40     38.27129    4.701408
41     71.65933    5.357658
42     0.05333265  66.97615
43     13.44786    73.28609
44     88.76240    57.90161
45     60.78329    49.29707
46     49.32210    44.33127
47     31.10895    57.56499
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48	98.53486	82.82607
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54	20.41525	20.00151
55	29.99108	97.84569
56	1.600656	31.91093
57	8.196033	53.61479
58	93.37204	81.96127
59	17.37637	3.234645
60	79.89794	69.29470
61	73.23530	3.516552
62	61.66229	76.21692
63	39.07028	55.98626
64	40.43836	82.38146
65	34.17589	93.48043
66	2.920247	11.75309
67	21.90077	90.82079
68	83.47937	0.7532253
69	5.377164	98.20734
70	50.77118	4.956087
71	78.30669	15.76029
72	97.31073	89.67884
73	12.83119	60.28922
74	28.00509	90.70903
75	5.274328	89.64942
76	39.89201	38.21560
77	51.32383	5.425887
78	98.00252	78.41403
79	99.81419	87.18874
80	98.56321	21.72269
81	94.24414	62.24405
82	20.75435	96.36739
83	39.07690	62.87573
84	66.16791	60.46888
85	32.66101	8.428264
86	67.93967	78.15014
87	71.84602	66.45140
88	37.41978	70.23481
89	4.171658	57.51369
90	31.91764	20.67130
91	23.85141	36.57860
92	48.71384	85.91735
93	51.09293	90.57127
94	9.924737	9.660517
95	91.73389	37.64818
96	28.92132	77.34607
97	6.413306	83.55153
98	77.27571	70.55213
99	85.50469	77.97169
100	12.24642	33.71323
101	14.63347	81.80290
102	42.46992	74.83726
103	30.83824	31.02363
104	91.82702	98.97739

105	85.00578	30.46024
106	43.65514	86.39286
107	55.37026	56.47917
108	20.94187	55.72761
109	23.04242	43.69839
110	84.54787	21.07792
111	4.662736	50.54809
112	82.30179	97.15681
113	94.97723	83.49603
114	72.59208	60.65033
115	33.07363	33.14111
116	24.39463	17.66719
117	88.50487	69.86374
118	18.13205	74.39529
119	50.26938	96.05260
120	74.70836	94.43445
121	3.893218	-13.78201
122	55.23331	-33.73033
123	90.01073	-10.88073
124	10.78644	-41.83717
125	96.47095	-75.43540
126	73.40738	-39.85003
127	2.667080	-20.08269
128	81.15484	-99.53230
129	96.36806	-80.61897
130	9.697385	-45.51669
131	34.46012	-66.03290
132	97.29998	-51.93504
133	94.36726	-69.92912
134	69.72619	-11.01519
135	0.08778676	-33.09792
136	47.55744	-18.68129
137	24.86821	-69.73831
138	28.06028	-50.74297
139	45.32713	-97.90646
140	10.74921	-25.98000
141	84.01284	-91.06176
142	73.60751	-3.415890
143	7.426881	-21.42541
144	55.87601	-22.91401
145	97.88502	-30.79554
146	22.76037	-67.36913
147	97.38531	-42.86231
148	49.14758	-37.65877
149	94.26276	-64.00504
150	37.90158	-52.30997
151	81.66790	-9.588895
152	7.896714	-60.85367
153	23.04673	-26.41189
154	17.42454	-26.60684
155	99.03294	-44.81728
156	91.85238	-79.44330
157	39.58489	-70.67477
158	64.10680	-39.11610
159	38.29198	-31.14926
160	23.33476	-44.58682
161	64.37099	-14.70326

162	75.32015	-42.87780
163	20.56563	-31.12572
164	92.05051	-81.83931
165	33.74429	-84.40234
166	25.12699	-93.03021
167	47.81702	-22.42007
168	74.58263	-90.76009
169	54.17833	-68.97194
170	65.63883	-26.42263
171	59.03748	-40.27639
172	31.91282	-21.94414
173	26.05199	-84.31078
174	9.069711	-63.67085
175	97.60160	-14.58666
176	7.004617	-74.39791
177	33.21286	-86.43901
178	35.29563	-84.84131
179	41.24214	-82.01340
180	23.74234	-49.46952
181	12.96170	-41.75023
182	5.850444	-94.02257
183	18.70294	-57.81414
184	16.67147	-83.22124
185	97.16926	-65.55706
186	15.37239	-94.62787
187	16.90204	-69.71657
188	53.13284	-22.64999
189	69.12182	-9.728058
190	26.03100	-67.81059
191	95.72418	-5.943171
192	74.48946	-75.61989
193	47.53881	-3.366709
194	55.83599	-15.49979
195	56.61848	-80.22906
196	19.96951	-95.14033
197	76.72091	-85.41640
198	96.39670	-17.07236
199	85.31412	-38.89431
200	70.27675	-91.25731
201	98.61837	-33.65011
202	18.84668	-15.22146
203	30.76735	-50.18920
204	68.50208	-62.22789
205	36.03433	-30.75661
206	19.65698	-95.94187
207	94.69186	-65.16708
208	36.06281	-86.13529
209	36.31440	-47.27665
210	68.90316	-41.37080
211	43.70543	-13.73760
212	71.87720	-37.60412
213	67.01665	-31.29654
214	61.50138	-63.75137
215	35.68452	-10.40338
216	74.74142	-76.61919
217	58.26713	-52.10616
218	40.42651	-81.03390

219	61.84644	-98.47036
220	63.95093	-88.94212
221	2.011735	-84.48705
222	74.33743	-0.8864935
223	87.54485	-33.99046
224	12.54970	-72.83411
225	11.72688	-92.82195
226	16.83330	-39.22080
227	45.83137	-28.27488
228	60.33362	-43.92990
229	39.49952	-64.61546
230	90.92171	-10.18062
231	10.21037	-88.91806
232	12.38650	-80.85024
233	86.70856	-18.74436
234	50.44008	-6.343576
235	85.97804	-11.94587
236	67.58082	-37.64250
237	86.97109	-5.721368
238	67.22437	-33.25130
239	27.05903	-38.57314
240	68.25275	-58.57361
241	77.02297	-89.09825
242	-10.51088	97.50013
243	-88.82052	-59.99891
244	31.80560	35.17087
245	-97.33866	-25.59221
246	14.48627	-65.98274
247	-55.15345	32.81556
248	-74.41171	-44.01618
249	-68.73238	83.29793
250	-33.11353	43.11159
251	-30.47441	40.95126
252	20.28404	-41.42830
253	35.48848	80.79060
254	70.96568	53.36907
255	-46.11007	-21.35527
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257	-72.14214	-92.40809
258	98.09011	-46.71556
259	88.00276	-98.70196
260	-75.58428	41.82999
261	34.10263	-51.63908
262	-10.37173	-53.98134
263	-99.78542	-11.88659
264	-38.99232	53.33445
265	91.87856	-65.28861
266	-97.08105	24.06893
267	81.91030	59.01745
268	39.20878	-1.313793
269	25.77852	-96.47666
270	85.79516	-8.535744
271	-23.02750	-14.67880
272	67.08415	-89.78967
273	89.52017	1.367348
274	23.35172	-3.840618
275	77.19539	-3.551881

276	-86.79736	-92.68842
277	-39.05290	-22.13017
278	-12.37496	71.72987
279	-34.05478	-72.23478
280	-62.40521	-96.03223
281	-41.79392	-82.52380
282	-86.76979	83.16768
283	-83.19150	11.30469
284	-98.46227	-63.97581
285	-39.61463	83.06229
286	-98.58105	-77.69759
287	-62.32023	91.98283
288	17.57578	-97.96471
289	6.722140	-6.749836
290	-78.74195	-10.27147
291	98.44003	-47.27801
292	57.44088	-59.94645
293	32.31489	51.36396
294	-81.57813	43.86831
295	22.96678	-53.38676
296	77.05966	-11.56522
297	-80.98964	-18.42852
298	21.13885	62.55920
299	-50.60768	70.91702
300	-15.41434	-12.69731
301	36.83114	58.72333
302	-82.46940	14.12065
303	-97.76660	57.07059
304	-24.50584	46.34564
305	21.27855	52.45921
306	-78.18530	87.28841
307	41.63752	18.52074
308	79.68547	66.13056
309	-80.32035	-95.88116
310	-48.49358	-98.64448
311	-3.889525	51.37729
312	1.131313	-64.88860
313	-4.874434	32.48169
314	-21.22562	-0.8607270
315	-90.57503	58.30759
316	32.39082	91.44028
317	95.94196	-0.5370903
318	15.17841	-14.47455
319	59.41482	-9.368243
320	-31.01243	-78.77878
321	-5.163551	84.24940
322	17.57131	85.62763
323	-56.86321	21.28301
324	-51.79858	-33.14759
325	37.26793	-22.64099
326	4.714975	94.46205
327	-43.37735	46.47869
328	-36.90710	-83.31474
329	93.47852	-49.38853
330	-2.598077	-49.64955
331	-51.44746	61.50843
332	28.23077	-92.80440

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333   35.63039    72.81892
334   46.77469    -71.29237
335   -36.16468   9.374928
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337   83.36885    -87.94728
338   -90.68606   79.03645
339   -92.88530   -68.70472
340   0.7580587   43.68170
341   40.58731    4.786241
342   1.224277    62.40913
343   -90.56461   -29.12238
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345   49.64035    54.70131
346   64.16336    -34.36410
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348   92.30367    -91.74883
349   -55.21247   85.18786
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353   -57.28822   96.93443
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DEMAND_SECTION
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2     1
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359   1
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DEPOT_SECTION
0.00000      0.00000
-1
SEGMENT_LENGTH: 10
SCENARIOS: 10
SCENARIO_DETAIL:
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2     120   110   130
3     120   130   110
4     110   130   120
5     130   110   120
6     110   120   130
7     130   120   110
8     130   100   130
9     100   130   130
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EOF
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NAME: N360_SL10_norm_1
TYPE: CVRP
COMMENT: 1000000
DIMENSION: 361
CAPACITY: 120
VEHICLES: 3
EDGE_WEIGHT_TYPE: FUNCTION
EDGE_WEIGHT_FORMAT: EUC_2D
NODE_COORD_TYPE: TWOD_COORDS
NODE_COORD_SECTION
1      -1.066750   -21.45350
2      9.336839    -6.735276
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4      -38.87342   -26.80228
5      4.228099    -17.76065
6      7.209219    -46.23550
7      43.89378    -55.76428
8      -9.264471   29.32879
9      -12.39773   -20.45034
10     -3.080351   -57.21335
11     -11.92776   26.68585
12     29.64108    30.54859
13     1.360248    13.78919
14     -63.54087   -15.48323
15     -43.71671   -12.16139
16     -39.03626   17.17640
17     -16.67978   -4.546427
18     -29.59559   9.086218
19     -36.18882   20.83972
20     -1.685906   9.303432
21     -53.13086   48.11222
22     19.59787    10.76360
23     6.489056    -38.89964
24     -30.14357   -3.073093
25     6.877055    -19.73268
26     18.78460    -1.446490
27     -31.98943   -25.51725
28     -14.44533   -0.1517255
29     -6.761243   6.275863
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31     -17.52429   -6.555092
32     -21.00996   -7.384506
33     -58.43131   11.70740
34     3.201117    45.62759
35     -12.23219   1.484570
36     -8.372419   49.23772
37     -56.22476   -14.47602
38     -10.85775   34.43987
39     47.73875    50.40984
40     -33.30070   35.91572
41     28.97753    2.219893
42     -63.44578   4.452529
43     20.33137    -9.509494
44     40.37987    -4.443314
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46     14.43293    9.862420
47     7.046501    -29.13680
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52    8.324578    23.40706
53    1.839724    16.95839
54    -53.61329   -18.22591
55    20.21568    -1.647401
56    33.30738    5.714078
57    42.07775    -17.44339
58    15.25945    -18.08100
59    -17.00498   14.00901
60    25.58104    -25.53034
61    -1.514972   34.09547
62    -7.883694   81.44688
63    -40.55070   -22.97000
64    -4.576085   11.01488
65    17.92328    58.02214
66    -8.885828   -21.65941
67    -0.5616525  -24.84522
68    -37.60278   8.082146
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254	7.774665	58.80999
255	-25.01871	14.35846
256	-3.481864	-50.11630
257	23.29740	-4.800802
258	-25.40760	22.56732
259	-12.25974	-37.31043
260	8.213730	-23.10121
261	-18.98675	31.87850
262	51.62049	-48.93916
263	-19.60005	-16.23821
264	4.960182	54.64902
265	-5.420973	41.34744
266	-54.74945	-24.41473
267	17.30212	35.79498
268	11.47128	-5.895688
269	17.39565	-17.99615
270	-44.90495	-39.93238
271	-10.78161	16.14209
272	40.10112	24.86850
273	15.01517	-15.16667
274	4.657844	0.4923361
275	-62.36141	-3.960745

276	32.23056	9.187054
277	-6.571157	39.34061
278	14.34394	26.19643
279	10.68325	74.82487
280	11.66352	41.16040
281	-14.89408	-9.622825
282	-13.09316	5.930722
283	16.74615	-7.154249
284	26.20871	34.06694
285	-1.308714	5.980169
286	-8.628078	46.46138
287	12.11460	68.75999
288	-16.01960	32.04633
289	18.21257	11.89585
290	24.46374	23.65300
291	-6.192603	-20.60338
292	-19.60900	12.18714
293	7.607701	-1.227039
294	-3.483982	-25.10595
295	-16.01559	-37.58624
296	-28.42628	-6.524286
297	10.31745	40.82078
298	-38.72060	-23.20251
299	69.89815	-28.90993
300	-35.35384	-30.90030
301	-0.6136580	-16.65168
302	-38.62498	39.59890
303	-25.79942	14.63196
304	-59.44057	21.79469
305	22.00609	-30.49017
306	44.94803	-10.49190
307	-5.114318	7.278430
308	0.6053975	-2.770835
309	-3.948815	12.37528
310	-27.88083	34.20437
311	6.359681	33.04488
312	-7.139561	59.99960
313	33.33997	-3.451554
314	-8.511277	19.26521
315	-71.84624	33.44693
316	-5.447106	8.022609
317	1.940839	5.548323
318	24.20844	23.23640
319	13.08236	-28.40947
320	-58.63282	-27.32957
321	25.20713	-22.83820
322	-23.13475	-42.59329
323	-27.89894	9.964978
324	-29.63045	5.597673
325	35.22388	12.03855
326	-27.02354	39.17275
327	21.90351	7.523195
328	-72.18977	-2.382939
329	-43.54886	5.133258
330	-37.27194	28.53502
331	-3.327556	31.60318
332	-33.58607	47.94522

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333   45.54512    27.72562
334   10.84232    43.02013
335   11.11094    -13.47239
336   -1.512902   40.27179
337   6.856861    -17.78889
338   -33.74322   41.14567
339   40.54741    36.07437
340   -37.83598   -10.17191
341   -4.516546   -29.83484
342   3.132956    -18.79408
343   -32.16103   -7.436952
344   -49.26471   12.77053
345   6.351770    -20.91131
346   -6.472490   42.81154
347   21.90575    -21.09548
348   31.78346    -4.241395
349   -23.85536   33.57891
350   59.90318    17.46680
351   -6.902666   45.40066
352   7.070451    -50.09706
353   30.78891    7.340656
354   40.62471    8.701442
355   -34.52553   34.33706
356   1.262530    21.61631
357   -43.24789   -11.22266
358   45.58397    17.76174
359   -10.14633   47.39017
360   47.01164    56.52042
DEMAND_SECTION
1     1
2     1
3     1
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358   1
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DEPOT_SECTION
0.00000      0.00000
-1
SEGMENT_LENGTH: 10
SCENARIOS: 10
SCENARIO_DETAIL:
1     120   120   120
2     120   110   130
3     120   130   110
4     110   130   120
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6     110   120   130
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10    130   130   100
EOF
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NAME: N360_SL10_norm_3
TYPE: CVRP
COMMENT: 1000000
DIMENSION: 361
CAPACITY: 120
VEHICLES: 3
EDGE_WEIGHT_TYPE: FUNCTION
EDGE_WEIGHT_FORMAT: EUC_2D
NODE_COORD_TYPE: TWOD_COORDS
NODE_COORD_SECTION
1     8.320731    18.90029
2     -10.34069   67.00987
3     9.571223    -27.15177
4     -10.04681   -1.920840
5     -8.513481   33.83372
6     2.775505    9.836134
7     2.638900    33.35349
8     6.192736    13.34208
9     -16.04014   7.389061
10    -18.78527   -16.07136
11    13.77050    2.973190
12    3.295140    22.67413
13    19.01979    -7.230750
14    22.51949    41.71447
15    -24.39761   15.18389
16    -37.62226   -45.87569
17    49.01484    18.22097
18    -7.033907   71.81994
19    -58.72932   30.48365
20    8.238957    34.34620
21    4.156148    -64.03850
22    -34.96161   17.01191
23    -49.95157   31.25938
24    2.735431    22.06647
25    -28.03514   26.83150
26    40.42286    -37.70869
27    -10.96236   -7.931613
28    1.477049    -20.38571
29    22.28879    -16.11617
30    -15.84965   -22.50518
31    -12.54732   1.713623
32    11.59050    -0.2146637
33    -62.52510   10.34662
34    2.167959    9.577909
35    0.05021576  -16.19137
36    33.05491    19.62660
37    -14.07574   -21.46509
38    -3.976914   47.00768
39    -10.28525   12.51755
40    -62.79146   -36.60890
41    6.286351    9.079491
42    -17.22894   -15.02086
43    24.05971    10.82318
44    -46.38488   14.19080
45    0.5211311   53.72976
46    12.46049    -0.3947275
47    -34.63788   8.164055
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48	-11.90773	-19.10765
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50	28.59435	-7.033634
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53	-11.59757	26.50624
54	28.00611	-26.70956
55	20.16252	-1.699159
56	17.33791	0.007951755
57	23.95639	58.04634
58	40.69571	6.737952
59	38.58349	-2.869767
60	24.89618	28.98751
61	51.78188	-24.38232
62	-9.205771	-32.61617
63	8.060743	14.87980
64	39.61554	-44.73215
65	-21.30317	-21.94145
66	-16.16781	15.21794
67	-19.06196	24.02745
68	-17.16500	-20.20374
69	-0.7872817	-4.786026
70	-35.12492	40.76240
71	-31.63739	27.31118
72	45.74838	21.32418
73	8.018465	-3.627113
74	4.551014	33.42313
75	42.26487	22.82337
76	-13.32248	19.88640
77	-54.46249	-39.76081
78	-55.72750	-3.008586
79	-29.11084	-29.45109
80	53.13271	-12.68203
81	-12.44833	-12.71841
82	31.04598	24.01159
83	-32.11965	1.969040
84	18.91121	25.19288
85	-16.79473	5.807039
86	-10.87918	3.496835
87	-48.18439	-68.74862
88	4.672538	-20.65565
89	-3.477941	59.01254
90	24.70747	-1.663472
91	27.95123	-20.32647
92	-50.43783	-13.90876
93	51.57150	-56.56086
94	-9.238718	15.17981
95	3.503330	-25.41882
96	-3.258086	-4.033535
97	1.239225	31.98625
98	-15.52647	42.41147
99	5.781043	-51.79514
100	39.33385	46.49532
101	8.046293	28.11278
102	-8.224677	-34.59379
103	-2.919260	-79.60236
104	46.59109	4.636271

105	-10.63637	-39.45071
106	0.4352784	14.96228
107	32.80738	-43.97340
108	18.29165	-28.84577
109	43.42737	2.062116
110	-48.23632	-18.96152
111	15.04362	-2.643921
112	25.21534	-0.8109051
113	-2.761899	15.02189
114	-16.07357	79.00333
115	-35.08117	7.165754
116	-2.796035	15.97047
117	15.44781	-88.69276
118	22.35099	41.62901
119	20.99712	-44.55427
120	-36.67239	-3.945869
121	18.66258	-21.10303
122	-2.130535	-25.49308
123	13.02442	35.21379
124	-6.152743	13.91807
125	-36.74813	26.04578
126	11.24210	-18.12360
127	66.78150	47.31015
128	-3.215570	-46.64562
129	60.53531	-12.55600
130	-37.86457	-15.56194
131	20.28589	-22.44212
132	-3.514097	-24.91339
133	25.55986	54.24979
134	10.82381	13.00843
135	-24.73852	29.12188
136	-12.77133	0.2270217
137	-14.64895	2.222485
138	-29.85546	43.13229
139	31.14263	-13.77970
140	-44.87095	-2.786362
141	3.311005	-13.60384
142	-11.09994	-14.49757
143	-5.988325	-2.412787
144	-56.58526	-12.92869
145	11.27883	-44.49923
146	7.706419	32.47942
147	-21.90152	6.706575
148	6.518291	-21.40989
149	-15.02848	36.92191
150	13.90290	11.01518
151	-4.409552	-42.14403
152	-37.05943	-10.52084
153	11.18145	7.926197
154	16.38196	27.14152
155	-22.61293	-16.48651
156	14.03372	9.671050
157	-1.629598	-41.81746
158	19.03075	-5.100442
159	2.150225	12.75933
160	11.75254	-4.670995
161	20.65779	-1.676951

162	44.73199	-40.10926
163	20.53244	63.09907
164	-3.217680	45.63398
165	40.96727	-30.22660
166	-6.235425	0.7708699
167	38.46720	-6.063389
168	-63.40841	11.97279
169	45.44066	10.85540
170	-3.314503	13.86519
171	-42.73786	-22.08173
172	-20.04241	-40.62222
173	-4.760349	12.28443
174	3.324251	10.15419
175	-20.41340	-2.179888
176	21.63595	44.26950
177	-2.186233	21.37494
178	-19.25503	-36.63305
179	4.271498	31.42733
180	-29.26277	25.10463
181	-48.48053	43.12190
182	23.82850	-5.161331
183	-46.95627	11.44244
184	4.296971	-17.28870
185	24.85402	33.83455
186	16.57429	10.62933
187	-30.63010	-21.41509
188	-22.67970	-9.233140
189	-0.4792514	7.121795
190	2.661645	19.82909
191	-6.210853	-16.03495
192	30.76058	15.08886
193	-49.73623	-5.227088
194	-47.70473	25.31546
195	1.762889	21.67809
196	-57.17019	18.88429
197	26.37310	6.603213
198	7.691036	-10.18155
199	18.61489	-32.59700
200	17.23937	-20.51351
201	-36.72937	-34.65399
202	-0.5649068	35.81760
203	-20.63186	-28.10177
204	24.04908	-3.864860
205	-40.44887	39.57216
206	-15.90053	21.24007
207	61.86085	-36.49447
208	-11.93783	-39.75316
209	8.960140	-33.52403
210	-50.69600	3.023835
211	5.785562	0.3464854
212	-38.79008	-26.90178
213	7.630426	-28.32680
214	15.58813	26.32468
215	14.57595	-14.64496
216	-18.23727	-12.63990
217	24.51427	18.97624
218	-7.852610	-0.7766989

219	-12.42748	-50.32910
220	17.89209	-28.83875
221	46.61580	42.16253
222	-30.72212	-0.5582527
223	4.617915	34.45448
224	-23.16810	18.77825
225	-4.278687	-62.97112
226	-24.56133	-20.83679
227	-52.13309	19.84405
228	-34.73568	-29.18590
229	17.23379	28.55079
230	-70.33733	30.52006
231	-23.08733	14.93590
232	-10.38664	-24.91640
233	0.4906125	54.92231
234	-34.01144	-15.77615
235	21.10329	20.77650
236	32.85153	-39.52287
237	-22.90711	-66.39992
238	-6.713192	37.33700
239	22.13527	16.39801
240	1.008851	9.963943
241	-12.88599	54.62039
242	24.52059	-5.100587
243	-17.74975	-51.11337
244	0.9642696	0.3377534
245	-47.11974	-0.09548991
246	-52.45514	-24.43442
247	-22.47866	11.71142
248	-9.710577	12.87317
249	9.359641	-61.60077
250	27.57732	28.44379
251	-16.88449	6.562114
252	-15.95731	1.729720
253	-4.159907	-9.219189
254	25.80394	33.22061
255	-10.61562	7.764923
256	14.87286	14.65859
257	14.82267	-33.54535
258	-4.176216	8.630769
259	-1.466869	-54.60008
260	-14.17055	22.60874
261	-56.30350	52.76362
262	-58.02715	31.66590
263	52.43574	69.83631
264	15.88975	3.061598
265	13.77922	45.28424
266	-1.872946	-6.620103
267	-26.51031	19.41772
268	26.07434	16.29520
269	6.747728	-17.72193
270	-30.83567	10.24236
271	27.78086	-4.242829
272	-5.382581	16.14556
273	2.171140	28.81557
274	-8.262889	-2.086557
275	-45.45945	-20.18042

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276   11.17630    2.898705
277   34.85382    31.83629
278   12.14365    -6.311126
279   34.03361    -15.52131
280   11.65588    18.12743
281   -57.63447   -26.99446
282   -11.26457   -6.175535
283   -0.7423395  -45.40294
284   22.75462    -2.359443
285   29.43487    -10.23923
286   28.60277    -11.13763
287   -25.22452   -14.94064
288   22.16681    64.21539
289   6.853000    -6.181877
290   -5.150510   29.13207
291   0.9644015   -10.98792
292   -17.01917   -5.416935
293   -5.036179   -19.53048
294   -11.07112   20.98507
295   11.51484    17.72719
296   -6.826102   38.91716
297   10.55581    10.98492
298   24.51035    -3.192100
299   -0.05059677 -20.97694
300   -34.53877   -10.11905
301   -5.981377   35.61744
302   25.48502    40.55596
303   -7.992924   16.92435
304   38.69933    9.160910
305   11.16197    20.91945
306   -19.31165   11.32491
307   -3.933070   -28.09207
308   2.371353    0.5235683
309   16.37266    6.757296
310   -17.21521   28.55469
311   5.035910    -18.75550
312   35.90539    -3.178061
313   7.784024    30.11078
314   3.626219    6.672200
315   -22.61427   -25.35285
316   8.769916    -34.30792
317   3.658468    -3.396490
318   -21.81716   11.79575
319   11.83773    32.68438
320   49.15130    -47.03327
321   -7.780692   3.638451
322   -15.97655   -9.202901
323   13.91118    15.19469
324   14.82370    -49.63809
325   -22.51590   11.15343
326   11.75754    -9.392814
327   -31.31877   13.80286
328   13.36993    -52.13162
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330   -1.366429   23.83344
331   -27.68488   -24.64621
332   -9.280562   -3.421965
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333   12.32513    60.53379
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335   24.49710    -7.113070
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338   -14.54367   -17.09859
339   21.70114    82.51987
340   3.570725    -12.59863
341   26.82340    -21.83395
342   43.99774    -7.190133
343   12.12840    14.98978
344   25.32463    -19.23333
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347   -4.272917   -34.98299
348   -28.65549   -6.534785
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351   -5.121434   9.795590
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353   -22.50169   33.49127
354   47.84626    -32.48762
355   -10.42529   8.913166
356   -12.51763   -37.68679
357   17.69128    -19.12523
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DEMAND_SECTION
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2     1
3     1
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358   1
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DEPOT_SECTION
0.00000      0.00000
-1
SEGMENT_LENGTH: 10
SCENARIOS: 10
SCENARIO_DETAIL:
1     120   120   120
2     120   110   130
3     120   130   110
4     110   130   120
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7     130   120   110
8     130   100   130
9     100   130   130
10    130   130   100
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NAME: N360_SL10_norm_4
TYPE: CVRP
COMMENT: 1000000
DIMENSION: 361
CAPACITY: 120
VEHICLES: 3
EDGE_WEIGHT_TYPE: FUNCTION
EDGE_WEIGHT_FORMAT: EUC_2D
NODE_COORD_TYPE: TWOD_COORDS
NODE_COORD_SECTION
1     34.63031    -11.47048
2     -46.93474   -11.81080
3     -11.17843   -50.91003
4     42.07919    -14.10128
5     -17.59683   -32.24953
6     24.32476    48.55865
7     -18.35891   -33.74034
8     25.82098    19.49656
9     -7.527487   50.68965
10    -0.8506014  -35.42265
11    98.79456    27.23209
12    -36.51757   1.950246
13    28.81788    30.21103
14    34.47258    11.92044
15    -16.74844   -47.25026
16    -68.64640   5.074390
17    39.86850    -47.68503
18    2.791083    48.14151
19    -31.60374   43.82858
20    2.864815    -8.155836
21    -47.84412   20.25923
22    22.74628    -15.24735
23    8.523792    -58.21246
24    13.54842    -27.33647
25    33.90489    29.97740
26    -64.63798   -37.30643
27    -33.94927   -14.19407
28    26.17379    -54.12518
29    30.28375    -75.83770
30    -3.693540   -56.26791
31    10.38164    20.22082
32    13.72737    16.63185
33    24.94633    18.53709
34    17.55660    -31.33818
35    -2.444397   -20.79801
36    -9.665482   51.33254
37    -9.311309   -29.25032
38    -38.39009   0.5506884
39    -49.60111   -0.8614079
40    18.41270    54.93898
41    42.07576    -13.22077
42    -23.34930   10.76596
43    -48.85442   19.97153
44    -15.35316   37.25480
45    0.04791127  10.17923
46    -29.09689   -52.04469
47    4.052207    -20.80600
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51    8.887022    12.03613
52    48.97635    -34.94563
53    -9.331934   17.81718
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235	-48.36173	38.03115
236	-20.04342	22.60987
237	11.04171	-29.48027
238	7.963780	45.61603
239	17.66965	-24.91329
240	-23.63253	-14.85230
241	-43.43447	1.941916
242	10.14169	-2.406183
243	7.095225	-23.99535
244	3.604734	-11.71924
245	-30.47484	3.220130
246	-48.12130	-3.202017
247	36.70028	25.92541
248	-21.78058	-27.79782
249	-33.56697	29.53949
250	10.46609	24.98875
251	11.11431	35.62101
252	-8.457264	-20.48461
253	0.01767864	-46.90725
254	-18.56921	-31.50833
255	-50.68229	27.31945
256	-8.157990	-4.577230
257	24.59605	26.28427
258	-15.69660	-25.01284
259	-23.10399	-12.63519
260	25.80326	7.482696
261	-25.39585	24.35137
262	-27.39796	59.29527
263	-20.32541	-20.31837
264	-50.03373	-5.781079
265	-9.234679	28.77626
266	65.02139	-19.08891
267	-0.2156205	40.08069
268	18.43783	-12.34443
269	6.096558	-38.95360
270	55.72960	47.59281
271	38.95124	16.82193
272	-7.864284	28.84307
273	-9.625269	-12.27776
274	13.72325	10.10176
275	-12.95750	-40.13195

276	-13.01379	-11.21904
277	24.07813	-44.94394
278	-34.10806	-38.28458
279	26.57034	13.35345
280	-21.01537	17.82876
281	-27.62063	31.05417
282	-30.84314	12.49360
283	-34.74514	46.16380
284	14.08400	58.21222
285	-5.635234	-0.4398142
286	24.36201	1.210141
287	-0.4714130	43.75315
288	-35.07449	12.74098
289	-8.604836	-1.968723
290	39.31090	8.529485
291	-4.693899	-70.33424
292	-17.23128	55.36501
293	19.54155	23.53388
294	16.58083	-23.13943
295	47.45900	12.41008
296	-7.724429	3.345590
297	-1.522066	44.73322
298	-15.23615	15.00807
299	-54.51795	43.38812
300	32.48455	-18.80299
301	49.90424	-16.62594
302	18.23082	6.712699
303	-0.4311636	-2.822213
304	-27.88233	-3.863261
305	-16.66821	-53.90040
306	5.696013	-42.54305
307	-11.42305	4.237704
308	-16.67811	27.25468
309	-0.8499790	65.51983
310	47.82657	-4.147534
311	31.83660	2.056679
312	49.46429	20.39959
313	2.508161	35.56036
314	-1.616328	14.17452
315	48.47461	15.94360
316	23.22155	-55.42653
317	-29.35366	69.55908
318	43.35649	9.912983
319	-1.102080	-27.87316
320	7.858336	13.29853
321	32.94992	-2.854326
322	-72.26524	-8.014792
323	-16.63822	11.81684
324	-54.68598	8.476339
325	8.502364	33.01743
326	-18.58371	-27.95303
327	-25.32910	-33.05980
328	-18.86758	-1.567090
329	-21.53503	32.53428
330	-26.43954	22.06252
331	39.31732	2.068211
332	61.71544	54.17550

```
333   -0.6304039  -31.75661
334   20.85853    1.453789
335   -4.322672   -18.07594
336   45.88343    -31.64455
337   43.45095    -7.065457
338   -28.24468   1.722401
339   41.38111    57.89814
340   11.95194    -9.491873
341   28.74468    19.31359
342   32.86002    -23.03521
343   8.632637    0.1404954
344   13.71902    25.09286
345   -2.054576   -25.77273
346   14.55802    0.4876939
347   -22.48676   -10.52650
348   -32.23801   -10.07297
349   -2.481696   8.817308
350   -16.29830   9.401065
351   -1.162032   -22.51889
352   10.65688    -27.81251
353   17.68316    -0.6146954
354   -35.50297   9.663585
355   3.466864    0.4626216
356   -6.187171   -20.87195
357   -31.16178   4.421199
358   7.063693    60.60347
359   22.55745    -3.310128
360   35.95702    36.81628
DEMAND_SECTION
1     1
2     1
3     1
…
358   1
359   1
360   1
DEPOT_SECTION
0.00000      0.00000
-1
SEGMENT_LENGTH: 10
SCENARIOS: 10
SCENARIO_DETAIL:
1     120   120   120
2     120   110   130
3     120   130   110
4     110   130   120
5     130   110   120
6     110   120   130
7     130   120   110
8     130   100   130
9     100   130   130
10    130   130   100
EOF
```

Appendix E: 20 Node Robust Vehicle Routing Problem Instance

The TSPLIB file for the 20 node RVRP instances given as a counter example in Section 3.1 is given below.

```
NAME: N20_counterExample
TYPE: CVRP
COMMENT: 1000000
DIMENSION: 21
CAPACITY: 10
VEHICLES: 2
EDGE_WEIGHT_TYPE: FUNCTION
EDGE_WEIGHT_FORMAT: EUC_2D
NODE_COORD_TYPE: TWOD_COORDS
NODE_COORD_SECTION
1     3.00  2.00
2     3.10  1.90
3     4.00  1.50
4     3.40  .65
5     4.70  .60
6     4.70  -.60
7     3.40  -.65
8     4.00  -1.50
9     3.10  -1.90
10    3.00  -2.00
11    -3.00 2.00
12    -3.10 1.90
13    -4.00 1.50
14    -3.40 .65
15    -4.70 .60
16    -4.70 -.60
17    -3.40 -.65
18    -4.00 -1.50
19    -3.10 -1.90
20    -3.00 -2.00
DEMAND_SECTION
1     1
2     1
3     1
4     1
5     1
6     1
7     1
8     1
9     1
10    1
11    1
12    1
13    1
14    1
15    1
16    1
17    1
18    1
19    1
```

```
20    1
DEPOT_SECTION
0.00000      0.00000
-1
SEGMENT_LENGTH: 5
SCENARIOS: 3
SCENARIO_DETAIL:
1     10    10
2     5     15
3     15    5
EOF
```

Appendix F: Numerical Results for Additional Solution Approaches

Tables C.1 through C.30 give numerical results for solution approaches discussed in Chapter 4 but not presented in Chapter 5.

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	31146.1	1	25.2	30946.2
Forced Cross I	30578.3	--	385.2	30575
Forced Cross II	30570.8	0.15	30.1	30572
Forced Cross III	32104.9	45	24.5	32101.9
Percentage I	30066.9	0.95	161.5	30067.2
Percentage II	31685.76	0.98	208.8	30641.1
Great Circle w/Center(EP,SW)	30807.7	0.2	107.1	30792.9
Great Circle w/Center(MP,SW)	30647.6	0.45	140.6	30641.7
Route Centers w/Center	30684.2	0.02	167.7	30648.9
w/Center(EP,SW)	30122	0.05	152.7	30138.9
w/Center(EP,SW)*	30298	0.15	168.3	30293.5

Table C.1: N360_SL10_Rand_1

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	31083.6	1	15.8	30803.9
Forced Cross I	30172.7	--	417.3	30154.8
Forced Cross II	30767.2	0.03	34.7	30723.6
Forced Cross III	31127.1	90	26.5	31156
Percentage I	30017.5	0.95	165.2	29998.2
Percentage II	30125.9	0.98	205	30116.2
Great Circle w/Center(EP,SW)	31155.7	0.2	86	31183.1
Great Circle w/Center(MP,SW)	30787	0.4	123	30764
Route Centers w/Center	30462	0.08	138	30391.7
w/Center(EP,SW)	30286	0.25	156.3	30296.6
w/Center(EP,SW)*	30119.8	0.15	149.7	30093.6

Table C.2: N360_SL10_Rand_2

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	31580.6	1	20.2	31561.9
Forced Cross I	30135.3	--	333	30137.9
Forced Cross II	30468	0.03	34.8	30452.4
Forced Cross III	31546	45	21.9	31582
Percentage I	30039.2	0.95	158.3	30037.1
Percentage II	30151.9	0.99	191.2	30164.4
Great Circle w/Center(EP,SW)	30588.7	0.05	88.3	30667.7
Great Circle w/Center(MP,SW)	30402.3	0.45	122.3	30421.6
Route Centers w/Center	30214.2	0.06	207.2	30292.9
w/Center(EP,SW)	30337.2	0.35	136.9	30362.7
w/Center(EP,SW)*	29838.2	0.2	152.7	29866.2

Table C.3: N360_SL10_Rand_3

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	31299.7	1.6	19.2	31102.4
Forced Cross I	30649.5	--	352.8	30651.5
Forced Cross II	30909.9	0.03	39.9	30929.5
Forced Cross III	31873.6	60	21.3	31835.7
Percentage I	30573.83	0.95	153.3	30446.3
Percentage II	30511.3	0.99	186.3	30537.1
Great Circle w/Center(EP,SW)	30662.5	0.3	95.3	30703.7
Great Circle w/Center(MP,SW)	30421.9	0.1	136.6	30444.6
Route Centers w/Center	30907.2	0.08	135.5	30917.7
w/Center(EP,SW)	30255.3	0.35	155.4	30262.7
w/Center(EP,SW)*	30259	0.3	129.9	30222

Table C.4: N360_SL10_Rand_4

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	32058.2	1.6	19.2	32025.1
Forced Cross I	31180.7	--	404.5	31222.1
Forced Cross II	31095.5	0.07	45.6	31095.9
Forced Cross III	32227.2	60	25.6	32206.3
Percentage I	31208.38	0.95	149.9	30686.5
Percentage II	30867.5	0.99	191.9	30830.9
Great Circle w/Center(EP,SW)	31220.3	0.15	96.1	31246.2
Great Circle w/Center(MP,SW)	31107.8	0.45	106.8	31119.5
Route Centers w/Center	31184.7	0.04	323.6	31203.6
w/Center(EP,SW)	30652.6	0.15	174.6	30665.7
w/Center(EP,SW)*	30764.6	0.1	146.6	30763.7

Table C.5: N360_SL10_Rand_5

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	30314	1	22.9	30375
Forced Cross I	29333.6	--	325.5	29335
Forced Cross II	29532.4	0.03	38.9	29582.5
Forced Cross III	30684	75	20.3	30706.6
Percentage I	29327.09	0.95	155.1	29022.2
Percentage II	30801.98	0.99	199	29501.4
Great Circle w/Center(EP,SW)	29562.9	0.2	94.7	29650.6
Great Circle w/Center(MP,SW)	29638.5	0.35	113.7	29633.6
Route Centers w/Center	29317.8	0.08	263	29293.1
w/Center(EP,SW)	28927.9	0.35	177.6	28910.5
w/Center(EP,SW)*	29050.2	0.3	192.4	29026.1

Table C.6: N360_SL10_RightBias_1

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	29479.8	0.6	23.9	29454.1
Forced Cross I	28513.2	--	373.1	28470.7
Forced Cross II	28915.5	0.1	44.3	28932.5
Forced Cross III	30676.6	90	23.2	30737.2
Percentage I	28416.6	0.95	167.5	28432.7
Percentage II	29033.1	0.95	211.5	29048.6
Great Circle w/Center(EP,SW)	29435.6	0.3	80.1	29453.9
Great Circle w/Center(MP,SW)	29276.5	0.55	120.1	29257.4
Route Centers w/Center	28248.9	0.04	275.2	28227.6
w/Center(EP,SW)	28579.2	0.35	157.6	28555.9
w/Center(EP,SW)*	28330.5	0.15	150.3	28277.1

Table C.7: N360_SL10_RightBias_2

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	28929.7	1.6	20.8	28833
Forced Cross I	28244.8	--	431	28275
Forced Cross II	27831.6	0.03	38.4	27819.7
Forced Cross III	29348.8	60	25.5	29347.5
Percentage I	28255.9	0.95	174.2	28280.1
Percentage II	28923.01	0.99	222.1	28920
Great Circle w/Center(EP,SW)	29433.4	0.2	92.7	29409.8
Great Circle w/Center(MP,SW)	29108.8	0.15	128.3	29154.8
Route Centers w/Center	28599.6	0	345.7	28568.9
w/Center(EP,SW)	28375.2	0.1	189.3	28351.2
w/Center(EP,SW)*	27948.1	0.15	156.6	27977

Table C.8: N360_SL10_RightBias_3

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	29919	1.4	20.4	29530.3
Forced Cross I	28515.6	--	312.4	28509.3
Forced Cross II	28874.6	0.2	42.9	28880.1
Forced Cross III	29767.9	75	27.8	29735.9
Percentage I	28474.5	0.75	180.8	28437.8
Percentage II	28623.57	0.98	214.3	28445.6
Great Circle w/Center(EP,SW)	29209.9	0.05	93.6	29211.8
Great Circle w/Center(MP,SW)	28912.7	0.1	109.8	28891
Route Centers w/Center	28810.6	0.1	229.7	28781.1
w/Center(EP,SW)	28432	0.05	151.4	28440.9
w/Center(EP,SW)*	28527.5	0.05	165.6	28516

Table C.9: N360_SL10_RightBias_4

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	29273.4	0.6	18.4	29270.9
Forced Cross I	28296.2	--	381.5	28299.5
Forced Cross II	28480	0.05	36	28492
Forced Cross III	29722.7	30	18.8	29730.4
Percentage I	27955.8	0.95	163.5	27974.4
Percentage II	29516.82	0.94	207.8	28633.6
Great Circle w/Center(EP,SW)	28801.7	0.1	92.2	28798.4
Great Circle w/Center(MP,SW)	28553.4	0.1	106.8	28562.4
Route Centers w/Center	27879.9	0.06	138.8	27850.6
w/Center(EP,SW)	28441.4	0.35	173	28419.9
w/Center(EP,SW)*	28237.5	0.15	166.1	28244

Table C.10: N360_SL10_RightBias_5

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	20485.7	1.4	23.7	20341.3
Forced Cross I	20282.5	--	370.6	20282.2
Forced Cross II	20468.4	0.03	58.2	20493.5
Forced Cross III	20999.9	15	33.8	21022.8
Percentage I	20081.31	0.8	189.4	19679.7
Percentage II	20029.6	0.99	242	20038
Great Circle w/Center(EP,SW)	20070.2	0.15	104.6	20081.8
Great Circle w/Center(MP,SW)	20037.3	0.25	147.7	20046.2
Route Centers w/Center	19992.8	0.04	511.1	19983.2
w/Center(EP,SW)	20065.8	0.15	213.8	20057.5
w/Center(EP,SW)*	20077.3	0.15	178.6	20077.1

Table C.11: N360_SL10_Norm_1

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	21125.4	0.6	21.1	20889
Forced Cross I	20644.2	--	491.5	20625.9
Forced Cross II	21317.5	0.03	48.8	21311
Forced Cross III	21261.5	60	35	21261.2
Percentage I	20656.9	0.95	211.8	20654
Percentage II	20648.9	0.99	252.4	20667.9
Great Circle w/Center(EP,SW)	20679.7	0.25	92.8	20661.2
Great Circle w/Center(MP,SW)	20659.8	0.15	156.2	20670.7
Route Centers w/Center	20690.6	0.18	327.3	20721.2
w/Center(EP,SW)	20659.1	0.15	152.1	20663.9
w/Center(EP,SW)*	20583	0.2	157.8	20584.6

Table C.12: N360_SL10_Norm_2

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	19664.1	1.4	17.6	19586.2
Forced Cross I	19139.5	--	347.8	19151
Forced Cross II	20173.6	0.03	46.3	20217.1
Forced Cross III	19823.8	90	24	19829.4
Percentage I	19289.6	0.95	200	19294.3
Percentage II	19328.4	0.95	240	19322.7
Great Circle w/Center(EP,SW)	19524.9	0.15	95.1	19516.6
Great Circle w/Center(MP,SW)	19458.4	0.2	136.3	19466.5
Route Centers w/Center	19185.7	0.12	449.3	19176.3
w/Center(EP,SW)	19485.9	0.2	160	19478.9
w/Center(EP,SW)*	19387.7	0.15	157.9	19389.3

Table C.13: N360_SL10_Norm_3

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	19997.6	1.4	17.6	19832.2
Forced Cross I	19415.6	--	348.3	19423
Forced Cross II	19838.8	0.15	50.1	19829
Forced Cross III	20108.7	30	26.3	20099.6
Percentage I	19215.8	0.95	155	19207.3
Percentage II	19631.84	0.97	188.5	19486.7
Great Circle w/Center(EP,SW)	19673.7	0.1	97.2	19668.2
Great Circle w/Center(MP,SW)	19546.6	0.45	155.5	19556.7
Route Centers w/Center	19434.3	0.02	350.8	19411.5
w/Center(EP,SW)	19408.2	0.05	183.2	19415.4
w/Center(EP,SW)*	19463.7	0.05	165.7	19455.1

Table C.14: N360_SL10_Norm_4

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	19220.5	0.6	23.2	19226.9
Forced Cross I	19178.6	--	343.6	19196.9
Forced Cross II	19539.6	0.05	39.7	19532.1
Forced Cross III	19743.9	75	29.3	19732.8
Percentage I	19152.6	0.95	169.3	19146.5
Percentage II	19308.62	0.99	203.3	19160
Great Circle w/Center(EP,SW)	19272	0.25	113.8	19274.7
Great Circle w/Center(MP,SW)	19328.7	0.25	128	19325
Route Centers w/Center	19203.6	0.04	403.5	19193.8
w/Center(EP,SW)	19093.5	0.25	176.5	19090.4
w/Center(EP,SW)*	19121.9	0.1	157.7	19110.6

Table C.15: N360_SL10_Norm_5

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	31236	1	25.2	30991.8
Forced Cross I	30764.7	--	387.7	30733.5
Forced Cross II	30735.1	0.05	30.6	30754.4
Forced Cross III	32105.4	60	24.7	32156.3
Percentage I	30288.4	0.95	162.5	30245.8
Percentage II	31830.32	0.98	209.4	30944.3
Great Circle w/Center(EP,SW)	30949.2	0.2	107.3	30903.5
Great Circle w/Center(MP,SW)	30793.4	0.45	142.1	30789.9
Route Centers w/Center	30784.2	0.02	170.5	30760.7
w/Center(EP,SW)	30223.1	0.05	152.1	30253.9
w/Center(EP,SW)*	30336.5	0.15	169.2	30347.8

Table C.16: N360_SL15_Rand_1

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	31164.7	1	16	30887.4
Forced Cross I	30218.5	--	419.3	30256.6
Forced Cross II	30861.8	0.03	35.2	30867.5
Forced Cross III	31201.7	90	26.4	31171
Percentage I	30082.5	0.95	165.9	30117.9
Percentage II	30219.4	0.98	205.6	30246
Great Circle w/Center(EP,SW)	31328.7	0.2	85.7	31399.1
Great Circle w/Center(MP,SW)	30770.9	0.4	123.6	30780.8
Route Centers w/Center	30475.1	0.08	140.4	30456.1
w/Center(EP,SW)	30274.6	0.1	156.9	30250.5
w/Center(EP,SW)*	30136.3	0.15	150.8	30153.5

Table C.17: N360_SL15_Rand_2

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	31782.5	1	20.4	31639.1
Forced Cross I	30213.5	--	335.4	30187.9
Forced Cross II	30711.1	0.03	34.8	30632.8
Forced Cross III	31792.6	45	22.2	31744
Percentage I	30181.3	0.95	158.4	30204.4
Percentage II	30331.8	0.99	191.7	30326.2
Great Circle w/Center(EP,SW)	30824.8	0.05	88.2	30878.6
Great Circle w/Center(MP,SW)	30600.4	0.45	123.4	30632.4
Route Centers w/Center	30441.1	0.06	210.5	30429.7
w/Center(EP,SW)	30503.4	0.2	138	30492.7
w/Center(EP,SW)*	30008.2	0.2	153.6	29986.8

Table C.18: N360_SL15_Rand_3

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	31550.4	0.6	19.5	31792.3
Forced Cross I	30828.4	--	359.9	30807.9
Forced Cross II	31052.5	0.13	39.2	31104.2
Forced Cross III	31983.4	60	22.1	31983.2
Percentage I	30652.6	0.95	155.7	30677.2
Percentage II	30720.8	0.99	189.4	30716.3
Great Circle w/Center(EP,SW)	30779.3	0.3	97.4	30761.2
Great Circle w/Center(MP,SW)	30595.2	0.1	140.4	30592.6
Route Centers w/Center	31014.2	0.08	140.2	31008
w/Center(EP,SW)	30356.4	0.35	158.6	30380
w/Center(EP,SW)*	30206.1	0.3	133.1	30187.9

Table C.19: N360_SL15_Rand_4

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	32419.7	1.6	19.7	32121.1
Forced Cross I	31330.6	--	413.5	31370.2
Forced Cross II	31187.5	0.07	46	31200.6
Forced Cross III	32290	60	26.7	32277.1
Percentage I	31333.3	0.95	152.8	30772.8
Percentage II	31019.2	0.99	194.7	30933.9
Great Circle w/Center(EP,SW)	31283	0.2	97.8	31330.3
Great Circle w/Center(MP,SW)	31309.2	0.45	109.3	31287.5
Route Centers w/Center	31309.4	0.04	326	31336.4
w/Center(EP,SW)	30712.4	0.15	175.5	30713.9
w/Center(EP,SW)*	30846.5	0.1	145	30856.7

Table C.20: N360_SL15_Rand_5

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	30639.7	1	23.8	30263.6
Forced Cross I	29341.4	--	332.8	29362.5
Forced Cross II	29646.8	0.03	39.5	29674.8
Forced Cross III	30807.3	75	20.8	30791.3
Percentage I	29454.77	0.95	157.7	29213.5
Percentage II	30856.48	0.99	202.4	29471.4
Great Circle w/Center(EP,SW)	29826.2	0.2	96.9	29824.7
Great Circle w/Center(MP,SW)	29818.9	0.45	114.3	29822
Route Centers w/Center	29384.7	0.08	264	29377.2
w/Center(EP,SW)	29046.8	0.35	179.6	29053
w/Center(EP,SW)*	29293.1	0.2	194.3	29278.5

Table C.21: N360_SL15_RightBias_1

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	29800.3	0.6	23.9	29561.9
Forced Cross I	28660.9	--	373.7	28627.7
Forced Cross II	29068	0.1	44.1	29070.9
Forced Cross III	30868.5	90	23.4	30916.3
Percentage I	28503.7	0.95	168.9	28539.4
Percentage II	29092.9	0.95	213.3	29091.3
Great Circle w/Center(EP,SW)	29514.9	0.3	81	29481
Great Circle w/Center(MP,SW)	29327.6	0.55	120.4	29345.3
Route Centers w/Center	28395.3	0.04	279.1	28401.9
w/Center(EP,SW)	28577.2	0.35	158.7	28585.4
w/Center(EP,SW)*	28410	0.15	152	28389.8

Table C.22:N360_SL15_RightBias_2

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	29290	1.6	19.1	29172.5
Forced Cross I	28394.6	--	400.5	28396.1
Forced Cross II	27896.5	0.03	35.2	27933.5
Forced Cross III	29419.4	60	24	29457.4
Percentage I	28349.2	0.95	161.9	28372.8
Percentage II	29134.44	0.99	204.9	29015.6
Great Circle w/Center(EP,SW)	29449	0.2	86	29449.7
Great Circle w/Center(MP,SW)	29303.2	0.15	123.3	29315.6
Route Centers w/Center	28745.3	0.08	326.9	28744.3
w/Center(EP,SW)	28434.5	0.1	175.3	28418.7
w/Center(EP,SW)*	28080.5	0.15	144.6	28063.7

Table C.23: N360_SL15_RightBias_3

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	30101.3	1.4	19.1	30066.9
Forced Cross I	28663.3	--	297	28640.1
Forced Cross II	29016.5	0.2	40.5	29002.1
Forced Cross III	29847.5	75	26.1	29828.4
Percentage I	28582.4	0.75	166.8	28559.9
Percentage II	28778.85	0.98	199.6	28526.7
Great Circle w/Center(EP,SW)	29291.2	0.05	85.1	29274.1
Great Circle w/Center(MP,SW)	28988.2	0.1	103.7	28967.9
Route Centers w/Center	28945	0.1	222.7	28943.6
w/Center(EP,SW)	28501.8	0.05	143.6	28505.6
w/Center(EP,SW)*	28580.5	0.05	157.3	28583.7

Table C.24: N360_SL15_RightBias_4

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	29631.1	0.6	17.6	29422.9
Forced Cross I	28372.9	--	358.1	28359.5
Forced Cross II	28608.2	0.05	34.8	28604.2
Forced Cross III	29778.3	30	17.9	29796.1
Percentage I	28198	0.95	158	28202
Percentage II	29731.54	0.94	200.6	28791.4
Great Circle w/Center(EP,SW)	28890.9	0.1	89.2	28900.1
Great Circle w/Center(MP,SW)	28862	0.1	103.3	28835.4
Route Centers w/Center	27946.1	0.06	136.1	27934.9
w/Center(EP,SW)	28541.6	0.35	167.4	28509.8
w/Center(EP,SW)*	28368.2	0.15	156.2	28370.5

Table C.25: N360_SL15_RightBias_5

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	20560.7	1.4	23.9	20279.8
Forced Cross I	20301	--	373.5	20315
Forced Cross II	20553.1	0.03	59	20556.1
Forced Cross III	21015.8	15	34.2	21029.6
Percentage I	20102.01	0.8	189.5	19745.2
Percentage II	20052	0.99	242.3	20068.2
Great Circle w/Center(EP,SW)	20189.7	0.15	96.6	20180.3
Great Circle w/Center(MP,SW)	20104	0.2	123.8	20116.8
Route Centers w/Center	20043.5	0.04	418.5	20044.5
w/Center(EP,SW)	20115.2	0.15	172.8	20116
w/Center(EP,SW)*	20141.5	0.15	151.6	20144

Table C.26: N360_SL15_Norm_1

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	21281.8	0.6	17.7	21331.3
Forced Cross I	20705.4	--	432.3	20693.5
Forced Cross II	21466.5	0.03	40.2	21457.4
Forced Cross III	21331.3	60	28.6	21317
Percentage I	20699.3	0.95	177.6	20684.8
Percentage II	20699.9	0.99	212.4	20713.8
Great Circle w/Center(EP,SW)	20702.7	0.25	82.8	20693.9
Great Circle w/Center(MP,SW)	20717.6	0.15	138.3	20741.2
Route Centers w/Center	20811.9	0.18	329.8	20808.7
w/Center(EP,SW)	20751.2	0.15	149.7	20735.4
w/Center(EP,SW)*	20651.9	0.2	154.9	20653.8

Table C.27: N360_SL15_Norm_2

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	19596.7	1.4	17.6	19650.8
Forced Cross I	19258.5	--	347.7	19250.3
Forced Cross II	20315.6	0.03	46.5	20305.7
Forced Cross III	19907.3	90	23.9	19909.5
Percentage I	19391.59	0.95	201.5	19379
Percentage II	19383	0.95	241.6	19373.1
Great Circle w/Center(EP,SW)	19516.7	0.15	95.2	19517.5
Great Circle w/Center(MP,SW)	19530.8	0.1	135.7	19539.1
Route Centers w/Center	19241.4	0.12	490.8	19245.4
w/Center(EP,SW)	19559.1	0.2	175.2	19556.3
w/Center(EP,SW)*	19478.1	0.15	184.9	19467.7

Table C.28: N360_SL15_Norm_3

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	20005.5	1.4	17.7	19939.3
Forced Cross I	19504.8	--	345.4	19515.9
Forced Cross II	19889	0.15	50.2	19883.1
Forced Cross III	20194.9	30	26.4	20180
Percentage I	19231.3	0.95	156.1	19239.8
Percentage II	19663.83	0.97	189.7	19556.2
Great Circle w/Center(EP,SW)	19639.6	0.1	97.3	19651.8
Great Circle w/Center(MP,SW)	19602.4	0.45	156.1	19616.2
Route Centers w/Center	19416.2	0.02	354.1	19426.3
w/Center(EP,SW)	19468	0.05	183.7	19474.6
w/Center(EP,SW)*	19503.1	0.05	200.5	19491.5

Table C.29: N360_SL15_Norm_4

Approach	Result	Parameter Value	Time	Robust Score
Great Circle	19301.5	0.6	25.4	19259.6
Forced Cross I	19233.1	--	368.7	19227.8
Forced Cross II	19638.2	0.05	43.1	19624.7
Forced Cross III	19831.3	75	31.9	19833.9
Percentage I	19217	0.95	182.6	19214.8
Percentage II	19333.96	0.99	219.8	19200.5
Great Circle w/Center(EP,SW)	19210.1	0.3	122.6	19211
Great Circle w/Center(MP,SW)	19399.4	0.25	137.5	19388.4
Route Centers w/Center	19245.5	0.04	435.5	19240.4
w/Center(EP,SW)	19157.9	0.25	200.1	19152.3
w/Center(EP,SW)*	19190.9	0.1	190.9	19180.8

Table C.30: N360_SL15_Norm_5

Appendix G: Growth Rate Test Instance Data

Tables D.1 through D.25 give numerical results, for the solution approaches discussed in Chapter 5, for the RVRP instances used in computation time analysis. The relative quality of the solution approaches on these small problems is consistent with the discussion of Section 5.4.

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	17829.4	1.6	3.3	2513353.3
All Sweeps	17180.2	--	27.7	17203.1
Sweep Neighbor	17484.7	0	7.8	17486.9
Sweep MST	17484.7	0	1.8	17486.9
Sweep Angles	17708.8	1	6.9	17710.4
w/Center(EP,CW)	17392.1	0.25	14.5	17587.2
w/Center(MP,SW)	17250.6	0.45	20.8	17391.1
w/Center(MP,CW)	17117.9	0.55	14.3	2512834.1
w/Center(EP,CW)*	17167.8	0.05	16.4	17201.2
w/Center(MP,SW)*	17003.1	0.25	20.5	16999.5
w/Center(MP,CW)*	16978.9	0.3	17.6	16997.7

Table D.1: N90_SL10_Rand_1

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	17384.5	1	3.3	17470.9
All Sweeps	17400.9	--	28.7	17454.6
Sweep Neighbor	17970.3	1.5	9.7	18042.6
Sweep MST	17970.3	10	1.7	18042.6
Sweep Angles	17726.8	3	7.3	17696.4
w/Center(EP,CW)	17577.7	0.3	15.3	17504.6
w/Center(MP,SW)	17373.4	0.45	20.1	17382.7
w/Center(MP,CW)	17602.5	0.45	21.2	17624.8
w/Center(EP,CW)*	17552.9	0.3	21.1	17557.9
w/Center(MP,SW)*	17400.9	0	27.1	17454.6
w/Center(MP,CW)*	17358.4	0.3	20.3	17400

Table D.2: N90_SL10_Rand_2

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	17020	1.4	4.3	17065.2
All Sweeps	16776.3	--	26.7	16801.3
Sweep Neighbor	17530.4	0.5	9.8	17555.7
Sweep MST	17720.5	5	1.8	17632.8
Sweep Angles	17111.1	3	7.2	17135
w/Center(EP,CW)	16730.4	0.35	16.2	16794.2
w/Center(MP,SW)	16661.2	0.55	20.8	16651.3
w/Center(MP,CW)	16661.2	0.3	15.9	16651.3
w/Center(EP,CW)*	16751.7	0.2	18.2	16708.3
w/Center(MP,SW)*	16786.1	0.45	20.6	16860.4
w/Center(MP,CW)*	16661.2	0.4	17.7	16651.3

Table D.3: N90_SL10_Rand_3

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	16134	0.6	3.4	16244
All Sweeps	16215	--	28.1	16216.9
Sweep Neighbor	16621.9	3	9.4	16652
Sweep MST	16381.6	10	1.8	16462.9
Sweep Angles	16621.9	21	7.4	16652
w/Center(EP,CW)	16225	0.1	15	16264.6
w/Center(MP,SW)	16225.5	0.35	17.8	16253.5
w/Center(MP,CW)	16056.9	0.5	17.9	16201.1
w/Center(EP,CW)*	16414.9	0.15	18.4	16453.3
w/Center(MP,SW)*	16196.9	0.2	19.8	16316.1
w/Center(MP,CW)*	16225.3	0.55	17.4	16222.3

Table D.4: N90_SL10_Rand_4

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	17145.1	1	4.2	17166.2
All Sweeps	17058.2	--	27.7	17077.5
Sweep Neighbor	17118.9	3	9.1	17238.7
Sweep MST	17337.5	0	1.9	17329.9
Sweep Angles	17307.7	12	6.9	17337.4
w/Center(EP,CW)	16932.2	0.4	14.3	16909.1
w/Center(MP,SW)	17093	0.5	22	17072.2
w/Center(MP,CW)	17066.1	0.25	14	17093.7
w/Center(EP,CW)*	17088.9	0.35	15.2	2512781.8
w/Center(MP,SW)*	16929.3	0.45	20.1	16966.4
w/Center(MP,CW)*	16934.1	0.2	19	16962.8

Table D.5: N90_SL10_Rand_5

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	20000.4	1.4	6.7	19996.7
All Sweeps	19559.1	--	57.3	19522
Sweep Neighbor	19665	2	10.9	19743.6
Sweep MST	19743.5	5	3.7	19690.1
Sweep Angles	19623	6	9.4	19587.7
w/Center(EP,CW)	19810.6	0	24.1	19829.1
w/Center(MP,SW)	19493.6	0.5	35.3	19511.1
w/Center(MP,CW)	19522.9	0.5	25.3	19503
w/Center(EP,CW)*	19594.1	0.15	29.2	19517.9
w/Center(MP,SW)*	19660.6	0.3	32.1	19809.6
w/Center(MP,CW)*	19286	0.55	24.1	19307.9

Table D.6: N120_SL10_Rand_1

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	20228.5	1.6	5.3	20232.7
All Sweeps	19439.2	--	56.7	19491.6
Sweep Neighbor	19900.1	0.5	12	19870
Sweep MST	19900.1	5	3.7	19870
Sweep Angles	19845.4	1	9.9	19975.3
w/Center(EP,CW)	19578	0.2	23.1	19604.3
w/Center(MP,SW)	19498.9	0.4	37.2	19455.6
w/Center(MP,CW)	19810.6	0.4	22.9	19755.2
w/Center(EP,CW)*	19858.9	0.15	32.2	19806.4
w/Center(MP,SW)*	19580.3	0.4	31.8	19571.5
w/Center(MP,CW)*	19843.8	0.2	24.6	19711.4

Table D.7: N120_SL10_Rand_2

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	19044.5	1.6	5.1	19075
All Sweeps	18907.2	--	56.9	18981.1
Sweep Neighbor	19523.4	1	13.8	19538.5
Sweep MST	19606.6	15	3.6	19590
Sweep Angles	19523.4	21	9.3	19538.5
w/Center(EP,CW)	18999.4	0	27.2	19131
w/Center(MP,SW)	19027.2	0.45	36	19026.1
w/Center(MP,CW)	18875	0.3	20	19005.6
w/Center(EP,CW)*	18918.2	0.15	22.8	19013.4
w/Center(MP,SW)*	19036.1	0.2	31.7	19016.4
w/Center(MP,CW)*	18923.2	0.1	26.3	19083.5

Table: D.8: N120_SL10_Rand_3

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	18843.7	1.6	5.6	18867.3
All Sweeps	18109	--	51.6	18152.6
Sweep Neighbor	18299.9	3	11.6	18271.9
Sweep MST	18354.5	5	3.1	18400
Sweep Angles	18724.2	1	8.7	18671.1
w/Center(EP,CW)	18042.6	0.2	20.1	18108.7
w/Center(MP,SW)	18070.6	0.55	30.4	18084.5
w/Center(MP,CW)	17930.4	0.05	23.9	17926.4
w/Center(EP,CW)*	17964.5	0.25	26.4	17939
w/Center(MP,SW)*	18084.4	0.5	27.2	18148.6
w/Center(MP,CW)*	18012.6	0.2	24.5	18109.8

Table D.9: N120_SL10_Rand_4

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	19266.4	1.6	5	19319.2
All Sweeps	18826.5	--	55	18851.5
Sweep Neighbor	19327.7	0	12.9	19275.6
Sweep MST	19327.7	0	3.6	19275.6
Sweep Angles	19092.2	21	10	19224.5
w/Center(EP,CW)	18954.9	0	25.6	19044
w/Center(MP,SW)	18812.2	0.15	33.3	18897.1
w/Center(MP,CW)	18912.6	0.5	23.3	19017.9
w/Center(EP,CW)*	18902.4	0.2	27.9	18865.2
w/Center(MP,SW)*	18960.2	0	34.1	19040.3
w/Center(MP,CW)*	18757.5	0.4	23.4	18814.7

Table D.10: N120_SL10_Rand_5

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	22940.5	1.6	9.5	22977.4
All Sweeps	22763.4	--	161.6	22773.9
Sweep Neighbor	23206.8	1.5	17.8	23174.7
Sweep MST	23294.5	5	11.9	23199.5
Sweep Angles	23051.9	21	16	23045
w/Center(EP,CW)	22770.2	0.1	44.6	22845.4
w/Center(MP,SW)	22465	0.35	70.2	22421.8
w/Center(MP,CW)	22805.2	0.6	48.6	22826.2
w/Center(EP,CW)*	22773.6	0.35	55.4	22807.9
w/Center(MP,SW)*	22778.3	0.6	67	22748.3
w/Center(MP,CW)*	22839.4	0.4	51.4	22903.8

Table D.11: N180_SL10_Rand_1

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	23547.7	0.6	8.5	23571.8
All Sweeps	22976.8	--	147.2	23015.9
Sweep Neighbor	23027.1	3.5	24.7	23040.2
Sweep MST	23327.6	0	9.2	23330
Sweep Angles	23271	1	18.4	23203.5
w/Center(EP,CW)	23113.8	0.3	53.4	23149
w/Center(MP,SW)	22851.8	0.25	74.7	22903.8
w/Center(MP,CW)	22843.3	0.4	47.8	22906
w/Center(EP,CW)*	23253.7	0.25	47.5	23293.7
w/Center(MP,SW)*	22997.5	0.4	68.1	23012.7
w/Center(MP,CW)*	22698.2	0.25	45.6	22712.9

Table D.12: N180_SL10_Rand_2

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	22101.9	1.4	10.3	22154.5
All Sweeps	21848.3	--	139.1	21847.2
Sweep Neighbor	22395.5	2	20.8	22435.4
Sweep MST	21970.6	25	10.2	22013
Sweep Angles	22475.7	27	16.6	22488.5
w/Center(EP,CW)	22297.3	0.35	42.1	22289
w/Center(MP,SW)	22261.7	0.45	65.4	22335.2
w/Center(MP,CW)	21952.6	0.45	44	21945.4
w/Center(EP,CW)*	22136.4	0.2	40.7	22154.2
w/Center(MP,SW)*	21941.3	0.55	64.7	21966
w/Center(MP,CW)*	21757.8	0.3	55.7	21762.6

Table D.13: N180_SL10_Rand_3

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	22370	1.4	9.8	22346.3
All Sweeps	21673.8	--	142	21674.4
Sweep Neighbor	21906.4	0	21.6	21898.7
Sweep MST	21906.4	0	8	21898.7
Sweep Angles	21780	6	14.2	21732.5
w/Center(EP,CW)	21791.4	0.4	44.4	21819.5
w/Center(MP,SW)	21698.8	0.6	69.3	21698.3
w/Center(MP,CW)	21805.3	0.55	44.2	21799
w/Center(EP,CW)*	22100.8	0.1	44.8	22143.7
w/Center(MP,SW)*	21956.4	0.55	59.8	21890.8
w/Center(MP,CW)*	21539.9	0.55	48.2	21630.1

Table D.14: N180_SL10_Rand_4

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	22291.4	1.6	11.2	22205.2
All Sweeps	22291.6	--	152.3	22295.1
Sweep Neighbor	22477.4	1.5	19	22450.1
Sweep MST	22376	25	9.1	22448.3
Sweep Angles	22612.7	24	17.9	22678.5
w/Center(EP,CW)	22434.5	0.4	48.7	22437.4
w/Center(MP,SW)	22350.1	0.45	62.5	22377.5
w/Center(MP,CW)	22102.4	0.25	49	22114.2
w/Center(EP,CW)*	22048.8	0.05	50.8	22041.1
w/Center(MP,SW)*	22387.8	0.35	79.9	22390.2
w/Center(MP,CW)*	22365.4	0.35	53.4	22377.1

Table D.15: N180_SL10_Rand_5

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	25084.7	1.6	13.2	25099.4
All Sweeps	25127.2	--	310.6	25096.6
Sweep Neighbor	25773.5	1	27.2	25759.7
Sweep MST	25564.9	5	19.5	25566.1
Sweep Angles	25277.5	18	21.8	25348
w/Center(EP,CW)	25682.2	0.1	78.6	25685.3
w/Center(MP,SW)	25565.9	0.15	117.8	25541.3
w/Center(MP,CW)	25555.2	0.55	57.7	25541.3
w/Center(EP,CW)*	25714	0.35	86	25748.2
w/Center(MP,SW)*	25398.8	0.15	122	25380.6
w/Center(MP,CW)*	25259.2	0.5	70.7	25295.6

Table D.16: N240_SL10_Rand_1

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	25545.4	1	12.9	25580.4
All Sweeps	25645.4	--	306	25648.5
Sweep Neighbor	25971.6	0	33.2	25963.1
Sweep MST	25971.6	0	17.9	25963.1
Sweep Angles	25983.6	30	23	25974.9
w/Center(EP,CW)	25543.3	0.05	71	25494.3
w/Center(MP,SW)	25470.1	0.5	123.1	25462.4
w/Center(MP,CW)	25427.3	0.25	70.8	25480.1
w/Center(EP,CW)*	25472.4	0.35	77.4	25545.7
w/Center(MP,SW)*	25623.7	0.35	102.3	25672.4
w/Center(MP,CW)*	25401.8	0.4	80.7	25442.4

Table D.17: N240_SL10_Rand_2

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	25361.5	1.6	11.4	25404.8
All Sweeps	24983.8	--	287.1	24991.8
Sweep Neighbor	25123.9	0	33.2	25142.7
Sweep MST	24995.2	15	19.8	25004.9
Sweep Angles	25134.8	21	31.1	25174.6
w/Center(EP,CW)	24878.8	0.25	77.1	24828.8
w/Center(MP,SW)	24815	0.5	102	24834.7
w/Center(MP,CW)	25020.6	0.35	65.9	25059.7
w/Center(EP,CW)*	24990.3	0.25	78.3	24965.8
w/Center(MP,SW)*	24911.8	0.4	95.6	24861.6
w/Center(MP,CW)*	25194.7	0.5	75.8	25175.9

Table D.18: N240_SL10_Rand_3

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	25789.4	1.4	13	25773.7
All Sweeps	25491.8	--	320.6	25523.2
Sweep Neighbor	25507.5	5.5	44.5	25514.9
Sweep MST	25784.2	10	32.5	25749.2
Sweep Angles	25577.5	1	31.5	25616
w/Center(EP,CW)	25845.7	0.2	59.7	25822.8
w/Center(MP,SW)	25301.5	0.4	113.4	25289.1
w/Center(MP,CW)	25348.9	0.55	67.2	25352.1
w/Center(EP,CW)*	25224.9	0.25	75.1	25250
w/Center(MP,SW)*	25289.4	0.3	127.8	25335.1
w/Center(MP,CW)*	25469.5	0.4	75.4	25429.6

Table D.19: N240_SL10_Rand_4

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	25880.4	1.6	16.9	25866.6
All Sweeps	25820.6	--	330.8	25805.5
Sweep Neighbor	26158.3	1.5	33.1	26160.5
Sweep MST	26003.9	35	21.6	26067.2
Sweep Angles	26003.9	12	27.8	26067.2
w/Center(EP,CW)	25696.2	0.1	76.6	25652.1
w/Center(MP,SW)	25783.4	0.3	124.8	25747.2
w/Center(MP,CW)	25668.9	0.6	61.9	25695.1
w/Center(EP,CW)*	25833.3	0.2	83.3	25828.2
w/Center(MP,SW)*	25798.2	0.5	112.9	25852.5
w/Center(MP,CW)*	25792.4	0.05	76	25782.8

Table D.20: N240_SL10_Rand_5

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	28285.2	1	20.6	28297
All Sweeps	27518.9	--	572	27534.5
Sweep Neighbor	28173.9	1.5	48.7	28138.3
Sweep MST	27961.1	25	40.2	27982.2
Sweep Angles	27830	1	31	27798.8
w/Center(EP,CW)	27630	0.25	102.3	27659.5
w/Center(MP,SW)	27389	0.35	161.7	27439.9
w/Center(MP,CW)	28029.2	0.25	100.3	27999.7
w/Center(EP,CW)*	27972.1	0.3	123.3	27956
w/Center(MP,SW)*	27913.6	0.4	158.5	27901.2
w/Center(MP,CW)*	27702.6	0.4	115.7	27711.5

Table D.21N300_SL10_Rand_1

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	27945.5	1	19.1	27972.2
All Sweeps	28226.9	--	526.9	28290.2
Sweep Neighbor	28037.5	1	44.9	28014.8
Sweep MST	28240.7	0	30.5	28271.6
Sweep Angles	28104.9	27	44.1	28039.6
w/Center(EP,CW)	28371.5	0.35	109.7	28376.4
w/Center(MP,SW)	28315.9	0.4	137.4	28332.3
w/Center(MP,CW)	28476.4	0.2	95.1	28457.8
w/Center(EP,CW)*	28368.8	0.25	106.8	28329
w/Center(MP,SW)*	28328.1	0.3	154.5	28366.3
w/Center(MP,CW)*	28068	0.3	109.2	28092.1

Table D.22: N300_SL10_Rand_2

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	27220.4	0.6	19	27230.3
All Sweeps	27500.9	--	533.3	27497.5
Sweep Neighbor	27775.9	1.5	51.1	27782.9
Sweep MST	27627.3	35	55.1	27620.5
Sweep Angles	27320.4	6	43.5	27344.6
w/Center(EP,CW)	27238.2	0.15	92.4	27257.4
w/Center(MP,SW)	27188.4	0.3	182.5	27184.8
w/Center(MP,CW)	27453.4	0.15	107	27473.1
w/Center(EP,CW)*	27590.9	0.05	102.9	27562.8
w/Center(MP,SW)*	27096.5	0.5	169.3	27100.1
w/Center(MP,CW)*	27393.6	0.45	107.6	27401.7

Table D.23: N300_SL10_Rand_3

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	28622.3	1.6	17.8	28634
All Sweeps	27980.8	--	502.5	27977.3
Sweep Neighbor	28397.1	0.5	35.9	28425.2
Sweep MST	28271.9	10	45.7	28293.2
Sweep Angles	28212.3	21	39.4	28233.9
w/Center(EP,CW)	28015.2	0.25	102.3	28023
w/Center(MP,SW)	28171.1	0.45	180.1	28200.8
w/Center(MP,CW)	27884.2	0.5	75	27896.1
w/Center(EP,CW)*	28440.9	0.25	103.6	28438
w/Center(MP,SW)*	28331.3	0.5	139.4	28332.6
w/Center(MP,CW)*	27684.4	0.5	112.2	27689.7

Table D.24: N300_SL10_Rand_4

Approach	Result	Parameter Value	Time	Robust Score
Traditional VRP	28804.9	1.4	20.8	28795.4
All Sweeps	28369	--	546	28328.6
Sweep Neighbor	28780	1.5	58	28766
Sweep MST	28667.1	5	38	28638.4
Sweep Angles	28717.2	12	41.9	28667.5
w/Center(EP,CW)	28378.8	0.2	92.9	28379.9
w/Center(MP,SW)	28310.1	0.25	159.3	28326.2
w/Center(MP,CW)	28577.8	0.5	103.2	28542
w/Center(EP,CW)*	28984.3	0.35	121.1	28965
w/Center(MP,SW)*	28512	0.35	199.4	28508.7
w/Center(MP,CW)*	28099.9	0.2	144.5	28126.6

Table D.25: N300_SL10_Rand_5

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