WINTER ROAD MAINTENANCE SYSTEM DESIGN FOR SNOW PLOWING

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

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In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Department:
Industrial and Manufacturing Engineering

September 2010

Fargo, North Dakota

North Dakota State University
Graduate School

Title

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

ABSTRACT

Kayabas, Poyraz, M.S., Department of Industrial and Manufacturing Engineering, College of Engineering and Architecture, North Dakota State University, September 2010. Winter Road Maintenance System Design for Snow Plowing. Major Professor: Canan Bilen-Green.

Winter road maintenance is critical to ensuring safety and mobility of transportation systems in regions with heavy snowfall. Winter road maintenance system design involves several inter-related decision making problems for different operations that are often performed with expensive and limited resources. This study involves developing an integrated solution methodology for depot location selection, district design, and vehicle routing problems for winter road maintenance system design in the context of snow plowing. The methodology allows decision makers to evaluate and compare different system alternatives based on a number of service level related system design criteria. The solution methodology is illustrated using the example of the road network of the Fargo District of North Dakota's transportation system. Results indicate that the methodology can be used as a decision making support tool for planning winter road maintenance operations.

ACKNOWLEDGMENTS

I would like to thank the Graduate School and the Department of Industrial and Manufacturing Engineering for providing me an opportunity to attend North Dakota State University.

I would like to thank my adviser, Dr. Bilen-Green, for her support, encouragement, and guidance. She was my motivator and disciplinarian. I would also like to thank my committee members: Dr. Cook, Dr. Tolliver, and Dr. Yadav for their insight, service, and commitment.

I especially would like to thank my sister and parents for their love and sacrifice.

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CHAPTER 1. INTRODUCTION

Winter road maintenance is critical to ensuring safety and mobility of transportation systems in regions with heavy snowfall. Winter road maintenance operations are costly processes that are often performed with expensive and limited resources. However, even small improvements in winter road maintenance operations have the potential for significant cost savings [1].

Traditionally, the complexity involved in winter road maintenance operations has resulted in problem solving procedures that consider each of the winter road maintenance system design problems separately [1, 2]. As highlighted by Perrier et al. [1], due to strong interactions between winter road maintenance system design problems, separate problem solving procedures can lead to suboptimal solutions. Therefore, more integrated solution approaches should be considered. An integrated problem solving approach, related to district design, vehicle depot location selection, and snow plow routing operations, is proposed in this thesis. A case study involving the Fargo District snow removal will be used to demonstrate the potential usefulness of the proposed approach.

1.1. Problem Statement

Snow plow routing problem is generally considered separately in the context of winter road maintenance operations. When snow plowing is integrated with other winter road maintenance operations, it becomes more complicated. Cases like this occur, for example, when some of the vehicles, equipment and infrastructure allocated for snow plowing operations can also be used for different winter road maintenance operations and tasks other than winter road maintenance. In such cases, models that take all aspects of snow plow routing into consideration are extremely complex. It is therefore necessary to develop an efficient system design approach for snow plow routing when snow plow routing problem cannot be completely integrated with and separated from other winter road maintenance system design components.

This study involves developing an integrated solution methodology for depot location selection, district design, and vehicle routing problems for winter road maintenance system design in the context of snow plowing. The methodology allows decision makers to evaluate a number of system design criteria for each system design alternative in a reasonable solution time. The flexible mathematical model formulation in the district design phase and step-by-step algorithmic structure used in the routing phase of the methodology make possible to evaluate and compare different system alternatives based on a number of service level related system design criteria.

1.2. Outline of the Thesis

This section briefly describes the contents of the upcoming chapters of this thesis.

Chapter 2 presents an overview of winter road maintenance system design and literature review on system design problems studied in this thesis. In this chapter, winter road maintenance operations, decision making problems, and operation costs are described. The chapter includes description of district design problem and literature review on districting problems in the context of winter road maintenance as well as description of vehicle routing problem and review of snow plow routing studies presented in the literature.

Chapter 3 presents the solution methodology used in this thesis for depot location selection, district design, and vehicle routing problems in the context of snow plowing. Solution methodology includes three phases: network initialization, network partitioning, and network routing.

Chapter 4 presents the implementation of the solution methodology for the Fargo District road network of North Dakota transportation system. The methodology is executed for a number of different system design scenarios and results are discussed.

Chapter 5 presents conclusions and future research directions of this study.

CHAPTER 2. LITERATURE REVIEW

This chapter first presents an overview of winter road maintenance system design. The literature review on winter road maintenance system design problems involving district design and vehicle depot location selection, and snow plow routing is presented in later sections.

2.1. Winter Road Maintenance System Design

Although winter road maintenance is an expensive investment, nevertheless it is demanded by the public. Winter road maintenance system design involves several decision making processes to achieve desired outcomes of winter road maintenance operations. This section contains brief descriptions of winter road maintenance operations, winter road maintenance decision making problems, and costs associated with them to develop a background for the later sections of this chapter.

2.1.1. Winter Road Maintenance Operations

Winter road maintenance operations are generally categorized into three types: chemical, mechanical and thermal. A detailed review of winter road maintenance operations is presented in the book by Minsk [3].

As highlighted by Minsk [3], deicing and anti-icing are two basic winter road maintenance chemical operations. Deicing is used to melt ice formations on pavement and anti-icing is used to prevent in advance any ice formation. Deicing and anti-icing operations, generally, include application of freezing point depressants on a road surface. The most common chemical used is salt (sodium chloride) because of its availability, lower cost and solubility in the water. Salt works by lowering the freezing point of water. When pavement temperature is too low for chemical treatments to be effective, abrasives are used to increase the traction. Sand is the main abrasive used for this purpose because of its availability and lower cost. Chemicals and abrasives used in winter road maintenance may have side effects. These side effects increase direct and indirect costs of winter road maintenance; sand and salt-sand mix applications may require additional cleanup operations. According to Perrier et al. [1], it is important to use chemicals and abrasives at the right time and in the right quantity in winter road maintenance operations to increase the effectiveness of chemical applications, decrease the side effects, and minimize the associated costs with them.

Thermal operations used in winter road maintenance are applications of heat to the pavement from either above or below [3]. Heat is generally used to treat hazardous ice and snow formations such as snow packs, black ice, and glaze ice for traffic safety. Snow packs are compacted form of snow and are formed by traffic action. Black ice and glaze ice are types of thin coating of ice on the road surface. Black ice is nearly invisible; glaze ice is clear and glasslike. Although thermal operations are too expensive for general use, they can be used at critical locations, such as on/off ramps, bridges, decks, steep grades and toll plazas to increase service quality and safety [3].

Mechanical operations include physical removal of snow and ice from the road surface and transporting to the storage or disposal areas [3]. Plowing and brooming are two basic mechanical operations. Plowing is used to move as much snow as possible from the road surface before deicing and anti-icing applications start up. Brooming is an alternative way of deicing without using any chemicals. In some road and weather conditions, deicing is required before mechanical removal of ice and snow packs on the road.

2.1.2. Winter Road Maintenance Decision Making Problems

Winter road maintenance system design involves several inter-related decision making problems. According to Perrier et al. [1], winter road maintenance decision making problems can be categorized into four levels based upon their immediate impacts or long term significance. Table 1 presents examples of relevant problems addressed at each level of this classification scheme: strategic, tactical, operational and real time. Strategic level is the highest level of the classification scheme. Strategic level decision making problems consider long term issues related to winter road maintenance system design. Resources used at strategic level decision making processes are long-lasting and require significant investment, such as acquiring a vehicle depot in a district. Therefore, the goal of winter road maintenance system design at this level is the best utilization of resources. Tactical level decision making problems consider medium and short term issues, which can be updated every few months, such as assignment of vehicle depots to districts. Operational level decision making problems are related with daily winter road maintenance tasks, such as routing of vehicles, and their impact is immediate. At this level, decisions are made to support tactical level decisions. There are also real time decision making problems which are related to sudden and unexpected changes in the system, such as weather changes and accidents. System design approaches should consider relations between different levels of winter road maintenance decision making problems. Therefore, decisions can be made in a much more comfortable and intelligent way by providing guidelines and goals.

Table 1 Four-level classification scheme for winter road maintenance decision making problems and examples of relevant problems addressed at each level, Perrier et al. [1]

Strategic Level • Service level policy-making • Partitioning a region or road network into sectors • Scheduling of fleet replacement • Location of various facilities such as disposal sites, vehicle and material depots
Tactical Level • Assignment of sectors to disposal sites • Assignment of facilities such as disposal sites, vehicle and material depots to districts • Sizing vehicle fleets for sectors
Operational Level • Routing of vehicles • Scheduling of vehicles • Crew staffing of vehicles
Real Time Level • Effects of weather changes • Accidents • Vehicle and equipment breakdowns

2.1.3. Winter Road Maintenance Operation Cost

In the United States, cost directly associated with winter road maintenance is over $2.3 billion annually [4] and indirect costs are estimated at $5 billion per year [5]. Material, vehicle, equipment, infrastructure and labor expenses for winter road maintenance are the primary direct cost components. Since, some of the vehicles, equipment and infrastructure may be used for tasks other than winter road maintenance operations, the quantification of direct costs for winter road maintenance operations is a challenging task. Indirect costs are attributed to loss of productivity and wages due to decreased mobility, and effects of chemicals on infrastructure, vehicles and environment.

Delay costs and accidental costs due to poor road conditions are other important indirect cost components, although they are generally difficult to express in monetary values. Each year, 10 percent of vehicle crashes (39 percent of weather-related vehicle crashes) occur on snowy or icy road conditions (Table 2). The cost of delay in travel time due to congestion or weather conditions increases every year. According to the Bureau of Transportation Statistics, the cost of delay in travel time is estimated at $15.47 per hour of person travel and $102.42 per hour of truck travel [6].

Table 2 Weather-related crash statistics, eleven-year averages from 1995 to 2005 analyzed by Noblis [4], based on National Highway Traffic Safety Administration data

Road Weather Conditions	Annual Rates (Approximately)	Percentages	
Snow/Sleet	232,600 crashes	4% of vehicle crashes	15% of weather-related crashes
	75,700 persons injured	2% of crash injuries	11% of weather-related crash injuries
	900 persons killed	2% of crash fatalities	12% of weather-related crash fatalities
Icy Pavement	197,300 crashes	3% of vehicle crashes	13% of weather-related crashes
	67,300 persons injured	2% of crash injuries	10% of weather-related crash injuries
	700 persons killed	2% of crash fatalities	10% of weather-related crash fatalities
Snow/Slushy Pavement	168,400 crashes	3% of vehicle crashes	11% of weather-related crashes
	49,500 persons injured	2% of crash injuries	7% of weather-related crash injuries
	600 persons killed	2% of crash fatalities	9% of weather-related crash fatalities

2.2. Winter Road Maintenance District Design

This section contains a review of district design applications in the context of winter road maintenance.

The aim of district design is to divide a geographical area into parts, pieces, or sections to satisfy some set of constraints. Some typical applications of district design include design of political districts [7, 8], school board boundary districts [9, 10], logistics districts [11], electrical power districts [12], police districts [13], and health care districts [14]. Criterion for districting in various applications often includes socio-economic, demographic, and political factors.

District design for winter road maintenance operations involves partitioning a road network into smaller ones by assigning basic units of the road network, such as road segments, to their closest service facility [1]. In winter road maintenance, applications of district design include design of districts for snow disposal operations [15, 16], districts for salt spreading operations [17], districts for gritting operations [18], and districts for snow removal operations [19, 20]. The aim of district design is to provide better winter road maintenance service while satisfying administrative, organizational and jurisdictional needs and operational requirements.

Snow disposal operations start after the snow is plowed and accumulated as close as possible to road side or sidewalk. There are two major steps in snow disposal operations: snow loading and operations in snow disposal sites. Campbell and Langevin [21, 22] discussed that snow disposal operations are expensive and challenging tasks due to the complexity involved in the fundamental problem of partitioning service areas into districts and evaluating potential locations, such as river sites, surface sites, sewer chutes, and quarries for snow disposal assignment.

Labelle et al. [15] proposed a heuristic approach for district design for snow removal in urban areas. The snow removal problem is described as designing a set of service districts for snow disposal operations and determining the assignment of service districts to the disposal sites. The authors discussed that district design problem for snow disposal operations can be solved by aggregating smaller road network units into sectors. The non-linear integer programming model proposed for district design problem is presented below; definitions for decision variables and parameters used in the model formulation are given in Table 3.

Table 3 Definitions for decision variables and parameters, Labelle et al. [15]

x_{ij}= 1 if zone i is assigned to sector j and 0 otherwise
y_{jk}= 1 if sector j is assigned to disposal site k and 0 otherwise
d_{ik}= distance from zone i to disposal site k (km)
v_i= annual volume of snow in zone i (m^3/yr)
r_j= snow removal rate in sector j (m^3/h)
V_k= annual capacity of disposal site k (m^3/yr)
R_k= maximum snow receiving rate of disposal site k (m^3/hr)
M= maximum number of zones per sector
t_v= truck capacity (m^3)
v_s= truck speed (km/hr)
c_{ik}= cost per cubic meter for hauling snow from zone i to disposal site k (m^3/$)
CV_k= variable cost for disposal site k (m^3/$)
CT= fixed cost for trucks($/yr)

$$\text{Minimize} \sum_i \sum_j \sum_k C_{ik} v_i x_{ij} y_{jk} + \sum_k CV_k \sum_i \sum_j v_i x_{ij} y_{jk} + CT \sum_j \left(\left[\frac{2r_j}{t_s \times t_v} \times \max_{i,k} \left\{ d_{ik} x_{ik} y_{jk} \right\} \right] + \tau \right) \quad (1.1)$$

$$\sum_j x_{ij} = 1 \quad \text{for all zones i} \quad (1.2)$$

$$x_{ij} \leq \sum_k y_{jk} \quad \text{for all zones i and sectors j} \quad (1.3)$$

$$\sum_i x_{ij} \leq M \quad \text{for all sectors j} \quad (1.4)$$

$$\sum_i \sum_j v_i x_{ij} y_{jk} \leq V_k \quad \text{for all disposal sites k} \quad (1.5)$$

$$\sum_i \sum_j r_i x_{ij} y_{jk} \leq R_k \quad \text{for all disposal sites k} \quad (1.6)$$

each sector is a contiguous collection of zones (1.7)

$$x_{ij}, y_{jk} \in \{0,1\} \quad \text{for all i, j, and k} \quad (1.8)$$

The objective function (1.1) minimizes the sum of three costs: the total transportation cost of hauling snow from service sectors to the disposal sites; the total variable cost of operating disposal sites; and the total fixed cost of operating service trucks. The third term in the objective function has non-linearity: the product of two decision variables t_s and t_v, and the maximum function. Constraint set (1.2) ensures that each zone i must be assigned to a sector j. Constraint set (1.3) ensures that if a zone i is assigned to a sector j, then sector j must be assigned to some disposal site k. Constraint set (1.4) limits the maximum allowable sector size, where M is the maximum allowable number of zones. Constraint set (1.5) ensures that annual capacity of disposal site k is large enough to handle the annual volume of snow hauled from sectors assigned to it. Constraint set (1.6) ensures that hourly capacity of disposal site k is large enough to handle the hourly volume of snow hauled from sectors assigned to it. Constraint set (1.7) represents the set of constraints that is needed to ensure that aggregated zones are all connected. Constraint set (1.8) is the restrictions on model decision variables.

As highlighted by Labelle et al. [15], there are no feasible solutions to the model due to the non-linearity of the third term in the objective function and difficulty in formulating a set of constraints for district contiguity. Thus, a heuristic procedure is developed for the solution to the district design and disposal site assignment problem. The proposed heuristic has three phases. The first phase of the heuristic is an assignment procedure. A penalty cost, Penalty (i), is calculated and used to assign zones directly to the disposal sites. The penalty cost (1.9) is the difference between the cost of assigning zone i to the lowest cost facility, f(i), and the cost of assigning zone i to the second lowest cost facility, s(i),

$$\text{Penalty}(i)=C(i,s(i))-C(i,f(i)) \tag{1.9}$$

where C(i,k) describes the cost of snow removal and hauling from zone i to disposal site k. The algorithmic description of the first phase of the heuristic, by Labelle et al. [15], is as follows:

Step 1. Calculate the penalty for each zone i: Penalty(i)=C(i,s(i))-C(i,f(i)).

Step 2. Find the unassigned zone with the largest penalty, say i^*, and assign it to its best disposal site $f(i^*)$.

Step 3. Update the set of feasible zones for site $f(i^*)$, and update f(i), s(i), and penalty (i) for all zones i for which $f(i)=f(i^*)$ or $s(i)=f(i^*)$.

Step 4. Repeat Step 2 and Step 3 until no more zones can be assigned.

Step 5. Assign any unassigned zones to a dummy site at infinite cost. The output from step is an initial zone-disposal site assignment.

The second phase of the heuristic is an improvement procedure. An exchange procedure is used to consider reassigning zone pairs between disposal sites and to improve total assignment cost. The algorithmic description of the second phase of the heuristic, by Labelle et al. [15], is as follows:

Step 1. For each pair of zones i and j, with assigned sites site (i) and site (j), reassign zones i and j to every other pair of sites k ($k \neq$ site (i)) and l ($l \neq$ site (j)).

Step 2. Repeat Step 1 until no more zones can be assigned. The outcome from this step is the final zone-disposal site assignment.

The third phase of the heuristic uses final zone-disposal site assignment as an input and creates a number of sectors for each disposal site with the given zones already assigned to them. The algorithmic description of the third phase of the heuristic, by Labelle et al. [15], is as follows:

Step 1. For each pair of adjacent zones i and j, calculate the savings, $\min\{d_{ik}, d_{jk}\}$, where d_{ik} represents the distance between the center of zone i to the disposal site k.

Step 2. If a zone has only one neighbor zone, then merge the zones if their union does not exceed maximum sector size.

Step 3. Repeat Step 2 until there are no zones with only one neighbor.

Step 4. Merge the two adjacent zones with the largest savings value if their union does not exceed maximum sector size.

Step 5. Repeat Step 1- Step 5 until all zones are joined to some sector.

The heuristic approach was tested on a road network in Montreal, Quebec, Canada, involving 390 zones and 60 sectors. Based on the test results, authors concluded that the districting is mostly guided by minimizing the number of service vehicles required for the disposal operations. The reader should note that minimizing the number of service vehicles was the non-linear objective function term in the non-linear integer programming model proposed by Labelle et al. [15] earlier. Authors built a GIS based decision support system for the test network area and integrated the heuristic approach for use by snow disposal practitioners.

Perrier et al. [16] proposed a mathematical model for sector design and assignment problem for snow disposal operations. The proposed mathematical model is similar to the non-linear integer programming model developed by Labelle et al. [15]. However, compared with the Labelle et al. [15], Perrier et al. [16] used a multi-commodity network flow structure to successfully represent the contiguity constraints in a linear form. Model was tested using data from Montreal, Quebec, Canada. Test results showed that feasible solutions are obtained for only two small sized problems. The authors discussed that introducing a number of decision variables and constraints to the model, to ensure contiguity requirements, increased the model size dramatically; even for medium sized test scenarios large computation time and memory requirements were needed. Thus, Perrier et al. [16] developed two constructive solution heuristics to solve the districting problem efficiently: the assign first, partition second heuristic and the partition first, assign second heuristic.

The assign first, partition second heuristic contains two mixed integer programming models. The first integer programming model is used to assign road segments to the disposal sites. The objective function of the first integer programming model minimizes the sum of the total annual cost of hauling snow from road segments to the disposal sites and the total annual operating cost of disposal sites. A multi-commodity network flow is integrated into the model formulation to ensure that influence areas are contiguous. The term "influence area" is used to describe the set of road segments assigned to each disposal site. Therefore, the output of the first integer programming model solution is an influence area for each disposal site. The second integer programming model uses the influence areas as an input and partitions each influence area into service sectors while minimizing the sum of the total annual fixed cost for trucks. Therefore, the output of the second integer programming model is a number of sectors for each disposal site and a number of trucks servicing these sectors. The assign first, partition second heuristic can be summarized as follows:

Step 1. Solve the first integer programming model, given in constraints (2.1)-(2.15) in Perrier et al. [16], to determine the influence area for each disposal site.

Step 2. For each influence area assigned to a disposal site solve the second integer programming model, given in constraints (2.16)-(2.29) in Perrier et al. [16], to determine the service sectors and the number of trucks servicing them.

Similarly, the partition first, assign second heuristic contains two mixed integer models. The first integer programming model aggregates road segments to form service sectors. Since sector contiguity is the major design concern at this stage, a multi-commodity network flow is integrated in the model formulation. The objective function of the model considers only the contiguity by minimizing the sum of the total multi-commodity flow through each road segment. The model solution provides a number of service sectors. The service sector sizes can be determined with a set of constraints given in the model formulation. The second integer programming model uses service sectors as an input and assigns them to the disposal sites. The objective function of the model minimizes the sum of the total annual cost of hauling snow from road segments to the disposal sites and the total annual operating cost of disposal sites. The model solution provides a set of service sectors assigned to each disposal site. The partition first, assign second heuristic can be summarized as follows:

Step 1. Solve the first integer programming model, given in constraints (2.30)-(2.39) in Perrier et al. [16], to form service sectors.

Step 2. Solve the second integer programming model, given in constraints (2.40)-(2.44) in Perrier et al. [16], to assign service sectors to the disposal sites.

A number of computational experiments were performed to compare these two heuristic approaches. The authors concluded that in terms of determining number of trucks both heuristics compete with each other. However, the first heuristic can provide better results in terms of minimizing total design costs and with respect to computing time.

Muyldermans et al. [17] used an elemental cycling approach for partitioning a road network into service districts for salt spreading operations. Salt spreading is a common winter road maintenance practice that is often studied in the context of vehicle routing. However, as highlighted by Muyldermans et al. [17], salt spreading operations are organized within districts and long-term savings can be achieved if effect of districting is taken into account in earlier stages of winter road maintenance planning. Muyldermans et al. [17] defined districting problem as partitioning a road network into a number of sectors, in which depots are already located.

The proposed elemental cycling approach for winter road maintenance districting has four stages. The first stage is the preprocessing stage and creates small service cycles in the road network. Service cycles are then used as basic units of district formation process. The second stage is the partial assignment stage and assigns any service cycle to a depot if distance between service cycle and depot is too small. The cycle ratio is used as the assignment criteria. The cycle ratio is the average distance to reach service cycle j from depot i. The third stage is the iterative assignment stage and it has two phases. In the first phase, relatively close service cycles are assigned to depots based on the cycle ratio value. In the second phase, a multi-criteria assignment approach is used to assign any unassigned service cycle to depots. The fourth stage of the heuristic is the user interaction stage. In this stage user can interchange service cycles between depots based on site specific constraints that cannot be considered in the earlier stages. Therefore, small service cycles are aggregated to form bigger cycles, referred to as clusters. Then, big enough clusters are referred to as districts and depots already located in them are responsible for organization of winter road maintenance activities within their district borders. The elemental cycling approach for districting, by Muyldermans et al. [17], can be summarized as follows:

Stage 1: Preprocessing

This stage partitions network into elemental cycles by elemental cycling approach. Elemental cycling approach in districting is first introduced by Male and Liebman [23] in the context of solid waste collection. According to elemental cycling approach, an Eulerian Graph (G) is generated for the road network, and then G is partitioned into small cycles using a "checkerboard pattern" to obtain a set of elemental cycles. In elemental cycle pattern, every edge belongs to exactly one cycle. Therefore, elemental cycles can be used as basic building blocks for constructing districts instead of individual road segments. In later part of this stage, cycle weights and cycle ratios for service cycle-depot assignments are calculated.

The cycle weight (CW_j) corresponds to the amount of salt to service roads in cycle j. The cycle ratio (R_{ij}) is a measure of average distance to reach cycle j from depot i and is given by:

$$R_{ij}=\frac{\overline{D_{ij}}}{\min_{i'\neq i}\{\overline{D_{i'j}}\}} \tag{2.1}$$

$$\overline{D_{ij}}=\frac{\sum_{k\in CN_j} D_{ik}}{|CN_j|} \tag{2.2}$$

where CN_j represents the set of nodes in cycle j, and D_{ik} represents the shortest path distance from depot i to node k.

Stage 2: Initial Partial Assignment

In this stage, if a cycle j is adjacent to a depot i, then cycle j is assigned to depot i. The cycle ratio (R_{ij}) determines the assignment criteria; $R_{ij}\leq 0.5$ indicates that cycle j is very close to depot i. This stage speeds up the districting procedure by assigning service cycle-depot pairs which are adjacent.

Stage 3: Two-Phase Iterative Assignment

This stage consists of two phases. Phase A considers only cycles relatively close to depots; $0.5<R_{ij}<1$ indicates that cycle j is relatively close to depot i. The authors discussed that a simple bin packing heuristic, described by Levy and Bodin [24], is used as the assignment procedure. At each iteration, the cycle with the largest cycle weight is assigned to the depot with the smallest workload. Phase A ends when all relatively closed cycles are assigned to the depots.

Phase B considers a multi-criteria approach; three criteria are considered for assignments: compactness, number of trucks, and workload balance. Individual scores for each criterion are calculated for all cycle depot assignments.

Compactness score is a closeness measure of the cycle to depot, defined by $\max\{BR_i, R_{ij}\}$ where BR_i, is a specified benchmarking value for depot i, $0.5 < R_{ij} < 1$ for all i. Table 4 represents a scale for compactness scores for the corresponding closeness measure of the cycle to depot.

Table 4 Compactness score scale for closeness, Muyldermans et al. [17]

Evaluation Criteria	Compactness Score
$\max\{BR_i, R_{ij}\} \leq BR_i$	0
$BR_i < \max\{BR_i, R_{ij}\} \leq 1$	1
$1 < \max\{BR_i, R_{ij}\} \leq 1.5$	2
$1.5 < \max\{BR_i, R_{ij}\} \leq 2$	3
$2 < \max\{BR_i, R_{ij}\}$	Not Allowed

Number of trucks score, N, is an approximation of the number of trucks to be used in district. The mathematical representation is given by:

$$N = \frac{\sum_i \text{Total workload in district}}{\text{Vehicle capacity}} \quad (2.3)$$

The workload balance measure evaluates the workload balance between districts; if addition of a cycle to a depot will either increase or decrease workload balance then it is equal to 1, otherwise 0. By comparing individual scores of different cycle depot assignments, assignments with the smallest scores are chosen.

The weighted sum of these three scores is calculated and remaining cycle-depot assignments are chosen with the smallest weighted scores.

Stage 4: Improvement and User Interaction

In this stage, topological, climatic, shift or interchange cycles between depots, and other site specific constraints are addressed. The authors discussed that a user interactive improvement procedure, presented in Li and Eglese [25], can be developed for this stage.

The proposed approach was tested on a road network in Antwerp, Belgium, consisting of four existing districts and a network of 244 road segments. The authors concluded that existing districting is improved, and compact and workload balanced new districts are achieved.

In another study, Muyldermans et al. [18] presented three district design heuristics for arc-routing applications; specifically, districting for winter road maintenance is addressed in the context of gritting. A number of test problems are used to compare the heuristic performances. The main characteristics of test problems differ in vehicle capacities, and local and radial travel costs. Based on test results, Muyldermans et al. [18] concluded that heuristics propose different districting guidelines for different types of district design concerns. The algorithmic descriptions of heuristics, by Muyldermans et al. [18], are given using the following notation:

G(V,E) is the connected planar graph that represents road network. V and E are the vertex set the edge set in G, respectively. X represents the set of facilities in G and is a subset of V.

H(W,F) is the unit-adjacency graph of G. W is the vertex set and has a vertex w_j for each unit and each facility in G. F is the edge set and has an edge f_{ij} between w_i and w_j if (1) the corresponding units u_i and u_j in G have a vertex in common or (2) if the facility associated with w_i is located on the unit presented by w_j in H. Vertex set W has two subsets: W_U is for units in H and W_F is for facilities in H. With every vertex $w_j \in W$, there exists a corresponding weight $q(w_j)$ which represents the demand on unit u_j if $w_j \in W_U$ and 0 otherwise.

R_{ij} is the proximity ratio between the facility $v_i \in X$ ($w_i \in W_F$) and the edges of unit u_j in G ($w_j \in W_U$).

$$R_{ij}=\frac{D(v_i,u_j)}{\min\{D(v_k,u_j)|\ v_k \in X,\ v_k \neq v_i\}} \tag{3.1}$$

$D(v_i, u_j)$ – The sum of shortest distances between v_i and u_j.

$$D(v_i,u_j)=\sum_{e_{rs} \in u_j} (d(v_i,v_r)+d(v_i,v_s)) \tag{3.2}$$

The algorithmic descriptions for the proposed heuristics, the $C_{min\ ratio}$ heuristic, the $E_{min\ ratio}$ heuristics, and the C_{ILP} heuristic, by Muyldermans et al. [18], are as follows:

The $C_{min\ ratio}$ heuristic:

Step 1. Define the unit u_j in G by the cycle decomposition method [23] and the edge exchange heuristic [26].

Step 2. Construct the unit-adjacency graph H and calculate the ratios R_{ij}. Initially all units $w_j \in W_U$ are unassigned.

Step 3. If all units $w_j \in W_U$ are allocated, go to Step 5.

Step 4. For each facility $w_j \in W_F$, select the unassigned unit $w_j \in W_U$ with the lowest ratio value R_{ij} adjacent to w_i or to a unit w_k already assigned to facility in the pair with the lowest R_{ij} value. Go to Step 3.

Step 5. Translate unit allocations in H into a district partition G.

$C_{min\ ratio}$ heuristic aggregates edges to form cycles, then cycles are assigned to facilities. The authors discussed that when vehicle capacity is a major concern in districting and vehicle capacities are large, $C_{min\ ratio}$ heuristic can perform well. The reason is that when a vehicle reaches to a cycle, there is still a routing required to complete service (local travel); and, generally, the cost and the importance of the local travel dominates the average distance required reaching the cycle (radial travel).

The $E_{min\ ratio}$ heuristic:

Step 1. Define the units u_j in G by taking every edge $e_{rs} \in E$ as a unit.

Step 2. Construct the unit-adjacency graph H and calculate ratio R_{ij}. Initially all units $w_j \in W_U$ are unassigned.

Step 3. If all units $w_j \in W_U$ are allocated, go to Step 5.

Step 4. For each facility $w_j \in W_F$, select the unassigned unit $w_j \in W_U$ with the lowest ratio value R_{ij} adjacent to w_i or to a unit w_k already assigned to facility in the pair with the lowest R_{ij} value. Go to Step 3.

Step 5. Translate the unit allocations in H into a district partition G.

The procedure in $E_{min\ ratio}$ heuristic is similar to the $C_{min\ ratio}$ heuristic except the first step, where the description of basic units to be assigned. The authors recommended $E_{min\ ratio}$ heuristic for districting when vehicle capacity is a major concern and vehicle capacities are small. The reason is that when a vehicle services single or only a few numbers of road segments at a time, the average distance to reach road segments (radial travel) becomes more important. Therefore, $E_{min\ ratio}$ heuristic should be used to assign network units to the closest facilities.

The C_{ILP} heuristic:

The C_{ILP} heuristic has two phases. The first phase is a preprocessing stage which reduces the size of the unit-adjacency graph, H. The adjacency graph reduction is done by assigning units to their very near depots and aggregating some units by their structural properties. For a detailed description of the adjacency graph reduction procedure, the reader is referred to the Stage 2 of the elemental cycling approach based districting heuristic proposed by Mulydermans et al. [17]. The second phase of the heuristic uses reduced unit-adjacency graph, H, as an input. An integer linear programming model is presented to assign units in H to facilities. The model minimizes the number of vehicles to be used and constructs compact districts by penalizing any distant units assigned to facilities. Therefore, focus of this model is mainly on the fixed and variable cost of vehicles to be used in service. The complete formulation of the integer linear programming model is presented below; definitions for decision variables and parameters used in the model formulation are given in Table 5.

Table 5 Definitions for decision variables and parameters, Mulydermans et al. [18]

y_i= lower bound on the number of vehicles assigned to the corresponding facility w_i
α= scale factor for sum of the ratio of the most distant units
$R_{max,i}$= the maximum of the R_{ij} values among the units assigned to facility $w_i \in W_F$
x_{ij}= 1 if unit $w_i \in W_U$ is assigned to facility $w_i \in W_F$ and 0 otherwise
Q= vehicle capacity

$$\text{Minimize} \sum_{w_i \in W_F} y_i + \alpha \sum_{w_i \in W_F} R_{max,i} \tag{3.3}$$

$$\sum_{w_i \in W_j} x_{ij} = 1 \quad \forall\, w_j \in W_U \tag{3.4}$$

$$\sum_{w_j \in W_i} \left(q(w_j)x_{ij} + q(w_i)\right) \leq Q y_i \quad \forall\, w_i \in W_F \tag{3.5}$$

$$x_{ij} \leq \sum_{w_k \in W_{ij}} x_{ik} \quad \forall\, W_{ij} \neq \emptyset,\ w_i \in W_F,\ w_j \in W_i \tag{3.6}$$

$$R_{ij} x_{ij} \leq R_{max,i} \quad \forall\, w_i \in W_F,\ w_j \in W_i \tag{3.7}$$

$$x_{ij} \in \{0,1\} \quad \forall\, w_i \in W_F,\ w_j \in W_i \tag{3.8}$$

$$y_{ij} \text{ integer} \quad \forall\, w_i \in W_F \tag{3.9}$$

$$R_{max,i} \geq 0 \quad \forall\, w_i \in W_F \tag{3.10}$$

The objective function (3.3) minimizes the sum of the lower bound on the number of vehicles to be used and the sum of the ratio of the most distant units. Minimizing the sum of $R_{max,i}$ ratios, the second term in the objective function, penalizes the non-compactness of each district. The authors discussed that the scale factor, α, should be chosen small enough to set an upper bound on the second term so that the value of second term does not affect the value of the first term. Constraint set (3.4) ensures that every unit must be assigned to a facility. Constraint set (3.5) ensures that the total capacity of vehicles assigned to a facility is large enough to satisfy the service demand assigned to that facility. Constraint set (3.6) ensures that all units assigned to a facility are connected. Constraint set (3.7) selects the maximum ratio value for each district. The maximum ratio value within each district must be at least greater than the ratio value of any unit in that district. Constraint sets (3.8)-(3.10) are restrictions on model decision variables. The C_{ILP} heuristic is recommended for districting applications with large vehicle capacities and there is a lower limit on number of vehicles available. Compared with the first two heuristics, C_{ILP} heuristic requires more computation time.

Kandula and Wright [19] presented an optimization model for partitioning a road network into service districts for winter road maintenance in the La Porte District of Indiana. The proposed optimization model is a mixed integer programming model and combines district design, depot location selection, and fleet sizing problems. The objective function of the model is described as a measure of compactness value and it minimizes the sum of the shortest distances from service depots to road segments. The model solution provides depot site locations to operate, road segment assignments to depots, and number of service vehicles to allocate at each depot location for service. While model cannot generate plowing and spreading routes, deadheading distances can be approximated with a deadheading factor integrated in the contiguity constraints. The overall goal of the model is to construct service districts for better vehicle routing operations. The quality of districting is measured with a compactness measure and number of vehicles required for service. The model was tested on a road network in Indiana consisting of four depots and a network of 79 road segments. The authors concluded that choice of deadheading factors have significant effects on the quality of model solutions. For the test data, the number of service vehicles is overestimated than the number of vehicles currently used in service. As highlighted by Kandula and Wright [19], deadheading speed assumption was the reason for the overestimation; deadheading speed was assumed equal to service. However, in practical operations deadheading speed is faster than service speed due to the nature of plowing or spreading operations. The authors also developed LP relaxation of the model. It is found that LP relaxation model solution was close to integer programming model solution in terms of compactness value and locations of depots. Required number of service vehicles in LP relaxation model solution was reduced by 15 percent. However, it was observed that LP relaxation model solution was not practically feasible since it included several fractional road segment-depot assignments and a non-contiguous district design. According to Kandula and Wright [19], manual modifications can be used to improve the relaxed LP model solution so that model solution can be practically feasible. The complete formulation of the district design model, by Kandula and Wright [19], is presented below; definitions for decision variables and parameters used in the model formulation are given in Table 6.

$$\text{Minimize} \sum_{p} \sum_{(i,j)} L_{ijp} \tag{4.1}$$

$$\sum_{p} X_{ijp} = 1 \quad \forall\, (i,j) \tag{4.2}$$

$$\sum_{i,j} W_{ij} \cdot X_{ijp} - U_p \cdot CAP_p \leq 0 \quad \forall\, p \tag{4.3}$$

$$\sum_{i,j \in \text{Class 1}} W_{ij} \cdot X_{ijp} - CL_p^1 \leq 0 \quad \forall\, p \tag{4.4}$$

$$\sum_{i,j \in \text{Class 2}} W_{ij} \cdot X_{ijp} - CL_p^2 \leq 0 \quad \forall\, p \tag{4.5}$$

$$\sum_{i,j \in \text{Class 3}} W_{ij} \cdot X_{ijp} - CL_p^3 \leq 0 \quad \forall\, p \tag{4.6}$$

$$40N_P^1 - dhf_p \cdot CL_p^1 \geq 0 \quad \forall\, p \tag{4.7}$$

$$60N_P^2 - dhf_p \cdot CL_p^2 \geq 0 \quad \forall\, p \tag{4.8}$$

$$60N_P^3 - dhf_p \cdot CL_p^3 \geq 0 \quad \forall\, p \tag{4.9}$$

$$N_p - N_P^1 - N_P^2 - N_P^3 = 0 \quad \forall\, p \tag{4.10}$$

$$\sum_p N_p \le NUMT \tag{4.11}$$

$$\sum_p U_p = NUMU \tag{4.12}$$

$$Y_{ijp} - MF \cdot X_{ijp} \le 0 \quad \forall\, (i,j),\, p \tag{4.13}$$

$$Y_{jip} - MF \cdot X_{ijp} \le 0 \quad \forall\, (i,j),\, p \tag{4.14}$$

$$\sum_k Y_{kip} - \sum_j Y_{ijp} - Y_{i0p} = 0 \quad \forall\, i \text{ non-depot nodes} \tag{4.15}$$

$$\sum_k Y_{kdp} - \sum_j Y_{djp} - Y_{0dp} = 0 \quad \forall\, d \text{ depot nodes} \tag{4.16}$$

$$\sum_p Y_{i0p} \ge 1 \quad \forall\, i \text{ non-depot nodes} \tag{4.17}$$

$$\sum_p \sum_d Y_{0dp} \ge ND \quad \forall\, d \text{ depot nodes} \tag{4.18}$$

$$Y_{0dp} = 0 \quad \forall\, d \text{ not in partition } p \tag{4.19}$$

$$X_{ijp} - Y_{i0p} \le 0 \quad \forall\, (i,j),\, p \tag{4.20}$$

$$X_{ijp} - Y_{j0p} \le 0 \quad \forall\, (i,j),\, p \tag{4.21}$$

$$L_{ijp} - SP_{ip} \cdot X_{ijp} - SP_{jp} \cdot X_{ijp} = 0 \quad \forall\, (i,j),\, p \tag{4.22}$$

$$LMAX - L_{ijp} \ge 0 \quad \forall\, (i,j),\, p \tag{4.23}$$

$$LMAX - ML \le 0 \tag{4.24}$$

$$\sum_{(i,j)} L_{ijp} - SUML_p \le 0 \quad \forall\, p \tag{4.25}$$

$$\text{COST} - C^T \cdot \sum_P N_p - C^U \cdot \sum_P U_p = 0 \quad (4.26)$$

$$U_p, X_{ijp} \in (0,1) \quad (4.27)$$

$$Y_{ijp}, Y_{i0p}, Y_{0dp} \geq 0 \quad \forall \text{ i, j, p, and d} \quad (4.28)$$

$$N_P, N_P^1, N_P^2, N_P^3 \in \{\text{integers}\} \quad (4.29)$$

The objective function (4.1) minimizes the sum of all shortest distances from depots to the road segments that are serviced from service vehicles assigned to the depots (in kilometers). Constraint set (4.2) requires that each road segment must be assigned to a single depot. Constraint set (4.3) ensures that service to a partition from depot p can only be available if that depot is in service and depot service capacity is more than the total workload assigned to it. Constraint sets (4.4)-(4.6) ensure that service vehicles at each depot p can service homogeneous classes of road segments of Class1, Class 2, and Class3. Different road segments have different service recovery times such that Class1 roads have to be serviced in every two hours and Class 2 and Class 3 road segments have to be serviced in every three hours. Constraint sets (4.7)-(4.10) ensure that there is a lower bound on the number of trucks at each depot for each road class. Coefficients used in these constraint sets represent lane mile service capacity for service vehicles such that vehicles assigned to Class 1 road segments can service 40 lane miles in every two hours while vehicles assigned to Class 2 and Class 3 road segments can service 60 lane miles in every three hours. Constraint set (4.11) is the upper bound on the total number of service vehicles required. Constraint set (4.12) determines the number of depots in operation. Constraint sets (4.13) and (4.14) represent imaginary network flows from depots to nodes. Imaginary network flows make sure that all road segments assigned to a depot are connected so that the design of continuous routes can be possible. Constraint sets (4.15) and (4.16) represent

Table 6 Definitions for decision variables and parameters, Kandula and Wright [19]

C^T= cost of a truck

C^U= cost of unit operations

CAP_p= capacity of partition p

CL_p^k= number of class k kilometers in partition p

COST= total cost of alternative

dhf_p= deadhead factor for partition p

L_{ijp}= sum of the shortest distances to the node i and the node j from the depot in the partition p to which the road segment (i,j) is assigned

LMAX= maximum of all L_{ijp}'s

MF= maximum imaginary flow in any arc

ML= maximum allowable LMAX

N_p= total number of service vehicles (i.e. trucks) in partition p

N_p^k= number of trucks for class k routes in partition p

ND= number of non-depot nodes

NUMT= number of service vehicles (i.e. trucks) chosen to service the area

NUMU= number of units to be operative

SP_{ip}= shortest path from node i to depot in partition p

$SUML_p$= sum of L_{ijp} in partition p

U_p= 1 if depot p is open and 0 otherwise

X_{ijp}= 1 if road segment (i,j)is assigned to depot p and 0 otherwise

Y_{ijp}= flow in road segment (i,j)assigned to partition p

Y_{0dp}= flow into depot d from supernode 0

Y_{i0p}= flow out of non-depot node i as a result of flow in road segments assigned to unit p

W_{ij}= workload associated with road segment (i,j) balance constraints for imaginary network flows that must be satisfied at depot and non-depot nodes. Constraint sets (4.17) and (4.18) ensure that non-depots transmit at least some positive flow and the sum of the flows into depot nodes is sufficient to meet demands at all nodes, respectively. Constraint sets (4.19)-(4.21) are used to satisfy network flow requirements and are described as: (4.19) ensures that each depot is associated with a single road segment; (4.20) and (4.21) ensure that any road segment can be assigned to a partition only when both ends of that road segment are connected to that partition. Constraint set (4.22) represents the calculation of the sum of the shortest distances from both ends of a road segment to the depot in partition p. Constraint sets (4.23) and (4.24) are the upper bounds on the maximum allowable sum of the shortest distances from both ends of a road segment to the depot in partition p and the limit to the maximum allowable sum, respectively. Constraint set (4.25) represents the calculation of the compactness measure value for each depot p. Constraint set (4.26) represents the calculation of the estimated total cost value for the depots and the number of trucks assigned to them. Constraint sets (4.27)-(4.29) are the restrictions on model decision variables.

In the LP relaxation model, constraint sets (4.13)-(4.21) are relaxed with a change in the decision variable requirement for X_{ijp} such that the X_{ijp} is changed to a continuous decision variable. Thus, in the LP relaxation model, partial units of a road segment can be assigned to a number of depots rather than being assigned to a single depot. However, as discussed earlier, the feasible solution to the LP relaxation model cannot be used for practical applications without any modification in the model solution.

Authors also compared computational time required for both models. As concluded by Kandula and Wright [19], LP relaxation model solution is cheaper than the integer model solution in terms of computational requirements. However, there is a trade-off between modifying LP relaxation model solution and computational difficulties in the integer model solution.

Kandula and Wright [20] presented an improved version of their optimization model, proposed in [19], for winter road maintenance districting. Compared with their previous model, new constraints and decision variables were introduced to the improved model to better estimate the deadheading distances and the number of service vehicles required. The objective function of the improved model integrates a number of design characteristics rather than only representing compactness. The model was formulated as a mixed integer programming model. The model solution provides depot site locations to operate, road segment assignments to depots, estimates for the number of service vehicles required at each depot location and estimates of number of routes required for service. The model cannot generate actual vehicle routes. However, the number of deadheading vehicles on road segments can be estimated using the estimates of number of routes required. The model was tested on five different road networks in Indiana, in which two to three service depots are located at each network. The authors concluded that model improved districting in all five road networks by improving compactness measure. The quality of the routing for service vehicles is measured by deadheading distances. The lower- bound deadheading procedure, first introduced by Golden and Wong [27], is used to set a lower bound on the total deadheading distance for each depot. However, the lower bound procedure only considers deadheading distance between depot and the start or the end points of routes to be serviced; not considering whether the road segments in the routes has been serviced [20]. Therefore, as highlighted by Kandula and Wright [20], route lengths become an issue in practice. There is a trade-off between target service times, previously denoted as service recovery time [19], and deadheading distances. The complete formulation of the district design model, by Kandula and Wright [20], is presented below; definitions for decision variables and parameters used in the model formulation are given in Table 7.

$$\text{Minimize}\left(\begin{array}{c}\sum_{p} SUML_p + \sum_{p}\sum_{(i,j)}\left(P_{ijp}+P_{jip}\right) + \sum_{p}\sum_{(i,j)}\left(Y_{ijp}+Y_{jip}\right) \\ + \sum_{p}\sum_{k}\left(Y_{k0p}\right) + \sum_{p} N_p\end{array}\right) \tag{5.1}$$

$$\sum_{p} X_{ijp} = 1 \quad \forall\ (i,j) \tag{5.2}$$

$$\sum_{p} X_{ijp} - D_p \leq 0 \quad \forall\ p, (i,j) \tag{5.3}$$

$$\sum_{p} D_p = NUMD \tag{5.4}$$

$$L_{ijp} - S_{ip} \cdot X_{ijp} - S_{jp} \cdot X_{ijp} = 0 \quad \forall\ (i,j), p \tag{5.5}$$

$$\sum_{(i,j)} L_{ijp} - SUML_p \leq 0 \quad \forall\ p \tag{5.6}$$

$$LMAX - L_{ijp} \geq 0 \quad \forall\ (i,j), p \tag{5.7}$$

$$LMAX - ML \leq 0 \tag{5.8}$$

$$N_p \leq NUMT(p) \quad \forall\ p \tag{5.9}$$

$$\sum_{(i,j)} W_{ij} \cdot X_{ijp} - RL \cdot SS \cdot N_p \leq 0 \quad \forall\ p \tag{5.10}$$

$$Y_{0dp} - RL \cdot N_p = 0 \quad \forall\ d \text{ depot nodes} \tag{5.11}$$

$$\sum_{p} Y_{k0p} \geq 0.05 \quad \forall\ k \tag{5.12}$$

$$Y_{0dp} = 0 \quad \text{if } d \notin \text{partition } p \tag{5.13}$$

$$X_{ijp} - 100 \cdot Y_{i0p} \leq 0 \quad \forall (i,j), p \tag{5.14}$$

$$X_{ijp} - 100 \cdot Y_{j0p} \leq 0 \quad \forall (i,j), p \tag{5.15}$$

$$Y_{ijp} - MF \cdot X_{ijp} \leq 0 \quad \forall (i,j), p \tag{5.16}$$

$$Y_{jip} - MF \cdot X_{ijp} \leq 0 \quad \forall (i,j), p \tag{5.17}$$

$$\sum_{p} \left(Y_{ijp} + Y_{jip} \right) \geq \frac{S_{ij}}{2.0} \quad \forall (i,j) \tag{5.18}$$

$$Y_{ijp} - MF \cdot Q_{ijp} \leq 0 \quad \forall (i,j), p \tag{5.19}$$

$$Y_{jip} - MF \cdot Q_{jip} \leq 0 \quad \forall (i,j), p \tag{5.20}$$

$$\sum_{p} \left(Q_{ijp} + Q_{jip} \right) = 1 \quad \forall (i,j) \tag{5.21}$$

$$\sum_{k} Y_{kip} - \sum_{j} Y_{ijp} - Y_{i0p} = 0 \quad \forall \text{ i not depot, p} \tag{5.22}$$

$$\sum_{k} Y_{kdp} - \sum_{j} Y_{djp} + Y_{0dp} - Y_{d0p} = 0 \quad \forall \text{ d depot nodes, p} \tag{5.23}$$

$$Y_{ijp} - P_{ijp} \leq RL \quad \forall (i,j), p \tag{5.24}$$

$$Y_{jip} - P_{jip} \leq RL \quad \forall (i,j), p \tag{5.25}$$

$$Y_{k0p} - \sum_{(i,k)} \frac{S_{ik}}{(2.0)} \cdot X_{ikp} - \sum_{(i,k)} \left(\frac{D_{ik}}{DS} + \frac{P_{ikp}}{RL} \right) \leq 0 \quad \forall k, p \tag{5.26}$$

$$COST - C^{T} \cdot \sum_{P} N_p - C^{D} \cdot \sum_{P} D_p = 0 \tag{5.27}$$

$$D_p, X_{ijp}, Q_{ijp} \in (0,1) \tag{5.28}$$

$$P_{ijp}, Y_{ijp}, Y_{i0p}, Y_{0dp} \geq 0 \tag{5.29}$$

$$N_P, N_P^1, N_P^2, N_P^3 \in \{\text{integers}\} \geq 0 \quad (5.30)$$

The objective function (5.1) minimizes the sum of all shortest distances from depots to the road segments that are serviced from depots (distance), of all deadheading estimates (duration), of all flows from depots to depots (duration), of all outflows from depots (duration), and of all number of vehicles required (positive integer). Constraint set (5.2) requires that each road segment must be assigned to a single depot. Constraint set (5.3) ensures that road segment must be assigned to depots that are in operation. Constraint set (5.4) determines the total number of depots in operation. Constraint set (5.5) represents the calculation of the sum of the shortest distances from both ends of a road segment to the depot in partition p. Constraint set (5.6) represents the calculation of the sum of the L_{ijp} values for each partition p. Constraint sets (5.7) and (5.8) are the upper bounds on the maximum allowable sum of shortest distances from both ends of a road segment to the depot in partition p and the limit to the maximum allowable sum, respectively. Constraint set (5.9) represents an upper bound on the maximum allowable number of trucks at each partition. Constraint set (5.10) represents the calculation of the workload associated with each partition. Constraint sets (5.11)-(5.23) describe the system of flows to ensure that partitions will be connected. Flows are originated at depots, flowing through network, and terminate the network at the nodes defined by the ends of a road segments. Constraint set (5.11) represents the available service capacity (inflow) at depots. Constraint set (5.12) represents the minimum allowable outflow capacity accepted for termination at both ends of a road segments. Constraint set (5.13) ensures that depots associated with partitions create non-zero inflows for those partitions. Constraint sets (5.14) and (5.15) ensure that there must be positive flow at both ends of a road segments if the road segment is

Table 7 Definitions for decision variables and parameters, Kandula and Wright [20]

C^D= cost of depot operations
C^T= cost of a service vehicle (i.e. truck)
COST= total cost of alternative
D_p= 1 if depot p is open and 0 otherwise
D_{ij}= deadhead distance estimate associated with the road segment (i,j)
LMAX= maximum of all L'_{ijp}s
L_{ijp}= sum of the shortest distances to the node i and the node j from the depot p
ML= maximum allowable LMAX
ML= service speed
MF= maximum imaginary flow in any arc
N_p= total number of service vehicles (i.e. trucks) in partition p
NUMD= number of depots chosen to service the area
NUMT(p)= maximum number of service vehicles chosen to service the partition p
P_{ijp}= deadheading travel estimate for road segment (i,j) which is assigned to depot p
RL= route length
S_{ij}= time spent in servicing road segment (i,j)
$SUML_p$= sum of L_{ijp} in partition p
SP_{ip}= shortest path to i from depot in partition p
SS= service speed
Y_{ijp}= flow in road segment (i,j)assigned to partition p
Y_{k0p}= minimum positive outflow from depot p
Y_{0dp}= flow into depot d from supernode 0
Y_{i0p}= flow out of non-depot node i as a result of flow in road segments assigned to unit p
X_{ijp}= 1 if road segment (i,j)is assigned to depot p and 0 otherwise
W_{ij}= workload associated with road segment (i,j)

assigned to a depot. Constraint sets (5.16) and (5.17) ensure that flow through two ends of a road segment must use the same depot assigned to it. Constraint set (5.18) represents the calculation of outflow values defined for both ends of road segments. Constraint sets (5.19)-(5.21) ensure that flow on road segments is unidirectional. Constraint sets (5.22) and (5.23) satisfy the network flow balance at depot and non-depot nodes. Constraint sets (5.24) and (5.25) represent the calculation of the overcapacity flows. Constraint set (5.26) represents the calculation of the deadhead travels based on the overcapacity flows. Constraint set (5.27) represents the calculation of the estimated total cost value for selected number of depots and number of trucks assigned. Constraint sets (5.28)-(5.30) are the restrictions on model decision variables. Authors concluded that the model can be used to evaluate existing maintenance districts to support winter road maintenance routing practices.

2.3. Winter Road Maintenance Vehicle Routing

This section contains a review of the vehicle routing problem, standard problem formulation, and solution techniques. Review of vehicle routing problem studies that have addressed winter road maintenance operations is also presented.

2.3.1. The Vehicle Routing Problem

The Vehicle Routing Problem (VRP) is an important distribution management problem which aims to increase the distribution efficiency in the concept of logistics systems [28]. There are several versions of the problem available because of the diversity of the vehicle routing applications in practice. Laporte [29] describes the standard version of the problem as the problem of designing optimal routes for collection from or delivery to a number of geographically distributed units, subject to some side constraints. The mathematical description of the problem in a unidirected graph, G, by Laporte [29], is as follows: G=(V,A) is the unidirected graph with V={1,2,...,n} representing the vertex set with depot located at vertex 1, and A representing the arc set. There is a non-negative distance matrix $C=(c_{ij})$ associated with every arc $(i,j)\in A$, where $i\neq j$. Then, the vehicle routing problem consists of designing a set of vehicle routes such that (1) all vehicle routes start and end at vertex 1, (2) each vertex in $V\setminus\{1\}$ is visited exactly once and exactly by a single vehicle, and (3) the total routing cost is minimized, subject to some side constraints.

Most commonly used side constraint sets in vehicle routing problem formulation are total time restriction, time window restrictions, number of cities on any route, capacity restrictions, and precedence relations [29, 30]. Total time restrictions aim to minimize the sum of total travel time (distance) that is required to complete service on a given route. The vehicle routing problem with total time constraints is referred to as time- or distance constrained vehicle routing problem (T- or DVRP). Time window restrictions are used to ensure that customers must be visited and supplied on their required time periods. The vehicle routing problem with time windows is referred to as vehicle routing problem with time windows (VRPTW). Number of stops on any route can be determined with the upper or lower bounds according to service characteristics, i.e. when pick-up and delivery performed together. Capacity restrictions specify that the total service demand on a given route must not exceed the capacity of the vehicle which serves that route. Precedence constraint sets define precedence relations between pairs of cities according to service characteristics, i.e. multi-depot routing or any conditional routing requirements among customers. A detailed review of side constraints can be found in the book by Golden and Assad [30].

The vehicle routing problem is generally formulated as a node routing problem. Node routing problems have many real-life applications in transportation and logistics planning. One famous node routing problem is the Traveling Salesman Problem (TSP). In the TSP, a salesperson is required to visit each of n given cities (nodes) once and only once, starting from any city (node) and returning to the original place of departure (node). The TSP solution provides the minimum (cheapest) travel distance route for the salesperson to complete the service tour. Bektas [31] presented a survey of variants of integer linear programming models proposed for traveling salesman problem. The standard mathematical formulation of the problem, by Bektas [31], is given below. The problem considers single depot and multiple vehicles assignment policies to visit a number of cities. Therefore, model solution provides a number of vehicle routes starting from and returning to the depot and visiting all cities once and only once. Definitions for decision variables and parameters used in the model formulation are given in Table 8.

$$\text{Minimize} \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ij} \tag{6.1}$$

$$\sum_{j=2}^{n} x_{1j} = m \tag{6.2}$$

$$\sum_{j=2}^{n} x_{j1} = m \tag{6.3}$$

$$\sum_{i=1}^{n} x_{ij} = 1, \quad j=2,3,\ldots,n \tag{6.4}$$

$$\sum_{j=1}^{n} x_{ij} = 1, \quad i=2,3,\ldots,n \tag{6.5}$$

subtour elimination constraints (6.6)

$$x_{ij} \in \{0,1\} \quad \forall\ (i,j) \in A \tag{6.7}$$

The model objective function (6.1) minimizes the cost of visiting all cities exactly once by exactly one of the vehicles. Therefore, minimization of the term in the objective function creates routing plans for vehicles such that the total cost of the distance traveled to complete the service tours is minimized. Constraint set (6.2) ensures that exactly m number of vehicles must start from the depot (node 1) to start service. Constraint set (6.3) ensures that exactly m number of vehicles must return back to the depot (node 1) after service is completed. Constraint sets (6.4) and (6.5) require that each city (node 2 to node n) in the network must be assigned to one of the vehicles starting from and returning back to the depot (node 1). Constraint set (6.6) is the subtour elimination constraints. Subtour constraints are used when they are necessary; when the model solution is not feasible because of the subtours. Constraint set (6.7) specifies restrictions on model decision variables.

$$\sum_{i \in S} \sum_{j \in S} x_{ij} \leq |S|-1 \qquad \forall S \subseteq V \backslash \{1\},\ S \neq \emptyset \tag{6.8}$$

$$\sum_{i \notin S} \sum_{j \in S} x_{ij} \geq 1 \qquad \forall S \subseteq V \backslash \{1\},\ S \neq \emptyset \tag{6.9}$$

Bektas [31] discussed that the standard model formulation can be improved by introducing constraint sets (6.8) or (6.9) to prevent the formation of subtours. However, as was highlighted by Bektas [31], introducing these constraint sets is not practical since the number of constraints added increases with the number of nodes in the problem. For a detailed survey of variants of models proposed for the traveling salesman problem and annotated literature review on location-routing problems the reader is referred to papers by Min et al. [28] and by Bektas [31].

Table 8 Decision variable and parameter definitions, Bektas [31]

x_{ij}= 1 if arc(i,j) is used in a tour and 0 otherwise
c_{ij}= the non-negative cost associated with every arc $(i,j) \in A$, where $i \neq j$; the cost of travel from city (node) i to city (node) j
m= the number of vehicles assigned to depot (node 1)
i= vertex set, where i=2,3,…,n
j= vertex set, where i=2,3,…,n
n= total number of cities, including the depot located city (node 1)
S= any subset of V such that S has at least 2 and at most n-1 members, given that the depot node (node 1) is not a member of S

The vehicle routing problem is also formulated as an arc routing problem. In contrast to the node routing problem, arc routing problem involves traversing a set of arcs instead of the nodes, where there are a number of customers per each arc. In arc routing problems, the aim is to determine the least cost travel path of a specified subset of a graph, subject to some constraints, and covering all arcs of the subset of a graph [32, 33]. Arc routing problems occur in a variety of different contexts such as waste collection, mail delivery, school bus routing, road maintenance, and meter reading. According to Eiselt et al. [32], the earliest reference to arc routing problem is the famous Königsberg Bridge problem. Königsberg Bridge problem aims to determine whether there exists a closed travel path through each of seven bridges exactly once on the Pregel River in Königsberg (now Kaliningrad), and was solved by a Swiss mathematician, Leonard Euler, in 1736 [34].

Another well-known arc routing problem is the Chinese Postman Problem (CPP). The CPP aims to find a shortest walking path for a mailperson, who has to cover an assigned mail delivery segment, before returning to the post office. In contrast to the Königsberg Bridge problem, the Chinese Postman Problem involves traversing a set of arcs where a solution for finding a closed walking path in which traversing all arcs only once is not feasible. Eiselt et al. [32, 33] presented an extensive literature review on the CPP variants and solution algorithms for the CPP. The mathematical formulation of the standard CPP, by Eiselt et al. [32], is as follows:

$$\text{Minimize} \sum_{(i,j)\in A} \left(c_{ij}x_{ij} + c_{ji}x_{ji}\right) \tag{7.1}$$

$$x_{ij} + x_{ji} \geq 1 \quad \forall\, (i,j)\in A \tag{7.2}$$

$$\sum_{(i,j)\in\delta(i)} \left(x_{ij} - x_{ji}\right) = 0 \quad \forall\, i\in V \tag{7.3}$$

$$x_{ij}, x_{ji} \geq 0 \text{ and integer } \forall\, i,j\in V \tag{7.4}$$

Definitions for decision variables and parameters used in the model formulation are given in Table 9. The model objective function (7.1) minimizes the cost of traversing all arcs in G; it should be noted that the cost of traversing depends on the direction of the arc traversed. The minimization of the term in objective the function creates a routing plan complete the service (traversing) requirement for the given arc set. Constraint set (7.2) ensures that every arc (i,j) must be traversed at least once, from any direction. Constraint set (7.3) ensures that the number of times node i traversed is equal in both directions; from and to node i. Therefore, in any optimal solution, one of the following three cases occur for every arc(i,j): either $x_{ij}=0$ and $x_{ji}\geq 1$, or $x_{ji}=0$ and $x_{ij}\geq 1$, or $x_{ij}=1$ and $x_{ji}=1$. Constraint set (7.4) specifies restrictions on model decision variables.

Table 9 Decision variable and parameter definitions, Eiselt et al. [32]

x_{ij}= the number of times that the arc(i,j) is traversed from node i to node j
x_{ji}= the number of times that the arc(i,j) is traversed from node j to node i
$\delta(i)$= the set of arcs connected to node i
c_{ij}= the non-negative cost associated with every arc $(i,j) \in A$, where $i \neq j$; the cost of travel from node i to node j
c_{ij}= the non-negative cost associated with every arc $(i,j) \in A$, where $i \neq j$; the cost of travel from node j to node i
i= node set
j= node set

There exists a number of exact and approximate solution algorithms for the vehicle routing problem. Exact algorithms are, generally, used to solve small problems, while approximate algorithms are preferred for large scale problems to minimize solution computation times [29]. The most common exact solution algorithm for the vehicle routing problem is the branch-and-bound algorithm. In the branch-and-bound algorithm, the optimal solution is found by keeping the best solution found so far through the solution process; pathways are created from the best solution found so far to reach the optimal solution [35]. The algorithm starts with an initial best solution procedure. The initial best solution is obtained from the relaxed version of the original problem. The initial best solution ignores the integer constraints of the original problem. Then the variables of the original problem are integer values, above or below the non-integer values of the initial best solution to create a branching tree of the candidate solutions to the original problem. If a given candidate problem solution cannot improve the next best solution found so far, then it is abandoned. Other commonly used exact solution algorithms for the vehicle routing problem include the branch-and-cut algorithm, dynamic programming, commodity flow algorithms, and set partitioning algorithms [29, 36]. Approximate solution algorithms can be categorized in two: heuristics and meta-heuristics. As discussed by Laporte [29] and Cordeau et al [37], heuristic algorithms, such as the Clarke and Wright algorithm, the Sweep algorithm, and the Fisher and Jaikumar algorithm, consider limited solution space search to reach the best solution in a reasonable computation time. In meta-heuristic procedures, the solution space of the problem is explored to improve candidate solutions considering some quality measures [36, 37]. The commonly used meta-heuristic solution algorithms for the vehicle routing problem include the ant algorithm, the genetic algorithm, the deterministic annealing algorithm, the simulated annealing algorithm, and the tabu search algorithm.

2.3.2. The Snowplow Routing Problem

Snowplow routing problems are generally formulated as arc routing problems. However, the vehicle routing problem literature related to the snow plowing operations consists of different solution approaches depending on the nature of the problem. Perrier et al. [38, 39] classify methods used to solve winter road maintenance vehicle routing problems in five categories: simulation models, rule-based decision support systems, composite methods, adaptation of metaheuristics, and constructive methods. Simulation models (e.g. Damodaran and Krishnamurthi [40]) are mostly used to support decision makers evaluate the quality of feasible routing plans, as well as to construct alternative routes. Outputs for simulation models can be summarized as total working hours, expenditures on manpower, delays caused by weather conditions, equipment and material shortages, and crew performance [39]. Rule-based decision support systems (e.g. Fu et al. [41]) help winter road maintenance practitioners make decisions regarding operation details, especially, when operation conditions are rapidly changing and cannot be estimated in advance. Inputs, user knowledge and expertise, outputs, and decisions are the four main components of rule-based decision support systems. The instructions or rules are the knowledge and expertise database of the system and are used to manage the decision making processes [39]. Composite methods generally built upon class continuity and maximum route length constraints. For example, the commercially available routing software GeoRoute [42] uses a two-phase composite solution method. GeoRoute software allows users to optimize and manage winter road maintenance vehicle routing operations such as plowing and spreading subject to some set of operational constraints. Meta-heuristics, such as genetic algorithm (e.g. Toobaie and Haghani [43]), are used by researchers to assist winter road maintenance planners in the design of vehicle routes. Meta-heuristics do not guarantee finding the optimum solution, however they have quite fast algorithms and they can be used to search large solution spaces [43]. Constructive methods (e.g. Lemieux and Campagna [44]) used for winter road maintenance operations deal with the snowplow routing problem generally in multi steps [39]. In the initial stages, road segments are organized for plow routing according to a set of operational constraints; in the later stages, vehicle routing plans are determined. According to Perrier et al. [39], optimization models used for winter road maintenance vehicle routing problems are generally considered as constructive methods.

The later part of this section presents a brief review of studies in which snowplow routing has been analyzed from a system design perspective.

Savas [45] described the analysis carried out for a snow emergency plan for New York City. The city experienced a major snowstorm on February 9, 1969 which resulted in a serious snow emergency and a political crisis. This study analyzed difficulties and capability of the city to remove snow from streets and to perform salt spreading operations. As highlighted by Savas [45], 1,600 miles of the city road network (or 33% of the city road network) was labeled as the high service priority network and defined as the minimum service area to be snowplowed and salted to maintain the city road network functioning during a snow emergency.

Soyster [46] presented one of the earliest linear programming models in the context of winter road maintenance vehicle routing. The proposed model attempts to minimize the total truck miles required to complete winter road maintenance operations. The service network consists of a collection of equal length road segments and a number of depot locations for trucks. The service trucks were assumed to return to their starting depots after service. The model output is a number of service routes for each truck. The mathematical formulation of the winter road maintenance truck routing model, by Soyster [46], is as follows;

$$\text{Minimize} \sum_{i} \sum_{j\text{-}k} x_{ijk} \tag{8.1}$$

$$\sum_{i} \left(x_{ijk} + x_{ikj} \right) \geq 1 \quad \forall\, j\text{-}k \tag{8.2}$$

$$\sum_{j\text{-}k} x_{ijk} \geq b_i \quad \forall\, i \tag{8.3}$$

$$\sum_{i} \sum_{k} \left(x_{ijk} - x_{ikj} \right) = 0 \quad \forall\, j \tag{8.4}$$

$$\sum_{k} x_{ijk} \geq 1 \quad \forall\, i \tag{8.5}$$

$$\sum_{j} x_{ijk} \geq 1 \quad \forall\, i \tag{8.6}$$

$$0 \leq x_{ijk} \leq 1 \quad \forall\, i, j\text{-}k \tag{8.7}$$

A two-dimensional index is used for the model decision variable x_{ijk}, such that x_{ijk} is 1 if truck i traverses road segment j-k and 0 otherwise. Then, the model objective function (8.1) minimizes the sum of the total distance traveled by each truck, i. The author discussed that if road segments, j-k pairs, were not equal in length, a scale factor $a_{j\text{-}k}$ would be used to adjust road segment lengths. The constraint set (8.2) ensures that each road segment must be traversed at least once. These constraints suggest that road segments can be serviced from either direction. The constraint set (8.3) represents an upper bound on the distance traveled by each truck, where b_i is the maximum allowable mileage for truck i. The constraint set (8.4) equals the number of trucks leaving from node j and the number of trucks entering node j. The constraint sets (8.5) and (8.6) ensure that, for each truck, the starting location and the returning location in the network is same. The constraint set (8.7) represents lower and upper bounds on decision variables. The model was tested with a number of sample problems. As discussed by Soyster [46], in the model formulation process it was thought that trucking routes could be generated with a non-integer linear programming model. However, as was highlighted, it was difficult to create trucking routes from the non-integer model solution since many of the decision variable values in the non-integer model solution were between 0.4 and 0.6; integer solution by rounding was not feasible. It was concluded that converting non-integer solutions into integer solutions in the context of routing was difficult and results could be subjective. Thus, Soyster [46] presented another approach to determine truck routes for winter road maintenance operations: the route construction via structured random sampling. The algorithmic description of the structured random sampling approach was not presented in [46] in detail, however, it can be summarized as follows: At time t=0, each truck starts service and by time t=1 each truck travels its first road segment given that truck-road segment service pairs are chosen randomly. At time t=1, each truck starts service again and by time t=2 each truck travels its second road segment given that truck-road segment service pairs are chosen randomly from a set of feasible truck-road segment service pairs. This process is repeated until all road segments are served and all trucks return to their starting locations. As discussed, after each iteration the feasible set for truck-road segment service pair service segment set is updated. The updating procedure eliminates infeasible truck-road segment service pairs for the very next iteration process using a number of constraints. A computer program was developed to apply the approach on a number of test problems. The results were considered to be satisfactory for the given test problems, but a large amount of time and resources are consumed to prepare the program inputs even for small sized test problems.

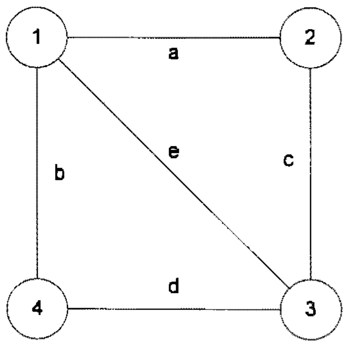
Cook and Alprin [47] presented a routing heuristic for salt spreading problem in the city of Tulsa, Oklahoma. As highlighted by Cook and Alprin [47], at the time of their study, Tulsa had no snow plowing equipment and just depended on salt spreading operations for snow and ice control. The authors discussed that the key objective for routing design was balancing workload among vehicles, not minimizing deadheading. In this way, the number of service vehicles required for service can be minimized. The heuristic performance was evaluated within a simulation model developed for salt spreading operations for Tulsa. Authors concluded that the heuristic decreased total salt spreading service time by 33% (or by 3 hours).

Tucker and Clohan [48] presented a simulation model for snow removal operations. The model accepts user defined vehicle routes for service vehicles as an input. Then, the number of service vehicles required for service and total time required completing service are estimated based on different snowfall, road network, and traffic characteristics. The model was tested on sections of a road network in Newington, Connecticut.

Lemieux and Campagna [44] presented a constructive method, a graph theory algorithm, to solve the snow plowing problem. The problem involves a road network and a depot location with a single service truck. The truck starts from the depot location, services all road segments only once from both directions, and returns to the depot. The algorithm creates an Eulerian circuit on a given connected directed graph G. An Eulerian circuit is path defined on a directed graph G, which starts and ends at the same node, and it covers every arc in G once and only once. G must be a connected directed graph to better represent the road network. According to Lemieux and Campagna [44] such a requirement is necessary in the context of snow plowing since streets must be plowed in both directions. The algorithm was tested on a small road network, involving nine nodes and 24 arcs. Extensions to the multi-truck problem case were suggested as a future study.

Haghani and Qiao [49] presented two integer programming models to design snow emergency routes for Calvert County, Maryland. The first integer programming model formulation involves minimizing the total number of trucks required for service. The second integer programming model involves the minimization of total distance traveled for a given number of trucks. As was discussed by Haghani and Qiao [49], in both models, it was difficult to formulate service continuity constraints in the context of arc routing formulation. Therefore, a network transformation procedure was used to formulate original arc routing problems as node routing problems. An example was given by Haghani and Qiao [49] shown in Figure 1 to represent the network transformation procedure. In Figure 1, the network given in (i) is transformed into the network given in (iii) by using the unit-connection matrix presented in (ii); links in the original network are transformed into the nodes in the transformed network. Given the transformed network, Haghani and Qiao [49] formulated a capacitated minimum spanning tree model to find a solution to the first integer programming model. The model solution provides minimum number of spanning trees that can be created from the transformed network, subject to some capacity constraints. Then, the number of sub-trees is converted into number of trucks for the original problem solution.

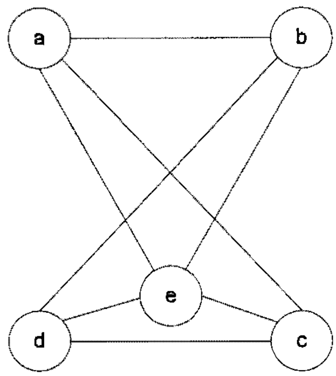
Figure 1 Network transformation procedure example, Haghani and Qiao [49]



(i)

.	*a*	*b*	*c*	*d*	*e*
a	0	1	1	0	1
b	1	0	0	1	1
c	1	0	0	1	1
d	0	1	1	0	1
e	1	1	1	1	0

(ii)



(iii)

The same solution approach is used for the second problem. The converted model solution determines feasible route assignments for trucks. Then, the route assignments converted into total distance traveled for a given number of trucks. The model formulations were tested on different sections of a road network in Calvert County, Maryland, involving 42 nodes and 104 arcs. The authors concluded that it was difficult to reach optimal solutions for the first integer programming model as test network size increased.

Fu et al. [41] introduced a real-time optimization model for winter road maintenance scheduling. The winter road maintenance scheduling problem is described as (1) minimization of total operating costs, defined as a function of service kilometers; (2) minimization of negative environmental effects, defined as a road condition index or snow depth factor; and (3) providing service level for a given class of road segments, defined as service level and fleet size restriction. The model considers several parameters such as road network topology, service priorities, real-time weather information, and fleet size as an input. The inputs used to calculate several coefficients used in the winter road maintenance scheduling problem formulation. The model is implemented in AMPL linear programming language and solved using a branch-and-bound method. The model was tested on a road network in Waterloo, Ontario, Canada. Fu et al. [41] discussed that solution run time for different problem scenarios was fixed for 1000 seconds so that problems can be solved in a reasonable time period and solutions can be comparable. Therefore, solutions found by the model were the best approximations for the fixed time period, not the optimal solutions. Fu et al. [41] concluded that real-time weather information has the most effect on model solutions; development of better routing algorithms, a user interface to update model parameters faster, and potential applications in garbage collection, emergency vehicle dispatching, and transit routing are suggested for future research.

Toobaie and Haghani [43] presented a heuristic algorithm to design routes for salt spreading operations. As highlighted in [43], although the study was for salt spreading operations, snow plowing operations could be integrated as well. The aim of the proposed heuristic is to construct a number of vehicle routes for a given road network and to efficiently assign a number of vehicles to constructed routes. Efficiency is defined as the ratio of time spent servicing routes to time spent on the road network. A minimal arc problem is formulated to represent salt spreading problem. The minimal arc problem is defined as partitioning road network into minimum number of districts while satisfying a number of operational constraint sets. The constraint sets are defined as capacity constraints, service route connectivity constraints, coverage constraints, and routing constraints. The first phase of the heuristic is the route construction phase and uses random keys genetic algorithm with first fit-heuristic to solve the minimal arc problem. The solution to this phase provides a number of vehicle routes. The second phase of the heuristic is defined as workload balancing. Vehicle routes created in route construction phase are improved in terms of workload balance by exchanging arcs between neighborhood routes. The last phase assigns a number of trucks to routes and determines final vehicle routes. The algorithm is tested on a road network of Calvert County, Maryland, involving 2 depots and 52 road segments. Toobaie and Haghani [43] concluded that algorithm can be applied to the real-world problems. However, the model needs improvements such as incorporating different size service trucks in the model.

Damodaran and Krishnamurthi [40] presented a simulation model for salt spreading and snow plowing operations. The objective of the model considers servicing high priority road segments as soon as possible, and servicing other road segments later. The model is coded in SIMAN language and user-coded C language routines are integrated. The model has a dynamic planning perspective and can update in progress vehicle service routes if there is a change in weather or road conditions. In case of a weather or road condition change, user calls associated C routines and updates weather or road conditions so that in progress service routes are revised. The model assumes that road segments in the network are all single lane. Thus, deadheading estimates are not accurate. However, as discussed by Damodaran and Krishnamurthi [40], single road service design can be modified to a multi-lane service design by setting multi-pass requirements on each road segment. The model was tested and implemented on a road network of DeKalp, Illinois. Damodaran and Krishnamurthi [40] concluded that performance of service routes determined by the model is better than service routes determined by manual calculations.

Perrier et al. [50] proposed an integer programming model for planning snow plowing operations in rural areas. The objective function of the model considers a multi-criteria decision making process. The objective function minimizes total time required to service first (or high) priority routes, then minimizes total time required to service second priority routes, and so on. An imaginary multi-commodity network flow is integrated into the model to satisfy route connectivity. The model formulation is capable of customizing any turn restrictions for vehicles such as U-turns or left turns. Perrier et al. [50] discussed that even for small sized test problems large computation time and memory requirements were needed. Thus, Perrier et al. [50] proposed two constructive methods to solve the model; the parallel algorithm and the cluster first, route second algorithm. The parallel algorithm solves a number of rural postman problems for different priority classes of road network. The objective of parallel algorithm is to minimize total service time and total turn restriction penalties. The cluster first, route second algorithm partitions the network into sub-networks so that workload balance constraints can be satisfied. Then, a rural postman problem is solved for each priority class of road segments, considering any priority class updates. The objective function of the cluster phase minimizes total shortest paths from arcs to depot and from depot to arcs. Then, the routing phase minimizes the total service time. The algorithms were tested on a road network in city of Dieppe, New Brunswick, Canada, involving 462 nodes and 3 service priority classes for 1,234 arcs. As discussed by Perrier et al. [50], both models provide better routing plans than existing routing plans of Dieppe. In terms of computing times, authors noted that cluster first, route second algorithm is faster than parallel algorithm. However, the time it took the cluster first, route second algorithm to solve the problem was nine hours [50].

Dali [51] formulated the vehicle routing problem for snow emergency operations. According to Dali [50] there is a trade-off between two components of snow emergency operations; cost of operations and social costs. The cost of snow emergency operations involves cost of vehicles, cost of fuel, and labor cost. The social costs are described as the service time [51]. Thus, an integer programming model was presented to minimize the total variable cost of snowplowing operations by minimizing total travel distance for trucks. Dali [50] discussed that minimizing total distance traveled by trucks can reduce total service time so that service time associated social cost can be reduced. The model was not tested on any network. However, Dali [51] concluded that it is more important to design efficient solution algorithms for snow emergency operations than to formulate challenging mathematical models.

In a recent study, Jang et al. [2] presented a heuristic approach for winter road maintenance system design problem for Boone County, Missouri. The problem studied involves decisions for depot location selection, sector design, vehicle route assignment, vehicle scheduling, and fleet configuration for combined plowing and spreading operations. The objective of the study is to provide same level of service in the service district with less amount of resource. The proposed methodology has five phases: network initialization, depot and sector selection, route construction, route improvement, and fleet configuration and scheduling. The network initialization phase verifies that given network is strongly connected. The depot and sector selection phase involves an integer programming model to assign road segments to a number of depots. The number of depots is a user defined value and depot locations are chosen from a set of candidate depot locations. The objective function of assignment model minimizes total compactness value for depot and sector selection. The compactness value is defined as the average distance between depot and two end nodes of associated arcs. A compactness value multiplier is defined to improve the compactness value. The compactness value multiplier is used as service frequency of associated road segments based on their service levels. The constraint set of the model only satisfies that a given number of depots are in operation in the network and all road segments are assigned to one of the depots in operation. Once the depots are located and road segments are assigned to them, route construction phase determines vehicle routes for each service level of road segments, separately. As discussed in [2], route-first cluster-second methodology described by Marks and Strikes (1971) is used in this phase. The solution improvement phase uses a movement and exchange algorithm to improve the routes obtained from the third phase. In the last phase, routes obtained from the fourth phase are assigned to a set of service vehicles. The route-vehicle assignment problem is described as an integer programming model which minimizes the number of trucks required. The methodology was tested on a road network in Boone County of Missouri, involving 152 nodes, and 4 service priority classes for 452 arcs. According to Jang et al. [2], the proposed methodology improved resource utilization significantly; same level of service is provided with approximately 20% less resources. Authors also discussed that winter road maintenance system design methodologies should be easy to implement, but sophisticated enough to consider several practical design criteria.

2.4. Chapter Summary

A number of criteria are used to assign road segments to districts. Some assignment models seek to minimize the total compactness value for districting (i.e. [17], [19], and [20]), while other models attempt to minimize the total fixed and variable costs of winter road maintenance operations (i.e. [15] an [16]). Other system design objectives are generally presented in model constraints. Criteria used in district design for winter road maintenance includes compactness, cost, contiguity, service level, number of depots, number of vehicles, and workload balance.

Compactness. In winter road maintenance districting, compactness is a numerical quantity that represents the measure of a two-dimensional district shape. It is the degree to which basic network units, such as road segments, assigned to district are close together. There are several mathematical ways to measure compactness. Maceachren [55] classified compactness measures into four: perimeter-area relations, parameters of related circles, direct comparison to standard shapes, and dispersion of elements of area around a center point. For example, according to Maceachren's classification [55], compactness measure used by Kandula and Wright [19, 20] can be categorized as parameters of related circles.

Cost. As highlighted in several studies, winter road maintenance costs are difficult to quantify. Direct cost components are generally represented as number of depots or sites to operate and number of vehicles to be used in service. However, many of these assets are used for multiple purposes and are utilized in different services when not being used for winter road maintenance.

Contiguity. District contiguity is a common system design requirement and provides service continuity in district routing. There are two main approaches discussed in literature for district contiguity: (i) integrating district contiguity in district design model formulations, i.e. using imaginary multi-commodity network flow constraints to ensure district contiguity, and (ii) modifying district design models to avoid undesirable district formations, i.e. if an undesirable district formation is observed in a model solution, then the corresponding road segment-depot location assignment can be restricted with a user defined constraint set, to eliminate the discontiguity. As discussed in several studies, the first approach guarantees district contiguity. However, the use of additional decision variables and constraints increases model size and complexity. Feasible solutions cannot be obtained even for medium-sized problems. On the other hand, the second approach requires at least one additional model solution process, if there is a discontiguity in the current model solution.

Service Level. Service level is generally used to classify road segments based on desired frequency of service, i.e. higher level road segments require service more frequently than others. The routing phases of system design models seek either service level upgrades in small road networks or homogenous road segment routes in large road networks.

Number of Depots. Existing district design models involve the problem of choosing a number of depot locations from alternatives. Models that aim to minimize total system design cost tend to decrease the number of depots chosen for service. However, models that aim to minimize overall system compactness tend to increase the number of depots chosen for service.

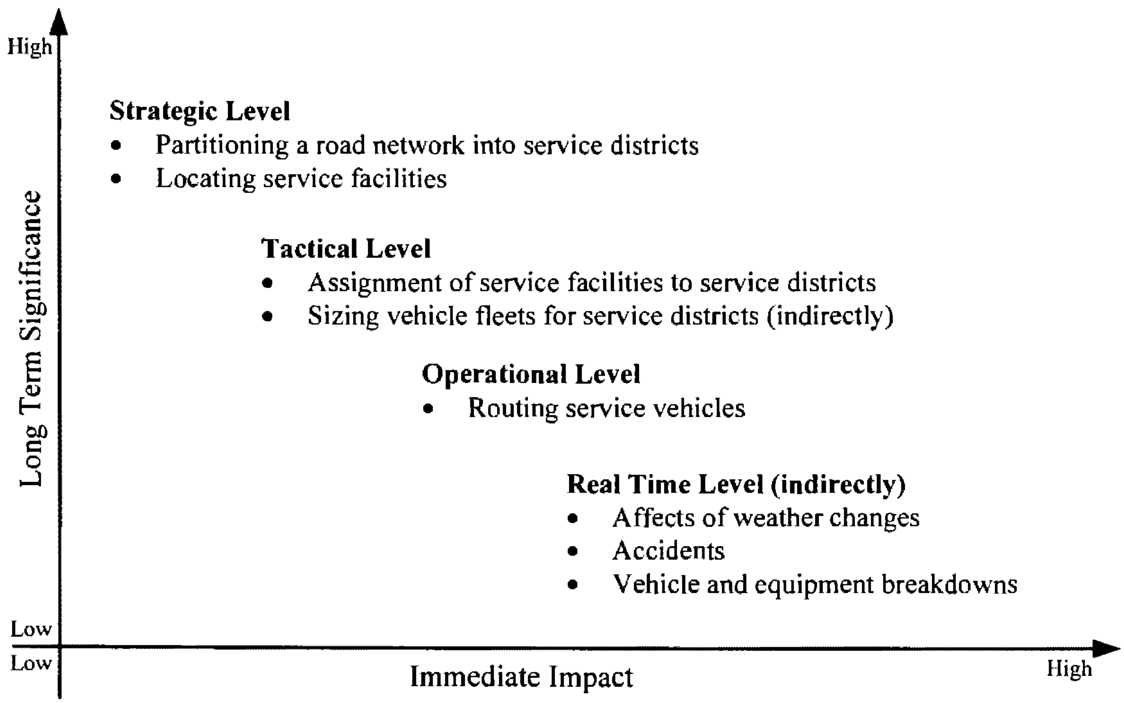
Number of Vehicles. Two major design parameters that affect number of vehicles required for service are vehicle capacity and vehicle speed. Vehicle capacity is generally defined as the number of miles that a vehicle can provide service before returning to depot. Vehicle speed is defined as service speed when vehicle is snow plowing and as deadheading speed when vehicle is passing a road segment without service. As discussed in the literature, the assumption of equal vehicle speed for plowing and deadheading may result in overestimated number of vehicles for service.

Workload Balance. Districts with balanced workload are generally assigned equivalent resources, such as number vehicles and crews. Balancing workload helps ensure that operations are completed approximately at the same time in all districts. Workload of a district can be measured in terms of number of basic entities, such as length of road segments and annual amount of snow. In model formulations, workload balance is represented by defining an upper bound on the maximum workload allowable for each depot or district.

CHAPTER 3. METHODOLOGY

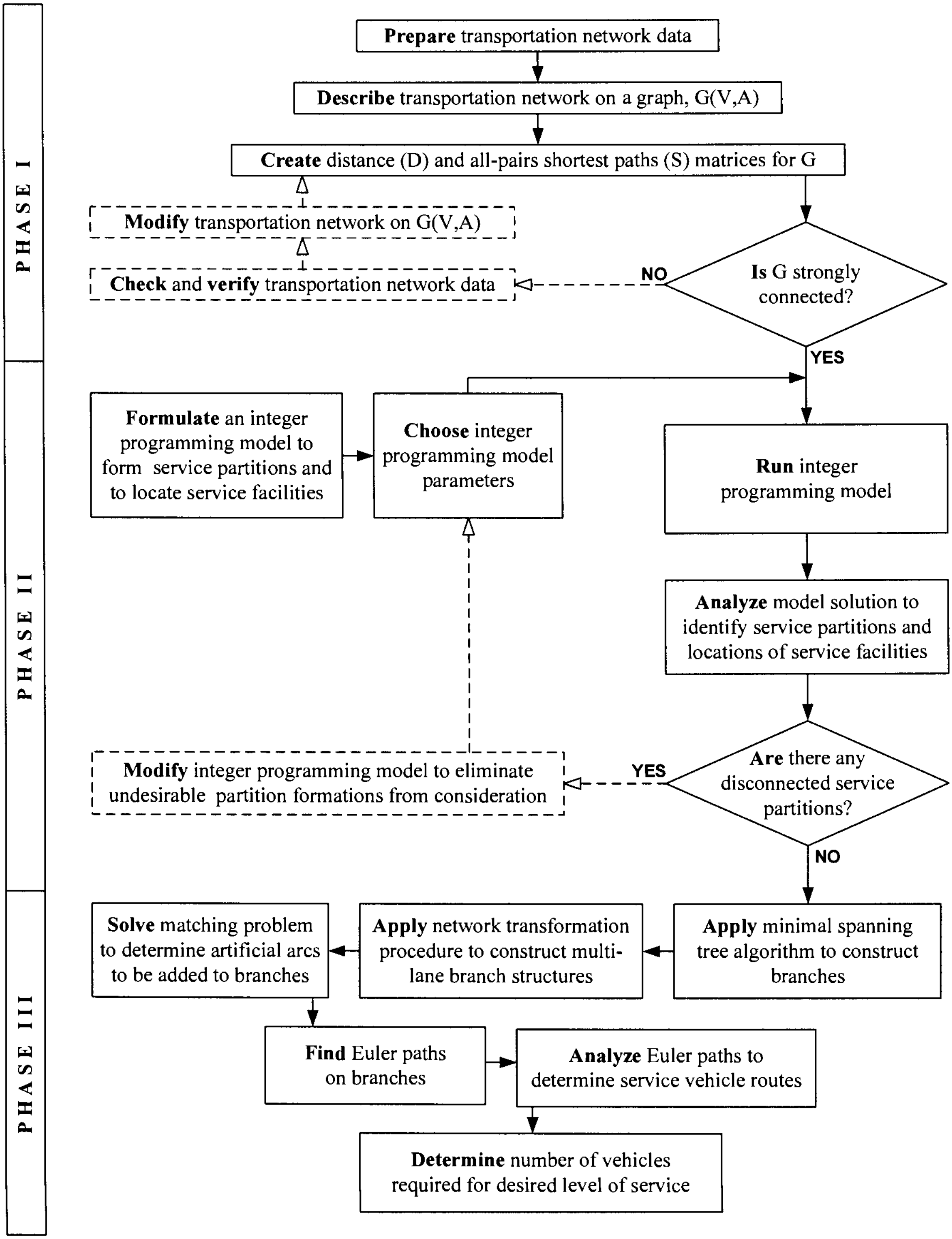
This chapter presents an integrated system design methodology for district design, facility location, and vehicle routing for snow plowing operations. In this methodology, principles of district design, facility location, and vehicle routing are used to determine the snow plow routing plans. Figure 2 presents decision making problems that are directly and indirectly addressed in this methodology according to their long term significance and immediate impacts.

Figure 2 Decision making problems addressed in the methodology



The complete methodology used for integrated system design for district design, facility location, and vehicle routing for snow plowing operations is shown in Figure 3. The entire methodology is divided into three phases. Phase I consists of network initialization and prepares the transportation network for input into Phase II. Phase II partitions the transportation network into service districts and locates maintenance

Figure 3 Methodology used in winter road maintenance system design



buildings in these service districts. The main objective in Phase II is to minimize total system compactness and to create service districts with centrally located depots.

Phase III determines snowplow routing plans for service districts and maintenance buildings obtained in Phase II. The main objective in Phase III is to construct feasible service routes for desired levels of service in the system, subject to other operational constraints.

3.1. Phase I: Network Initialization

The input of this phase includes road network data; specifically, location of existing vehicle depot locations and candidate depot locations on the road network and description for road segments to be serviced (i.e. milepost start (MP/S) and milepost end (MP/E) data, or length of road segments).

The first step in the network initialization phase is to describe the transportation network on a graph G=(V,A), where V is the vertex set representing existing and candidate depot locations and start and end points of road segments, and A is the arc set representing road segments. The distance matrix, D, associated with every arc in A is created. Next, distance matrix D is used to create the shortest path distance matrix, S. The shortest path distance matrix is one of the main inputs into network partitioning procedure of Phase II and helps verify that G is set up correctly by checking whether G is a connected graph. A graph is called connected if there is a path for every pair of vertices in the graph; otherwise, it is called disconnected [52].

The shortest distance between every pair of vertices in G can be calculated by using any of the several standard shortest path algorithms [53]. This study uses Floyd's algorithm presented in Taha [52]. Floyd's algorithm was chosen for several reasons:

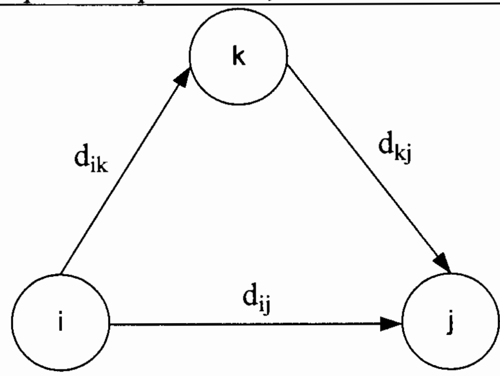
- Floyd's algorithm is an all-pairs shortest paths algorithm and it takes distance matrix D as an input and returns shortest path distance matrix S as an output;
- The algorithm is quick and efficient for medium sized graphs; and
- The algorithm is easy to code in almost every programming language.

The algorithm pseudo-code and the algorithm's triple operation mechanism used to calculate shortest path distances are presented in Figure 4(a) and Figure 4(b), respectively.

Figure 4 Floyd's algorithm pseudo-code and triple operation procedure, Phase I

- initialize distance matrix, D
- initialize node sequence matrix, N
- for k = 1 to n
- do for i = 1 to n
- do for j = 1 to n
- do d(i,j) = min(d(i,j), d(i,k) + d(k,j))
- return D

(a)



(b)

According to the triple operation procedure, the algorithm replaces the direct route from i⟶j with the indirect route i⟶k⟶j if $d_{ik} + d_{kj} < d_{ij}$ and updates the distance matrix D, if it is shorter to reach node j from i passing through k. The exchange mechanism is applied to the network systematically until all entries in D are updated for all nodes i, j, k= 1,…,n, where n∈N. The finalized distance matrix, D, is the all-pairs shortest paths distance matrix, S. As described earlier, if there is a path for every pair of vertices in S, then the graph G is called connected and ready to input into Phase II. If there is not a path for any pair of vertices in S, then road network data should be modified (i.e. by correcting input data or by adding dummy arcs) until a connected graph is obtained.

The output of this phase includes the transportation network on a connected graph G, the distance matrix D of G, and the shortest path distance matrix S of G.

3.2. Phase II: Network Partitioning

This phase uses Phase I output as an input. Other inputs required in this phase are listed in Table 11, network partitioning model parameters.

The network partitioning procedure is an integer programming model that is modified from Kandula and Wright [19, 20]. The goal of the model is to develop service partitions that support determination of snow plow routing plans. In the model formulation, it is assumed that each service partition in the model output has a single depot located on it. Therefore, model outputs are a set of service partitions and a set of depots that are located on them. The quality of partitioning is measured in terms of compactness.

The integer programming model presented in this phase integrates district design and depot location selection problems as in Kandula and Wright [19, 20]. However, a number of constraint sets used in Kandula and Wright [19, 20], specifically for road classification, network connectivity, and deadhead travel time estimate related imaginary network commodity flow, are not included in the model formulation for the reasons discussed in Section 4, Chapter 2. On the other hand, model presented in Kandula and Wright [19, 20] is enhanced by introducing upper and lower bounds on a number of decision variables such as number of depots in operation and number of service vehicles available at each depot location. Additional upper and lower bounds ensure the possibility of evaluating any capacity growth opportunities for existing depots in the system.

The complete model formulation of the integer programming model is presented below; definitions for decision variables and indices, and parameters used in the model formulation are given in Tables 10 and 11, respectively.

$$\text{Minimize} \sum_{p} SUML_p + \sum_{p} N_p \tag{9.1}$$

$$\sum_{p} x_{ijp} - 1 = 0 \quad \forall\ (i,j) \in A \tag{9.2}$$

$$x_{ijp} - D_p \leq 0 \quad \forall\ (i,j) \in A,\ p \tag{9.3}$$

$$\sum_{p} D_p - NDL \geq 0 \tag{9.4}$$

$$\sum_{p} D_p - NDU \leq 0 \tag{9.5}$$

$$L_{ijp} - SP_{ip} * x_{ijp} - SP_{jp} * x_{ijp} = 0 \quad \forall\ (i,j) \in A,\ p \tag{9.6}$$

$$\sum_{i} \sum_{j} \left(L_{ijp} * x_{ijp}\right) - SUML_p \leq 0 \quad \forall\ p \tag{9.7}$$

$$LMAX_p - \max_{(i,j) \in A} \left(L_{ijp} * x_{ijp} * D_p\right) \geq 0 \quad \forall\ p \tag{9.8}$$

$$LMAX_p * D_p - L_{BOUND} \leq 0 \quad \forall\ p \tag{9.9}$$

$$w_{ij} - D_{ij} * NL_{ij} = 0 \quad \forall\ (i,j) \in A \tag{9.10}$$

$$\sum_{i} \sum_{j} w_{ij} * x_{ijp} - C_p * N_p \leq 0 \quad \forall\ p \tag{9.11}$$

$$\sum_{i} \sum_{j} w_{ij} * x_{ijp} - SUMW_p \leq 0 \quad \forall\ p \tag{9.12}$$

$$WMAX_p - SUMW_p * D_p \geq 0 \quad \forall p \tag{9.13}$$

$$WMAX_p - W_{BOUND} \leq 0 \quad \forall p \tag{9.14}$$

$$N_p - NLBOUND_p \geq 0 \quad \forall p \tag{9.15}$$

$$N_p - NUBOUND_p \leq 0 \quad \forall p \tag{9.16}$$

$$N_p - N_p * D_p \leq 0 \quad \forall p \tag{9.17}$$

$$x_{ijp}, D_p \in \{0,1\} \tag{9.18}$$

$$LMAX_p, WMAX_p, SUML_p, SUMW_p \geq 0 \tag{9.19}$$

$$N_p \in \{integer\} \geq 0 \tag{9.20}$$

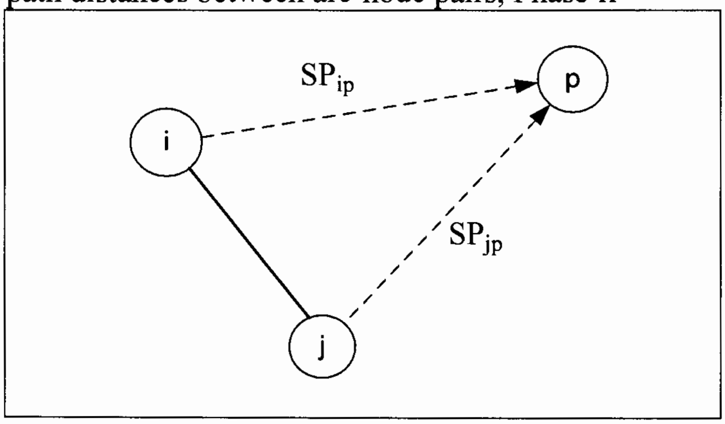
The objective function (9.1) minimizes sum of two terms: the total compactness value for all partitions and the total number of vehicles assigned to each partition. The minimization of the first term creates compact partitions in G. Arcs in G are assigned to the depot nodes in such a way that the sum of distances to reach arcs from their assigned depot node is minimized. The second term in the objective function ensures that the capacity and demand at each partition are well matched for better utilization of available vehicles. Constraint set (9.2) ensures that each arc in A must be assigned to a single node. Constraint set (9.3) ensures that arcs in A must be assigned to the nodes that are in operation (depot nodes). The total number of nodes in operation or the total number of partitions in the network can be specified by constraints (9.4) and (9.5). NDL in (9.4) represents a user defined positive integer value for the lower bound on the total number of depots in operation. NDU in (9.5) represents a user defined positive integer value for the upper bound on the total number of depots in operation. If NDL is set equal to NDU, the user determines a fixed number of total number of depots in operation in the network.

Table 10 Network partitioning model indices and decision variables, Phase II

Indices:
i= 1,..I, vertex in V; j= 1,..J, vertex in V; p= 1,..P, vertex in V; (i,j)= arc in A, ∀ i,j∈V
Decision Variables:
D_p= 1 if depot node p is in operation and 0 otherwise
N_p= total number of trucks assigned to partition p (or depot node p)
$LMAX_p$= maximum compactness value allowed for any arc assigned to partition p (or depot node p)
$SUML_p$= total compactness value of partition p (or depot node p)
$SUMW_p$= total workload of partition p (or depot node p)
x_{ijp}= 1 if arc (i,j) is assigned to partition p (or depot node p) and 0 otherwise
$WMAX_p$= maximum workload allowed for partition p (or depot node p)

Constraint set (9.6) represents compactness value calculation for each arc-node pair in the network. The compactness value for a given arc-node pair is the sum of the shortest path distances from both ends of an arc, (i,j), to the node, p, (Figure 5).

Figure 5 Shortest path distances between arc-node pairs, Phase II



Constraint set (9.7) represents the sum of compactness values for each node p. Constraint sets (9.8) and (9.9) limit the maximum compactness value allowed for each arc-depot node pair, and eliminate undesirable arc-depot node assignment alternatives, such as discontinued arc assignments, from consideration. Constraint set (9.10) represents calculation of workload for each arc in A. Workload is defined as the multiplication of the length of the arc by the number of lanes of that arc. Constraint set (9.11) ensures that service capacity available at each depot node p is equal to or more than the workload assigned to that depot node. Available service capacity is defined as the multiplication of average vehicle capacity by number of vehicles to be assigned to depot node p.

Table 11 Network partitioning model parameters, Phase II

Parameters:
C_p= average service capacity of vehicles assigned to partition p (or depot node p), in terms of travel distance in miles
D_{ij}= length of arc (i,j)
L_{ijp}= sum of shortest path distances to the node i and to the node j from depot p
L_{BOUND}= upper limit for the compactness value allowed for any arc-depot assignment
$NLBOUND_p$= lower bound on the total number of trucks assigned to partition p (or depot node p)
$NUBOUND_p$= upper bound on the total number of trucks assigned to partition p (or depot node p)
NDL= lower bound on the total number of partitions (or depot nodes in operation)
NDU= upper bound on the total number of partitions (or depot nodes in operation)
NL_{ij}= number of lanes associated with arc(i,j)
SP_{ip}= shortest path distance form node i of arc (i,j) to the depot node p
SP_{jp}= shortest path distance form node j of arc (i,j) to the depot node p
w_{ij}= workload associated with arc (i,j)
W_{BOUND}= upper limit for the total workload allowed for any partition (or depot)

Constraint set (9.12) represents sum of workload for each depot node p. Constraint sets (9.13) and (9.14) limit the maximum workload assignment allowed for each node, and eliminate undesirable sector design alternatives, such as too large partitions in terms of workload, from consideration. The total number of service vehicles assigned to each depot can be specified by constraints (9.15) and (9.16). $NLBOUND_p$ in (9.15) represents a user defined positive integer value for the lower bound on the total number of service vehicles assigned to depot p. $NUBOUND_p$ in (9.16) represents a user defined positive integer value for the upper bound on the total number of service vehicles assigned to depot p. If $NLBOUND_p$ is set equal to $NUBOUND_p$, the user determines a fixed number of service vehicles assigned to each depot in the network. Constraint set (9.17) ensures that service vehicles must be assigned to the nodes that are in operation, referred to as depot nodes. Constraint sets (9.18-9.20) are the restrictions on model decision variables.

The output of this phase is a set of service partitions and single depots located on them, and a number of service vehicles assigned for each service partition. If there is any disconnected service partitions in the model output, model parameters in constraint sets (9.8), (9.9), (9.13), and (9.14) or decision variables in constraint set (9.3) can be tuned for the specific arc-depot assignment to eliminate the disconnected design alternative.

Once connected service partitions, depot locations, and number of service vehicles are identified from the model solution, vehicle routing plans are determined through the network routing procedure in Phase III. It should be noted that the number of service vehicles is estimated based on capacity requirements. Therefore, this estimate is a lower bound on the actual number of vehicles required for service in practice.

3.3. Phase III: Network Routing

This phase uses Phase II output as an input. Other inputs required in this phase include number of lanes and desired service recovery time for each road segment, and vehicle service speed and deadheading speed.

Routing procedure is defined as a graph theory heuristic described in Eiselt et al. [33], for the directed rural postman problem. The heuristic has three steps: (1) construct minimal spanning trees, (2) solve minimum cost matching problem, and (3) find Euler cycles. Heuristic constructs a set of Euler cycles that support decision makers to determine routing plans.

The heuristic used in this phase is described in four steps. The first two steps are applied to the partitions and last two steps are applied to branches of those partitions.

Step 1. Minimal Spanning Tree

The aim of this step is to construct a set of node branches in partition p. The depot node is set as the root node for all the branches. In the later steps, vehicle routes are determined on these branches. The minimal spanning tree procedure, by Taha [52], is used for branching. At each partition p, depot location node is linked to other nodes of the partition so that all nodes in partition p are connected with the shortest length of the connecting branches. The algorithmic description of minimal spanning tree procedure, by Taha [52], is as follows: Let $G^p=(V^p, A^p)$ be network partition p obtained from Phase II, where V^p is the vertex set representing depot locations and start and end points of road segments in G^p, and A^p is the arc set representing road segments from vertex to vertex. The distance matrix, D^p, associated with every arc in A^p is created. Then, following steps apply:

Step 1.0. Define V^p, C^p_k, and $\overline{C}^p_k$, where $V^p=\{v^1,v^2,\ldots,v^n\}$ is the set of nodes in G^p and v^1 is the root node that the depot building is located; C^p_k is the set of nodes in G^p that have been permanently connected at iteration k; and $\overline{C}^p_k$ is the set of nodes in G^p as yet to be connected permanently.

Step 1.1. Set $C^p_0= \emptyset$ and $\overline{C}^p_0= V^p$

Step 1.2. Start with the root node v^1 that the depot building is located, and set $C^p_1= \{v^1\}$ and $\overline{C}^p_1= V^p- \{v^1\}$, then set k= 2

General Step k. Select any node, v^*, in the unconnected set $\overline{C}^p_{k-1}$ that yields the shortest arc to a node in the connected set C^p_{k-1}. Link v^* permanently to C^p_{k-1} and remove it from $\overline{C}^p_{k-1}$, that is, $C^p_k = C^p_{k-1} + \{v^*\}$ and $\overline{C}^p_k= \overline{C}^p_{k-1}- \{v^*\}$. If $\overline{C}^p_k$ is empty stop; otherwise set k= k+1 and repeat General Step k.

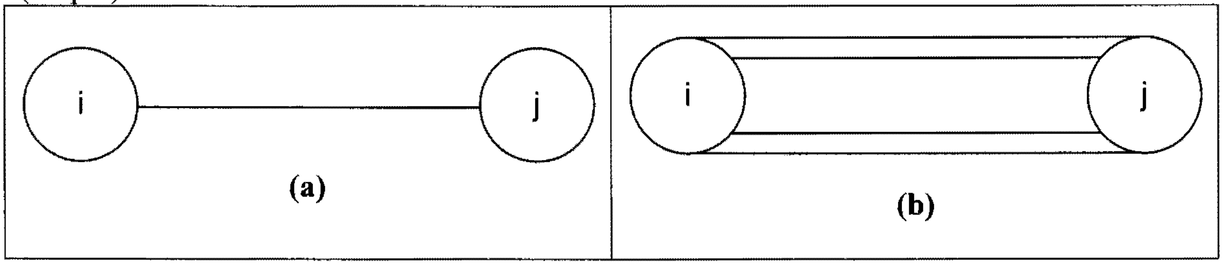
The output of this step is, for each partition p, a number of branches that connect all nodes in the partition to the root node (or the depot node).

Step 2. Network Transformation

Network transformation step prepares network partitions (and branches obtained in Step 1) for input into later steps. In this step, single-lane structure of the network is transformed to multi-lane structure for using a more realistic network scheme to determine vehicle routing plans. The transformation is done by simply replacing each arc in Phase II outcome with a number of arcs associated with the number of lanes of the corresponding Phase II arc. Figure 6 represents an example for the network transformation procedure. In Figure 6, the arc between node i and node j (Figure 6a) is replaced with four arcs (Figure

6b). In this example, it is assumed that the arc between node i and node j (Figure 6a) represents a four-lane road segment. The output of Step 2 is a multi-lane network structure.

Figure 6 Network transformation, single-lane structure to multi-lane structure, Phase III (Step 2)



Step 3. Matching Problem

This step determines artificial arcs to be added to each partition branch and prepares network partitions for input into the fourth step. In this step, artificial arcs are added to partition branches so that the Euler paths can be constructed in the next step of the methodology. Some of the definitions necessary for explaining Steps 3 and 4 are given in Table 12.

Table 12 Matching problem related definitions and Euler's Theorem, Gibbons [54]

Degree of a node: The number of edges incident with the node.
Euler Graph: An undirected graph which contains an Euler circuit.
Euler Path: A path of a graph which traverses every edge of the graph exactly once.
Euler Circuit (or Euler Cycle): A path of a graph which traverses every edge of the graph exactly once and ends at the same node which it starts.
Euler's Theorem: An undirected graph G has an Euler circuit if and only if it is connected and the number of odd-degree nodes is 0.

Then the algorithmic description of the matching problem, by Eiselt et.al [32], is as follows:

Step 3.0. Find the degree of each node in the branch.

Step 3.1. Identify all odd-degree nodes for the branch. If all nodes have even-degree, then go to Step 4; otherwise go to Step 3.2.

Step 3.2. Add artificial arcs, parallel to the existing arcs, which will turn all odd-degree nodes in a branch into even-degree nodes. Solve the matching problem to find number of arcs to be added.

The matching problem aims to assign odd-degree nodes of a branch to one other so that all odd-degree nodes in a branch are well matched and matching costs are minimized. The cost for matching any pair of odd-degree node is the shortest distance between that pair of odd-degree node. The matching problem is defined as a simple integer programming model. The model formulation, by Eiselt et al. [32], follows:

$$\text{Minimize} \sum_{i=1} \sum_{j=i+1} (x_{ij} * c_{ij}) \tag{10.1}$$

$$\sum_{i \neq j} x_{ij} = 1 \qquad \forall i \tag{10.2}$$

$$x_{ij} \in \{0,1\} \tag{10.3}$$

The objective function minimizes the sum of matching cost where x_{ij} is a binary decision variable and c_{ij} is the cost representing the shortest path distance between node i and node j. The constraint set satisfies that each odd-degree node is matched with another odd-degree node. It should be noted that the objective function value obtained for each branch represents a lower bound value on the deadheading distance associated with that branch.

Step 4. Find Euler Circuits

The final step of the network routing phase creates an Euler circuit for each branch of partition p and determines the number of vehicles to be assigned to the branches. The resulting Euler circuits are the suggested vehicle routing plans for decision makers. Vehicle routing plans start and end at the same depot and passes every road segment only and exactly once. The procedure to find Euler circuits, modified from Gibbons [54], is as follows:

Step 4.0. Set number of service vehicles assigned to the branch N = 1.

Step 4.1. Begin at depot node.

Step 4.2. Start to traverse the arcs and delete them as they are traversed. The choice of an arc from a node is arbitrary, except the following rule: never traverse an arc which is a bridge; an arc whose deletion disconnects the graph.

Step 4.3. If all arcs are traversed stop and vehicle returns to the depot.

At this point additional sub-steps are introduced to the heuristic described in [54]. The additional procedure breaks Euler cycles into appropriate pieces if the time required servicing all road segments in a given Euler cycle exceeds the desired recovery time for the corresponding road segments.

Step 4.4. Calculate service completion time (TC_V) for vehicle v. Find the minimum service recovery time (TR_V) for the road segments serviced by vehicle v, given that

$$TC_V = \frac{\text{Service Distance}}{\text{Service Speed}} + \frac{\text{Deadheading Distance}}{\text{Deadheading Speed}} \qquad (10.4)$$

$$TR_V = \min_{i \in p}(\text{service recovery time of road segment i serviced by vehicle v}) \qquad (10.5)$$

Step 4.5. If $TC_V \leq TR_V$, then stop; otherwise set number of service vehicles assigned to the branch N = N+1, and go to step 4.1.

The output of this procedure includes a number of Euler circuits that represents vehicle routes for plowing operations and a number of service vehicles assigned to each service branch of partition p. If necessary, Euler circuits are broken into appropriate pieces to satisfy service recovery times of the specific road segments.

The following chapter illustrates the implementation of system design methodology introduced in this chapter.

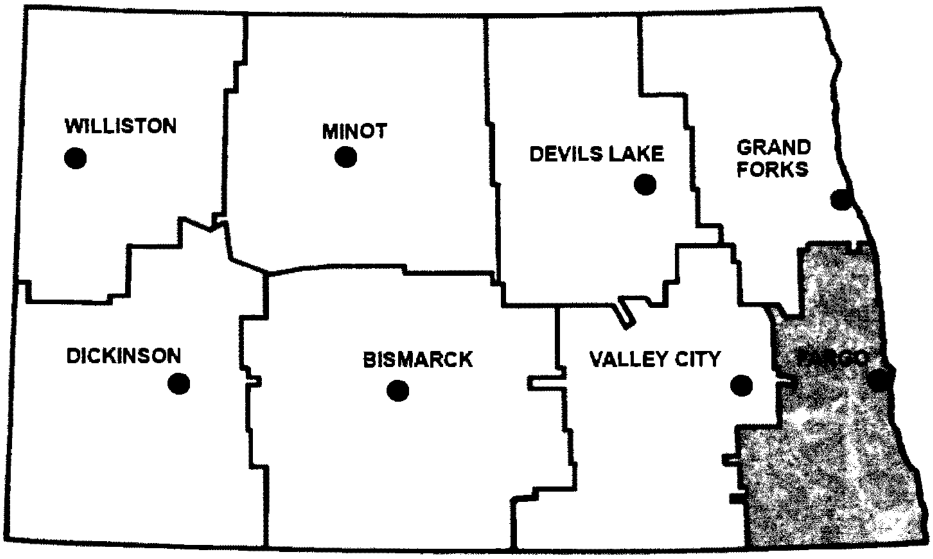
CHAPTER 4. IMPLEMENTATION

This chapter illustrates the solution methodology developed in Chapter 3, in which depot location selection, service district design, and snow plow routing problems are solved for the Fargo District of North Dakota's transportation system. Section 4.1 provides an overview of the Fargo District of North Dakota's transportation system. Section 4.2 involves network initialization phase and defines the transportation network used in this study on a strongly connected graph G. Section 4.3 involves discussion of parameters used in the later phases of the methodology. Section 4.4 illustrates implementation of district design phase on a number of test scenarios and describes system design scenarios to be considered in the later section. Finally, Section 4.5 presents implementation outcomes for system design scenarios considered.

4.1. The Fargo District

North Dakota's transportation system is divided into eight zones, or districts. The Fargo District is in the southeastern part of North Dakota and it is bounded by state limits to the east and south (Figure 7). The district has 1,817 lane miles of roadway and covers highways, interchanges, and a small amount of truck parking and safety roadside rest areas [56]. The Fargo district experiences heavy snowfall during winter seasons. The district has a constant workforce in the last few years although district's service area has growth, and car and truck traffic has increased [56]. Especially in winter seasons, workforce is supported by hiring temporary workers to maintain 24-hour service coverage. The district seeks to maintain traffic safety and continuity during winter seasons with snow plowing and chemical applications, and scheduling staggered work shifts.

Figure 7 Regional service districts of the North Dakota Transportation System, NDDOT Biennial Report 2007-2009 [57]



The district highway network that requires snow plowing operations is 1,760.4 lane miles, divided into 11 service sections and serviced by 34 vehicles (Table 13). There are currently nine maintenance buildings located in the road network.

Table 13 The Fargo District service sections, corresponding lane miles and number of service trucks [57]

Section	Lane Miles	Number of Service Vehicles	Number of Equipment Operators
Fargo North Section	99.7	2	6
Hillsboro Section	169.2	3	4
Mayville Section	150.2	2	3
Casselton Section	212.1	4	5
Fargo South Section	124.2	4	6
Fargo West Section	115.3	4	5
Forman Section	175.3	2	3
Lisbon Section	193.8	3	4
Lidgerwood Section	158.4	3	3
Wahpeton Section	194.1	4	4
Wyndmere Section	168.0	3	3
Total	1760.4	34	46

Six service levels are established for road segments that require plowing and each service level has a desired service recovery time (Table 14). A desired service recovery time is the time period that it takes to reach desired pavement conditions by snow plowing, which means all plowable snow and ice is removed from pavement surface. Based on service levels, road segments with higher service level have snow plow service priority.

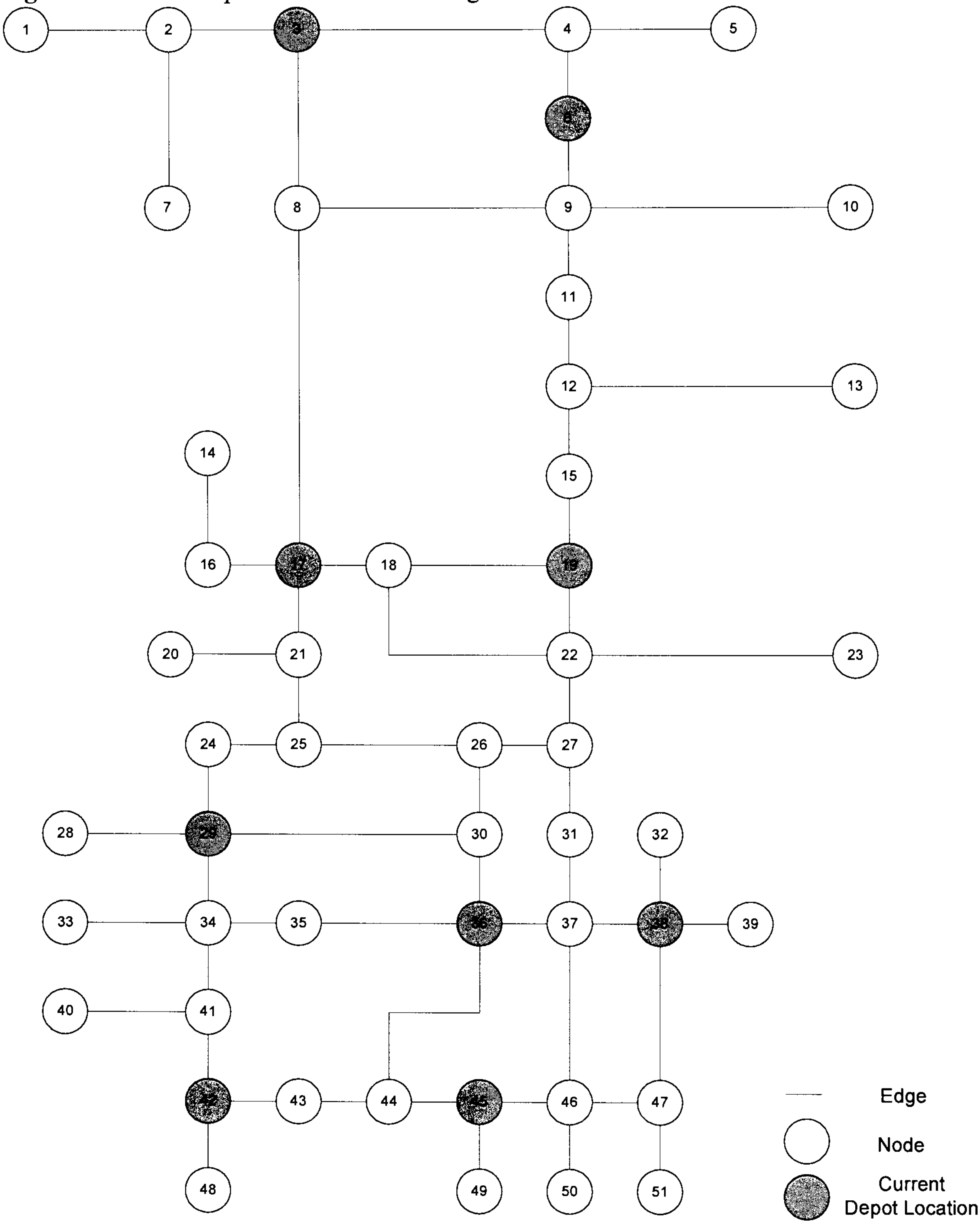
Table 14 Desired service recovery times for service levels [57]

Service Level	Desired Service Recovery Time
Level 1	1-3 hrs
Level 2	2-6 hrs
Level 3	2-8 hrs
Level 4	3-10 hrs
Level 5	6-12 hrs
Level 6	8-24 hrs

4.2. Network Initialization

This section involves network initialization phase of the system design methodology. As the first step, the Fargo District road network is illustrated in Figure 8, in which light-colored nodes represent start and end points of road segments, and candidate depot locations; dark-colored nodes represent existing depot locations; and edges connecting nodes represent road segments that require snow plowing. The network consists of 60 edges along with 51 nodes, of which nine are depots at their actual (original) locations. In the next step, the distance matrix (D) is created for the road network with the data presented in Appendix A. The distance matrix (D) is presented in Appendix B, in which the matrix cell value "M" represents a big number (i.e. M= 1000), if there is not any connection between corresponding node pairs of the matrix.

Figure 8 Network representation of the Fargo District road network



The next step in this phase is to check whether the road network is strongly connected or not. For this purpose all pairs shortest paths matrix (S) is created for the Fargo

District road network using Floyd's algorithm described in Section 3.1. The algorithm is coded in MATtrix LABoratory (Appendix C). Algorithm output, namely the all pairs shortest paths matrix for the Fargo District road network, is presented in Appendix D. As it can be seen in Appendix D, there is a path for every pair of nodes in the road network presented in Figure 8. This implies that the road network can be represented in a strongly connected graph. Therefore, as an output of this phase, the Fargo District road network is described on a strongly connected graph G= (V,A). In this notation, V is the vertex set representing existing and candidate depot locations, and start and end points of road segments, where V=1, 2, …, 51 and A is the arc set representing the road segments, where A= 1, 2, …, 60. The subset V'of V is described to specify existing depot locations on the road network, where V'= 3, 6, 17, 19, 29, 36, 38, 42, and 45.

4.3. Parameters

A number of parameters are required as input into later phases of the methodology. This section presents calculations and assumptions related to model parameters:

Vehicle Speed. Based on the information provided by the Fargo District of the North Dakota Department of Transportation, the average plowing speed is assumed to be 30 miles per hour and the average deadheading speed is assumed to be 60 miles per hour.

Number of Service Vehicles per Depot. Lower bound on the number of service vehicles per depot (or service district) is set to 1. This lower bound makes sure that each depot has at least one vehicle available for service so that the road segments can be assigned to that depot. Upper bound on the number of service vehicles per depot (or service district) is set to 6. This number is the maximum of (i) the average number of service vehicles per depot and (ii) the average number of equipment operators per depot (Table 13). If any of the scenarios considered in later sections result in an infeasible solution due to lower or upper bounds on the number of service vehicles, the bounds can be relaxed to eliminate infeasible solution alternatives.

(i) Average number of service vehicles per depot:

$$^{34}/_{9} = 3.77 \rightarrow \text{round up to the next integer} \rightarrow 4$$

(ii) Average number of equipment operators per depot:

$$^{46}/_{9} = 5.11 \rightarrow \text{round up to the next integer} \rightarrow 6$$

Service Level. Service levels used in this study are described in [57] and service levels for each road segment described in G are presented in Appendix A.

Desired Service Recovery Time. Desired service recovery times for corresponding service levels are adjusted and adjusted service recovery times are used in the implementation phase (Table 15). It is assumed that 10% of desired service recovery time is an idle time: either service vehicle or vehicle operator is not available for service, due to refueling vehicles, inspecting equipment, replacing service operators, using radio systems for communicating central offices, accidents or breakdowns. Therefore, adjusted service

Table 15 Adjusted service recovery times for service levels

Service Level	Calculations	Adjusted Service Recovery Time
Level 1	3 hrs * 0.9 = 2.7 hrs	1-2.7 hrs
Level 2	6 hrs * 0.9 = 5.4 hrs	2-5.4 hrs
Level 3	8 hrs * 0.9 = 7.2 hrs	2-7.2 hrs
Level 4	10 hrs * 0.9 = 9 hrs	3-9 hrs
Level 5	12 hrs * 0.9 = 10.8 hrs	6-10.8 hrs
Level 6	24 hrs * 0.9 = 21.6 hrs	8-21.6 hrs

recovery times are basically 10% less than desired service recovery times.

Vehicle Capacity. In district design phase, it is assumed that all vehicle capacities are equal and average vehicle capacity is 2.7 hours of continuous service. Hence, 80 lane miles of plowing is feasible before a vehicle must visit its starting depot. The minimum number of service vehicles required for service obtained from district design phase solution is the minimum number of service vehicles required for the highest level of service for the Fargo District road network. Thus, any service level upgrade possibility of road segments can be feasible in the network routing phase of the methodology.

Maximum Workload per Depot. This value is set as 480 lane miles and given by the multiplication of the upper bound on the service vehicles per depot and the vehicle capacity.

Upper Bound on the Maximum L_{ijp} Value. The L_{ijp} value represents sum of the shortest path distances from depot location p to the end points of road segments i and j. Upper bound on the maximum L_{ijp} value ensures that any undesirable depot-road segment assignments are to be eliminated. This value is initially set to 80 miles but it can be adjusted to consider different feasible system design alternatives. The validation of the initially chosen upper bound value on the maximum L_{ijp} is done by calculating the L_{ijp} matrix for the Fargo District road network. The calculation algorithm is coded in MATtrix LABoratory. The code and the algorithm output are presented in Appendices E and F, respectively. As it can be seen in Appendix F, the maximum L_{ijp} value for the Fargo District road network is 69.2 miles for the current service district system design. Therefore, it is concluded that the initial upper bound value of 80 miles on the L_{ijp} is a reasonable value that can be used to consider other system design alternatives.

Candidate Depot Location: It is assumed that any node in vertex set (V) can be a candidate depot location. However, the solution methodology used in this study also enables identifying any subset of V as the candidate depot locations. It should be noted that, as the number of candidate depot locations decreases, the problem size decreases. Thus, the solution methodology can be improved by decreasing the time required for solution.

4.4. Test Scenarios

In order to determine system design scenarios to be evaluated for the Fargo District road network, a number of test scenarios are executed. The primary outcomes from test scenarios are then used to determine final scenarios to be studied.

In test scenarios, network partition methodology is applied to depot location selection and district design problems for the Fargo District road network. The number of depots to open is set to 1 for the 1st test scenario and increased by 1 depot for each test scenario executed until all 51 candidate depots in vertex set V are covered. For each scenario, road segments are assigned to a given number of depots in the network. For example, in the 1st scenario, 1 depot location is selected from 51 candidate depot locations to create a single service district road network and for the nth scenario, n depot locations are selected from 51 candidate depot locations to create n districts in the road network.

The integer programming model presented in Section 3.2 is coded in LINGO and the Global Solver engine of LINGO is used for model solution. The Global Solver of LINGO guarantees finding global optima for nonlinear and integer mathematical models using the branch and bound/relax algorithms [58]. The solution of integer programming model involves three steps: input and output files are created for each scenario in *.xls format, then mathematical programming model formulation is generated in LINGO, and model is solved. An example for LINGO code used in this process is presented Appendix G.

Model parameters described in Section 4.3 are used for all test scenarios except for Test Scenario 1, Test Scenario 2, and Test Scenario 3. The parameter adjustments required to obtain feasible system design scenarios for the corresponding test scenarios are summarized in Table 16.

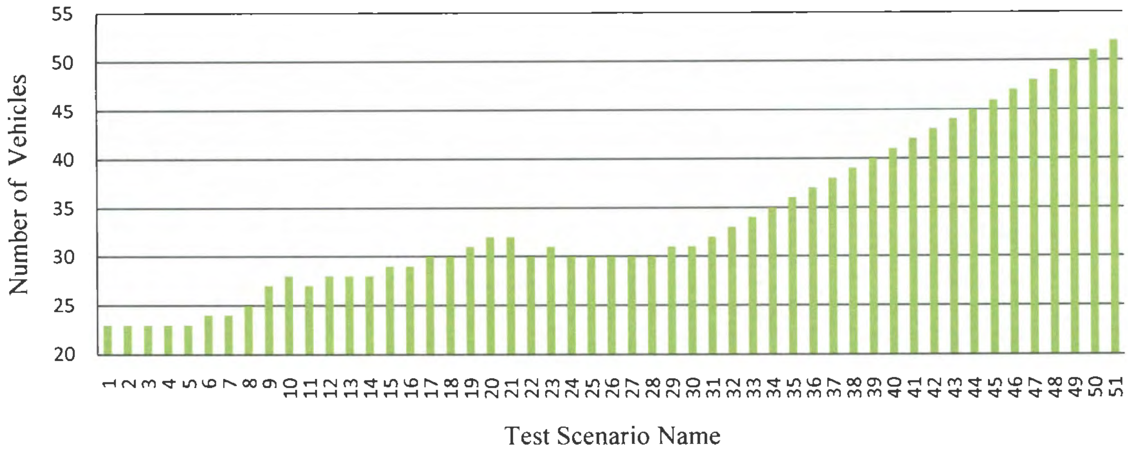
Table 16 Model Parameter Adjustments for Test Scenarios 1, 2, and 3

Model Parameter/ Test Scenario	n:1 Depot	n:2 Depots	n:3 Depots	n:{4,..,51} Depots
Upper bound on the number of vehicles per depot	50	50	30	6
Limit on the Maximum Workload per Depot	3000	3000	2400	480
Upper Bound on the Maximum L_{ijp} Value	1000	1000	500	80

The initial test scenarios are evaluated based on several system design characteristics: number of vehicles required for service (Figure 9), maximum workload assigned per depot (Figure 10), maximum L_{ijp} value in the system (Figure 11), and total system compactness value (Figure 12). Summary of test scenario outcomes is presented in Appendix H.

Figure 9 compares the number of vehicles required for service in test scenarios. It can be seen that there is an incremental trend on the number of vehicles required for service from n:29 to n:51. This trend is due to the lower bound on number of vehicles constraint used in the network partitioning model. The lower bound on number of vehicles constraint ensures that at least one vehicle must be assigned to depots in operation. Therefore, the

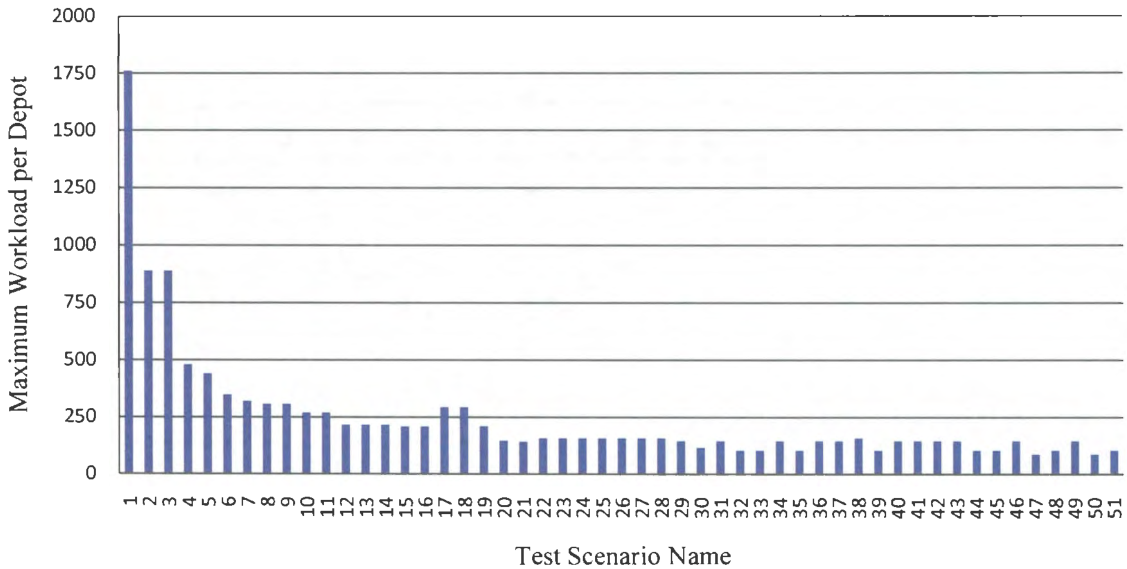
Figure 9 Number of vehicles required for service in test scenarios



number of vehicles required for service is overestimated when a large number of depots are in operation, i.e. when n>29.

Figure 10 compares the maximum workload per depot in test scenarios. As it can be seen in Figure 10, the maximum workload per depot decreases as the number of depots in the system increases.

Figure 10 Maximum depot workload in test scenarios (miles)



There are two scenarios in which such a decreasing trend is not observed, n:17 and n:18. Model solution outputs for these two cases are analyzed in detail. It is observed that the depot with maximum workload in both scenarios is the depot located at node 19. It should be noted that there is actually a depot located at node 19 in the existing road network of the Fargo District.

Figure 11 compares the maximum L_{ijp} value in test scenarios. As it can be seen in Figure 11, constant maximum L_{ijp} values of 52.2 and 33.5 are observed for scenarios 8-14 and 15-51, respectively.

Figure 11 Maximum L_{ijp} value in test scenarios (miles)

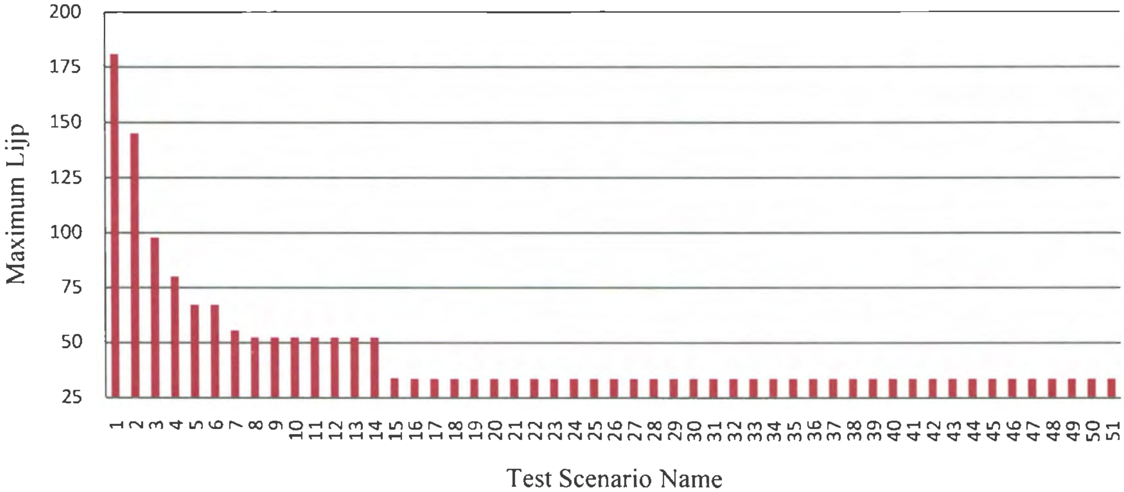
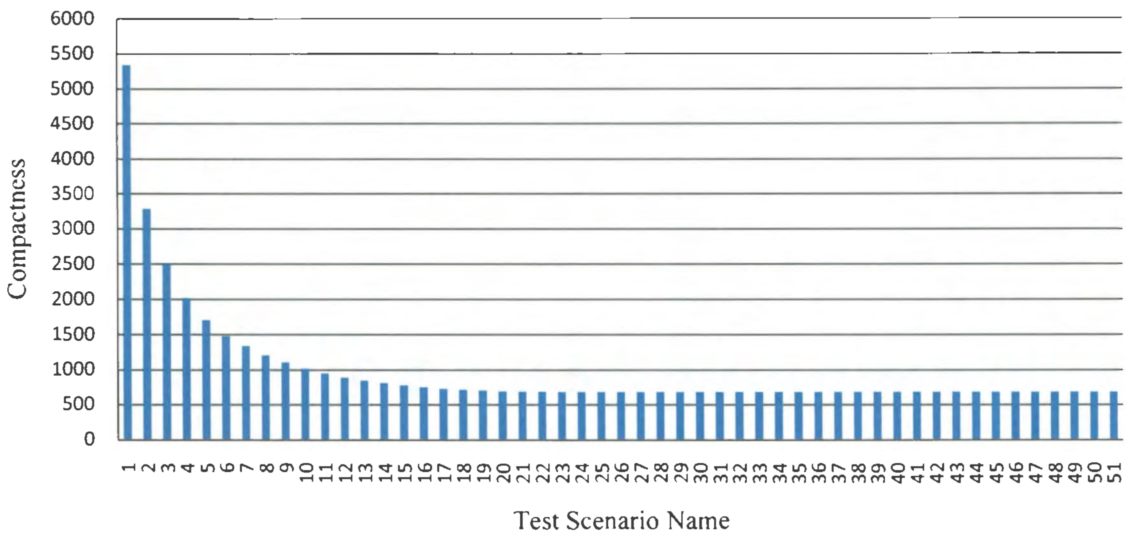


Figure 12 compares the total system compactness for test scenarios. Total system compactness value decreases as the number of depots located in the system increases. To better analyze the improvement in total system design compactness value, a rate of change in compactness value is defined as

$$RC^{i \to i+1} = \frac{CV^{i+1} - CV^{i}}{CV^{i+1}} \tag{11.1}$$

where $RC^{i \to i+1}$ represents the rate of improvement in compactness value for the test scenario i+1 compared to the test scenario i, and CV^i and CV^{i+1} are compactness values for test scenarios i and i+1, respectively. Based on the rate of improvement in compactness value, test scenarios are categorized into four: (i) more than 10% rate of improvement (test scenarios 1-6); (ii) between 5% to 10% rate of improvement (test scenarios 7-12); (iii) less than 5% rate of improvement (test scenarios 13-23); and (iv) no improvement (test scenarios 24-51).

Figure 12 Total system compactness value in test scenarios (miles)



The current number of depots in the road network is nine. Therefore, the second test scenario category is chosen to be analyzed further. Table 17 presents a summary of system design characteristics for the second test scenario category. As it is seen in Table 17, there

Table 17 Design criteria for test scenarios 7-12: category (ii)

Design Specification/ Test Scenario	**7**	**8**	**9**	**10**	**11**	**12**
Number of Depots Open	7	8	9	10	11	12
Number of Vehicles Required	24	25	27	28	27	28
Maximum L_{ijp} Value	55.3	52.2	52.2	52.2	52.2	52.2
Maximum Workload per Depot	319.4	306.5	306.5	269.0	269.0	215.3

can be potential system design benefits of decreasing and increasing number of depots in the Fargo District road network, in terms of minimum number of vehicles required for service and maximum workload per depot. There are currently nine depots in the road network. Therefore, the following 8-depot, 9-depot, and-10 depot system design scenarios are chosen to study in detail.

4.4.1. Current Setup

Current Setup scenario is a nine depot scenario. In this scenario, current depot locations and current depot-road segment assignments are used as the basis for determining vehicle routes for snow plowing operations. As discussed in Section 4.2, current depot locations are described as the subset V' of V in G, in which existing depots are located at nodes 3, 6, 17, 19, 29, 36, 38, 42, and 45. Current Setup scenario depot-road segment assignment data is presented in Appendix A. Based on the data provided in Appendix A, Figure 13 shows existing depot locations and their assigned service districts. Depot locations are indicated by colored circles and road segments assigned to them are labeled with colored square labels representing arc names presented in Appendix A.

4.4.2. Partial Redesign

Partial Redesign scenario is a nine depot scenario. In this scenario, modifications to current depot-road segment assignments are used as the basis for determining vehicle routes for snow plowing operations. This means that road segments are reassigned to the current depots. This scenario helps evaluate the impact of assigning road segments to depots, without changing number and locations of existing depots. Figure 14 shows system design layout for Partial Redesign scenario. Depot locations are indicated by colored circles. When solution methodology is applied to this scenario, road segments are assigned to depots and vehicle routes for snow plowing operations are determined.

Figure 13 Illustration of Current Setup scenario, current depot locations and current road segment assignments

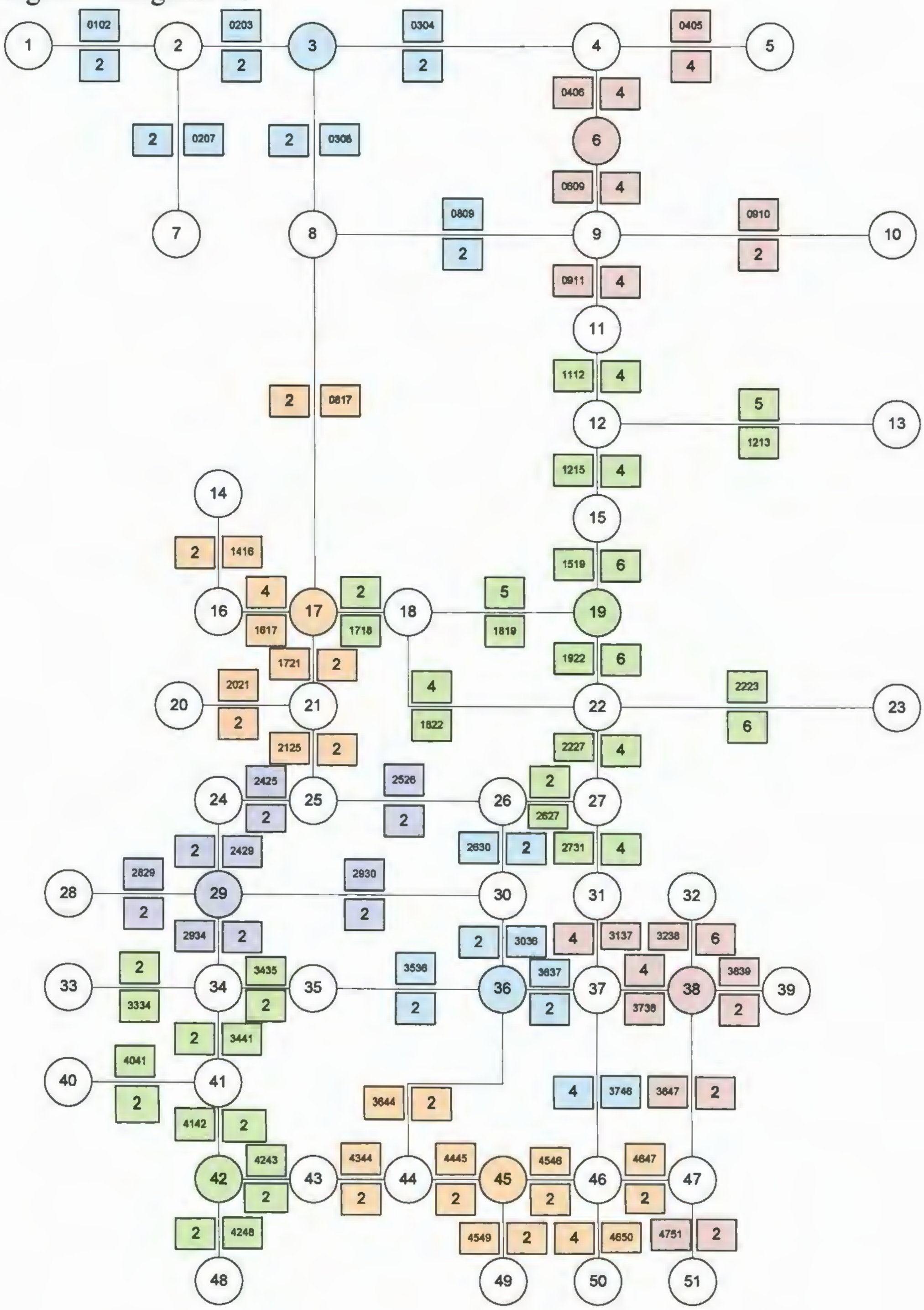
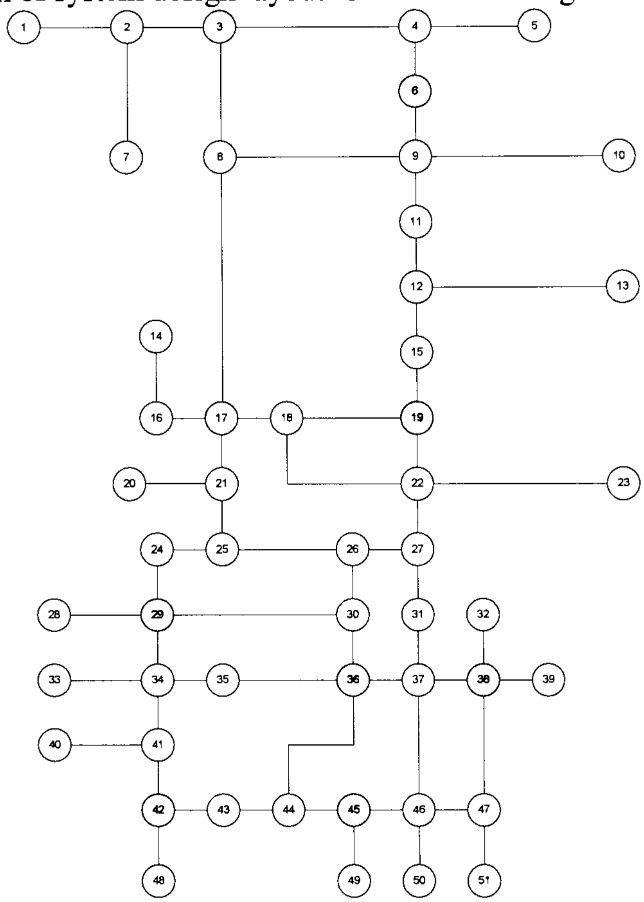


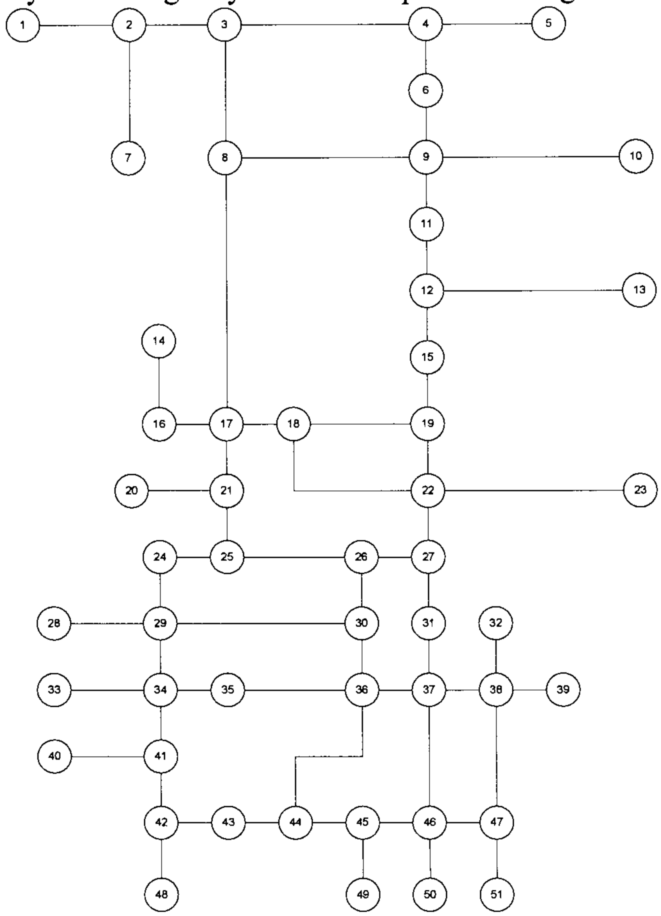
Figure 14 Illustration of system design layout for Partial Redesign scenario



4.4.3. Complete Redesign

Complete Redesign scenario is a nine depot scenario. In this scenario, a complete solution methodology is applied to depot location selection, service sector design, and vehicle routing problems for the Fargo District road network. When solution methodology is applied to this scenario, nine depots are opened in the road network, road segments are assigned to depots, and vehicle routes for snow plowing operations are determined. This scenario is an unconstrained solution for the Current Setup scenario, in terms of any given depot locations and any given depot-road segment assignments. Figure 15 shows system design layout for Complete Redesign scenario, as illustrated neither depot locations nor depot-road assignment are described in road network layout.

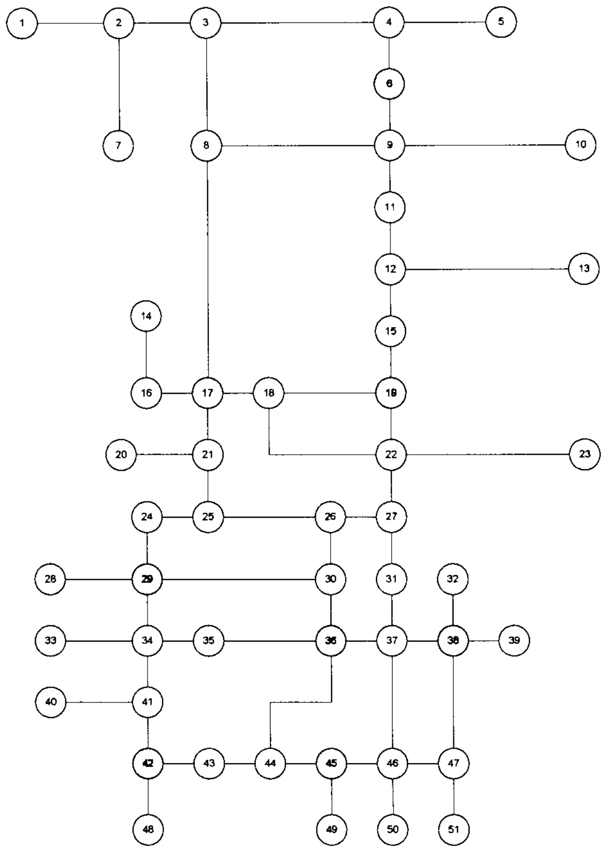
Figure 15 Illustration of system design layout for Complete Redesign scenario



4.4.4. Replace Redesign

Replace Redesign scenario is a nine depot scenario and is similar to Partial Redesign scenario. In this scenario, current depots in the Fargo District road network are replaced by one depot at a time. Nine scenarios are required to consider all replace redesign alternatives. Figure 16 represents an example of replace redesign scenario layout. In Figure 16, depot located at node 3 is to be replaced. Therefore, in the system design scenario layout all current depot locations are indicated by colored circles, except depot node 3. When solution methodology is applied to this scenario, the ninth depot is opened in the network to replace the depot at node 3. Then, road segments are assigned to nine depots and vehicle routes for snow plowing operations are determined.

Figure 16 Illustration of system design layout for Replace Redesign scenario, replacing depot at node 3

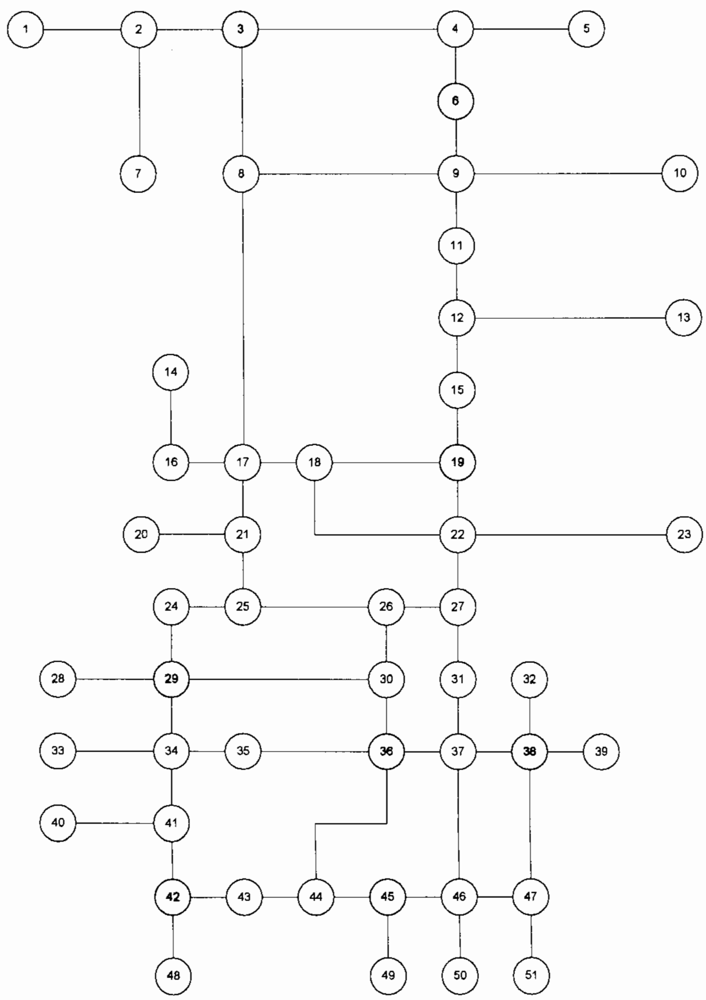


4.4.5. Close Redesign

Close Redesign scenario is an eight depot scenario and is similar to Partial Redesign scenario. In this scenario, each depot in the Fargo District road network is closed by one at a time. Nine scenarios are required to consider all close redesign alternatives. It should be noted that closing an open depot in the network decreases the number of operating depots in the system by one. The other way of decreasing the number of operating depots in the system by one is merging any two depots at a new depot location.

However, depot merging scenarios are not considered in this thesis. It is assumed that merging scenarios are always more costly than close redesign scenarios. Therefore, less expensive system design scenarios, close redesign scenarios, are chosen. Figure 17 represents an example of a close redesign scenario layout. In Figure 17, depot located at node 17 is to be closed. Therefore, in the system design scenario layout all current depot locations are indicated by colored circles, except depot node 17. When solution methodology is applied to this scenario, road segments are assigned to remaining eight depots, and then vehicle routes for snow plowing operations are determined.

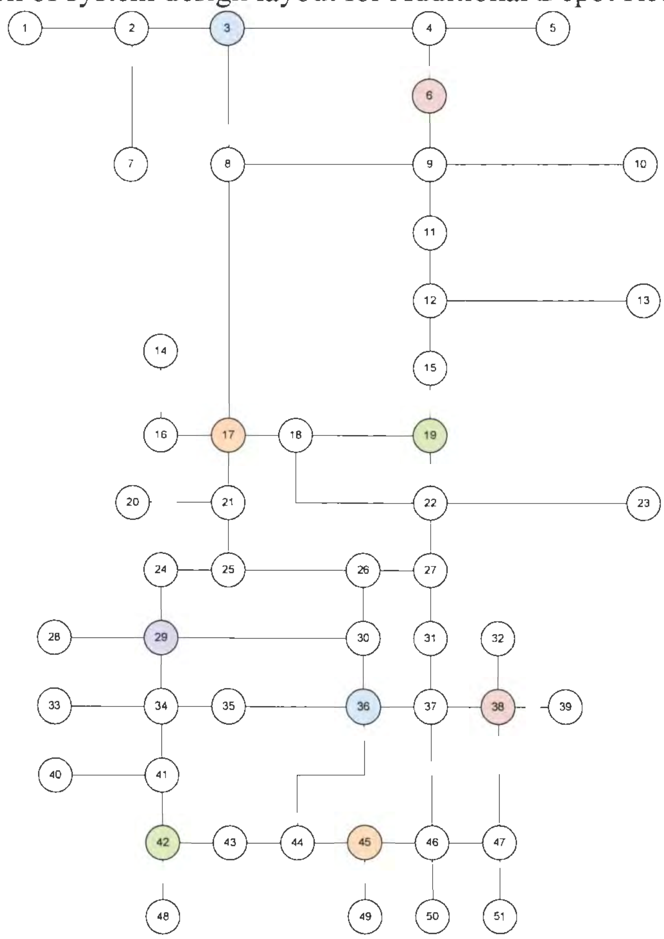
Figure 17 Illustration of system design layout for Close Redesign scenario, closing depot at node 17



4.4.6. Additional Depot Redesign

Additional Depot Redesign scenario is a ten depot scenario and is similar to Partial Redesign scenario. In this scenario, a new depot is to be opened in the Fargo District road network. It should be noted that there can be other approaches to increase by one the number of depots in the system. For example, n existing depots can be closed and then n+1 new depots can be opened in new locations. However, this type of system design approach is not considered in this thesis. It is assumed that the least expensive way of increasing number of depots in the system by one is basically opening a new depot at a new location. Figure 18 represents additional depot redesign scenario layout. In Figure 18, existing nine depot locations are indicated by colored circles. When solution methodology is applied to

Figure 18 Illustration of system design layout for Additional Depot Redesign scenario



this scenario, an additional depot is opened in the system. Then, road segments are assigned to ten depot locations, and vehicle routes for snow plowing operations are determined.

The next section involves application of system design methodology described in Chapter 3 for the system design scenarios chosen to be executed in this section.

4.5. Network Partitioning and Network Routing

This section involves determination of vehicle routing plans for scenarios described in the previous section. In order to determine vehicle routing plans, district design phase methodology is executed for all scenarios. Therefore, depot location problem and depot-road segment assignment problems for all scenarios are solved before network routing methodology is executed.

Table 18 summarizes results for network partitioning phase for scenarios. Elapsed solution time for each scenario is given in the very last column of this table. As presented in Table 18, depots located at nodes 17, 19, 29, and 38 are relocated to their existing locations. This means that, in terms of total system compactness, current system design cannot be improved by replacing these depots. Depots located at nodes 3, 6, 42, and 45 are relocated to one of their neighbor nodes of 7.32 miles, 4 miles, 2 miles, and 14.84 miles of distance, respectively. Relocation to neighbor nodes suggests that these depots are well located in the current design based on total system compactness. A major depot location replacement is observed for depot located at node 36; hence, depot at node 36 is relocated to node 26, which is 25.82 miles of distance.

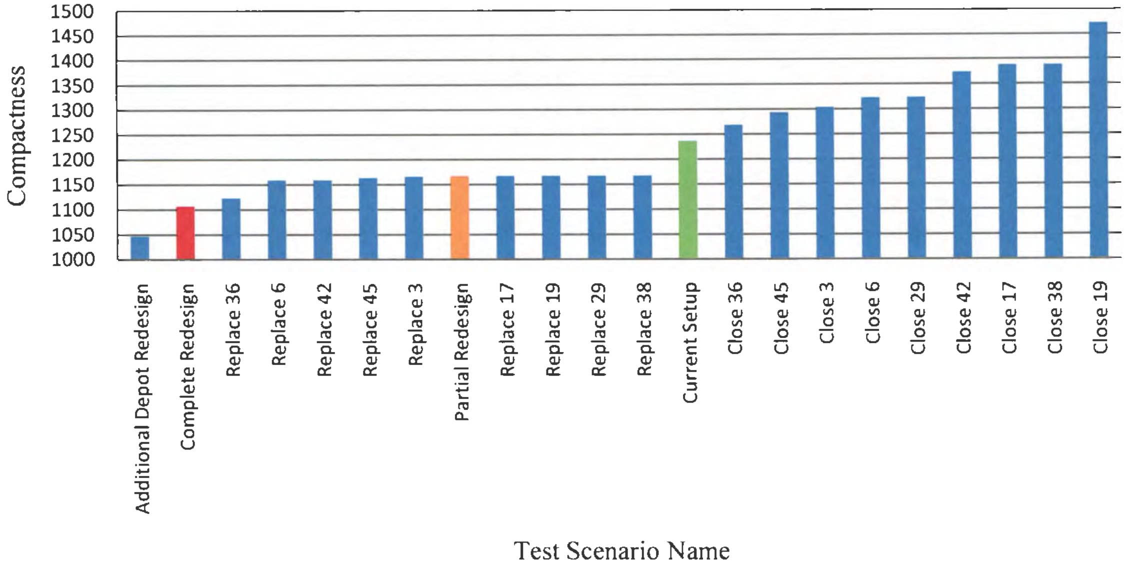
Figure 19 compares total system compactness in test scenarios. As it is seen in

Figure 19, close redesign scenarios have larger compactness values than other scenarios. Closing the depot located at node 36 has the least incremental impact on total system compactness, comparing to other closing scenarios. Interestingly, in additional depot redesign scenario, a new depot is chosen to be located at node 26. This supports outcomes from Replace Redesign and Close Redesign scenarios for depot located at node 36.

Table 18 Summary of results for network partitioning phase

Scenario Name	Modified depots in the network partitioning model solution compared to existing depots in the system	Number of depots	Total system compactness	Scenario Runtime (hh:mm:ss)
Current Setup	N/A	9	1236.45	00:00:15
Partial Redesign	N/A	9	1166.31	00:00:23
Complete Redesign	Closed:{6, 36, 42} Opened:{9, 26, 41}	9	1106.43	00:17:14
Replace Redesign				
Replace 3	Replaced to: {2}	9	1165.25	00:16:41
Replace 6	Replaced to: {9}	9	1158.31	00:13:19
Replace 17	N/A	9	1166.31	00:05:35
Replace 19	N/A	9	1166.31	00:10:28
Replace 29	N/A	9	1166.31	00:16:42
Replace 36	Replaced to: {26}	9	1122.43	00:11:28
Replace 38	N/A	9	1166.31	00:16:36
Replace 42	Replaced to: {41}	9	1158.31	00:16:37
Replace 45	Replaced to: {46}	9	1162.32	00:14:29
Close Redesign				
Close 3	Closed: {3}	8	1302.96	00:00:54
Close 6	Closed: {6}	8	1323.36	00:00:45
Close 17	Closed: {17}	8	1387.07	00:00:36
Close 19	Closed: {19}	8	1471.39	00:00:44
Close 29	Closed: {29}	8	1323.57	00:00:24
Close 36	Closed: {36}	8	1268.13	00:00:32
Close 38	Closed: {38}	8	1387.16	00:00:48
Close 42	Closed: {42}	8	1372.81	00:00:47
Close 45	Closed: {45}	8	1292.72	00:00:44
Additional Depot Redesign	Opened: {26}	10	1046.15	00:14:40

Figure 19 Total system compactness value in design scenarios (miles)



In general, scenarios with more number of depots in operation perform better in the network districting phase. Additional Depot Redesign scenario has the lowest compactness value. Nine depot redesign scenarios have lower compactness values than eight depot redesign scenarios. The other point that has to be mentioned is the performance of Partial Redesign scenario. Partial Redesign scenario can be considered as the least implementation cost scenario. As it is seen in Figure 19, Partial Redesign scenario outperforms many redesign alternatives including Current Setup scenario. Therefore, it can be concluded that there is a potential to improve vehicle routing with the implementation of the Partial Redesign scenario based on total system compactness values.

Network partitioning phase outcomes for all scenarios are presented in Appendix J in detail, involving depot location selections and depot-road segment assignments. Data provided in Appendix J is input into the network routing phase. Once the network partition phase is completed for all scenarios, the network routing phase is executed.

For all depots located in the network, minimal spanning trees are created in such a way that the depot node is set as the root node for all tree branches. The lists of branches for all depots are listed in Appendix K, in the second column of tables, for each scenario. In the next step, the single lane structure of road network is transformed into a multi-lane structure with "number of lanes per arc" data given in Appendix A. This transformation helps using a more realistic network scheme to determine vehicle routing plans. In the third step, artificial arcs to be added to each partition branch are determined. It is observed that for all scenarios an artificial arc is required for node pairs 12 and 13 (arc A1213 in Appendix A) and node pairs 18 and 19 (arc A1819 in Appendix A). The matching problem for these two cases is solved manually, since the problem size is small and calculation algorithm is easy. However, for more complex matching problem cases, the solution algorithm presented in Section 3.3 is coded in MATtrix LABoratory and an example code is presented in Appendix I. In the last step network routing phase, a number of routes are created for each branch of all depots in the network. Routes that do not satisfy service recovery constraints are then broken into smaller ones. In the route breaking procedure, the minimum service recovery time (TR_V) is assumed to be the adjusted service recovery time of Level 1 road segments at the first iteration and the desired service recovery time of Level 1 road segments at later iterations. This assumption prevents overestimating number of vehicles required for service and also does not conflict with the desired service recovery time constraints for Level 1 road segments.

The output of network routing phase is a number of vehicle routes starting from and returning to depots. Since routes are all represented by individual Euler cycles, routes on different branches of a depot can be merged to provide an estimate of number of service vehicles required. Thus, any routes starting from and returning to the same depot location are merged, given that the corresponding adjusted service recovery time constraints are not violated.

4.6. Results and Discussion

This section presents results of solution methodology developed in this study, in which problems of depot location selection, service district design, and vehicle routing problems are solved for the Fargo District road network.

For all design scenarios, network routing phase is solved for adjusted service recovery time of 2.7 hours (Service Level 1). In the route breaking step, service recovery time is relaxed to desired service recovery time of 3 hours (Service Level 1). Therefore, all routes constructed require less than 3-hour service cycle time, which is the desired service recovery time for Service Level 1. This means that service levels are automatically upgraded to Service Level 1 for all road segments.

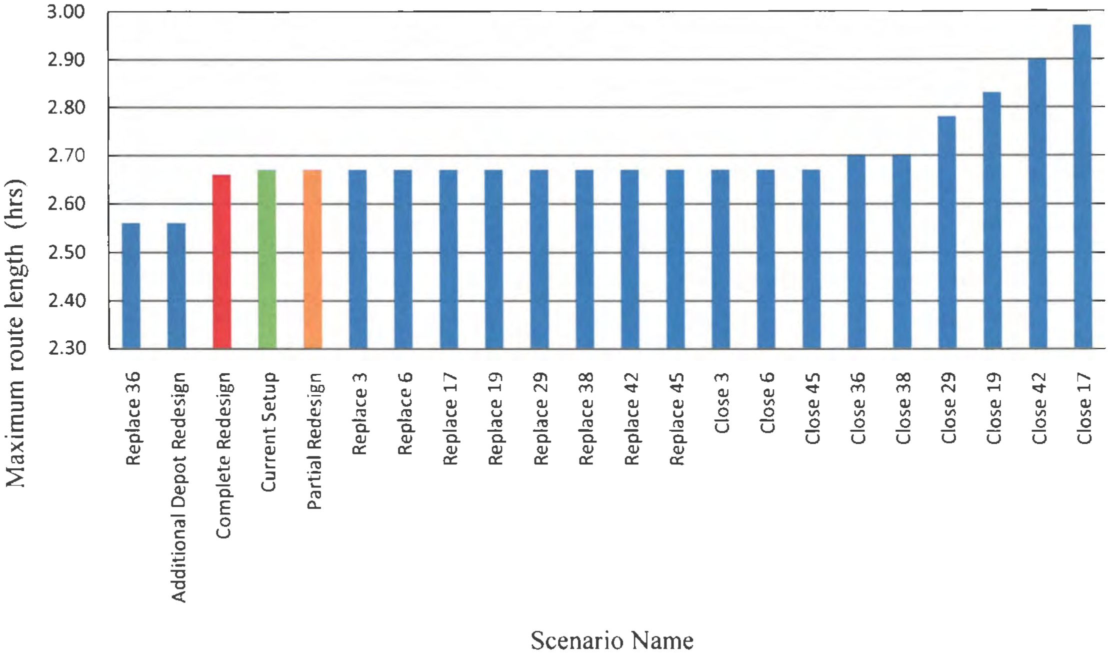
Table 19 summarizes results for network routing phase for scenarios. The average solution time for each scenario in this phase is approximately 2 hours. The first column in Table 19 lists the name of design scenarios considered in this study and the second column presents the total vehicle time required to complete a single service cycle. The total vehicle time per service cycle is calculated by summing up values presented in the very last column (Total Time (hours)) of Tables in Appendix K. The third column is the maximum route length (hours) per scenario. The fourth column is the number of routes constructed for each scenario. For all scenario considered, routes and route lengths (in hours) are presented in Appendix K, in detail. The last column of Table 19 gives the number of vehicles required for service. It should be noted that methodology used in this study does not involve any description for route merging or vehicle-route assignment to determine the minimum number of service vehicles required. However, routes can easily be merged by manual calculations to minimize the number of service vehicles required.

Table 19 Summary of results for network routing phase

Scenario Name	Total vehicle time per service cycle (hours)	Maximum route length (hours)	Number of vehicles
Current Setup	60.87	2.67	31
Partial Redesign	61.15	2.67	29
Complete Redesign	60.96	2.66	28
Replace Redesign			
Replace 3	60.66	2.67	29
Replace 6	61.15	2.67	28
Replace 17	61.15	2.67	29
Replace 19	61.15	2.67	29
Replace 29	61.15	2.67	29
Replace 36	61.22	2.56	28
Replace 38	61.15	2.67	29
Replace 42	60.48	2.67	29
Replace 45	60.46	2.67	29
Close Redesign			
Close 3	61.64	2.67	31
Close 6	62.37	2.67	32
Close 17	62.81	2.97	31
Close 19	63.00	2.83	30
Close 29	62.51	2.78	31
Close 36	61.38	2.70	28
Close 38	63.05	2.70	31
Close 42	62.04	2.90	30
Close 45	61.63	2.67	28
Additional Depot Redesign	61.15	2.56	31

Figure 20 compares the maximum route length in design scenarios. Maximum route length is an important design characteristic for route planning since it has direct impact on determining the number of vehicles required for service. The number of vehicles assigned to a single route can be at minimum, if it is possible to construct shorter routes. In other words, the number of routes that can be serviced at a time can be increased.

Figure 20 Maximum route length in scenarios (hours)



As it is seen in Figure 20, the maximum route length can be minimized by Replace 36 and Additional Depot Redesign scenarios. Closing a facility in the system increases maximum route length in all cases. In all scenarios, the maximum route length is less than 3 hours. Thus, it can be concluded that all scenarios are feasible even if the service level requirement is 1 (highest) for all road segments.

Figure 21 compares the total vehicle time per service cycle in design scenarios. Total vehicle time per service cycle of a scenario is the total of all route lengths in duration (hours) for that scenario. From a system design perspective, it is important to decrease total vehicle time for a given routing plan. In this way resources allocated for routing can be minimized, i.e. labor hours and vehicles. Total vehicle time per service cycle also affects average workload of vehicles in the system. Thus, minimizing total vehicle time per service cycle may improve service quality in terms of level of service provided, too. It should be noted that total vehicle time has two components: total service time and total deadheading time. If total deadheading time increases in the system, then total service time increases. Thus, results for total vehicle time only concludes that Replace 45 scenario minimizes vehicle deadheading at best.

Figure 21 Total vehicle time per service cycle in scenarios (hours)

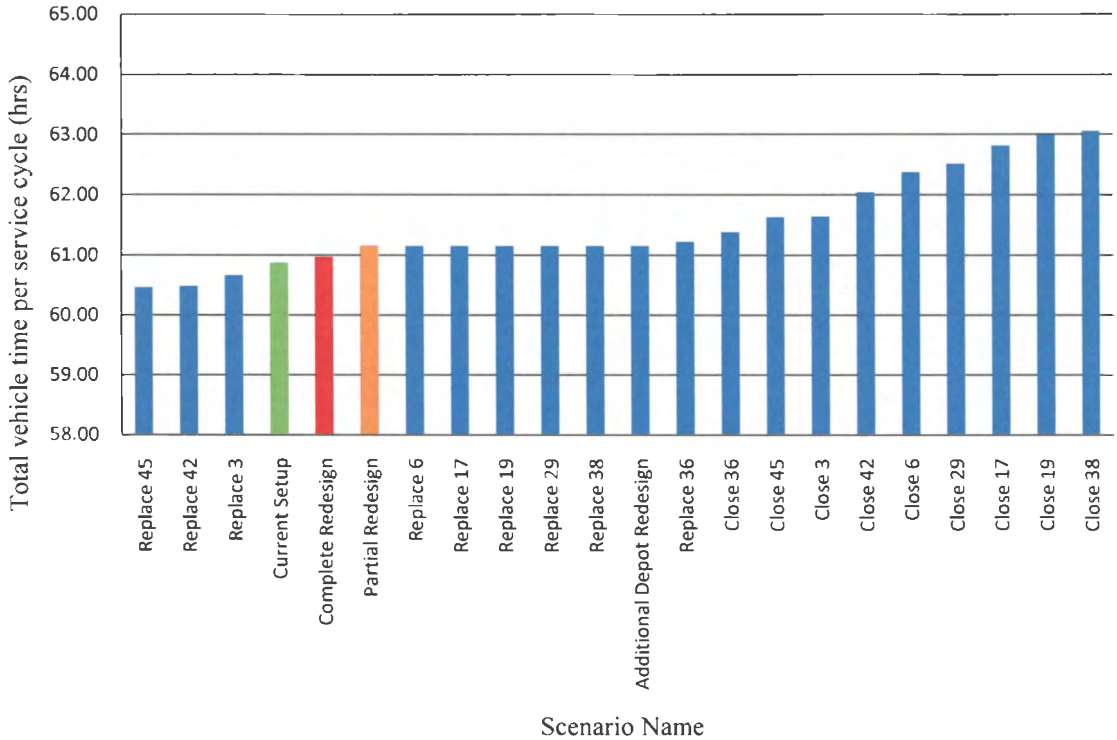
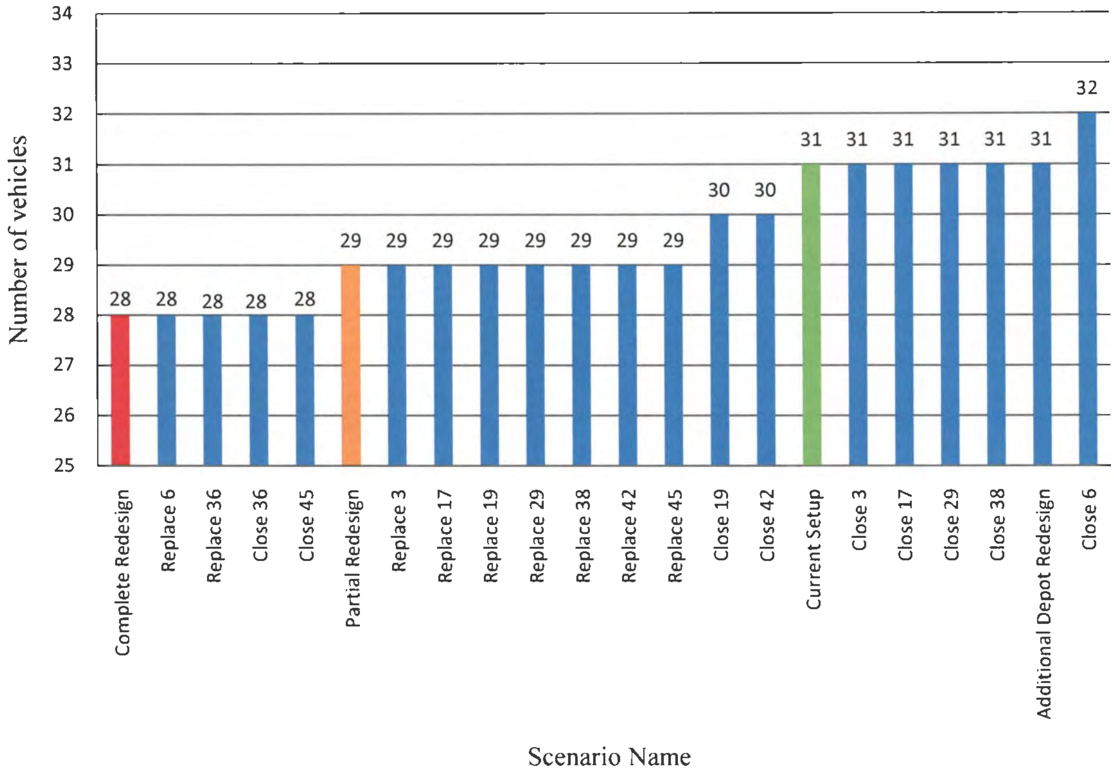


Figure 22 compares the number of vehicles required for service in each scenario. The numbers are determined by simply assigning routes to vehicles in such a way that existing service levels are maintained. As it is seen in Figure 22, several improvement attempts to the Current Setup scenario actually perform better than the Current Setup scenario. The only case for which the number of vehicles required for service increases is the Additional Depot Scenario. However, it should be noted that, there is a trade-off between number of vehicles required for service and the route length, and Additional Depot Redesign scenario is ranked as one of the best system design scenarios in terms of maximum route length.

Figure 22 Number of vehicles required for service in scenarios



Based on results presented in Section 4.6, the following system design scenarios are suggested for improving the Fargo District road network snow plowing operations.

Current Setup Scenario. Vehicle routes are determined for Service Level 1. This scenario is assumed to be the easiest implementation case, requires the shortest implementation period and its impact is immediate.

Partial Setup Scenario. Road segments are reassigned to depots and vehicle routes are determined for Service Level 1. Based on system design criteria discussed, this scenario performs better than several design alternatives. It may require an intermediate implementation period but its impact is immediate.

Additional Depot Scenario. Opening a new depot is suggested at node 26 in the Fargo District road network. This scenario may require a long implementation period. However, once completed, its impact is immediate and long lasting. It should be noted that there are three depot relocation scenarios that generally perform better than others: Replace 3, Replace 6, and Replace 36. Among these, Replace 36 should be chosen, since depot at node 36 is relocated at the farthest distance (at node 26), of 25.82 miles. Interestingly, the same node is chosen as a new depot location in Additional Depot Scenario. Since, it is assumed that Additional Depot Scenario is the least cost alternative for implementation among these three alternatives, the Replace 36 scenario is chosen.

CHAPTER 5. CONCLUSION AND DIRECTIONS FOR FUTURE RESEARCH

The objective of this study was to develop and implement a systematic solution methodology for depot location selection, service sector design, and vehicle routing problems for winter road maintenance operations, in the context of snow plow routing, for the Fargo District road network. The solution methodology achieves these objectives by forming compact service districts and determining the highest service level routing plans for different system design scenarios to be considered for implementation. Although, there is much opportunity for evaluating different system scenarios based on implementation costs, proposed solution approach considers a number of other design criteria such as maximum route length, service cycle time, and number of vehicles required for service. The integer programming model developed for the partitioning phase allows evaluating capacity growth opportunities for existing maintenance facilities. The overall methodology helps decision makers choose from alternative system design scenarios as well as compare performance of depots in operation. The methodology used in this thesis can easily be implemented for other winter road maintenance operations. The alternative design scenarios described in this study can be used to study a variety of different network partitioning and routing problems such as logistics districting, electrical power districting, and health care districting.

5.1. Directions for Future Research

The objective of network partitioning phase, Phase II, of the methodology used in this study is to minimize total system compactness to form compact service districts. However, this objective ensures the selection of largest number of depots possible in any system design scenario. Therefore, if the number of depots to be opened is not given as an input, it is difficult to make a decision on the optimal number of depots to be open in a given road network. This limitation can be eliminated by integrating a cost component to the objective function of the integer programming model presented in the network partitioning phase, Phase II, of the methodology. The cost component of new objective function may involve cost of opening, closing, and relocating depots at different locations, and cost of number of vehicles required for service. Such a modification in the definition of objective function may help discovering trade-offs between compactness and system design cost.

Based on the literature on compactness, if road segments can be represented by smaller pieces, network partitioning phase of this study may perform better in terms of forming more compact service districts. However, in such a case, problem size for partitioning and routing problems will increase because of the additional decision variables used to represent road segments in smaller pieces. At this point, a study that compares performance of the proposed solution methodology, with different road segment sizes, can be a contribution to the existing literature.

Another important concept to consider is the vehicle operator related system design characteristics. In practice, operator experience and live-in areas are important decision making criteria in winter road maintenance system planning, especially in rural areas. However, in the literature, there is not study that integrates vehicle operator related concepts into the winter road maintenance planning decision making process.

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APPENDIX A. FARGO DISTRICT ROAD NETWORK DATA [57]

Road Segment	Section	Arc Name (From Node to Node in Figure 6)	Current Depot Assignment	Arc Length (miles)	Number of lanes per arc	Lane Miles (miles)	Service Level
Mayville East to I-29	Mayville	A0304	3	11.16	2	22.32	4
Mayville to Blanchard	Mayville	A0308	3	14.93	2	29.86	5
Mayville to Jct ND 18	Mayville	A0102	3	14.99	2	29.98	4
Mayville to Jct ND 18	Mayville	A0203	3	7.32	2	14.64	4
Blanchard to I-29	Mayville	A0809	3	8.35	2	16.70	4
Finley East to ND 18	Mayville	A0207	3	18.37	2	36.74	4
Jct I-29 to Red River	Hillsboro	A0910	6	20.22	2	40.44	4
Mayville Exit to Buxton	Hillsboro	A0405	6	7.21	4	28.84	2
Mayville Exit to Hillsboro	Hillsboro	A0406	6	6.79	4	27.16	2
Hillsboro to 200/200A	Hillsboro	A0609	6	4.00	4	16.00	2
200/200A to Gardner	Hillsboro	A0911	6	14.17	4	56.68	2
Main Avenue to Gardner 29/81	Fargo North	A1112	19	18.83	4	75.32	2
Main Avenue to Gardner 29/294	Fargo North	A1215	19	1.00	4	4.00	2
I-94 to Main Avenue 10/29	Fargo North	A1519	19	1.00	6	6.00	1
I-94 to Main Avenue 94/29	Fargo North	A1922	19	1.73	6	10.40	1
19 th Avenue North	Fargo North	A1213	19	0.80	5	4.00	1
I-29 to the Red River	Fargo South	A2223	19	2.90	6	17.40	1
I-94 to Christine 46/29	Fargo South	A2227	19	15.14	4	60.57	2
I-94 to Christine 46/29	Fargo South	A2731	19	4.00	4	16.01	2
I-29 to East Jct ND 18	Fargo South	A2627	19	15.11	2	30.22	4
Casselton to I-28	Fargo West	A1822	19	18.32	4	73.28	1
Casselton Int. to Raymond Int.	Fargo West	A1718	19	12.01	2	24.02	6
45 th Street to West Fargo Int.	Fargo West	A1819	19	3.60	5	18.00	1
Casselton to Buffalo	Casselton	A1617	17	16.37	4	65.48	2
Jct I-94 to Page	Casselton	A1416	17	19.50	2	39.00	5
Leonard to Casselton main street	Casselton	A1721	17	7.41	2	14.82	5

APPENDIX A. (continued)

Road Segment	Section	Arc Name (From Node to Node in Figure 6)	Current Depot Assignment	Arc Length (miles)	Number of lanes per arc	Lane Miles (miles)	Service Level
Leonard to Casselton	Casselton	A2125	17	10.41	2	20.82	5
Casselton to Blanchard	Casselton	A0817	17	33.47	2	66.94	4
Lynchburg to Jct ND 18	Casselton	A2021	17	2.54	2	5.08	5
Jct ND 1 to Cayuga Forman	Forman	A4041	42	22.91	2	45.82	5
Jct ND 1 to Cayuga	Forman	A4243	42	12.50	2	25.00	5
Jct ND 1 to Gwinner	Forman	A3334	42	21.94	2	43.88	4
Gwinner to Milnor	Forman	A3435	42	10.20	2	20.40	4
State Line to S. Jct ND 11	Forman	A4248	42	10.31	2	20.62	5
Forman North to ND 13	Forman	A3441	42	7.79	2	15.57	4
Forman North to ND 13	Forman	A4142	42	2.00	2	4.00	4
ND 1 East to Lisbon	Lisbon	A2829	29	18.00	2	36.00	5
Lisbon East to ND 18	Lisbon	A2930	29	25.98	2	51.97	5
ND 13 North to Lisbon	Lisbon	A2934	29	14.70	2	29.39	4
Lisbon North to ND 46	Lisbon	A2429	29	12.47	2	24.93	4
Jct 32 & 46 to East Jct 46 & 18	Lisbon	A2526	29	5.71	2	11.42	4
Jct 32 & 46 to East Jct 46 & 18	Lisbon	A2425	29	20.07	2	40.13	4
Cayuga to Lidgerwood	Lidgerwood	A4344	45	11.03	2	22.06	5
Lidgerwood to I-29 18/11	Lidgerwood	A4445	45	2.00	2	4.00	5
Lidgerwood to I-29	Lidgerwood	A4546	45	14.84	2	29.68	5
I-29 to MN Line	Lidgerwood	A4647	45	12.94	2	25.88	5
SD Line to Jct ND 11	Lidgerwood	A4549	45	9.19	2	18.38	6
Lidgerwood to ND 13	Lidgerwood	A3644	45	13.06	2	26.12	5
SD Line to ND 11	Lidgerwood	A4650	45	8.07	4	32.29	2
SD Line to ND 11	Wahpeton	A4751	38	7.98	2	15.97	6
Jct ND 11 to Wahpeton	Wahpeton	A3847	38	14.71	2	29.42	5
210 Bypass in Wahpeton	Wahpeton	A3238	38	2.94	6	17.62	1
Wahpeton to I-29	Wahpeton	A3738	38	10.43	4	41.72	3

APPENDIX A. (continued)

Road Segment	Section	Arc Name (From Node to Node in Figure 6)	Current Depot Assignment	Arc Length (miles)	Number of lanes in the arc	Lane Miles (miles)	Service Level
ND 13 to Christine	Wahpeton	A3137	38	21.55	4	86.20	2
Old 13 in Wahpeton	Wahpeton	A3839	38	1.58	2	3.16	1
Milnor to Wyndreme	Wyndmere	A3536	36	14.93	2	29.86	4
Wyndreme to I-29	Wyndmere	A3637	36	14.24	2	28.48	4
Wyndreme to Jct ND 46	Wyndmere	A2630	36	10.65	2	21.30	5
Wyndreme to Jct ND 46	Wyndmere	A3036	36	15.17	2	30.34	5
ND 11 to ND 13	Wyndmere	A3746	36	14.51	4	58.03	2

APPENDIX B. FARGO DISTRICT DISTANCE MATRIX (D) [57]

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0.0	15.0	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
2	15.0	0.0	7.3	M	M	M	18.4	M	M	M	M	M	M	M	M	M	M
3	M	7.3	0.0	11.2	M	M	M	14.9	M	M	M	M	M	M	M	M	M
4	M	M	11.2	0.0	7.2	6.8	M	M	M	M	M	M	M	M	M	M	M
5	M	M	M	7.2	0.0	M	M	M	M	M	M	M	M	M	M	M	M
6	M	M	M	6.8	M	0.0	M	M	4.0	M	M	M	M	M	M	M	M
7	M	18.4	M	M	M	M	0.0	M	M	M	M	M	M	M	M	M	M
8	M	M	14.9	M	M	M	M	0.0	8.4	M	M	M	M	M	M	M	33.5
9	M	M	M	M	M	4.0	M	8.4	0.0	20.2	14.2	M	M	M	M	M	M
10	M	M	M	M	M	M	M	M	20.2	0.0	M	M	M	M	M	M	M
11	M	M	M	M	M	M	M	M	14.2	M	0.0	18.8	M	M	M	M	M
12	M	M	M	M	M	M	M	M	M	M	18.8	0.0	0.8	M	1.0	M	M
13	M	M	M	M	M	M	M	M	M	M	M	0.8	0.0	M	M	M	M
14	M	M	M	M	M	M	M	M	M	M	M	M	M	0.0	M	19.5	M
15	M	M	M	M	M	M	M	M	M	M	M	1.0	M	M	0.0	M	M
16	M	M	M	M	M	M	M	M	M	M	M	M	M	19.5	M	0.0	16.4
17	M	M	M	M	M	M	M	33.5	M	M	M	M	M	M	M	16.4	0.0
18	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	12.0
19	M	M	M	M	M	M	M	M	M	M	M	M	M	M	1.0	M	M
20	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
21	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	7.4
22	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
23	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
24	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
25	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
26	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
27	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
28	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
29	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
30	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
31	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
32	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
33	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
34	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
35	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
36	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
37	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
38	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
39	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
40	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
41	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
42	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
43	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
44	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
45	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
46	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
47	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
48	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
49	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
50	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
51	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M

APPENDIX B. (continued)

Node	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
2	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
3	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
4	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
5	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
6	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
7	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
8	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
9	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
10	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
11	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
12	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
13	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
14	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
15	M	1.0	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
16	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
17	12.0	M	M	7.4	M	M	M	M	M	M	M	M	M	M	M	M	M
18	0.0	3.6	M	M	18.3	M	M	M	M	M	M	M	M	M	M	M	M
19	3.6	0.0	M	M	1.7	M	M	M	M	M	M	M	M	M	M	M	M
20	M	M	0.0	2.5	M	M	M	M	M	M	M	M	M	M	M	M	M
21	M	M	2.5	0.0	M	M	M	10.4	M	M	M	M	M	M	M	M	M
22	18.3	1.7	M	M	0.0	2.9	M	M	M	15.1	M	M	M	M	M	M	M
23	M	M	M	M	2.9	0.0	M	M	M	M	M	M	M	M	M	M	M
24	M	M	M	M	M	M	0.0	20.1	M	M	M	12.5	M	M	M	M	M
25	M	M	M	10.4	M	M	20.1	0.0	5.7	M	M	M	M	M	M	M	M
26	M	M	M	M	M	M	M	5.7	0.0	15.1	M	M	10.7	M	M	M	M
27	M	M	M	M	15.1	M	M	M	15.1	0.0	M	M	M	4.0	M	M	M
28	M	M	M	M	M	M	M	M	M	M	0.0	18.0	M	M	M	M	M
29	M	M	M	M	M	M	12.5	M	M	M	18.0	0.0	26.0	M	M	M	14.7
30	M	M	M	M	M	M	M	M	10.7	M	M	26.0	0.0	M	M	M	M
31	M	M	M	M	M	M	M	M	M	4.0	M	M	M	0.0	M	M	M
32	M	M	M	M	M	M	M	M	M	M	M	M	M	M	0.0	M	M
33	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	0.0	21.9
34	M	M	M	M	M	M	M	M	M	M	M	14.7	M	M	M	21.9	0.0
35	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	10.2
36	M	M	M	M	M	M	M	M	M	M	M	M	15.2	M	M	M	M
37	M	M	M	M	M	M	M	M	M	M	M	M	M	21.6	M	M	M
38	M	M	M	M	M	M	M	M	M	M	M	M	M	M	2.9	M	M
39	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
40	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
41	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	7.8
42	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
43	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
44	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
45	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
46	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
47	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
48	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
49	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
50	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
51	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M

APPENDIX B. (continued)

Node	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
1	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
2	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
3	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
4	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
5	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
6	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
7	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
8	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
9	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
10	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
11	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
12	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
13	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
14	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
15	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
16	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
17	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
18	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
19	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
20	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
21	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
22	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
23	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
24	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
25	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
26	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
27	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
28	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
29	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
30	M	15.2	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
31	M	M	21.6	M	M	M	M	M	M	M	M	M	M	M	M	M	M
32	M	M	M	2.9	M	M	M	M	M	M	M	M	M	M	M	M	M
33	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
34	10.2	M	M	M	M	M	7.8	M	M	M	M	M	M	M	M	M	M
35	0.0	14.9	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
36	14.9	0.0	14.2	M	M	M	M	M	M	13.1	M	M	M	M	M	M	M
37	M	14.2	0.0	10.4	M	M	M	M	M	M	M	14.5	M	M	M	M	M
38	M	M	10.4	0.0	1.6	M	M	M	M	M	M	M	14.7	M	M	M	M
39	M	M	M	1.6	0.0	M	M	M	M	M	M	M	M	M	M	M	M
40	M	M	M	M	M	0.0	22.9	M	M	M	M	M	M	M	M	M	M
41	M	M	M	M	M	22.9	0.0	2.0	M	M	M	M	M	M	M	M	M
42	M	M	M	M	M	M	2.0	0.0	12.5	M	M	M	M	10.3	M	M	M
43	M	M	M	M	M	M	M	12.5	0.0	11.0	M	M	M	M	M	M	M
44	M	13.1	M	M	M	M	M	M	11.0	0.0	2.0	M	M	M	M	M	M
45	M	M	M	M	M	M	M	M	M	2.0	0.0	14.8	M	M	9.2	M	M
46	M	M	14.5	M	M	M	M	M	M	M	14.8	0.0	12.9	M	M	8.1	M
47	M	M	M	14.7	M	M	M	M	M	M	M	12.9	0.0	M	M	M	8.0
48	M	M	M	M	M	M	M	10.3	M	M	M	M	M	0.0	M	M	M
49	M	M	M	M	M	M	M	M	M	M	9.2	M	M	M	0.0	M	M
50	M	M	M	M	M	M	M	M	M	M	M	8.1	M	M	M	0.0	M
51	M	M	M	M	M	M	M	M	M	M	M	M	8.0	M	M	M	0.0

APPENDIX C. MATLAB CODE USED FOR FLOYD'S ALGORITHM

```
% The letter "D" in "S=[D];" represents the distance matrix D of the road network%
S=[D];
N=51;
P=-1*ones(N,N);
for k=1:N
   for i=1:N
      for j=1:N
if S(i,k)==1000 continue;
end
 if S(k,j)==1000 continue;
end
if S(i,j)>S(i,k)+S(k,j)
   if P(i,k)==-1
     P(i,j)=k;
    else
      P(i,j)=P(i,k);
    end
    S(i,j)=S(i,k)+S(k,j);
      K=k+1;
      end
    end
 end
end
dlmwrite('allpairshortestpaths.xlsx', S, '\t')
for i=1:5
display('open allpairshortestpaths.xls file from C:\Program Files\MATLAB71\work')
end
```

APPENDIX D. FARGO DISTRICT ALL PAIRS SHORTEST PATHS MATRIX (S)

Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	0.0	15.0	22.3	33.5	40.7	40.3	33.4	37.2	44.3	64.5	58.4	77.3	78.1	106.6	78.3	87.1	70.7
2	15.0	0.0	7.3	18.5	25.7	25.3	18.4	22.3	29.3	49.5	43.4	62.3	63.1	91.6	63.3	72.1	55.7
3	22.3	7.3	0.0	11.2	18.4	18.0	25.7	14.9	22.0	42.2	36.1	55.0	55.8	84.3	56.0	64.8	48.4
4	33.5	18.5	11.2	0.0	7.2	6.8	36.9	19.1	10.8	31.0	25.0	43.8	44.6	88.5	44.8	69.0	52.6
5	40.7	25.7	18.4	7.2	0.0	14.0	44.1	26.4	18.0	38.2	32.2	51.0	51.8	95.7	52.0	76.2	59.8
6	40.3	25.3	18.0	6.8	14.0	0.0	43.6	12.4	4.0	24.2	18.2	37.0	37.8	81.7	38.0	62.2	45.8
7	33.4	18.4	25.7	36.9	44.1	43.6	0.0	40.6	47.6	67.9	61.8	80.6	81.4	110.0	81.6	90.5	74.1
8	37.2	22.3	14.9	19.1	26.4	12.4	40.6	0.0	8.4	28.6	22.5	41.4	42.2	69.3	42.4	49.8	33.5
9	44.3	29.3	22.0	10.8	18.0	4.0	47.6	8.4	0.0	20.2	14.2	33.0	33.8	77.7	34.0	58.2	41.8
10	64.5	49.5	42.2	31.0	38.2	24.2	67.9	28.6	20.2	0.0	34.4	53.2	54.0	97.9	54.2	78.4	62.0
11	58.4	43.4	36.1	25.0	32.2	18.2	61.8	22.5	14.2	34.4	0.0	18.8	19.6	72.3	19.8	52.8	36.4
12	77.3	62.3	55.0	43.8	51.0	37.0	80.6	41.4	33.0	53.2	18.8	0.0	0.8	53.5	1.0	34.0	17.6
13	78.1	63.1	55.8	44.6	51.8	37.8	81.4	42.2	33.8	54.0	19.6	0.8	0.0	54.3	1.8	34.8	18.4
14	106.6	91.6	84.3	88.5	95.7	81.7	110.0	69.3	77.7	97.9	72.3	53.5	54.3	0.0	52.5	19.5	35.9
15	78.3	63.3	56.0	44.8	52.0	38.0	81.6	42.4	34.0	54.2	19.8	1.0	1.8	52.5	0.0	33.0	16.6
16	87.1	72.1	64.8	69.0	76.2	62.2	90.5	49.8	58.2	78.4	52.8	34.0	34.8	19.5	33.0	0.0	16.4
17	70.7	55.7	48.4	52.6	59.8	45.8	74.1	33.5	41.8	62.0	36.4	17.6	18.4	35.9	16.6	16.4	0.0
18	82.7	67.7	60.4	49.4	56.6	42.6	86.1	45.5	38.6	58.8	24.4	5.6	6.4	47.9	4.6	28.4	12.0
19	79.3	64.3	57.0	45.8	53.0	39.0	82.6	43.4	35.0	55.2	20.8	2.0	2.8	51.5	1.0	32.0	15.6
20	80.7	65.7	58.4	62.6	69.8	55.8	84.0	43.4	51.8	72.0	46.4	27.6	28.4	45.8	26.6	26.3	10.0
21	78.1	63.1	55.8	60.0	67.2	53.2	81.5	40.9	49.2	69.5	43.9	25.0	25.8	43.3	24.0	23.8	7.4
22	81.0	66.0	58.7	47.5	54.7	40.7	84.4	45.1	36.7	57.0	22.6	3.7	4.5	53.2	2.7	33.7	17.3
23	83.9	68.9	61.6	50.4	57.6	43.6	87.3	48.0	39.6	59.9	25.5	6.6	7.4	56.1	5.6	36.6	20.2
24	108.6	93.6	86.3	90.5	97.7	83.7	112.0	71.4	79.7	99.9	74.3	55.5	56.3	73.8	54.5	54.3	37.9
25	88.5	73.5	66.2	70.4	77.6	63.6	91.9	51.3	59.6	79.9	54.3	35.4	36.2	53.7	34.4	34.2	17.8
26	94.2	79.3	71.9	76.1	83.4	69.4	97.6	57.0	65.4	85.6	52.8	34.0	34.8	59.4	33.0	39.9	23.5
27	96.1	81.1	73.8	62.7	69.9	55.9	99.5	60.2	51.9	72.1	37.7	18.9	19.7	68.4	17.9	48.9	32.5
28	139.1	124.1	116.8	121.0	128.2	114.2	142.5	101.8	110.2	130.4	104.8	86.0	86.8	104.2	85.0	84.7	68.4
29	121.1	106.1	98.8	103.0	110.2	96.2	124.5	83.8	92.2	112.4	86.8	68.0	68.8	86.2	67.0	66.7	50.4
30	104.9	89.9	82.6	86.8	94.0	80.0	108.3	67.7	76.0	96.2	63.5	44.6	45.4	70.1	43.6	50.6	34.2
31	100.1	85.1	77.8	66.7	73.9	59.9	103.5	64.2	55.9	76.1	41.7	22.9	23.7	72.4	21.9	52.9	36.5
32	135.1	120.1	112.7	101.6	108.8	94.8	138.4	99.1	90.8	111.0	76.6	57.8	58.6	107.3	56.8	87.8	71.4
33	157.7	142.7	135.4	139.6	146.8	132.8	161.1	120.5	128.8	149.0	123.4	104.6	105.4	122.9	103.6	103.4	87.0
34	135.8	120.8	113.5	117.7	124.9	110.9	139.2	98.5	106.9	127.1	101.5	82.7	83.5	100.9	81.7	81.4	65.1
35	135.0	120.0	112.7	116.9	124.1	110.1	138.4	97.8	106.1	126.3	92.4	73.6	74.4	100.2	72.6	80.7	64.3
36	120.1	105.1	97.8	102.0	109.2	95.2	123.4	82.8	91.2	111.4	77.5	58.7	59.5	85.2	57.7	65.7	49.4
37	121.7	106.7	99.4	88.2	95.4	81.4	125.1	85.8	77.4	97.6	63.3	44.4	45.2	93.9	43.4	74.4	58.0
38	132.1	117.1	109.8	98.6	105.9	91.9	135.5	96.2	87.9	108.1	73.7	54.9	55.7	104.3	53.9	84.8	68.5
39	133.7	118.7	111.4	100.2	107.4	93.4	137.1	97.8	89.4	109.7	75.3	56.4	57.2	105.9	55.4	86.4	70.0
40	166.5	151.5	144.2	148.4	155.6	141.6	169.9	129.2	137.6	157.8	132.2	113.4	114.2	131.6	112.4	112.1	95.8
41	143.6	128.6	121.3	125.5	132.7	118.7	146.9	106.3	114.7	134.9	109.3	90.5	91.3	108.7	89.5	89.2	72.9
42	145.6	130.6	123.3	127.5	134.7	120.7	148.9	108.3	116.7	136.9	111.3	92.5	93.3	110.7	91.5	91.2	74.9
43	144.2	129.2	121.8	126.1	133.3	119.3	147.5	106.9	115.3	135.5	101.6	82.8	83.6	109.3	81.8	89.8	73.4
44	133.1	118.1	110.8	115.0	122.2	108.2	136.5	95.9	104.2	124.5	90.6	71.7	72.5	98.3	70.7	78.8	62.4
45	135.1	120.1	112.8	117.0	124.2	110.2	138.5	97.9	106.2	126.5	92.6	73.7	74.5	100.3	72.7	80.8	64.4
46	136.2	121.2	113.9	102.7	109.9	95.9	139.6	100.3	91.9	112.2	77.8	58.9	59.7	108.4	57.9	88.9	72.5
47	146.8	131.8	124.5	113.4	120.6	106.6	150.2	110.9	102.6	122.8	88.4	69.6	70.4	119.0	68.6	99.5	83.2
48	155.9	140.9	133.6	137.8	145.0	131.0	159.3	118.6	127.0	147.2	121.6	102.8	103.6	121.0	101.8	101.5	85.2
49	144.3	129.3	122.0	126.2	133.4	119.4	147.7	107.1	115.4	135.6	101.7	82.9	83.7	109.5	81.9	90.0	73.6
50	144.3	129.3	122.0	110.8	118.0	104.0	147.6	108.4	100.0	120.2	85.8	67.0	67.8	116.5	66.0	97.0	80.6
51	154.8	139.8	132.5	121.3	128.5	114.5	158.2	118.9	110.5	130.8	96.4	77.5	78.3	127.0	76.5	107.5	91.2

APPENDIX D. (continued)

Node	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	82.7	79.3	80.7	78.1	81.0	83.9	108.6	88.5	94.2	96.1	139.1	121.1	104.9	100.1	135.1	157.7	135.8
2	67.7	64.3	65.7	63.1	66.0	68.9	93.6	73.5	79.3	81.1	124.1	106.1	89.9	85.1	120.1	142.7	120.8
3	60.4	57.0	58.4	55.8	58.7	61.6	86.3	66.2	71.9	73.8	116.8	98.8	82.6	77.8	112.7	135.4	113.5
4	49.4	45.8	62.6	60.0	47.5	50.4	90.5	70.4	76.1	62.7	121.0	103.0	86.8	66.7	101.6	139.6	117.7
5	56.6	53.0	69.8	67.2	54.7	57.6	97.7	77.6	83.4	69.9	128.2	110.2	94.0	73.9	108.8	146.8	124.9
6	42.6	39.0	55.8	53.2	40.7	43.6	83.7	63.6	69.4	55.9	114.2	96.2	80.0	59.9	94.8	132.8	110.9
7	86.1	82.6	84.0	81.5	84.4	87.3	112.0	91.9	97.6	99.5	142.5	124.5	108.3	103.5	138.4	161.1	139.2
8	45.5	43.4	43.4	40.9	45.1	48.0	71.4	51.3	57.0	60.2	101.8	83.8	67.7	64.2	99.1	120.5	98.5
9	38.6	35.0	51.8	49.2	36.7	39.6	79.7	59.6	65.4	51.9	110.2	92.2	76.0	55.9	90.8	128.8	106.9
10	58.8	55.2	72.0	69.5	57.0	59.9	99.9	79.9	85.6	72.1	130.4	112.4	96.2	76.1	111.0	149.0	127.1
11	24.4	20.8	46.4	43.9	22.6	25.5	74.3	54.3	52.8	37.7	104.8	86.8	63.5	41.7	76.6	123.4	101.5
12	5.6	2.0	27.6	25.0	3.7	6.6	55.5	35.4	34.0	18.9	86.0	68.0	44.6	22.9	57.8	104.6	82.7
13	6.4	2.8	28.4	25.8	4.5	7.4	56.3	36.2	34.8	19.7	86.8	68.8	45.4	23.7	58.6	105.4	83.5
14	47.9	51.5	45.8	43.3	53.2	56.1	73.8	53.7	59.4	68.4	104.2	86.2	70.1	72.4	107.3	122.9	100.9
15	4.6	1.0	26.6	24.0	2.7	5.6	54.5	34.4	33.0	17.9	85.0	67.0	43.6	21.9	56.8	103.6	81.7
16	28.4	32.0	26.3	23.8	33.7	36.6	54.3	34.2	39.9	48.9	84.7	66.7	50.6	52.9	87.8	103.4	81.4
17	12.0	15.6	10.0	7.4	17.3	20.2	37.9	17.8	23.5	32.5	68.4	50.4	34.2	36.5	71.4	87.0	65.1
18	0.0	3.6	22.0	19.4	5.3	8.2	49.9	29.8	35.5	20.5	80.4	62.4	46.2	24.5	59.4	99.0	77.1
19	3.6	0.0	25.6	23.0	1.7	4.6	53.5	33.4	32.0	16.9	84.0	66.0	42.6	20.9	55.8	102.6	80.7
20	22.0	25.6	0.0	2.5	27.3	30.2	33.0	13.0	18.7	33.8	63.5	45.5	29.3	37.8	72.1	82.1	60.2
21	19.4	23.0	2.5	0.0	24.8	27.7	30.5	10.4	16.1	31.2	61.0	43.0	26.8	35.2	69.6	79.6	57.7
22	5.3	1.7	27.3	24.8	0.0	2.9	55.2	35.2	30.3	15.1	84.9	66.9	40.9	19.1	54.1	102.0	80.1
23	8.2	4.6	30.2	27.7	2.9	0.0	58.1	38.1	33.2	18.0	87.8	69.8	43.8	22.0	57.0	104.9	83.0
24	49.9	53.5	33.0	30.5	55.2	58.1	0.0	20.1	25.8	40.9	30.5	12.5	36.4	44.9	79.2	49.1	27.2
25	29.8	33.4	13.0	10.4	35.2	38.1	20.1	0.0	5.7	20.8	50.5	32.5	16.4	24.8	59.1	69.2	47.2
26	35.5	32.0	18.7	16.1	30.3	33.2	25.8	5.7	0.0	15.1	54.6	36.6	10.7	19.1	53.4	72.9	51.0
27	20.5	16.9	33.8	31.2	15.1	18.0	40.9	20.8	15.1	0.0	69.7	51.7	25.8	4.0	38.9	86.9	64.9
28	80.4	84.0	63.5	61.0	84.9	87.8	30.5	50.5	54.6	69.7	0.0	18.0	44.0	73.7	85.4	54.6	32.7
29	62.4	66.0	45.5	43.0	66.9	69.8	12.5	32.5	36.6	51.7	18.0	0.0	26.0	55.7	67.4	36.6	14.7
30	46.2	42.6	29.3	26.8	40.9	43.8	36.4	16.4	10.7	25.8	44.0	26.0	0.0	29.8	42.8	62.2	40.3
31	24.5	20.9	37.8	35.2	19.1	22.0	44.9	24.8	19.1	4.0	73.7	55.7	29.8	0.0	34.9	82.9	60.9
32	59.4	55.8	72.1	69.6	54.1	57.0	79.2	59.1	53.4	38.9	85.4	67.4	42.8	34.9	0.0	74.7	52.7
33	99.0	102.6	82.1	79.6	102.0	104.9	49.1	69.2	72.9	86.9	54.6	36.6	62.2	82.9	74.7	0.0	21.9
34	77.1	80.7	60.2	57.7	80.1	83.0	27.2	47.2	51.0	64.9	32.7	14.7	40.3	60.9	52.7	21.9	0.0
35	75.2	71.6	59.4	56.9	69.9	72.8	37.4	46.5	40.8	54.7	42.9	24.9	30.1	50.7	42.5	32.1	10.2
36	60.3	56.7	44.5	41.9	54.9	57.8	51.6	31.5	25.8	39.8	57.8	39.8	15.2	35.8	27.6	47.1	25.1
37	46.0	42.4	58.7	56.2	40.7	43.6	65.8	45.8	40.1	25.6	72.1	54.1	29.4	21.6	13.4	61.3	39.4
38	56.5	52.9	69.2	66.6	51.1	54.0	76.3	56.2	50.5	36.0	82.5	64.5	39.8	32.0	2.9	71.7	49.8
39	58.0	54.4	70.7	68.2	52.7	55.6	77.9	57.8	52.1	37.6	84.1	66.1	41.4	33.6	4.5	73.3	51.4
40	107.8	111.4	90.9	88.4	110.8	113.7	57.9	77.9	81.7	95.6	63.4	45.4	71.0	91.6	83.4	52.6	30.7
41	84.9	88.5	68.0	65.4	87.9	90.8	35.0	55.0	58.7	72.7	40.5	22.5	48.1	68.7	60.5	29.7	7.8
42	86.9	90.5	70.0	67.4	89.9	92.8	37.0	57.0	60.7	74.7	42.5	24.5	50.1	70.7	62.5	31.7	9.8
43	84.4	80.8	68.6	66.0	79.0	81.9	49.5	55.6	49.9	63.9	55.0	37.0	39.3	59.9	51.7	44.2	22.3
44	73.3	69.7	57.5	55.0	68.0	70.9	60.5	44.6	38.9	52.9	66.0	48.0	28.2	48.9	40.7	55.3	33.3
45	75.3	71.7	59.5	57.0	70.0	72.9	62.5	46.6	40.9	54.9	68.0	50.0	30.2	50.9	42.7	57.3	35.3
46	60.5	56.9	73.2	70.7	55.2	58.1	77.3	60.3	54.6	40.1	82.9	64.9	43.9	36.1	27.9	72.1	50.2
47	71.2	67.6	83.9	81.3	65.8	68.7	90.3	70.9	65.2	50.7	95.8	77.8	54.6	46.7	17.7	85.0	63.1
48	97.2	100.8	80.3	77.8	100.2	103.1	47.3	67.3	71.1	85.0	52.8	34.8	60.4	81.0	72.8	42.0	20.1
49	84.5	80.9	68.7	66.2	79.2	82.1	71.7	55.8	50.1	64.0	77.2	59.2	39.4	60.0	51.9	66.5	44.5
50	68.6	65.0	81.3	78.8	63.3	66.2	85.4	68.4	62.6	48.1	90.9	72.9	52.0	44.1	36.0	80.2	58.2
51	79.1	75.5	91.8	89.3	73.8	76.7	98.3	78.9	73.2	58.7	103.8	85.8	62.5	54.7	25.6	93.0	71.1

APPENDIX D. (continued)

Node	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
1	135.0	120.1	121.7	132.1	133.7	166.5	143.6	145.6	144.2	133.1	135.1	136.2	146.8	155.9	144.3	144.3	154.8
2	120.0	105.1	106.7	117.1	118.7	151.5	128.6	130.6	129.2	118.1	120.1	121.2	131.8	140.9	129.3	129.3	139.8
3	112.7	97.8	99.4	109.8	111.4	144.2	121.3	123.3	121.8	110.8	112.8	113.9	124.5	133.6	122.0	122.0	132.5
4	116.9	102.0	88.2	98.6	100.2	148.4	125.5	127.5	126.1	115.0	117.0	102.7	113.4	137.8	126.2	110.8	121.3
5	124.1	109.2	95.4	105.9	107.4	155.6	132.7	134.7	133.3	122.2	124.2	109.9	120.6	145.0	133.4	118.0	128.5
6	110.1	95.2	81.4	91.9	93.4	141.6	118.7	120.7	119.3	108.2	110.2	95.9	106.6	131.0	119.4	104.0	114.5
7	138.4	123.4	125.1	135.5	137.1	169.9	146.9	148.9	147.5	136.5	138.5	139.6	150.2	159.3	147.7	147.6	158.2
8	97.8	82.8	85.8	96.2	97.8	129.2	106.3	108.3	106.9	95.9	97.9	100.3	110.9	118.6	107.1	108.4	118.9
9	106.1	91.2	77.4	87.9	89.4	137.6	114.7	116.7	115.3	104.2	106.2	91.9	102.6	127.0	115.4	100.0	110.5
10	126.3	111.4	97.6	108.1	109.7	157.8	134.9	136.9	135.5	124.5	126.5	112.2	122.8	147.2	135.6	120.2	130.8
11	92.4	77.5	63.3	73.7	75.3	132.2	109.3	111.3	101.6	90.6	92.6	77.8	88.4	121.6	101.7	85.8	96.4
12	73.6	58.7	44.4	54.9	56.4	113.4	90.5	92.5	82.8	71.7	73.7	58.9	69.6	102.8	82.9	67.0	77.5
13	74.4	59.5	45.2	55.7	57.2	114.2	91.3	93.3	83.6	72.5	74.5	59.7	70.4	103.6	83.7	67.8	78.3
14	100.2	85.2	93.9	104.3	105.9	131.6	108.7	110.7	109.3	98.3	100.3	108.4	119.0	121.0	109.5	116.5	127.0
15	72.6	57.7	43.4	53.9	55.4	112.4	89.5	91.5	81.8	70.7	72.7	57.9	68.6	101.8	81.9	66.0	76.5
16	80.7	65.7	74.4	84.8	86.4	112.1	89.2	91.2	89.8	78.8	80.8	88.9	99.5	101.5	90.0	97.0	107.5
17	64.3	49.4	58.0	68.5	70.0	95.8	72.9	74.9	73.4	62.4	64.4	72.5	83.2	85.2	73.6	80.6	91.2
18	75.2	60.3	46.0	56.5	58.0	107.8	84.9	86.9	84.4	73.3	75.3	60.5	71.2	97.2	84.5	68.6	79.1
19	71.6	56.7	42.4	52.9	54.4	111.4	88.5	90.5	80.8	69.7	71.7	56.9	67.6	100.8	80.9	65.0	75.5
20	59.4	44.5	58.7	69.2	70.7	90.9	68.0	70.0	68.6	57.5	59.5	73.2	83.9	80.3	68.7	81.3	91.8
21	56.9	41.9	56.2	66.6	68.2	88.4	65.4	67.4	66.0	55.0	57.0	70.7	81.3	77.8	66.2	78.8	89.3
22	69.9	54.9	40.7	51.1	52.7	110.8	87.9	89.9	79.0	68.0	70.0	55.2	65.8	100.2	79.2	63.3	73.8
23	72.8	57.8	43.6	54.0	55.6	113.7	90.8	92.8	81.9	70.9	72.9	58.1	68.7	103.1	82.1	66.2	76.7
24	37.4	51.6	65.8	76.3	77.9	57.9	35.0	37.0	49.5	60.5	62.5	77.3	90.3	47.3	71.7	85.4	98.3
25	46.5	31.5	45.8	56.2	57.8	77.9	55.0	57.0	55.6	44.6	46.6	60.3	70.9	67.3	55.8	68.4	78.9
26	40.8	25.8	40.1	50.5	52.1	81.7	58.7	60.7	49.9	38.9	40.9	54.6	65.2	71.1	50.1	62.6	73.2
27	54.7	39.8	25.6	36.0	37.6	95.6	72.7	74.7	63.9	52.9	54.9	40.1	50.7	85.0	64.0	48.1	58.7
28	42.9	57.8	72.1	82.5	84.1	63.4	40.5	42.5	55.0	66.0	68.0	82.9	95.8	52.8	77.2	90.9	103.8
29	24.9	39.8	54.1	64.5	66.1	45.4	22.5	24.5	37.0	48.0	50.0	64.9	77.8	34.8	59.2	72.9	85.8
30	30.1	15.2	29.4	39.8	41.4	71.0	48.1	50.1	39.3	28.2	30.2	43.9	54.6	60.4	39.4	52.0	62.5
31	50.7	35.8	21.6	32.0	33.6	91.6	68.7	70.7	59.9	48.9	50.9	36.1	46.7	81.0	60.0	44.1	54.7
32	42.5	27.6	13.4	2.9	4.5	83.4	60.5	62.5	51.7	40.7	42.7	27.9	17.7	72.8	51.9	36.0	25.6
33	32.1	47.1	61.3	71.7	73.3	52.6	29.7	31.7	44.2	55.3	57.3	72.1	85.0	42.0	66.5	80.2	93.0
34	10.2	25.1	39.4	49.8	51.4	30.7	7.8	9.8	22.3	33.3	35.3	50.2	63.1	20.1	44.5	58.2	71.1
35	0.0	14.9	29.2	39.6	41.2	40.9	18.0	20.0	32.5	28.0	30.0	43.7	54.3	30.3	39.2	51.8	62.3
36	14.9	0.0	14.2	24.7	26.3	55.8	32.9	34.9	24.1	13.1	15.1	28.8	39.4	45.2	24.3	36.8	47.4
37	29.2	14.2	0.0	10.4	12.0	70.1	47.2	49.2	38.3	27.3	29.3	14.5	25.1	59.5	38.5	22.6	33.1
38	39.6	24.7	10.4	0.0	1.6	80.5	57.6	59.6	48.8	37.7	39.7	24.9	14.7	69.9	48.9	33.0	22.7
39	41.2	26.3	12.0	1.6	0.0	82.1	59.2	61.2	50.3	39.3	41.3	26.5	16.3	71.5	50.5	34.6	24.3
40	40.9	55.8	70.1	80.5	82.1	0.0	22.9	24.9	37.4	48.4	50.4	65.3	78.2	35.2	59.6	73.4	86.2
41	18.0	32.9	47.2	57.6	59.2	22.9	0.0	2.0	14.5	25.5	27.5	42.4	55.3	12.3	36.7	50.4	63.3
42	20.0	34.9	49.2	59.6	61.2	24.9	2.0	0.0	12.5	23.5	25.5	40.4	53.3	10.3	34.7	48.4	61.3
43	32.5	24.1	38.3	48.8	50.3	37.4	14.5	12.5	0.0	11.0	13.0	27.9	40.8	22.8	22.2	35.9	48.8
44	28.0	13.1	27.3	37.7	39.3	48.4	25.5	23.5	11.0	0.0	2.0	16.8	29.8	33.8	11.2	24.9	37.8
45	30.0	15.1	29.3	39.7	41.3	50.4	27.5	25.5	13.0	2.0	0.0	14.8	27.8	35.8	9.2	22.9	35.8
46	43.7	28.8	14.5	24.9	26.5	65.3	42.4	40.4	27.9	16.8	14.8	0.0	12.9	50.7	24.0	8.1	20.9
47	54.3	39.4	25.1	14.7	16.3	78.2	55.3	53.3	40.8	29.8	27.8	12.9	0.0	63.6	37.0	21.0	8.0
48	30.3	45.2	59.5	69.9	71.5	35.2	12.3	10.3	22.8	33.8	35.8	50.7	63.6	0.0	45.0	58.8	71.6
49	39.2	24.3	38.5	48.9	50.5	59.6	36.7	34.7	22.2	11.2	9.2	24.0	37.0	45.0	0.0	32.1	45.0
50	51.8	36.8	22.6	33.0	34.6	73.4	50.4	48.4	35.9	24.9	22.9	8.1	21.0	58.8	32.1	0.0	29.0
51	62.3	47.4	33.1	22.7	24.3	86.2	63.3	61.3	48.8	37.8	35.8	20.9	8.0	71.6	45.0	29.0	0.0

APPENDIX E. MATLAB CODE USED FOR L_{ijp} MATRIX CALCULATION

```
% The letter "S" in "IP=[S];" represents the all pairs shortest path distance matrix S of %
% the road network%

% The letter "S" in "JP=[S];" represents the all pairs shortest path distance matrix S of %
% the road network%

% The numbers in C matrix represent K values of road segments form node i to j %
% such that K= (j-1) * Number of all nodes in the network + i %
% For example, for road segment represented by arc A0304 the K value is %
% K = (4-1) *51 + 3 = 156 %
% K values are used in the matrix manipulation process and %
% they are the index number for arcs %

IP=[S];
JP=[S];
N=51;

for i=1:N
for j=1:N
for p=1:N
LIJP(i,j,p)= IP(i,p) + JP(j,p);
end
end
end
LIJP;
Y = reshape(LIJP,[],51);
C=[    156
       360
       52
       104
       416
       308
       468
       208
       259
       414
       519
       572
       726
       933
       1090
       624
       1144
       1348
```

```
        1557
        1352
        1089
        884
        936
        832
        779
        1037
        1245
        824
        1040
        2080
        2184
        1716
        1768
        2439
        2074
        2132
        1456
        1508
        1712
        1452
        1300
        1248
        2236
        2288
        2340
        2392
        2493
        2229
        2545
        2597
        2384
        1919
        1924
        1867
        1976
        1820
        1872
        1505
        1815
        2332];

B =Y(C, : );
```

```
B;
dlmwrite('LIJPRAW.xlsx', Y, '\t')
dlmwrite('LIJPFINAL.xlsx', B, '\t')

for i=1:5
display('go and get LIJPRAW.xls and LIJPFINAL.xls files from C:\Program
Files\MATLAB71\work')
end
```

APPENDIX F. FARGO DISTRICT L_{ijp} MATRIX

Arc /Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
A0304	55.78	25.8	11.16	11.16	25.58	24.74	62.54	34.07	32.74	73.18	61.08	98.74	100.3	172.8	100.7	133.8	101
A0308	59.55	29.57	14.93	30.3	44.72	30.3	66.31	14.93	30.3	70.74	58.64	96.3	97.9	153.6	98.3	114.6	81.87
A0102	14.99	14.99	29.63	51.95	66.37	65.53	51.73	59.49	73.53	114	101.9	139.5	141.1	198.2	141.5	159.2	126.4
A0203	37.3	7.32	7.32	29.64	44.06	43.22	44.06	37.18	51.22	91.66	79.56	117.2	118.8	175.9	119.2	136.9	104.1
A0809	81.5	51.52	36.88	29.93	44.35	16.35	88.26	8.35	8.35	48.79	36.69	74.35	75.95	147	76.35	108	75.29
A0207	48.35	18.37	33.01	55.33	69.75	68.91	18.37	62.87	76.91	117.4	105.3	142.9	144.5	201.6	144.9	162.6	129.8
A0910	108.7	78.76	64.12	41.8	56.22	28.22	115.5	36.92	20.22	20.22	48.56	86.22	87.82	175.6	88.22	136.6	103.9
A0405	74.15	44.17	29.53	7.21	7.21	20.79	80.91	45.49	28.79	69.23	57.13	94.79	96.39	184.2	96.79	145.2	112.4
A0406	73.73	43.75	29.11	6.79	21.21	6.79	80.49	31.49	14.79	55.23	43.13	80.79	82.39	170.2	82.79	131.2	98.43
A0609	84.52	54.54	39.9	17.58	32	4	91.28	20.7	4	44.44	32.34	70	71.6	159.4	72	120.4	87.64
A0911	102.7	72.71	58.07	35.75	50.17	22.17	109.5	30.87	14.17	54.61	14.17	51.83	53.43	150	53.83	111	78.26
A1112	135.7	105.7	91.07	68.75	83.17	55.17	142.5	63.87	47.17	87.61	18.83	18.83	20.43	125.8	20.83	86.79	54.05
A1215	155.5	125.5	110.9	88.58	103	75	162.3	83.7	67	107.4	38.66	1	2.6	106	1	66.96	34.22
A1519	157.5	127.5	112.9	90.58	105	77	164.3	85.7	69	109.4	40.66	3	4.6	104	1	64.96	32.22
A1922	160.3	130.3	115.6	93.31	107.7	79.73	167	88.43	71.73	112.2	43.39	5.73	7.33	104.7	3.73	65.69	32.95
A1213	155.3	125.3	110.7	88.38	102.8	74.8	162.1	83.5	66.8	107.2	38.46	0.8	0.8	107.8	2.8	68.76	36.02
A2223	164.9	134.9	120.3	97.94	112.4	84.36	171.6	93.06	76.36	116.8	48.02	10.36	11.96	109.3	8.36	70.32	37.58
A2227	177.1	147.1	132.5	110.2	124.6	96.6	183.9	105.3	88.6	129	60.26	22.6	24.2	121.6	20.6	82.56	49.82
A2731	196.3	166.3	151.6	129.3	143.7	115.7	203	124.4	107.7	148.2	79.4	41.74	43.34	140.7	39.74	101.7	68.96
A2627	190.4	160.4	145.8	138.8	153.2	125.2	197.1	117.2	117.2	157.7	90.51	52.85	54.45	127.8	50.85	88.75	56.01
A1822	163.7	133.7	119.1	96.91	111.3	83.33	170.5	90.56	75.33	115.8	46.99	9.33	10.93	101.1	7.33	62.09	29.35
A1718	153.4	123.5	108.8	102	116.4	88.42	160.2	78.95	80.42	120.9	60.87	23.21	24.81	83.75	21.21	44.75	12.01
A1819	162	132	117.4	95.18	109.6	81.6	168.7	88.83	73.6	114	45.26	7.6	9.2	99.36	5.6	60.36	27.62
A1617	157.8	127.8	113.2	121.6	136	108	164.6	83.31	100	140.5	89.25	51.59	53.19	55.37	49.59	16.37	16.37
A1416	193.7	163.7	149	157.5	171.9	143.9	200.4	119.2	135.9	176.3	125.1	87.46	89.06	19.5	85.46	19.5	52.24
A1721	148.8	118.9	104.2	112.6	127.1	99.05	155.6	74.35	91.05	131.5	80.29	42.63	44.23	79.15	40.63	40.15	7.41
A2125	166.7	136.7	122	130.5	144.9	116.9	173.4	92.17	108.9	149.3	98.11	60.45	62.05	96.97	58.45	57.97	25.23
A0817	108	77.97	63.33	71.75	86.17	58.17	114.7	33.47	50.17	90.61	58.96	58.96	60.56	105.2	58.96	66.21	33.47
A2021	158.8	128.8	114.2	122.6	137	109	165.5	84.3	101	141.4	90.24	52.58	54.18	89.1	50.58	50.1	17.36
A4041	310	280.1	265.4	273.8	288.3	260.3	316.8	235.6	252.3	292.7	241.5	203.8	205.4	240.4	201.8	201.4	168.6
A4243	289.7	259.7	245.1	253.5	267.9	239.9	296.5	215.2	231.9	272.4	212.9	175.2	176.8	220	173.2	181	148.3
A3334	293.5	263.5	248.9	257.3	271.7	243.7	300.2	219	235.7	276.1	224.9	187.3	188.9	223.8	185.3	184.8	152.1
A3435	270.8	240.8	226.1	234.6	249	221	277.5	196.3	213	253.4	193.9	156.3	157.9	201.1	154.3	162.1	129.3
A4248	301.4	271.5	256.8	265.2	279.7	251.7	308.2	227	243.7	284.1	232.9	195.2	196.8	231.8	193.2	192.8	160
A3441	279.3	249.4	234.7	243.1	257.6	229.6	286.1	204.9	221.6	262	210.8	173.1	174.7	209.7	171.1	170.7	137.9
A4142	289.1	259.1	244.5	252.9	267.3	239.3	295.9	214.6	231.3	271.8	220.6	182.9	184.5	219.4	180.9	180.4	147.7
A2829	260.1	230.2	215.5	223.9	238.4	210.4	266.9	185.7	202.4	242.8	191.6	153.9	155.5	190.5	151.9	151.5	118.7
A2930	226	196	181.3	189.8	204.2	176.2	232.7	151.5	168.2	208.6	150.3	112.6	114.2	156.3	110.6	117.3	84.54
A2934	256.8	226.9	212.2	220.6	235.1	207.1	263.6	182.4	199.1	239.5	188.3	150.6	152.2	187.2	148.6	148.2	115.4
A2429	229.7	199.7	185.1	193.5	207.9	179.9	236.4	155.2	171.9	212.3	161.1	123.5	125.1	160	121.5	121	88.25
A2526	182.8	152.8	138.2	146.6	161	133	189.5	108.3	125	165.4	107.1	69.41	71.01	113.1	67.41	74.09	41.35
A2425	197.1	167.2	152.5	160.9	175.4	147.4	203.9	122.7	139.4	179.8	128.6	90.93	92.53	127.5	88.93	88.45	55.71
A4344	277.3	247.3	232.7	241.1	255.5	227.5	284	202.8	219.5	259.9	192.1	154.5	156.1	207.6	152.5	168.6	135.9
A4445	268.2	238.3	223.6	232	246.5	218.5	275	193.8	210.5	250.9	183.1	145.4	147	198.6	143.4	159.6	126.8
A4546	271.3	241.3	226.7	219.7	234.2	206.2	278.1	198.2	198.2	238.6	170.3	132.7	134.3	208.7	130.7	169.7	137
A4647	283	253	238.4	216.1	230.5	202.5	289.8	211.2	194.5	234.9	166.2	128.5	130.1	227.5	126.5	188.5	155.7
A4549	279.4	249.5	234.8	243.2	257.7	229.7	286.2	205	221.7	262.1	194.3	156.6	158.2	209.8	154.6	170.8	138
A3644	253.2	223.2	208.6	217	231.4	203.4	259.9	178.7	195.4	235.8	168	130.4	132	183.5	128.4	144.5	111.8
A4650	280.5	250.5	235.8	213.5	227.9	199.9	287.2	208.6	191.9	232.4	163.6	125.9	127.5	224.9	123.9	185.9	153.2
A4751	301.6	271.6	257	234.7	249.1	221.1	308.4	229.8	213.1	253.5	184.8	147.1	148.7	246.1	145.1	207.1	174.3
A3847	278.9	249	234.3	212	226.4	198.4	285.7	207.1	190.4	230.9	162.1	124.4	126	223.4	122.4	184.4	151.6
A3238	267.2	237.2	222.5	200.2	214.6	186.6	273.9	195.3	178.6	219.1	150.3	112.6	114.2	211.6	110.6	172.6	139.9
A3738	253.8	223.8	209.2	186.9	201.3	173.3	260.6	182	165.3	205.7	136.9	99.27	100.9	198.2	97.27	159.2	126.5
A3137	221.8	191.8	177.2	154.9	169.3	141.3	228.6	150	133.3	173.7	105	67.29	68.89	166.3	65.29	127.3	94.51
A3839	265.8	235.8	221.2	198.9	213.3	185.3	272.6	194	177.3	217.7	148.9	111.3	112.9	210.2	109.3	171.2	138.5
A3536	255.1	225.1	210.4	218.9	233.3	205.3	261.8	180.6	197.3	237.7	169.9	132.3	133.9	185.4	130.3	146.4	113.6
A3637	241.7	211.8	197.1	190.2	204.6	176.6	248.5	168.6	168.6	209	140.7	103.1	104.7	179.1	101.1	140.1	107.4
A2630	199.1	169.2	154.5	162.9	177.4	149.4	205.9	124.7	141.4	181.8	116.3	78.61	80.21	129.5	76.61	90.45	57.71
A3036	225	195	180.3	188.8	203.2	175.2	231.7	150.5	167.2	207.6	141	103.3	104.9	155.3	101.3	116.3	83.53
A3746	257.9	227.9	213.3	190.9	205.4	177.4	264.6	186.1	169.4	209.8	141	103.4	105	202.3	101.4	163.3	130.6

APPENDIX F. (continued)

Arc /Node	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
A0304	109.8	102.7	120.9	115.8	106.2	112	176.8	136.7	148.1	136.5	237.7	201.7	169.4	144.5	214.3	275	231.1
A0308	105.9	100.3	101.8	96.69	103.8	109.6	157.7	117.5	128.9	134	218.6	182.6	150.2	142	211.9	255.9	212
A0102	150.5	143.5	146.3	141.3	147	152.8	202.2	162.1	173.5	177.3	263.2	227.2	194.8	185.3	255.1	300.4	256.6
A0203	128.1	121.2	124	118.9	124.7	130.5	179.9	139.8	151.2	155	240.8	204.8	172.5	163	232.8	278.1	234.2
A0809	84.08	78.35	95.19	90.11	81.81	87.61	151.1	110.9	122.4	112.1	212	176	143.7	120.1	189.9	249.3	205.4
A0207	153.8	146.9	149.7	144.6	150.4	156.2	205.6	165.5	176.9	180.7	266.5	230.5	198.2	188.7	258.5	303.8	259.9
A0910	97.42	90.22	123.8	118.7	93.68	99.48	179.6	139.5	150.9	124	240.6	204.6	172.2	132	201.8	277.9	234
A0405	106	98.79	132.3	127.3	102.3	108.1	188.2	148.1	159.5	132.5	249.2	213.2	180.8	140.5	210.4	286.4	242.6
A0406	91.99	84.79	118.3	113.3	88.25	94.05	174.2	134.1	145.5	118.5	235.2	199.2	166.8	126.5	196.4	272.4	228.6
A0609	81.2	74	107.5	102.5	77.46	83.26	163.4	123.3	134.7	107.7	224.4	188.4	156	115.7	185.6	261.6	217.8
A0911	63.03	55.83	98.16	93.08	59.29	65.09	154	113.9	118.2	89.57	215	179	139.5	97.57	167.4	252.3	208.4
A1112	30.03	22.83	73.95	68.87	26.29	32.09	129.8	89.69	86.79	56.57	190.8	154.8	108.1	64.57	134.4	228.1	184.2
A1215	10.2	3	54.12	49.04	6.46	12.26	110	69.86	66.96	36.74	170.9	134.9	88.26	44.74	114.6	208.2	164.3
A1519	8.2	1	52.12	47.04	4.46	10.26	108	67.86	64.96	34.74	168.9	132.9	86.26	42.74	112.6	206.2	162.3
A1922	8.93	1.73	52.85	47.77	1.73	7.53	108.7	68.59	62.23	32.01	168.9	132.9	83.53	40.01	109.9	204.6	160.7
A1213	12	4.8	55.92	50.84	8.26	14.06	111.8	71.66	68.76	38.54	172.7	136.7	90.06	46.54	116.4	210	166.1
A2223	13.56	6.36	57.48	52.4	2.9	2.9	113.4	73.22	63.4	33.18	172.7	136.7	84.7	41.18	111	206.9	163
A2227	25.8	18.6	61.06	55.98	15.14	20.94	96.12	55.98	45.36	15.14	154.6	118.6	66.66	23.14	92.98	188.9	145
A2731	44.94	37.74	71.54	66.46	34.28	40.08	85.78	45.64	34.22	4	143.5	107.5	55.52	4	73.84	169.7	125.8
A2627	56.01	48.85	52.43	47.35	45.39	51.19	66.67	26.53	15.11	15.11	124.4	88.37	36.41	23.11	92.35	159.8	115.9
A1822	5.33	5.33	49.25	44.17	5.33	11.13	105.1	64.99	65.79	35.61	165.3	129.3	87.09	43.61	113.5	201	157.1
A1718	12.01	19.21	31.91	26.83	22.67	28.47	87.79	47.65	59.07	52.95	148.7	112.7	80.37	60.95	130.8	186	142.1
A1819	3.6	3.6	47.52	42.44	7.06	12.86	103.4	63.26	67.52	37.34	164.3	128.3	88.82	45.34	115.2	201.6	157.7
A1617	40.39	47.59	36.27	31.19	51.05	56.85	92.15	52.01	63.43	81.33	153.1	117.1	84.73	89.33	159.2	190.4	146.5
A1416	76.26	83.46	72.14	67.06	86.92	92.72	128	87.88	99.3	117.2	189	153	120.6	125.2	195	226.2	182.4
A1721	31.43	38.63	12.49	7.41	42.09	47.89	68.37	28.23	39.65	63.71	129.3	93.31	60.95	71.71	141	166.6	122.7
A2125	49.25	56.45	15.49	10.41	59.91	65.71	50.55	10.41	21.83	52.05	111.5	75.49	43.13	60.05	128.7	148.8	104.9
A0817	57.49	58.96	53.37	48.29	62.42	68.22	109.3	69.11	80.53	92.7	170.2	134.2	101.8	100.7	170.5	207.5	163.6
A2021	41.38	48.58	2.54	2.54	52.04	57.84	63.5	23.36	34.78	65	124.4	88.44	56.08	73	141.6	161.7	117.8
A4041	192.6	199.8	158.9	153.8	198.6	204.4	92.83	133	140.4	168.3	103.9	67.89	119.1	160.3	144	82.37	38.49
A4243	171.2	171.2	138.6	133.5	168.9	174.7	86.42	112.7	110.7	138.6	97.48	61.48	89.35	130.6	114.2	75.96	32.08
A3334	176.1	183.3	142.3	137.2	182.1	187.9	76.28	116.4	123.8	151.8	87.34	51.34	102.5	143.8	127.4	21.94	21.94
A3435	152.3	152.3	119.6	114.5	149.9	155.7	64.54	93.7	91.7	119.6	75.6	39.6	70.4	111.6	95.28	54.08	10.2
A4248	184	191.2	150.3	145.2	190	195.8	84.23	124.4	131.8	159.7	95.29	59.29	110.5	151.7	135.4	73.77	29.89
A3441	161.9	169.1	128.2	123.1	167.9	173.7	62.13	102.3	109.7	137.6	73.19	37.19	88.39	129.6	113.3	51.67	7.79
A4142	171.7	178.9	138	132.9	177.7	183.5	71.92	112.1	119.5	147.4	82.98	46.98	98.18	139.4	123.1	61.46	17.58
A2829	142.7	149.9	109	103.9	151.8	157.6	42.94	83.08	91.26	121.5	18	18	69.96	129.5	152.9	91.28	47.4
A2930	108.6	108.6	74.8	69.72	107.8	113.6	48.9	48.9	47.28	77.5	61.98	25.98	25.98	85.5	110.2	98.88	55
A2934	139.4	146.6	105.7	100.6	146.9	152.7	39.64	79.78	87.58	116.7	50.7	14.7	66.28	116.7	120.2	58.58	14.7
A2429	112.3	119.5	78.51	73.43	122.1	127.9	12.47	52.61	62.41	92.63	48.47	12.47	62.41	100.6	146.7	85.75	41.87
A2526	65.37	65.41	31.61	26.53	65.41	71.21	45.85	5.71	5.71	35.93	105.2	69.17	27.01	43.93	112.6	142.1	98.19
A2425	79.73	86.93	45.97	40.89	90.39	96.19	20.07	20.07	31.49	61.71	81.01	45.01	52.79	69.71	138.4	118.3	74.41
A4344	157.7	150.5	126.1	121	147	152.8	110	100.2	88.79	116.7	121	85.01	67.49	108.7	92.37	99.49	55.61
A4445	148.6	141.4	117.1	112	138	143.8	123	91.18	79.76	107.7	134	98.04	58.46	99.7	83.34	112.5	68.64
A4546	135.9	128.7	132.8	127.7	125.2	131	139.8	106.9	95.45	94.91	150.9	114.9	74.15	86.91	70.55	129.4	85.48
A4647	131.7	124.5	157.1	152	121	126.8	167.6	131.2	119.8	90.75	178.7	142.7	98.47	82.75	45.53	157.1	113.3
A4549	159.8	152.6	128.3	123.2	149.2	155	134.2	102.4	90.95	118.9	145.2	109.2	69.65	110.9	94.53	123.7	79.83
A3644	133.6	126.4	102	96.94	122.9	128.7	112.1	76.12	64.7	92.64	123.9	87.85	43.4	84.64	68.28	102.3	58.45
A4650	129.1	121.9	154.5	149.5	118.5	124.3	162.7	128.6	117.2	88.19	173.8	137.8	95.91	80.19	63.83	152.3	108.4
A4751	150.3	143.1	175.7	170.6	139.6	145.4	188.5	149.8	138.4	109.4	199.6	163.6	117.1	101.4	43.28	178.1	134.2
A3847	127.6	120.4	153	147.9	117	122.8	166.5	127.1	115.7	86.67	178.3	142.3	94.39	78.67	20.59	156.8	112.9
A3238	115.8	108.6	141.2	136.2	105.2	111	155.5	115.3	103.9	74.9	167.9	131.9	82.62	66.9	2.94	146.4	102.5
A3738	102.5	95.27	127.9	122.8	91.81	97.61	142.1	102	90.55	61.53	154.6	118.6	69.25	53.53	16.31	133.1	89.17
A3137	70.49	63.29	96.49	91.41	59.83	65.63	110.7	70.59	59.17	29.55	145.8	109.8	59.17	21.55	48.29	144.2	100.3
A3839	114.5	107.3	139.9	134.8	103.8	109.6	154.1	114	102.6	73.54	166.6	130.6	81.26	65.54	7.46	145.1	101.2
A3536	135.5	128.3	103.9	98.81	124.8	130.6	88.97	77.99	66.57	94.51	100.7	64.73	45.27	86.51	70.15	79.21	35.33
A3637	106.3	99.08	103.2	98.12	95.62	101.4	117.4	77.3	65.88	65.34	129.9	93.9	44.58	57.34	40.98	108.4	64.5
A2630	81.73	74.61	47.97	42.89	71.15	76.95	62.21	22.07	10.65	40.87	98.61	62.61	10.65	48.87	96.21	135.1	91.25
A3036	106.5	99.29	73.79	68.71	95.83	101.6	88.03	47.89	36.47	65.55	101.8	65.81	15.17	65.55	70.39	109.3	65.43
A3746	106.6	99.35	132	126.9	95.89	101.7	143.2	106.1	94.63	65.61	154.9	118.9	73.33	57.61	41.25	133.4	89.53

APPENDIX F. (continued)

Arc /Node	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
A0304	229.6	199.7	187.6	208.4	211.6	292.5	246.7	250.7	247.9	225.8	229.8	216.6	237.9	271.3	248.2	232.7	253.8
A0308	210.4	180.6	185.1	206	209.2	273.4	227.6	231.6	228.8	206.7	210.7	214.2	235.4	252.2	229.1	230.3	251.4
A0102	255	225.1	228.4	249.2	252.4	318	272.1	276.1	273.3	251.3	255.3	257.4	278.7	296.8	273.6	273.5	294.6
A0203	232.7	202.8	206.1	226.9	230.1	295.6	249.8	253.8	251	228.9	232.9	235.1	256.3	274.4	251.3	251.2	272.3
A0809	203.9	174	163.2	184.1	187.2	266.8	221	225	222.2	200.1	204.1	192.2	213.5	245.6	222.5	208.4	229.4
A0207	258.4	228.5	231.8	252.6	255.8	321.3	275.5	279.5	276.7	254.6	258.6	260.8	282	300.1	277	276.9	298
A0910	232.4	202.6	175.1	195.9	199.1	295.4	249.6	253.6	250.7	228.7	232.7	204.1	225.3	274.2	251.1	220.2	241.3
A0405	241	211.1	183.6	204.5	207.7	304	258.1	262.1	259.3	237.3	241.3	212.7	233.9	282.8	259.6	228.8	249.9
A0406	227	197.1	169.6	190.5	193.7	290	244.1	248.1	245.3	223.3	227.3	198.7	219.9	268.8	245.6	214.8	235.9
A0609	216.2	186.3	158.8	179.7	182.9	279.2	233.3	237.3	234.5	212.5	216.5	187.9	209.1	258	234.8	204	225.1
A0911	198.5	168.7	140.7	161.5	164.7	269.8	224	228	216.8	194.8	198.8	169.7	191	248.6	217.2	185.8	206.9
A1112	166	136.2	107.7	128.5	131.7	245.6	199.8	203.8	184.3	162.3	166.3	136.7	158	224.4	184.7	152.8	173.9
A1215	146.2	116.3	87.84	108.7	111.9	225.7	179.9	183.9	164.5	142.4	146.4	116.9	138.1	204.5	164.8	133	154.1
A1519	144.2	114.3	85.84	106.7	109.9	223.7	177.9	181.9	162.5	140.4	144.4	114.9	136.1	202.5	162.8	131	152.1
A1922	141.5	111.6	83.11	104	107.1	222.1	176.3	180.3	159.8	137.7	141.7	112.1	133.4	200.9	160.1	128.3	149.4
A1213	148	118.1	89.64	110.5	113.7	227.5	181.7	185.7	166.3	144.2	148.2	118.7	139.9	206.3	166.6	134.8	155.9
A2223	142.6	112.8	84.28	105.1	108.3	224.4	178.6	182.6	160.9	138.9	142.9	113.3	134.6	203.2	161.3	129.4	150.5
A2227	124.6	94.72	66.24	87.1	90.26	206.4	160.6	164.6	142.9	120.8	124.8	95.26	116.5	185.2	143.2	111.4	132.5
A2731	105.4	75.58	47.1	67.96	71.12	187.2	141.4	145.4	123.8	101.7	105.7	76.12	97.38	166	124.1	92.26	113.3
A2627	95.47	65.61	65.61	86.47	89.63	177.3	131.5	135.5	113.8	91.73	95.73	94.63	115.9	156.1	114.1	110.8	131.9
A1822	145.1	115.2	86.71	107.6	110.7	218.5	172.7	176.7	163.4	141.3	145.3	115.7	137	197.3	163.7	131.9	153
A1718	139.5	109.6	104.1	124.9	128.1	203.5	157.7	161.7	157.8	135.7	139.7	133.1	154.3	182.3	158.1	149.2	170.3
A1819	146.8	116.9	88.44	109.3	112.5	219.1	173.3	177.3	165.1	143	147	117.5	138.7	197.9	165.4	133.6	154.7
A1617	144.9	115.1	132.4	153.3	156.5	207.9	162.1	166.1	163.3	141.2	145.2	161.5	182.7	186.7	163.6	177.6	198.7
A1416	180.8	150.9	168.3	189.2	192.3	243.8	197.9	201.9	199.1	177.1	181.1	197.3	218.6	222.6	199.4	213.5	234.5
A1721	121.2	91.29	114.2	135.1	138.2	184.1	138.3	142.3	139.5	117.4	121.4	143.2	164.5	162.9	139.8	159.4	180.5
A2125	103.3	73.47	102	122.8	126	166.3	120.5	124.5	121.7	99.59	103.6	131	152.2	145.1	122	147.1	168.2
A0817	162	132.2	143.8	164.7	167.8	225	179.2	183.2	180.4	158.3	162.3	172.8	194.1	203.8	180.7	189	210
A2021	116.3	86.42	114.9	135.8	138.9	179.2	133.4	137.4	134.6	112.5	116.5	143.9	165.2	158	134.9	160.1	181.1
A4041	58.89	88.75	117.2	138.1	141.3	22.91	22.91	26.91	51.91	73.97	77.97	107.7	133.5	47.53	96.35	123.8	149.5
A4243	52.48	59.01	87.49	108.4	111.5	62.32	16.5	12.5	12.5	34.56	38.56	68.24	94.12	33.12	56.94	84.38	110.1
A3334	42.34	72.2	100.7	121.5	124.7	83.34	37.52	41.52	66.52	88.58	92.58	122.3	148.1	62.14	111	138.4	164.1
A3435	10.2	40.06	68.54	89.4	92.56	71.6	25.78	29.78	54.78	61.31	65.31	93.84	117.4	50.4	83.69	110	133.4
A4248	50.29	80.15	108.6	129.5	132.7	60.13	14.31	10.31	35.31	57.37	61.37	91.05	116.9	10.31	79.75	107.2	132.9
A3441	28.19	58.05	86.53	107.4	110.6	53.61	7.79	11.79	36.79	58.85	62.85	92.53	118.4	32.41	81.23	108.7	134.4
A4142	37.98	67.84	96.32	117.2	120.3	47.82	2	2	27	49.06	53.06	82.74	108.6	22.62	71.44	98.88	124.6
A2829	67.8	97.66	126.1	147	150.2	108.8	62.98	66.98	91.98	114	118	147.7	173.6	87.6	136.4	163.9	189.6
A2930	55	55	83.48	104.3	107.5	116.4	70.58	74.58	76.25	76.25	80.25	108.8	132.4	95.2	98.63	124.9	148.3
A2934	35.1	64.96	93.44	114.3	117.5	76.1	30.28	34.28	59.28	81.34	85.34	115	140.9	54.9	103.7	131.2	156.9
A2429	62.27	91.43	119.9	140.8	143.9	103.3	57.45	61.45	86.45	108.5	112.5	142.2	168.1	82.07	130.9	158.3	184
A2526	87.21	57.35	85.83	106.7	109.9	159.6	113.8	117.8	105.5	83.47	87.47	114.9	136.1	138.4	105.9	131	152.1
A2425	83.83	83.13	111.6	132.5	135.6	135.8	89.99	93.99	105.1	105.1	109.1	137.6	161.2	114.6	127.5	153.8	177.1
A4344	60.48	37.15	65.63	86.49	89.65	85.85	40.03	36.03	11.03	11.03	15.03	44.71	70.59	56.65	33.41	60.85	86.55
A4445	57.98	28.12	56.6	77.46	80.62	98.88	53.06	49.06	24.06	2	2	31.68	57.56	69.68	20.38	47.82	73.52
A4546	73.67	43.81	43.81	64.67	67.83	115.7	69.9	65.9	40.9	18.84	14.84	14.84	40.72	86.52	33.22	30.98	56.68
A4647	97.99	68.13	39.65	39.65	42.81	143.5	97.68	93.68	68.68	46.62	42.62	12.94	12.94	114.3	61	29.08	28.9
A4549	69.17	39.31	67.79	88.65	91.81	110.1	64.25	60.25	35.25	13.19	9.19	38.87	64.75	80.87	9.19	55.01	80.71
A3644	42.92	13.06	41.54	62.4	65.56	104.3	58.45	58.45	35.12	13.06	17.06	45.59	69.16	79.07	35.44	61.73	85.12
A4650	95.43	65.57	37.09	57.95	61.11	138.6	92.81	88.81	63.81	41.75	37.75	8.07	33.95	109.4	56.13	8.07	49.91
A4751	116.6	86.74	58.26	37.4	40.56	164.4	118.6	114.6	89.6	67.54	63.54	33.86	7.98	135.2	81.92	50	7.98
A3847	93.91	64.05	35.57	14.71	17.87	158.7	112.9	112.9	89.57	67.51	67.51	37.88	14.71	133.5	85.89	54.02	30.67
A3238	82.14	52.28	23.8	2.94	6.1	163.9	118.1	122.1	100.5	78.4	82.4	52.82	32.36	142.7	100.8	68.96	48.32
A3738	68.77	38.91	10.43	10.43	13.59	150.6	104.8	108.8	87.09	65.03	69.03	39.45	39.85	129.4	87.41	55.59	55.81
A3137	79.89	50.03	21.55	42.41	45.57	161.7	115.9	119.9	98.21	76.15	80.15	50.57	71.83	140.5	98.53	66.71	87.79
A3839	80.78	50.92	22.44	1.58	1.58	162.6	116.8	120.8	99.1	77.04	81.04	51.46	31	141.4	99.42	67.6	46.96
A3536	14.93	14.93	43.41	64.27	67.43	96.73	50.91	54.91	56.58	41.05	45.05	72.43	93.69	75.53	63.43	88.57	109.7
A3637	44.1	14.24	14.24	35.1	38.26	125.9	80.08	84.08	62.42	40.36	44.36	43.26	64.52	104.7	62.74	59.4	80.48
A2630	70.85	40.99	69.47	90.33	93.49	152.7	106.8	110.8	89.17	67.11	71.11	98.49	119.8	131.5	89.49	114.6	135.7
A3036	45.03	15.17	43.65	64.51	67.67	126.8	81.01	85.01	63.35	41.29	45.29	72.67	93.93	105.6	63.67	88.81	109.9
A3746	72.85	42.99	14.51	35.37	38.53	135.4	89.53	89.53	66.2	44.14	44.14	14.51	38.08	110.2	62.52	30.65	54.04

APPENDIX G. LINGO CODE FOR THE NETWORK PARTITIONING MODEL

```
! This is an example of LINGO code used in the network partitioning phase;
! The scenario used in this example is the Test Scenario 9;
! In this example, 9 depot locations are chosen for the Fargo District road network;
! Then road segments are assigned to these nine depots to form 9 service districts;

MODEL:

TITLE
        Nine Depot Selection – Test Scenario Name: 9;

SETS:
        SumLPTotal /1/:                 Total ;
        NODE; DEPOT:                    DP,SumLP, SumWP, NumberTruck,
        NumTru,WMAX,LMAX;
        ARC:                            DISTANCE, WIJ;
        ARCDEPOT(ARC,DEPOT):            XIJP,LIJP;
ENDSETS

DATA:

! 9depotinput.xls is the input data file;
! Below is the data names used in the model;

        LBound, WBound,
        NumberDepotU, NumberDepotL,
        NUBound, NLBound, TruckCap,
        Node, Depot, Arc, Distance, LIJP,
        WIJ

         = @OLE('.\9depotinput.xls',

! Below is the data range names used in the input file;

        'LBound', 'WBound',
        'NumberDepotU', 'NumberDepotL',
        'NUBound', 'NLBound', 'TruckCap',
        'Node', 'Depot', 'Arc', 'Distance', 'LIJP',
        'WIJ'

        );
```

```
@TEXT()     =       @WRITE('-----------------------------------------------------------------
-----------------',@NEWLINE(1));
    @TEXT()     =       @WRITE('Column: Depot  Row: Arc    Column/ Row: 1 if
Arc is assigned to Depot',          @NEWLINE(1));
    @TEXT()     =       @WRITE('                              0 otherwise',
@NEWLINE(1));
    @TEXT()     =       @WRITE('---------------------------------------------------------
-------------------------',@NEWLINE(1));
    @TEXT()     =       @TABLE(XIJP,1,2,1);
    @TEXT()     =       @WRITE('---------------------------------------------------------
-------------------------',@NEWLINE(1));

ENDDATA

! OBJECTIVE FUNCTION (9.1) sum of total compactness + sum of total number of
trucks;
    MIN   =       @SUM(DEPOT:SumLP) +
                  @SUM(DEPOT:NumberTruck)
                ;

! Total compactness value calculation for output file;

    @FOR( SumLPTotal(I): Total(I)= @SUM(DEPOT:SumLP);
         );

!Restrictions on decision variables;

! Constraint set (9.18), if node is chosen as depot it is 1, otherwise 0;

! Constraint set (9.18), if arc is assigned to the depot it is 1, otherwise 0;

    @FOR( DEPOT: @BIN(DP));
    @FOR( ARCDEPOT: @BIN( XIJP));

! Constraint set (9.19), is as default;

! Constraint set (9.20), number of trucks assigned to the depot must be an integer;

    @FOR( DEPOT: @GIN( NumTru));

!Real constraints;
```

```
! Constraint set (9.2), each arc must be assigned to a sigle depot;

        @FOR(ARC(I):
                @SUM(DEPOT(P):
                        XIJP(I,P))=1;
                );

! Constraint set (9.3), arcs must be assigned to the depots that only are in operation;

        @FOR(ARCDEPOT(I,P):
                @FOR(DEPOT(P):
                        XIJP(I,P)<=DP(P);
                ));

! Constraint sets (9.4) and (9.5) are the upper and lower bounds on the total number of
depots in operation in the the system;

        @SUM(DEPOT:DP)>=NumberDepotL;
        @SUM(DEPOT:DP)<=NumberDepotU;

! Constraint set (9.6), LIJP calculation is done by MATLAB. LIJP data is given in the input
excel file.

! Number of decision variables used in the model dramatically reduced.

! Constraint set (9.7), total compactness value for each depot;

        @FOR(DEPOT(P):
                @SUM(ARCDEPOT(I,P):LIJP(I,P)*XIJP(I,P))-SumLP(P)=0;
                );

! Constraint sets (9.8) and (9.9) are the upper bound on maximum compactness value for
each depot-arc assignment;

! These constraint sets are used to eliminate undesirable depot-arc assignment alternatives;

                @FOR(DEPOT(P):
                        LMAX(P)=@MAX(ARCDEPOT(I,P):LIJP(I,P)*DP(P)*XIJP(I,P)));


                @FOR(DEPOT(P):
                        LMAX(P)*DP(P)<=LBound;
                );
```

! Constraint set (9.10), WIJ calculation is done by EXCEL. WIJ data is given in the input excel file;

! Constraint set (9.11), service capacity available at each depot is more than or equal to the workload assigned to that depot;

```
@FOR(DEPOT(P):
        @SUM(ARC(I):
                WIJ(I)*XIJP(I,P))-TruckCap*NumTru(P)<=0;
        );
```

! Constraint set (9.12), total workload value for each depot;

```
@FOR(DEPOT(P):
        @SUM(ARCDEPOT(I,P):WIJ(I)*XIJP(I,P))-SumWP(P)=0;
        );
```

! Constraint sets (9.13) and (9.14) are the upper bound on maximum workload value for each depot;

! These constraint sets are used to eliminate depot-arc assignment alternatives such as unbalanced workload assignments for depots;

```
@FOR(DEPOT(P):
        WMAX(P)=SumWP(P)*DP(P);
);

@FOR(DEPOT(P):
        WMAX(P)<=WBound;
);
```

! Constraint set (9.15) and (9.16) are the lower and upper bounds on the maximum number of trucks assigned to each depot that is in operation;

```
@FOR(DEPOT(P):
        NumTru(P)<=NUBound;
);

@FOR(DEPOT(P):
        NumTru(P)>=NLBound;
);
```

G. (continued)

```
! Constraint set (9.17), trucks must be assigned to the depots that only are in operation;

@FOR(DEPOT(P):
            NumberTruck(P)=DP(P)*NumTru(P);
      );

DATA:

! 9depotoutput.xls is the output data file;

@OLE('.\ 9depotoutput.xls',

! Below is the data range names used in the output (excel) file;

'XIJP', 'SUMLP', 'SUMWP', 'TOTAL', 'NumberTruck'  ) =

! Below is the data names used in the model;

XIJP, SumLP, SumWP, Total, NumberTruck;

ENDDATA

END
```

APPENDIX H. SUMMARY OF RESULTS FOR TEST SCENARIOS

Test Scenario				Minimum Compactness Design Chosen			
Name	# of Candidate Locations	# of Locations to Choose	Number of Combinations Possible	Compactness Value	Minimum # of vehicles required	Maximum Workload per Depot (miles)	Maximum Lijp Value (miles)
1	51	1	51	5338.01	23	1760.4	180.7
2	51	2	1,275	3283.39	23	889.7	144.9
3	51	3	20,825	2506.15	23	889.7	97.7
4	51	4	249,900	2020.77	23	479.8	79.8
5	51	5	2,349,060	1704.41	23	439.0	67.1
6	51	6	18,009,460	1479.22	24	347.4	67.1
7	51	7	115,775,100	1339.04	24	319.4	55.3
8	51	8	636,763,050	1207.97	25	306.5	52.2
9	51	9	3,042,312,350	1106.43	27	306.5	52.2
10	51	10	12,777,711,870	1017.64	28	269.0	52.2
11	51	11	47,626,016,970	949.36	27	269.0	52.2
12	51	12	158,753,389,900	891.4	28	215.3	52.2
13	51	13	476,260,169,700	847.18	28	215.3	52.2
14	51	14	1,292,706,174,900	812.02	28	215.3	52.2
15	51	15	3,188,675,231,420	779.28	29	208.4	33.9
16	51	16	7,174,519,270,695	753.4	29	208.4	33.5
17	51	17	14,771,069,086,725	726.6	30	293.0	33.5
18	51	18	27,900,908,274,925	715.18	30	293.0	33.5
19	51	19	48,459,472,266,975	705.18	31	209.7	33.5
20	51	20	77,535,155,627,160	693.06	32	145.9	33.5
21	51	21	114,456,658,306,760	689.06	32	142.3	33.5
22	51	22	156,077,261,327,400	687.06	30	156.4	33.5
23	51	23	196,793,068,630,200	683.06	31	156.4	33.5
24	51	24	229,591,913,401,900	683.06	30	156.4	33.5
25	51	25	247,959,266,474,052	683.06	30	156.4	33.5
26	51	26	247,959,266,474,052	683.06	30	156.4	33.5
27	51	27	229,591,913,401,900	683.06	30	156.4	33.5
28	51	28	196,793,068,630,200	683.06	30	156.4	33.5
29	51	29	156,077,261,327,400	683.06	31	144.2	33.5
30	51	30	114,456,658,306,760	683.06	31	114.7	33.5
31	51	31	77,535,155,627,160	683.06	32	144.2	33.5
32	51	32	48,459,472,266,975	683.06	33	102.2	33.5
33	51	33	27,900,908,274,925	683.06	34	102.2	33.5

APPENDIX H . (continued)

Scenario				Minimum Compactness Design Chosen			
Name	# of Candidate Locations	# of Locations to Choose	Number of Combinations Possible	Compactness Value	Minimum # of vehicles required	Maximum Workload per Depot (miles)	Maximum Lijp Value (miles)
34	51	34	14,771,069,086,725	683.06	35	144.2	33.5
35	51	35	7,174,519,270,695	683.06	36	102.2	33.5
36	51	36	3,188,675,231,420	683.06	37	144.2	33.5
37	51	37	1,292,706,174,900	683.06	38	144.2	33.5
38	51	38	476,260,169,700	683.06	39	156.4	33.5
39	51	39	158,753,389,900	683.06	40	102.2	33.5
40	51	40	47,626,016,970	683.06	41	144.2	33.5
41	51	41	12,777,711,870	683.06	42	144.2	33.5
42	51	42	3,042,312,350	683.06	43	144.2	33.5
43	51	43	636,763,050	683.06	44	144.2	33.5
44	51	44	115,775,100	683.06	45	102.2	33.5
45	51	45	18,009,460	683.06	46	102.2	33.5
46	51	46	2,349,060	683.06	47	144.2	33.5
47	51	47	249,900	683.06	48	86.2	33.5
48	51	48	20,825	683.06	49	102.2	33.5
49	51	49	1,275	683.06	50	144.2	33.5
50	51	50	51	683.06	51	86.2	33.5
51	51	51	1	683.06	52	102.2	33.5

APPENDIX I. MATLAB CODE FOR MATCHING PROBLEM

```
% This is an example code that can be used to solve any matching problem described in %
% methodology phase%

% y matrix represents the all pairs shortest paths matrix for the nodes to be matches%

y=[1000    18     32    128.5
   18    1000     10    146.5
   32     10    1000    4
   128.5  146.5    4    1000];

[m,n] = size(y);

% order list is the list of nodes to be matched, and it represents the order given in "y"  %

order=[16 17 10 11]

% v matrix represents the index numbers of nodes to be matched%

v=[1 2 3 4];
x=perms(v);
k=size(x);
for i=1:k
C(i)=y(x(i,1), x(i,2))+ y(x(i,3), x(i,4));
end
C';
number=(1:k);
total=[ number' x C'];

result=sortrows(total,m+2)
```

APPENDIX J. NETWORK PARTITIONING PHASE OUTPUT

Current Setup Scenario		Depot D3	Depot D6	Depot D17	Depot D19	Depot D29	Depot D36	Depot D38	Depot D42	Depot D45
Depot Compactness		132.93	81.97	152.08	173.05	185.33	128.32	109.47	134.81	138.49
Max L_{ijp}		36.88	28.22	52.24	48.85	69.17	42.99	42.41	41.52	42.62
Arc	A0304	1	0	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0	0
Arc	A0809	1	0	0	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0	0
Arc	A2731	0	0	0	1	0	0	0	0	0
Arc	A2627	0	0	0	1	0	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0	0
Arc	A1718	0	0	0	1	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	1	0	0	0	0
Arc	A2930	0	0	0	0	1	0	0	0	0
Arc	A2934	0	0	0	0	1	0	0	0	0
Arc	A2429	0	0	0	0	1	0	0	0	0
Arc	A2526	0	0	0	0	1	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	0	0	0	1
Arc	A4549	0	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	0	0	0	1
Arc	A4650	0	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	0	1	0	0	0
Arc	A3036	0	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	1	0	0	0

APPENDIX J. (continued)

Partial Redesign Scenario		Depot D3	Depot D6	Depot D17	Depot D19	Depot D29	Depot D36	Depot D38	Depot D42	Depot D45
Depot Compactness		96.05	98.32	205.44	153.84	116.16	98.39	184.49	134.81	78.81
Max L_{ijp}		33.01	28.22	52.24	48.85	45.01	40.99	42.41	41.52	37.75
Arc	A0304	1	0	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0	0
Arc	A2731	0	0	0	1	0	0	0	0	0
Arc	A2627	0	0	0	1	0	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	1	0	0	0	0
Arc	A2930	0	0	0	0	1	0	0	0	0
Arc	A2934	0	0	0	0	1	0	0	0	0
Arc	A2429	0	0	0	0	1	0	0	0	0
Arc	A2526	0	0	1	0	0	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	1	0	0	0
Arc	A4650	0	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	0	1	0	0	0
Arc	A3036	0	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Complete Redesign Scenario		Depot D3	Depot D9	Depot D17	Depot D19	Depot D26	Depot D29	Depot D38	Depot D41	Depot D45
Depot Compactness		96.05	90.32	138.86	67.25	155.48	71.15	219.59	126.81	140.92
Max L_{ijp}		33.01	28.79	52.24	22.83	36.47	25.98	42.41	37.52	45.05
Arc	A0304	1	0	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0	0
Arc	A2731	0	0	0	0	1	0	0	0	0
Arc	A2627	0	0	0	0	1	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0	0
Arc	A2125	0	0	0	0	1	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	0	1	0	0	0
Arc	A2930	0	0	0	0	0	1	0	0	0
Arc	A2934	0	0	0	0	0	1	0	0	0
Arc	A2429	0	0	0	0	0	1	0	0	0
Arc	A2526	0	0	0	0	1	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	0	0	0	1
Arc	A4650	0	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	0	0	0	0	1
Arc	A3637	0	0	0	0	0	0	1	0	0
Arc	A2630	0	0	0	0	1	0	0	0	0
Arc	A3036	0	0	0	0	1	0	0	0	0
Arc	A3746	0	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Replace 3 Scenario		Depot D2	Depot D6	Depot D17	Depot D19	Depot D29	Depot D36	Depot D38	Depot D42	Depot D45
Depot Compactness		70.25	123.06	205.44	153.84	116.16	98.39	184.49	134.81	78.81
Max L_{ijp}		29.57	28.22	52.24	48.85	45.01	40.99	42.41	41.52	37.75
Arc	A0304	0	1	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0	0
Arc	A2731	0	0	0	1	0	0	0	0	0
Arc	A2627	0	0	0	1	0	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	1	0	0	0	0
Arc	A2930	0	0	0	0	1	0	0	0	0
Arc	A2934	0	0	0	0	1	0	0	0	0
Arc	A2429	0	0	0	0	1	0	0	0	0
Arc	A2526	0	0	1	0	0	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	1	0	0	0
Arc	A4650	0	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	0	1	0	0	0
Arc	A3036	0	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Replace 6 Scenario		Depot D3	Depot D9	Depot D17	Depot D19	Depot D29	Depot D36	Depot D38	Depot D42	Depot D45
Depot Compactness		96.05	90.32	205.44	153.84	116.16	98.39	184.49	134.81	78.81
Max L_{ijp}		33.01	28.79	52.24	48.85	45.01	40.99	42.41	41.52	37.75
Arc	A0304	1	0	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0	0
Arc	A2731	0	0	0	1	0	0	0	0	0
Arc	A2627	0	0	0	1	0	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	1	0	0	0	0
Arc	A2930	0	0	0	0	1	0	0	0	0
Arc	A2934	0	0	0	0	1	0	0	0	0
Arc	A2429	0	0	0	0	1	0	0	0	0
Arc	A2526	0	0	1	0	0	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	1	0	0	0
Arc	A4650	0	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	0	1	0	0	0
Arc	A3036	0	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Replace 17 Scenario		Depot D3	Depot D6	Depot D17	Depot D19	Depot D29	Depot D36	Depot D38	Depot D42	Depot D45
Depot Compactness		96.05	98.32	205.44	153.84	116.16	98.39	184.49	134.81	78.81
Max L_{ijp}		33.01	28.22	52.24	48.85	45.01	40.99	42.41	41.52	37.75
Arc	A0304	1	0	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0	0
Arc	A2731	0	0	0	1	0	0	0	0	0
Arc	A2627	0	0	0	1	0	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	1	0	0	0	0
Arc	A2930	0	0	0	0	1	0	0	0	0
Arc	A2934	0	0	0	0	1	0	0	0	0
Arc	A2429	0	0	0	0	1	0	0	0	0
Arc	A2526	0	0	1	0	0	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	1	0	0	0
Arc	A4650	0	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	0	1	0	0	0
Arc	A3036	0	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Replace 19 Scenario		Depot D3	Depot D6	Depot D17	Depot D19	Depot D29	Depot D36	Depot D38	Depot D42	Depot D45
Depot Compactness		96.05	98.32	205.44	153.84	116.16	98.39	184.49	134.81	78.81
Max L_{ijp}		33.01	28.22	52.24	48.85	45.01	40.99	42.41	41.52	37.75
Arc	A0304	1	0	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0	0
Arc	A2731	0	0	0	1	0	0	0	0	0
Arc	A2627	0	0	0	1	0	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	1	0	0	0	0
Arc	A2930	0	0	0	0	1	0	0	0	0
Arc	A2934	0	0	0	0	1	0	0	0	0
Arc	A2429	0	0	0	0	1	0	0	0	0
Arc	A2526	0	0	1	0	0	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	1	0	0	0
Arc	A4650	0	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	0	1	0	0	0
Arc	A3036	0	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	0	1	0	0

Replace 29 Scenario		Depot D3	Depot D6	Depot D17	Depot D19	Depot D29	Depot D36	Depot D38	Depot D42	Depot D45
Depot Compactness		96.05	98.32	205.44	153.84	116.16	98.39	184.49	134.81	78.81
Max L_{ijp}		33.01	28.22	52.24	48.85	45.01	40.99	42.41	41.52	37.75
Arc	A0304	1	0	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0	0
Arc	A2731	0	0	0	1	0	0	0	0	0
Arc	A2627	0	0	0	1	0	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	1	0	0	0	0
Arc	A2930	0	0	0	0	1	0	0	0	0
Arc	A2934	0	0	0	0	1	0	0	0	0
Arc	A2429	0	0	0	0	1	0	0	0	0
Arc	A2526	0	0	1	0	0	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	1	0	0	0
Arc	A4650	0	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	0	1	0	0	0
Arc	A3036	0	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Replace 36 Scenario		Depot D3	Depot D6	Depot D17	Depot D19	Depot D26	Depot D29	Depot D38	Depot D42	Depot D45
Depot Compactness		96.05	98.32	138.86	67.25	155.48	71.15	219.59	134.81	140.92
Max L_{ijp}		33.01	28.22	52.24	22.83	36.47	25.98	42.41	41.52	45.05
Arc	A0304	1	0	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0	0
Arc	A2731	0	0	0	0	1	0	0	0	0
Arc	A2627	0	0	0	0	1	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0	0
Arc	A2125	0	0	0	0	1	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	0	1	0	0	0
Arc	A2930	0	0	0	0	0	1	0	0	0
Arc	A2934	0	0	0	0	0	1	0	0	0
Arc	A2429	0	0	0	0	0	1	0	0	0
Arc	A2526	0	0	0	0	1	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	0	0	0	1
Arc	A4650	0	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	0	0	0	0	1
Arc	A3637	0	0	0	0	0	0	1	0	0
Arc	A2630	0	0	0	0	1	0	0	0	0
Arc	A3036	0	0	0	0	1	0	0	0	0
Arc	A3746	0	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Replace 38 Scenario		Depot D3	Depot D6	Depot D17	Depot D19	Depot D29	Depot D36	Depot D38	Depot D42	Depot D45
Depot Compactness		96.05	98.32	205.44	153.84	116.16	98.39	184.49	134.81	78.81
Max L_{ijp}		33.01	28.22	52.24	48.85	45.01	40.99	42.41	41.52	37.75
Arc	A0304	1	0	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0	0
Arc	A2731	0	0	0	1	0	0	0	0	0
Arc	A2627	0	0	0	1	0	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	1	0	0	0	0
Arc	A2930	0	0	0	0	1	0	0	0	0
Arc	A2934	0	0	0	0	1	0	0	0	0
Arc	A2429	0	0	0	0	1	0	0	0	0
Arc	A2526	0	0	1	0	0	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	1	0	0	0
Arc	A4650	0	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	0	1	0	0	0
Arc	A3036	0	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Replace 42 Scenario		Depot D3	Depot D6	Depot D17	Depot D19	Depot D29	Depot D36	Depot D38	Depot D41	Depot D45
Depot Compactness		96.05	98.32	205.44	153.84	116.16	98.39	184.49	126.81	78.81
Max L_{ijp}		33.01	28.22	52.24	48.85	45.01	40.99	42.41	37.52	37.75
Arc	A0304	1	0	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0	0
Arc	A2731	0	0	0	1	0	0	0	0	0
Arc	A2627	0	0	0	1	0	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	1	0	0	0	0
Arc	A2930	0	0	0	0	1	0	0	0	0
Arc	A2934	0	0	0	0	1	0	0	0	0
Arc	A2429	0	0	0	0	1	0	0	0	0
Arc	A2526	0	0	1	0	0	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	1	0	0	0
Arc	A4650	0	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	0	1	0	0	0
Arc	A3036	0	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Replace 45 Scenario		Depot D3	Depot D6	Depot D17	Depot D19	Depot D29	Depot D36	Depot D38	Depot D42	Depot D46
Depot Compactness		96.05	98.32	205.44	153.84	116.16	126.51	72.07	170.84	123.09
Max L_{ijp}		33.01	28.22	52.24	48.85	45.01	40.99	42.41	41.52	38.87
Arc	A0304	1	0	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0	0
Arc	A2731	0	0	0	1	0	0	0	0	0
Arc	A2627	0	0	0	1	0	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	1	0	0	0	0
Arc	A2930	0	0	0	0	1	0	0	0	0
Arc	A2934	0	0	0	0	1	0	0	0	0
Arc	A2429	0	0	0	0	1	0	0	0	0
Arc	A2526	0	0	1	0	0	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	1	0
Arc	A4445	0	0	0	0	0	1	0	0	0
Arc	A4546	0	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	0	0	0	1
Arc	A4549	0	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	1	0	0	0
Arc	A4650	0	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	0	0	0	1
Arc	A3847	0	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	0	1	0	0	0
Arc	A3036	0	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	0	0	0	1

APPENDIX J. (continued)

Close 3 Scenario		Depot D6	Depot D17	Depot D19	Depot D29	Depot D36	Depot D38	Depot D42	Depot D45
Depot Compactness		331.02	205.44	153.84	116.16	98.39	184.49	134.81	78.81
Max L_{ijp}		68.91	52.24	48.85	45.01	40.99	42.41	41.52	37.75
Arc	A0304	1	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0
Arc	A0809	1	0	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0
Arc	A0910	1	0	0	0	0	0	0	0
Arc	A0405	1	0	0	0	0	0	0	0
Arc	A0406	1	0	0	0	0	0	0	0
Arc	A0609	1	0	0	0	0	0	0	0
Arc	A0911	1	0	0	0	0	0	0	0
Arc	A1112	0	0	1	0	0	0	0	0
Arc	A1215	0	0	1	0	0	0	0	0
Arc	A1519	0	0	1	0	0	0	0	0
Arc	A1922	0	0	1	0	0	0	0	0
Arc	A1213	0	0	1	0	0	0	0	0
Arc	A2223	0	0	1	0	0	0	0	0
Arc	A2227	0	0	1	0	0	0	0	0
Arc	A2731	0	0	1	0	0	0	0	0
Arc	A2627	0	0	1	0	0	0	0	0
Arc	A1822	0	0	1	0	0	0	0	0
Arc	A1718	0	1	0	0	0	0	0	0
Arc	A1819	0	0	1	0	0	0	0	0
Arc	A1617	0	1	0	0	0	0	0	0
Arc	A1416	0	1	0	0	0	0	0	0
Arc	A1721	0	1	0	0	0	0	0	0
Arc	A2125	0	1	0	0	0	0	0	0
Arc	A0817	0	1	0	0	0	0	0	0
Arc	A2021	0	1	0	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	1	0	0	0	0
Arc	A2930	0	0	0	1	0	0	0	0
Arc	A2934	0	0	0	1	0	0	0	0
Arc	A2429	0	0	0	1	0	0	0	0
Arc	A2526	0	1	0	0	0	0	0	0
Arc	A2425	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	1	0	0	0
Arc	A4650	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	1	0	0	0
Arc	A3036	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Close 6 Scenario		Depot D3	Depot D17	Depot D19	Depot D29	Depot D36	Depot D38	Depot D42	Depot D45
Depot Compactness		295.59	205.44	209.67	116.16	98.39	184.49	134.81	78.81
Max L_{ijp}		64.12	52.24	55.83	45.01	40.99	42.41	41.52	37.75
Arc	A0304	1	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0
Arc	A0809	1	0	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0
Arc	A0910	1	0	0	0	0	0	0	0
Arc	A0405	1	0	0	0	0	0	0	0
Arc	A0406	1	0	0	0	0	0	0	0
Arc	A0609	1	0	0	0	0	0	0	0
Arc	A0911	0	0	1	0	0	0	0	0
Arc	A1112	0	0	1	0	0	0	0	0
Arc	A1215	0	0	1	0	0	0	0	0
Arc	A1519	0	0	1	0	0	0	0	0
Arc	A1922	0	0	1	0	0	0	0	0
Arc	A1213	0	0	1	0	0	0	0	0
Arc	A2223	0	0	1	0	0	0	0	0
Arc	A2227	0	0	1	0	0	0	0	0
Arc	A2731	0	0	1	0	0	0	0	0
Arc	A2627	0	0	1	0	0	0	0	0
Arc	A1822	0	0	1	0	0	0	0	0
Arc	A1718	0	1	0	0	0	0	0	0
Arc	A1819	0	0	1	0	0	0	0	0
Arc	A1617	0	1	0	0	0	0	0	0
Arc	A1416	0	1	0	0	0	0	0	0
Arc	A1721	0	1	0	0	0	0	0	0
Arc	A2125	0	1	0	0	0	0	0	0
Arc	A0817	0	1	0	0	0	0	0	0
Arc	A2021	0	1	0	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	1	0	0	0	0
Arc	A2930	0	0	0	1	0	0	0	0
Arc	A2934	0	0	0	1	0	0	0	0
Arc	A2429	0	0	0	1	0	0	0	0
Arc	A2526	0	1	0	0	0	0	0	0
Arc	A2425	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	1	0	0	0
Arc	A4650	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	1	0	0	0
Arc	A3036	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Close 17 Scenario		Depot D3	Depot D6	Depot D19	Depot D29	Depot D36	Depot D38	Depot D42	Depot D45
Depot Compactness		96.05	156.49	398.91	116.16	221.35	184.49	134.81	78.81
Max L_{ijp}		33.01	58.17	83.46	45.01	65.61	42.41	41.52	37.75
Arc	A0304	1	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0
Arc	A1112	0	0	1	0	0	0	0	0
Arc	A1215	0	0	1	0	0	0	0	0
Arc	A1519	0	0	1	0	0	0	0	0
Arc	A1922	0	0	1	0	0	0	0	0
Arc	A1213	0	0	1	0	0	0	0	0
Arc	A2223	0	0	1	0	0	0	0	0
Arc	A2227	0	0	1	0	0	0	0	0
Arc	A2731	0	0	1	0	0	0	0	0
Arc	A2627	0	0	0	0	1	0	0	0
Arc	A1822	0	0	1	0	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0
Arc	A1819	0	0	1	0	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0
Arc	A0817	0	1	0	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	1	0	0	0	0
Arc	A2930	0	0	0	1	0	0	0	0
Arc	A2934	0	0	0	1	0	0	0	0
Arc	A2429	0	0	0	1	0	0	0	0
Arc	A2526	0	0	0	0	1	0	0	0
Arc	A2425	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	1	0	0	0
Arc	A4650	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	1	0	0	0
Arc	A3036	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Close 19 Scenario		Depot D3	Depot D6	Depot D17	Depot D29	Depot D36	Depot D38	Depot D42	Depot D45
Depot Compactness		96.05	153.49	541.23	116.16	98.39	252.45	134.81	78.81
Max L_{ijp}		33.01	55.17	56.01	45.01	40.99	67.96	41.52	37.75
Arc	A0304	1	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0
Arc	A1112	0	1	0	0	0	0	0	0
Arc	A1215	0	0	1	0	0	0	0	0
Arc	A1519	0	0	1	0	0	0	0	0
Arc	A1922	0	0	1	0	0	0	0	0
Arc	A1213	0	0	1	0	0	0	0	0
Arc	A2223	0	0	1	0	0	0	0	0
Arc	A2227	0	0	1	0	0	0	0	0
Arc	A2731	0	0	0	0	0	1	0	0
Arc	A2627	0	0	1	0	0	0	0	0
Arc	A1822	0	0	1	0	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0
Arc	A1819	0	0	1	0	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	1	0	0	0	0
Arc	A2930	0	0	0	1	0	0	0	0
Arc	A2934	0	0	0	1	0	0	0	0
Arc	A2429	0	0	0	1	0	0	0	0
Arc	A2526	0	0	1	0	0	0	0	0
Arc	A2425	0	0	0	1	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	1	0	0	0
Arc	A4650	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	1	0	0	0
Arc	A3036	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Close 29 Scenario		Depot D3	Depot D6	Depot D17	Depot D19	Depot D36	Depot D38	Depot D42	Depot D45
Depot Compactness		96.05	98.32	261.15	153.84	153.39	184.49	297.52	78.81
Max L_{ijp}		33.01	28.22	55.71	48.85	55.00	42.41	66.98	37.75
Arc	A0304	1	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0
Arc	A2731	0	0	0	1	0	0	0	0
Arc	A2627	0	0	0	1	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	0	0	1	0
Arc	A2930	0	0	0	0	1	0	0	0
Arc	A2934	0	0	0	0	0	0	1	0
Arc	A2429	0	0	0	0	0	0	1	0
Arc	A2526	0	0	1	0	0	0	0	0
Arc	A2425	0	0	1	0	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	1	0	0	0
Arc	A4650	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	1	0	0	0
Arc	A3036	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Close 36 Scenario		Depot D3	Depot D6	Depot D17	Depot D19	Depot D29	Depot D38	Depot D42	Depot D45
Depot Compactness		96.05	98.32	263.15	153.84	116.16	219.59	134.81	186.21
Max L_{ijp}		33.01	28.22	57.71	48.85	45.01	42.41	41.52	45.29
Arc	A0304	1	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0
Arc	A2731	0	0	0	1	0	0	0	0
Arc	A2627	0	0	0	1	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	1	0	0	0
Arc	A2930	0	0	0	0	1	0	0	0
Arc	A2934	0	0	0	0	1	0	0	0
Arc	A2429	0	0	0	0	1	0	0	0
Arc	A2526	0	0	1	0	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0
Arc	A4344	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	0	0	1
Arc	A4650	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	0	0	0	1
Arc	A3637	0	0	0	0	0	1	0	0
Arc	A2630	0	0	1	0	0	0	0	0
Arc	A3036	0	0	0	0	0	0	0	1
Arc	A3746	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Close 38 Scenario		Depot D3	Depot D6	Depot D17	Depot D19	Depot D29	Depot D36	Depot D42	Depot D45
Depot Compactness		96.05	98.32	205.44	153.84	116.16	397.57	134.81	184.97
Max L_{ijp}		33.01	28.22	52.24	48.85	45.01	64.05	41.52	63.54
Arc	A0304	1	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0
Arc	A2731	0	0	0	1	0	0	0	0
Arc	A2627	0	0	0	1	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	1	0	0	0
Arc	A2930	0	0	0	0	1	0	0	0
Arc	A2934	0	0	0	0	1	0	0	0
Arc	A2429	0	0	0	0	1	0	0	0
Arc	A2526	0	0	1	0	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0
Arc	A4344	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	0	0	1
Arc	A4549	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	1	0	0
Arc	A4650	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	0	0	1
Arc	A3847	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	0	1	0	0
Arc	A3637	0	0	0	0	0	1	0	0
Arc	A2630	0	0	0	0	0	1	0	0
Arc	A3036	0	0	0	0	0	1	0	0
Arc	A3746	0	0	0	0	0	1	0	0

APPENDIX J. (continued)

Close 42 Scenario		Depot D3	Depot D6	Depot D17	Depot D19	Depot D29	Depot D36	Depot D38	Depot D45
Depot Compactness		96.05	98.32	205.44	153.84	378.85	138.45	184.49	117.37
Max L_{ijp}		33.01	28.22	52.24	48.85	67.89	40.99	42.41	38.56
Arc	A0304	1	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0
Arc	A2731	0	0	0	1	0	0	0	0
Arc	A2627	0	0	0	1	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0
Arc	A4041	0	0	0	0	1	0	0	0
Arc	A4243	0	0	0	0	0	0	0	1
Arc	A3334	0	0	0	0	1	0	0	0
Arc	A3435	0	0	0	0	0	1	0	0
Arc	A4248	0	0	0	0	1	0	0	0
Arc	A3441	0	0	0	0	1	0	0	0
Arc	A4142	0	0	0	0	1	0	0	0
Arc	A2829	0	0	0	0	1	0	0	0
Arc	A2930	0	0	0	0	1	0	0	0
Arc	A2934	0	0	0	0	1	0	0	0
Arc	A2429	0	0	0	0	1	0	0	0
Arc	A2526	0	0	1	0	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0
Arc	A4344	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	0	1	0
Arc	A4549	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	1	0	0
Arc	A4650	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	0	1	0
Arc	A3847	0	0	0	0	0	0	1	0
Arc	A3238	0	0	0	0	0	0	1	0
Arc	A3738	0	0	0	0	0	0	1	0
Arc	A3137	0	0	0	0	0	0	1	0
Arc	A3839	0	0	0	0	0	0	1	0
Arc	A3536	0	0	0	0	0	1	0	0
Arc	A3637	0	0	0	0	0	1	0	0
Arc	A2630	0	0	0	0	0	1	0	0
Arc	A3036	0	0	0	0	0	1	0	0
Arc	A3746	0	0	0	0	0	0	1	0

APPENDIX J. (continued)

Close 45 Scenario		Depot D3	Depot D6	Depot D17	Depot D19	Depot D29	Depot D36	Depot D38	Depot D42
Depot Compactness		96.05	98.32	205.44	153.84	116.16	209.63	242.44	170.84
Max L_{ijp}		33.01	28.22	52.24	48.85	45.01	43.81	57.95	41.52
Arc	A0304	1	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0
Arc	A2731	0	0	0	1	0	0	0	0
Arc	A2627	0	0	0	1	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0
Arc	A2125	0	0	1	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	0	1
Arc	A4243	0	0	0	0	0	0	0	1
Arc	A3334	0	0	0	0	0	0	0	1
Arc	A3435	0	0	0	0	0	0	0	1
Arc	A4248	0	0	0	0	0	0	0	1
Arc	A3441	0	0	0	0	0	0	0	1
Arc	A4142	0	0	0	0	0	0	0	1
Arc	A2829	0	0	0	0	1	0	0	0
Arc	A2930	0	0	0	0	1	0	0	0
Arc	A2934	0	0	0	0	1	0	0	0
Arc	A2429	0	0	0	0	1	0	0	0
Arc	A2526	0	0	1	0	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0
Arc	A4344	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	1	0	0
Arc	A4546	0	0	0	0	0	1	0	0
Arc	A4647	0	0	0	0	0	0	1	0
Arc	A4549	0	0	0	0	0	1	0	0
Arc	A3644	0	0	0	0	0	1	0	0
Arc	A4650	0	0	0	0	0	0	1	0
Arc	A4751	0	0	0	0	0	0	1	0
Arc	A3847	0	0	0	0	0	0	1	0
Arc	A3238	0	0	0	0	0	0	1	0
Arc	A3738	0	0	0	0	0	0	1	0
Arc	A3137	0	0	0	0	0	0	1	0
Arc	A3839	0	0	0	0	0	0	1	0
Arc	A3536	0	0	0	0	0	1	0	0
Arc	A3637	0	0	0	0	0	1	0	0
Arc	A2630	0	0	0	0	0	1	0	0
Arc	A3036	0	0	0	0	0	1	0	0
Arc	A3746	0	0	0	0	0	0	1	0

APPENDIX J. (continued)

Additional Depot Scenario		Depot D3	Depot D6	Depot D17	Depot D19	Depot D26	Depot D29	Depot D36	Depot D38	Depot D42	Depot D45
Depot Compactness		96.05	98.32	138.86	67.25	119.01	71.15	57.40	184.49	134.81	78.81
Max L_{ijp}		33.01	28.22	52.24	22.83	34.22	25.98	15.17	42.41	41.52	37.75
Arc	A0304	1	0	0	0	0	0	0	0	0	0
Arc	A0308	1	0	0	0	0	0	0	0	0	0
Arc	A0102	1	0	0	0	0	0	0	0	0	0
Arc	A0203	1	0	0	0	0	0	0	0	0	0
Arc	A0809	0	1	0	0	0	0	0	0	0	0
Arc	A0207	1	0	0	0	0	0	0	0	0	0
Arc	A0910	0	1	0	0	0	0	0	0	0	0
Arc	A0405	0	1	0	0	0	0	0	0	0	0
Arc	A0406	0	1	0	0	0	0	0	0	0	0
Arc	A0609	0	1	0	0	0	0	0	0	0	0
Arc	A0911	0	1	0	0	0	0	0	0	0	0
Arc	A1112	0	0	0	1	0	0	0	0	0	0
Arc	A1215	0	0	0	1	0	0	0	0	0	0
Arc	A1519	0	0	0	1	0	0	0	0	0	0
Arc	A1922	0	0	0	1	0	0	0	0	0	0
Arc	A1213	0	0	0	1	0	0	0	0	0	0
Arc	A2223	0	0	0	1	0	0	0	0	0	0
Arc	A2227	0	0	0	1	0	0	0	0	0	0
Arc	A2731	0	0	0	0	1	0	0	0	0	0
Arc	A2627	0	0	0	0	1	0	0	0	0	0
Arc	A1822	0	0	0	1	0	0	0	0	0	0
Arc	A1718	0	0	1	0	0	0	0	0	0	0
Arc	A1819	0	0	0	1	0	0	0	0	0	0
Arc	A1617	0	0	1	0	0	0	0	0	0	0
Arc	A1416	0	0	1	0	0	0	0	0	0	0
Arc	A1721	0	0	1	0	0	0	0	0	0	0
Arc	A2125	0	0	0	0	1	0	0	0	0	0
Arc	A0817	0	0	1	0	0	0	0	0	0	0
Arc	A2021	0	0	1	0	0	0	0	0	0	0
Arc	A4041	0	0	0	0	0	0	0	0	1	0
Arc	A4243	0	0	0	0	0	0	0	0	1	0
Arc	A3334	0	0	0	0	0	0	0	0	1	0
Arc	A3435	0	0	0	0	0	0	0	0	1	0
Arc	A4248	0	0	0	0	0	0	0	0	1	0
Arc	A3441	0	0	0	0	0	0	0	0	1	0
Arc	A4142	0	0	0	0	0	0	0	0	1	0
Arc	A2829	0	0	0	0	0	1	0	0	0	0
Arc	A2930	0	0	0	0	0	1	0	0	0	0
Arc	A2934	0	0	0	0	0	1	0	0	0	0
Arc	A2429	0	0	0	0	0	1	0	0	0	0
Arc	A2526	0	0	0	0	1	0	0	0	0	0
Arc	A2425	0	0	0	0	1	0	0	0	0	0
Arc	A4344	0	0	0	0	0	0	0	0	0	1
Arc	A4445	0	0	0	0	0	0	0	0	0	1
Arc	A4546	0	0	0	0	0	0	0	0	0	1
Arc	A4647	0	0	0	0	0	0	0	1	0	0
Arc	A4549	0	0	0	0	0	0	0	0	0	1
Arc	A3644	0	0	0	0	0	0	1	0	0	0
Arc	A4650	0	0	0	0	0	0	0	0	0	1
Arc	A4751	0	0	0	0	0	0	0	1	0	0
Arc	A3847	0	0	0	0	0	0	0	1	0	0
Arc	A3238	0	0	0	0	0	0	0	1	0	0
Arc	A3738	0	0	0	0	0	0	0	1	0	0
Arc	A3137	0	0	0	0	0	0	0	1	0	0
Arc	A3839	0	0	0	0	0	0	0	1	0	0
Arc	A3536	0	0	0	0	0	0	1	0	0	0
Arc	A3637	0	0	0	0	0	0	1	0	0	0
Arc	A2630	0	0	0	0	1	0	0	0	0	0
Arc	A3036	0	0	0	0	0	0	1	0	0	0
Arc	A3746	0	0	0	0	0	0	0	1	0	0

APPENDIX K. NETWORK ROUTING PHASE OUTPUT

Current Setup Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-5-4-6-4-6	1.87	0.00	1.87
	6,9,10,11				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-6	1.61	0.00	1.61
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20,25	17-21-25-21-20-21-17	1.36	0.00	1.36
Depot 19	19,15,12,11,13				
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,18,17	19-18-17-18-19-18-19-18+19	1.40	0.06	1.46
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-22-23-22-23-22-23-22-19	1.71	0.00	1.71
		19-22-27-26-27-31-27-31-27-22-19	2.67	0.00	2.67
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24,25,26	29-24-25-26-25-24-29	2.55	0.00	2.55
Depot 36	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,37,46				
		36-37-46-37+36	1.44	0.24	1.68
		36-37-46-37+36	1.44	0.24	1.68
	36,35	36-35-36	1.00	0.00	1.00
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31				
		38-37-31-37-38	2.13	0.00	2.13
		38-37-31-37-38	2.13	0.00	2.13
	38,47,51	38-47-51-47-38	1.51	0.00	1.51
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,47,50				
		45-46-47-46+45	1.36	0.25	1.60
		45-46-50-46-+45	1.57	0.25	1.82
	45,44,43,36	45-44-43-44-36-44-45	1.74	0.00	1.74

APPENDIX K. (continued)

Partial Redesign Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-5-4-6-4-6	1.87	0.00	1.87
	6,9,10,11,8				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20,25,26	17-21-25-26-25-21-20-21-17	1.74	0.00	1.74
Depot 19	19,15,12,11,13				
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,18	19-18-19-18-19-18+19	0.60	0.06	0.66
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-22-23-22-23-22-23-22-19	1.71	0.00	1.71
		19-22-27-26-27-31-27-31-27-22-19	2.67	0.00	2.67
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24,25	29-24-25-24-29	2.17	0.00	2.17
Depot 36	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44	36-44-36	0.87	0.00	0.87
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37+38	1.31	0.17	1.49
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43	45-44-43-44-45	0.87	0.00	0.87

APPENDIX K. (continued)

Complete Redesign Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 9	9,6,4,5	9-6-4-5-4-5-4-6-4-6-9-6-9	2.40	0.00	2.40
	9,8	9-8-9	0.56	0.00	0.56
	9,10	9-10-9	1.35	0.00	1.35
	9,11	9-11-9	1.89	0.00	1.89
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20	17-21-20-21-17	0.66	0.00	0.66
Depot 19	19,15,12,11,13				
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,18	19-18-19-18-19-18+19	0.60	0.06	0.66
	19,22,18,27,23				
		19-22-18-22-18-22+19	2.50	0.03	2.53
		19-22-23-22-23-22-23-22-19-22-19	0.81	0.00	0.81
		19-22-27-22-27-22+19	2.08	0.03	2.11
Depot 26	26,27,31	26-27-31-27-31-27-26	1.54	0.00	1.54
	26,30,36	26-30-36-30-26	1.72	0.00	1.72
	26,25,24,21	26-25-21-25-24-25-26	2.41	0.00	2.41
Depot 29	29,24	29-24-29	0.83	0.00	0.83
	29,28	29-28-29	1.20	0.00	1.20
	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46,36				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37+38	1.31	0.17	1.49
		38+37-36-37+38	0.95	0.35	1.30
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 41	41,40	41-40-41	1.53	0.00	1.53
	41,42,43,48	41-42-43-42-48-42-41	1.65	0.00	1.65
	41,34,33,35	41-34-33-34-35-34-41	2.66	0.00	2.66
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43,36,35	45-44-43-44-36-35-36-44-45			
		45-44-43-44+45	0.80	0.03	0.84
		45-44-36-35-36-44+45	1.93	0.03	1.97

APPENDIX K. (continued)

Replace 3 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 2	2,1	2-1-2	1.00	0.00	1.00
	2,7	2-7-2	1.22	0.00	1.22
	2,3,8	2-3-8-3-2	1.48	0.00	1.48
Depot 6	6,4,5,3	6-4-5-4-5-4-3-4-6-4-6	2.61	0.00	2.61
	6,9,10,11,8				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20,25,26	17-21-25-26-25-21-20-21-17	1.74	0.00	1.74
Depot 19	19,15,12,11,13		2.98	0.01	2.99
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,18	19-18-19-18-19-18+19	0.60	0.06	0.66
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-22-23-22-23-22-23-22-19	1.71	0.00	1.71
		19-22-27-26-27-31-27-31-27-22-19	2.67	0.00	2.67
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24,25	29-24-25-24-29	2.17	0.00	2.17
Depot 36	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44	36-44-36	0.87	0.00	0.87
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37+38	1.31	0.17	1.49
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43	45-44-43-44-45	0.87	0.00	0.87

APPENDIX K. (continued)

Replace 6 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 9	9,8	9-8-9	0.56	0.00	0.56
	9,10	9-10-9	1.35	0.00	1.35
	9,11	9-11-9-11-9	1.89	0.00	1.89
	9,6,4,5	9-6-4-5-4-5-4-6-4-6-9-6-9	2.40	0.00	2.40
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20,25,26	17-21-25-26-25-21-20-21-17	1.74	0.00	1.74
Depot 19	19,15,12,11,13				
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,18	19-18-19-18-19-18+19	0.60	0.06	0.66
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-22-23-22-23-22-23-22-19	1.71	0.00	1.71
		19-22-27-26-27-31-27-31-27-22-19	2.67	0.00	2.67
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24,25	29-24-25-24-29	2.17	0.00	2.17
Depot 36	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44	36-44-36	0.87	0.00	0.87
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37+38	1.31	0.17	1.49
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43	45-44-43-44-45	0.87	0.00	0.87

APPENDIX K. (continued)

Replace 17 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-5-4-6-4-6	1.87	0.00	1.87
	6,9,10,11,8				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20,25,26	17-21-25-26-25-21-20-21-17	1.74	0.00	1.74
Depot 19	19,15,12,11,13				
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,18	19-18-19-18-19-18+19	0.60	0.06	0.66
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-22-23-22-23-22-23-22-19	1.71	0.00	1.71
		19-22-27-26-27-31-27-31-27-22-19	2.67	0.00	2.67
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24,25	29-24-25-24-29	2.17	0.00	2.17
Depot 36	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44	36-44-36	0.87	0.00	0.87
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37+38	1.31	0.17	1.49
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43	45-44-43-44-45	0.87	0.00	0.87

APPENDIX K. (continued)

Replace 19 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-5-4-6-4-6	1.87	0.00	1.87
	6,9,10,11,8				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20,25,26	17-21-25-26-25-21-20-21-17	1.74	0.00	1.74
Depot 19	19,15,12,11,13				
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,18	19-18-19-18-19-18+19	0.60	0.06	0.66
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-22-23-22-23-22-23-22-19	1.71	0.00	1.71
		19-22-27-26-27-31-27-31-27-22-19	2.67	0.00	2.67
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24,25	29-24-25-24-29	2.17	0.00	2.17
Depot 36	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44	36-44-36	0.87	0.00	0.87
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37+38	1.31	0.17	1.49
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43	45-44-43-44-45	0.87	0.00	0.87

APPENDIX K. (continued)

Replace 29 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-5-4-6-4-6	1.87	0.00	1.87
	6,9,10,11,8				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20,25,26	17-21-25-26-25-21-20-21-17	1.74	0.00	1.74
Depot 19	19,15,12,11,13				
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,18	19-18-19-18-19-18+19	0.60	0.06	0.66
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-22-23-22-23-22-23-22-19	1.71	0.00	1.71
		19-22-27-26-27-31-27-31-27-22-19	2.67	0.00	2.67
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24,25	29-24-25-24-29	2.17	0.00	2.17
Depot 36	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44	36-44-36	0.87	0.00	0.87
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37+38	1.31	0.17	1.49
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43	45-44-43-44-45	0.87	0.00	0.87

APPENDIX K. (continued)

Replace 36 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-5-4-5-4-6	1.87	0.00	1.87
	6,9,10,11,8				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20	17-21-20-21-17	0.66	0.00	0.66
Depot 19	19,15,12,11,13				
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,18	19-18-19-18-19-18+19	0.60	0.06	0.66
	19,22,18,27,23				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-23-22-23-22-23-22-19	0.70	0.00	0.70
		19-22-27-22-27-22-19	2.13	0.00	2.13
Depot 26	26,27,31	26-27-31-27-31-27-26	1.54	0.00	1.54
	26,30,36	26-30-36-30-26	1.72	0.00	1.72
	26,25,21,24	26-25-24-25-21-25-26	2.41	0.00	2.41
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24	29-24-29	0.83	0.00	0.83
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46,36				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37-36-37+38	2.26	0.17	2.44
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43,36,35				
		45-44-43-44+45	0.80	0.03	0.84
		45-44-36-35-36-44+45	1.93	0.03	1.97

APPENDIX K. (continued)

Replace 38 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-5-4-6-4-6	1.87	0.00	1.87
	6,9,10,11,8				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20,25,26	17-21-25-26-25-21-20-21-17	1.74	0.00	1.74
Depot 19	19,15,12,11,13				
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,18	19-18-19-18-19-18+19	0.60	0.06	0.66
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-22-23-22-23-22-23-22-19	1.71	0.00	1.71
		19-22-27-26-27-31-27-31-27-22-19	2.67	0.00	2.67
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24,25	29-24-25-24-29	2.17	0.00	2.17
Depot 36	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44	36-44-36	0.87	0.00	0.87
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37+38	1.31	0.17	1.49
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43	45-44-43-44-45	0.87	0.00	0.87

APPENDIX K. (continued)

Replace 42 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-5-4-5-4-6	1.87	0.00	1.87
	6,9,10,11,8				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20,25,26	17-21-25-26-25-21-20-21-17	1.74	0.00	1.74
Depot 19	19,15,12,11,13				
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,18	19-18-19-18-19-18+19	0.60	0.06	0.66
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-22-23-22-23-22-23-22-19	1.71	0.00	1.71
		19-22-27-26-27-31-27-31-27-22-19	2.67	0.00	2.67
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24,25	29-24-25-24-29	2.17	0.00	2.17
Depot 36	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44	36-44-36	0.87	0.00	0.87
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37+38	1.31	0.17	1.49
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 41	41,40	10-40-41	1.53	0.00	1.53
	41,34,33,35	41-34-33-34-35-34-41	2.66	0.00	2.66
	41,42,43,48	41-42-43-42-48-42-41	1.65	0.00	1.65
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43	45-44-43-44-45	0.87	0.00	0.87

Replace 45 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-5-4-5-4-6	1.87	0.00	1.87
	6,9,10,11,8				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20,25,26	17-21-25-26-25-21-20-21-17	1.74	0.00	1.74
Depot 19	19,15,12,11,13				
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,18	19-18-19-18-19-18+19	0.60	0.06	0.66
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-22-23-22-23-22-23-22-19	1.71	0.00	1.71
		19-22-27-26-27-31-27-31-27-22-19	2.67	0.00	2.67
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24,25	29-24-25-24-29	2.17	0.00	2.17
Depot 36	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44,45	36-44-45-44-36	1.00	0.00	1.00
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31				
		38-37-31-37-38	2.13	0.00	2.13
		38-37-31-37-38	2.13	0.00	2.13
	38,47	38-47-38	0.98	0.00	0.98
Depot 42	42,43,34	42-43-44-43-42	1.57	0.00	1.57
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46
Depot 46	46,37	46-37-46-37-46	1.93	0.00	1.93
	46,47,51	46-47-51-47-46	1.40	0.00	1.40
	46,50	46-50-46-50-46	1.08	0.00	1.08
	46,45,49	46-45-49-45-46	1.60	0.00	1.60

APPENDIX K. (continued)

Close 3 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 6	6,4,5,3,1,2,7				
		6-4-5-4-6	1.41	0.00	1.41
		6-4-3-2-1-2+3+4+6	1.84	0.42	2.26
		6-4-3-2-7-2+3+4+6	2.07	0.42	2.49
	6,9,8,10,11,3				
		6-9-10-9-6	1.61	0.00	1.61
		6-9-11-9+6	2.02	0.07	2.09
		6-9-8-3-8-9+6	1.69	0.07	1.75
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20,25,26	17-21-25-26-25-21-20-21-17	1.74	0.00	1.74
Depot 19	19,15,12,11,13				
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,18	19-18-19-18-19-18+19	0.60	0.06	0.66
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-22-23-22-23-22-23-22-19	1.71	0.00	1.71
		19-22-27-26-27-31-27-31-27-22-19	2.67	0.00	2.67
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24,25	29-24-25-24-29	2.17	0.00	2.17
Depot 36	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44	36-44-36	0.87	0.00	0.87
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37+38	1.31	0.17	1.49
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43	45-44-43-44-45	0.87	0.00	0.87

APPENDIX K. (continued)

Close 6 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,2,1,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
	3,8,9,10				
		3-8-9+8+3	0.78	0.39	1.16
		3-8-9-10-9+8+3	2.12	0.39	2.51
	3,4,5,6,9				
		3-4-5-4-5-4+3	1.33	0.19	1.52
		3-4-6-9-6-9-6-4-6-4+3	1.81	0.19	2.00
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20,25,26	17-21-25-26-25-21-20-21-17	1.74	0.00	1.74
Depot 19	19,15,12,11,13,9				
		19-15-12-13-12-13-12-13+12-15-19-15-19	0.33	0.01	0.35
		19-15-12-11-9-11-12+15+19	2.27	0.03	2.30
		19-15-12-11-9-11-12+15+19	2.27	0.03	2.30
	19,18	19-18-19-18-19-18+19	0.60	0.06	0.66
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-22-23-22-23-22-23-22-19	1.71	0.00	1.71
		19-22-27-26-27-31-27-31-27-22-19	2.67	0.00	2.67
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24,25	29-24-25-24-29	2.17	0.00	2.17
Depot 36	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44	36-44-36	0.87	0.00	0.87
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37+38	1.31	0.17	1.49
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43	45-44-43-44-45	0.87	0.00	0.87

APPENDIX K. (continued)

Close 17 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-6-4-5-4-6	1.87	0.00	1.87
	6,9,8,10,11,17				
		6-9-11-9-11-9+6	2.02	0.07	2.09
		6-9-10-9+6	1.48	0.07	1.55
		6-9-8+9+6	0.41	0.21	0.62
		6-9-8-17-89+6	2.64	0.21	2.85
Depot 19	19,15,12,11,13				
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,22,18,27,23,31				
		19-22-23-22-23-22-23-22-19	0.70	0.00	0.70
		19-22-27-31-27-31-27-22-27-22-19	2.67	0.00	2.67
		19-22-18-22-18-22-19	2.56	0.00	2.56
	19,18,17,16,14,21,20,25				
		19-18-17-21-25-21-20-21-17+18-19	2.00	0.20	2.20
		19-18-17-16-17+18-19	1.73	0.20	1.93
		19-18+17-16-14-16-17+18+19	2.51	0.46	2.97
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24,25	29-24-25-24-29	2.17	0.00	2.17
Depot 36	36,30,26,27,25				
		36-30-26-27-26+30+36	1.87	0.43	2.30
		36-30-26-25-26+30+36	1.24	0.43	1.67
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44	36-44-36	0.87	0.00	0.87
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37+38	1.31	0.17	1.49
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43	45-44-43-44-45	0.87	0.00	0.87

APPENDIX K. (continued)

Close 19 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-6-4-5-4-6	1.87	0.00	1.87
	6,9,8,10,11				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,8	17-8-17	2.23	0.00	2.23
	17,21,20,25,26,27				
		17-21-20-21+17	0.42	0.12	0.54
		17-21-26-26-27-26-25-21+17	2.33	0.12	2.45
	17,18,19,22,15,23,12,11,13				
		17-18-22-27-22-18+17	2.63	0.20	2.83
		17-18-22-27-22-18+17	2.63	0.20	2.83
		17+18-19-22-23-22-23-22-23-22-19-22-19-22-19-18+17	1.17	0.40	1.57
		17+18-19-15-12-11-12-13-12-13-12-13+12-15-19-18+17	1.76	0.41	2.18
		17+18-19-15-12-11-12-15-19-15-19+18+17	1.58	0.46	2.04
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24,25	29-24-25-24-29	2.17	0.00	2.17
Depot 36	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44	36-44-36	0.87	0.00	0.87
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46,27,47				
		38-37-31-27-31-37+38	2.05	0.17	2.23
		38-37-31-27-31-37+38	2.05	0.17	2.23
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-47-46-37+38	2.18	0.17	2.35
	38,47,51	38-47-51-47-38	1.51	0.00	1.51
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43	45-44-43-44-45	0.87	0.00	0.87

APPENDIX K. (continued)

Close 29 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-6-4-5-4-6	1.87	0.00	1.87
	6,9,8,10,11				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,21,20,25,24,26				
		17-21-20-21+17	0.42	0.12	0.54
		17-21-25-24-25-26-25-21+17	2.66	0.12	2.78
Depot 19	19,18	19-18-19-18-19+18	0.60	0.06	0.66
	19,15,12,11,13				
		19-15-12-13-12-13-12-13+12-15-12+15-19-15-19-15+19	0.40	0.05	0.45
		19-15-12-11-12-11-12+15+19	2.58	0.03	2.61
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-31-27-22-23-22-23-22-23-22-19	1.97	0.00	1.97
		19-22-27-31-27-26-27-22-19	2.40	0.00	2.40
Depot 36	36,30,26,29				
		36-30-29-30+36	1.22	0.25	1.47
		36-30-26-30+36	2.24	0.25	2.49
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44	36-44-36	0.87	0.00	0.87
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,47,46,51	38-47-51-47-46-47-38	2.38	0.00	2.38
	38,37,46,31				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37+38	1.31	0.17	1.49
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35,29,28,24				
		42-41-40-41+42	1.59	0.03	1.63
		42-41-34-33-34-35-34+41+42	2.47	0.16	2.63
		42+41-34-29-28-29+34+41+42	1.95	0.44	2.39
		42+41+34-29-24-29+34+41+42	1.32	0.57	1.89
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43	45-44-43-44-45	0.87	0.00	0.87

APPENDIX K. (continued)

Close 36 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-6-4-5-4-6	1.87	0.00	1.87
	6,9,8,10,11				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,21,20,25,26,30	17-21-20-21-25-26-30-26-25-21-17	2.45	0.00	2.45
Depot 19	19,18	19-18-19-18-19+18	0.60	0.06	0.66
	19,15,12,11,13				
		19-15-12-13-12-13-12-13+12-15-12+15-19-15-19-15+19	0.40	0.05	0.45
		19-15-12-11-12-11-12+15+19	2.58	0.03	2.61
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-31-27-22-23-22-23-22-23-22-19	1.97	0.00	1.97
		19-22-27-31-27-26-27-22-19	2.40	0.00	2.40
Depot 29	29,24,25	29-24-25-24-29	2.17	0.00	2.17
	29,28	29-28-29	1.20	0.00	1.20
	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,47,46,51	38-47-51-47-46-47-38	2.38	0.00	2.38
	38,37,46,31,36				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37-36-37+38	2.26	0.17	2.44
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-34-35-34+41-40-41+42	2.53	0.16	2.70
		42-41-34-33-34+41+42	1.79	0.16	1.95
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43,36,30,35				
		45-44-36-30-36+44+45	1.51	0.25	1.76
		45-44-36-35-36+44-43-44+45	2.23	0.25	2.48

APPENDIX K. (continued)

Close 38 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-6-4-5-4-6	1.87	0.00	1.87
	6,9,8,10,11				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,21,20,25,26	17-21-20-21-25-26-25-21-17	1.74	0.00	1.74
Depot 19	19,18	19-18-19-18-19+18	0.60	0.06	0.66
	19,15,12,11,13				
		19-15-12-13-12-13-12-13+12-15-12+15-19-15-19-15+19	0.40	0.05	0.45
		19-15-12-11-12-11-12+15+19	2.58	0.03	2.61
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-31-27-22-23-22-23-22-23-22-19	1.97	0.00	1.97
		19-22-27-31-27-26-27-22-19	2.40	0.00	2.40
Depot 29	29,24,25	29-24-25-24-29	2.17	0.00	2.17
	29,28	29-28-29	1.20	0.00	1.20
	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
Depot 36	36,35	36-35-36	1.00	0.00	1.00
	36,44	36-44-36	0.87	0.00	0.87
	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,37,31,38,46,32,39,47				
		36-37-31-37+36	1.91	0.24	2.15
		36-37-31-37+36	1.91	0.24	2.15
		36+37-46-37+36	0.97	0.47	1.44
		36+37-46-37+36	0.97	0.47	1.44
		36+37-38-32-38-39-38-37+36	1.39	0.47	1.86
		36+37-38-47-38-37+36	1.68	0.47	2.15
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-34-35-34+41-40-41+42	2.53	0.16	2.70
		42-41-34-33-34+41+42	1.79	0.16	1.95
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50,47,51				
		45-46-47-51-47-46+45	1.89	0.25	2.14
		45-46-50-46-50-46+45	1.57	0.25	1.82
	45,44,43	45-44-43-44-45	0.87	0.00	0.87

APPENDIX K. (continued)

Close 42 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-6-4-5-4-6	1.87	0.00	1.87
	6,9,8,10,11				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,21,20,25,26	17-21-20-21-25-26-25-21-17	1.74	0.00	1.74
Depot 19	19,18	19-18-19-18-19+18	0.60	0.06	0.66
	19,15,12,11,13				
		19-15-12-13-12-13-12-13+12-15-12+15-19-15-19-15+19	0.40	0.05	0.45
		19-15-12-11-12-11-12+15+19	2.58	0.03	2.61
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-31-27-22-23-22-23-22-23-22-19	1.97	0.00	1.97
		19-22-27-31-27-26-27-22-19	2.40	0.00	2.40
Depot 29	29,24,25	29-24-25-24-29	2.17	0.00	2.17
	29,28	29-28-29	1.20	0.00	1.20
	29,30	29-30-29	1.73	0.00	1.73
	29,33,34,41,40,42,48				
		29-34-33-34+29	1.95	0.24	2.20
		29-34-41-40-41+34+29	2.28	0.62	2.90
		29+34-41-42-48-42-41+34+29	1.08	0.62	1.70
Depot 36	36,37	36-37-36	0.95	0.00	0.95
	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,35,34	36-35-34-35-36	1.68	0.00	1.68
	36,44	36-44-36	0.87	0.00	0.87
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,46,31				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37+38	1.31	0.17	1.49
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-50-46-45	2.07	0.00	2.07
	45,44,43,42	45-44-43-42-43-44-45	1.70	0.00	1.70

APPENDIX K. (continued)

Close 45 Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-6-4-5-4-6	1.87	0.00	1.87
	6,9,8,10,11				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20,25,26	17-21-25-26-25-21-20-21-17	1.74	0.00	1.74
Depot 19	19,15,12,11,13				
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,18	19-18-19-18-19-18+19	0.60	0.06	0.66
	19,22,18,27,23,26,31				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-22-23-22-23-22-23-22-19	1.71	0.00	1.71
		19-22-27-26-27-31-27-31-27-22-19	2.67	0.00	2.67
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24,25	29-24-25-24-29	2.17	0.00	2.17
Depot 36	36,30,26	36-30-26-30-36	1.72	0.00	1.72
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44,45,49,46	36-44-45-49-45-46-45-44-36	2.61	0.00	2.61
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46,50				
		38-37-31-37+38	1.96	0.17	2.13
		38-37-31-37+38	1.96	0.17	2.13
		38-37-46-37-46+37+38	1.80	0.42	2.21
		38-37-46-50-46-50-46+37+38	1.56	0.42	1.98
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 42	42,43,44	42-43-44-43-42	1.57	0.00	1.57
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46

APPENDIX K. (continued)

Additional Depot Scenario	Branch List	Route	Service Time (hrs)	Deadhead Time (hrs)	Total Time (hrs)
Depot 3	3,4	3-4-3	0.74	0.00	0.74
	3,8	3-8-3	1.00	0.00	1.00
	3,1,2,7				
		3-2-1-2+3	0.99	0.25	1.24
		3-2-7-2+3	1.72	0.24	1.97
Depot 6	6,4,5	6-4-5-4-5-4-6-4-6	1.87	0.00	1.87
	6,9,10,11,8				
		6-9-11-9-11-9-6	2.16	0.00	2.16
		6-9-10-9-8-9-6	2.17	0.00	2.17
Depot 17	17,8	17-8-17	2.23	0.00	2.23
	17,18	17-18-17	0.80	0.00	0.80
	17,16,14				
		17-16-17-16+17	1.64	0.27	1.91
		17-16-14-16+17	1.85	0.27	2.12
	17,21,20	17-21-20-21-17	0.66	0.00	0.66
Depot 19	19,15,12,11,13				
		19-15-12-11-12-15-19-15-19	1.46	0.00	1.46
		19-15-12-11-12-13-12-13-12-13+12-15-19	1.52	0.01	1.54
	19,18	19-18-19-18-19-18+19	0.60	0.06	0.66
	19,22,18,27,23				
		19-22-18-22-18-22-19	2.56	0.00	2.56
		19-22-27-22-23-22-23-22-23-22-19	1.71	0.00	1.71
		19-22-27-22-19	1.13	0.00	1.13
Depot 26	26,27,31	26-27-31-27-31-27-26	1.54	0.00	1.54
	26,30	26-30-26	0.71	0.00	0.71
	26,25,24,21	26-25-24-25-21-25-26	2.41	0.00	2.41
Depot 29	29,30	29-30-29	1.73	0.00	1.73
	29,34	29-34-29	0.98	0.00	0.98
	29,28	29-28-29	1.20	0.00	1.20
	29,24	29-24-29	0.83	0.00	0.83
Depot 36	36,30	36-30-36	1.01	0.00	1.01
	36,37	36-37-36	0.95	0.00	0.95
	36,35	36-35-36	1.00	0.00	1.00
	36,44	36-44-36	0.87	0.00	0.87
Depot 38	38,39	38-39-38	0.11	0.00	0.11
	38,32	38-32-38-32-38-32-38	0.59	0.00	0.59
	38,37,31,46				
		38-37-31-37+38	1.78	0.17	1.96
		38-37-31-37+38	1.78	0.17	1.96
		38-37-46-37+38	1.31	0.17	1.49
		38-37-46-37+38	1.31	0.17	1.49
	38,47,51,46	38-47-51-47-46-47-38	2.38	0.00	2.38
Depot 42	42,43	42-43-42	0.83	0.00	0.83
	42,48	42-48-42	0.69	0.00	0.69
	42,41,40,34,33,35				
		42-41-40-41-34-35+34+41+42	2.19	0.33	2.53
		42-41-34-33-34-35+34+41+42	2.13	0.33	2.46
Depot 45	45,49	45-49-45	0.61	0.00	0.61
	45,46,50	45-46-50-46-45	2.07	0.00	2.07
	45,44,43	45-44-43-44-45	0.87	0.00	0.87