ON MODELING THE SINGLE PERIOD SPARE PARTS DISTRIBUTION SYSTEM DESIGN PROBLEM BY MIXED INTEGER LINEAR OPTIMIZATION

by

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Submitted to the Graduate School of
Engineering and Natural Sciences
in partial fulfillment of the requirements for the degree of
Master of Science

Sabancı University,
July, 2019

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DATE OF APPROVAL: 19.07.2019

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitudes to Tübitak for giving me the opportunity of involving in the project 117M588.

I am heartily thankful to my supervisors Assoc. Prof. Dr. Güvenç Şahin and Asst. Prof. Dr. Tevhide Altekin for their patience, motivation, guidance and encouragement. I owe my deepest gratitudes to them, for not only inspring me every single day but also believing in me more than myself. Besides my supervisors, I would like to express my special appreciation to Assoc. Prof. Dr. Abdullah Daşçı and Asst. Prof. Dr. Ajinkya Tanksale for their expert advices and assistances.

Without my family, I would not be able to complete this thesis. Hence, I would like to thank my grandfather Salih Ercan and my grandmother Nafize Ercan for their endless support. Also, I am grateful to my father İskender Ercan and my mother Hale Özeren for always encouraging me throughout my thesis.

Last but not least, I would like to thank to my friends Lütfi Yiğit Erol, İmge Şipkan and Irmak Aktuğ for supporting me, believing in me and being there for me whenever I needed.

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Industrial Engineering, Master's Thesis, 2019

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Keywords: Distribution network, location-transportation problem, facility location, route generation, spare parts supply chain, post sale services

Abstract

Efficiency and effectiveness of spare parts logistics play a significant role in changing customers' service levels. A company providing high quality after-sales support to their customers gains competitive advantages. To study a single period multi commodity spare parts distribution system design problem, we present a mathematical model in the form of a mixed integer linear programming problem formulation. The mathematical model incorporates facility location decisions and vehicle size selection as well as routing decisions. The problem formulation minimizes the total cost including opening and operating costs of the depots and transportation costs for the vehicles. In order to define and solve a realistic spare parts distribution system design problem, we use aggregation on the commodity flow data to reduce the size of the problem and generate the outbound distribution routes from the regional depots to the service points apriori to simplify the mathematical model. The main focus of this study is the apriori route generation; we aim to observe the impact of different route sets obtained by different heuristic methods. The solution quality and the computation time to solve the problems to optimality are used to compare the performance of the three routing heuristics.

TEK DÖNEMLİ YEDEK PARÇA DAĞITIM SİSTEMİ TASARIM PROBLEMİNİN KARIŞIK TAM SAYILI DOĞRUSAL OPTİMİZASYON İLE MODELLENMESİ ÜZERİNE

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Endüstri Mühendisliği, Yüksek Lisans Tezi, 2019

Tez Danışmanı: Doç. Dr. Güvenç Şahin

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Anahtar Kelimeler: Ağ tasarımı, yer-seçimi ulaştırma problemi, tesis yer seçimi, rota oluşturma, yedek parça tedarik zinciri, satış sonrası hizmetleri

Özet

Yedek parça lojistik sistemlerinin etkinliği ve verimliliği müşterilerin hizmet düzeylerinin değiştirilmesinde önemli bir rol oynar. Yüksek kaliteli bir satış sonrası servisi vermesi firmaya rekabet üstünlüğü sağlar. Tek dönemli çok parçalı yedek parça dağıtım sistemi tasarım problemini çalışmak için, tesis yer seçimi ve araç büyüklüğü ile birlikte rotalama kararları da içeren tek amaç fonksiyonlu karmaşık tam sayılı doğrusal programlama problem gösterimi, depoların kurulum ve işletme maliyetleri ve araçların taşıma maliyetlerini içeren toplam maliyetini en küçükler. Gerçekçi bir yedek parça dağıtım sistemi probleminin tanımlanmasının ve çözülmesinin mümkün olması için, problemi küçültmek amacıyla ürün akış verisinde toplulaştırma ve matematiksel modelin kolaylaştırılması amacıyla servis noktalarına dağıtım rotalarının önceden yaratılması yoluna gidilmiştir. Çalışmamızın ana odağı rotaların önceden yaratılmasıdır. Farklı rotalama sezgiselleriyle yaratılan rota kümelerinin etkilerini gözlemlemeyi hedeflemekteyiz. Üç farklı rotalama sezgiselinin performansları, çözüm kalitesi ve optimal çözüm elde etmek için gerekli hesaplama zamanına bakılarak karşılaştırılacaktır.

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1. Introduction

After-sales service refers to the processes that are undertaken by the company for the care of the customers after they purchase a good or a service. In most manufacturing companies, after-sales service has a critical role since it increases profitability, customer satisfaction and customer retention potential (Saccani *et al.* 2007; Alexander *et al.* 2002). The profit margins for initial sales of a company is approximately 10%, whereas for after-sales services it is three times larger (Murthy *et al.* 2004). In some of the industries such as automobiles, white goods and information technology, the after-sales service market sizes are up to five times larger than the equipment businesses (Bundschuh and Dezvane 2003; Cohen 2006). Therefore, the companies that provide high quality after-sales support to their customers can gain also competitive advantage in the market (Cohen 2006).

We investigate a spare parts distribution system design problem which is inspired from the case of a white household goods manufacturer in Turkey. The household appliances company engages in the production as well as the marketing of the durable goods, components and multiple product parts. We consider an after-sales services supply chain that consists of a distribution center, regional depots and service points representing authorized repair vendors. The inbound transportation of the spare parts from the distribution center to the regional depot can be done using different vehicles. Similarly, the outbound transportation from regional depots to the service points can be done utilizing different vehicles and routes. Our aim is to determine intermediate regional depot locations and assign service points to the regional depots while considering other real life aspects such as routing decisions and selecting vehicle sizes. While minimizing the total cost of the network, both strategic (regional depot location determination) and tactical (route and vehicle size selection) level decisions are included. Therefore, this spare parts distribution system design problem can be associated with location-routing and location-transportation problems.

In order to design the after-sales spare parts distribution system, a static single period multi-commodity system design problem is defined and a mixed integer linear mathematical model is developed. The mathematical programming formulation's objective function is based on minimizing the total cost and includes the opening and operating costs of the regional depots and both inbound and outbound transportation costs. The proposed mathematical formulation is solved using a commercial solver for instances of four different problem sizes. However, route optimization is beyond the scope of our study. Alternative routes are generated using the savings algorithm, nearest neighbor algorithm and expanded neighbor search algorithm in order to analyze the impact of given route sets. Our contributions can be summarized as follows:

- We define a realistic new spare parts distribution system design problem that incorporates route and vehicle size selection decisions. Hence, staircase cost structures are used to represent different vehicle sizes for inbound and outbound transportations.
- We develop the mathematical model for the spare parts distribution system design problem.
- Three different heuristics are used to provide different route sets as input. Based on the analysis of the given routes of the white household goods manufacturer in Turkey, we adopt two algorithms from the literature and propose an extension.
- Similarly, the determination of the number of spare parts to include in our multi-commodity problem is based on aggregating more than 40,000 spare parts of the same manufacturer.
- We demonstrate the impact of the given route sets on the solution quality and computation time.

The remainder of this thesis is organized as follows: Chapter 2 consists of a literature review, problem definition and the proposed mathematical model. Demand aggregation strategies and route generation heuristics are given in Chapter 3. In Chapter 4, we present the computational results. Finally, we conclude with the main findings in Chapter 5.

2. Spare Parts Distribution System Design

In this chapter, we first summarize the literature of after-sales logistics systems. Then, we continue with comparing our study with the most similar studies. We also present our problem definition and underline the distinguishing features of our study, which involve the inclusion of vehicle size (type) selection and route selection. Finally, we present our mixed integer linear programming model.

2.1. Literature Review

After-sales logistics systems provide spare parts, maintenance and repair services to their customers (Cohen *et al.* 1997). Typically, the profit margin for initial sale products is approximately 10% in contrast to 30% on the post-sale service products (Murthy *et al.* 2004). For a typical manufacturing company, after-sales services and parts can contribute up to 50% of all profits (Dennis and Kambil 2003). After-sales activities are one of the most important types of sources of income, which provide a competitive advantage to the producers (Saccani *et al*. 2007; Cohen *et al*. 2006).

Hertz *et al.* (2012) suggest that planning problems of the traditional supply chains have been investigated for decades but they are newly investigated for the after-sales networks. In the literature, spare part distribution systems are claimed to differ from the production distribution systems due to various factors such as large number of parts, high prices, short lead times, uncertainty in demand, multiple classes of services and the requirement to meet service requests in a timely manner (Cohen *et al.* 1999; Cohen *et al.* 2006; Huiskonen 2001). Our system is considered as a spare part distribution system rather than a production-distribution system due to the various differentiations such as large number of spare parts, unpredictable demands, heterogeneous product portfolio, quick response needs of services.

The variety of the operational control characteristics of the spare parts have a huge impact on network structure, positioning of materials, responsibility of control and control principles. Operational control characteristics such as criticality, specificity, value of parts and demand pattern are evaluated due to their impact on the plan and the design of the network logistics system (Huiskonen 2001). Due to the difference between the operational control characteristics, spare part distribution systems are prominently different than the traditional production distribution networks.

Hu *et al.* (2018) provide a review of operational research models used in spare parts management. However, their analysis on optimization techniques used has excluded the studies on the design of distribution networks for spare parts. The literature on distribution network design for spare part supply chains is somehow very limited.

Murthy *et al.* (2004) summarize product warranty logistics literature. Bacchetti and Saccani (2012) investigate theoretical contributions about spare parts classification and demand forecasting for stock control. Cohen *et al*. (1997) present a comparison analysis between high value products and technologically complicated products. The literature of supply chain spare part distribution design also involves empirical studies which are from different industries. For instance, Saccani *et al*. (2006) examine household appliances, information technologies, consumer electronics and automotive industries, whereas Saccani *et al.* (2007) investigate durable consumer goods industry. In addition to the industry based studies, there are also studies on the improvement of after-sales services of particular production companies such as:

- IBM (Cohen *et al.* 1990; Jalil *et al.* 2011)
- Teradyne (Cohen *et al*. 1999)
- Saturn (Cohen *et al*. 2000)
- Heavy duty equipment producer (Persson and Saccani, 2009)
- Digital cinema projector producer (Landrieux and Vandaele, 2012)
- High valued fixed asset producer (Driessen *et al*. 2015)
- Household appliances manufacturer (Altekin *et al.* 2017)

Among the literature that involves the design of the after-sales logistics networks, in order to determine the locations of the facilities and determine the flow among those facilities, quantitative methods are proposed by Persson and Saccani (2009), Wu *et al.* (2011), Jalil *et al.* (2011) and Landrieux and Vandaele (2012). Persson and Saccani (2009) analyze the allocation of parts and suppliers for a second European warehouse through a simulation model. This study focuses on evaluating possible choices of spare part inventory locations, as well as analyzing the classification criteria of the spare parts that determine the inventory policy to be used. The study of Wu *et al.* (2011) involves decisions such as logistic network design, service point selection and transportation mode selection in order to solve a comprehensive design problem. Jalil *et al.* (2011) evaluate the potential economic value of spare parts logistics through an installed based real-life case. Also, the data errors of their installed base case are identified and the effects of these errors on the performance of spare parts planning are determined. Landrieux and Vandaele (2012) develop a model for the distribution of the spare parts. Under four different scenarios, solutions of the spare parts inventory management and facility location problem are evaluated based on the total cost and facility assignment of the customers.

Altekin *et al.* (2017) have formulated the multi-level, multi-commodity spare parts distribution network of a household appliances manufacturer in Turkey. The large-scale problem consisting of more than 40,000 spare parts and nearly 700 facility locations has been transformed into a realistic smaller scale problem. The proposed mixed integer programming model minimizes the total cost of the network, determines the locations of the facilities, assigns the service points to the selected facilities and selects transportation modes. For eight scenarios representing different network configurations, optimal solutions obtained using a commercial solver are evaluated.

Our study is inspired by the spare parts distribution system design problem in Altekin *et al.* (2017). Two of their scenarios included 73 routes given by the company for the outbound shipments of the spare parts from regional depots to service points. Hence, we include the selection of route decisions for outbound shipments. We also incorporate vehicle size selection decisions for both the inbound and outbound transportations using a staircase cost structure. Stochastic multi-period location-transportation problem in Klibi *et al.* (2010) also consists of determining vehicle sizes and routes to be used from given alternative routes in addition to facility location decisions. Their objective function is maximizing profit and they exclude inbound transportations.

We develop a mathematical model that will be solved by a commercial solver. The main decisions include the number and location of regional depots, number and size of inbound and outbound vehicles, selection of routes and transportation quantities. Our objective includes understanding the effect of the given routes on the solution time and quality.

Weak lower bounds may rise because of the staircase cost structures (Croxton *et al*. 2003a) which also lead to create weak formulations in some of the transportation problems (Croxton *et al.* 2003b; Harks *et al.* 2014). Staircase cost structures arise and cause computational challenges not only in transportation problems but also in location and capacity problems

(Holmberg 1994; Holmberg and Ling 1997; Correia and Captivo 2003; Correia and Captivo 2006; Correie *et al.* 2010), design problems (Mahey *et al.* 2001; Christensen 2013), and supplier selection problems (Andrade-Pineda *et al.* 2017).

The differences between our study and most similar studies are given in Table 2.1. Our objective is to provide a realistic spare parts distribution system design problem definition, to formulate it as a mixed integer linear programming model, to solve it using a commercial solver and to demonstrate the impact of the given routes on solution time and quality.

Table 2.1 The differences between our study and most similar studies

	Persson & Saccani (2009)	Wu *et al.* (2011)	Jalil *et al.* (2011)	Landrieux & Vandaele (2012)	Altekin *et al.* (2017)	Klibi *et al.* (2010)	**Our Study**
Problem*	ASND	ASND	ASND	ASND	ASND	PDND	**ASND**
Number of Periods	Single	Single	Single	Single	Single	Multi	**Single**
Objective Function+	MTC	MTC	MTC	MTC	MTC	MTP	**MTC**
Multi Commodity	X			X	X		**X**
Installed Base Products			X	X			
Imposed Time Limit			X	X			
Transportation Cost	Linear	Constant	Linear	Linear	Linear	Staircase	Staircase
Inbound Logistics Costs	X	X		X	X		**X**
Outbound Logistics Costs	X	X	X	X	X	X	**X**
Facility Decisions				X	X	X	**X**
Flow (Allocation) Decisions	X		X	X	X	X	**X**
Transportation Mode Decision	X	X		X	X		
Inventory Decisions		X	X	X			
Staffing Decisions		X					
Station Opening & Assignment		X					
Vehicle Decisions						X	**X**
Routing Decisions						X	**X**
Different Service Levels							**X**
Impact of Seasonality							
Impact of Uncertainty						X	
Scenario Basis±	NS		BS-EA	TL	ATL-TL		
Number of Scenarios	4		8	4	8		
Solution Method#	S	M	HIS	CS	CS	HH	**CS**

* ASND: After-Sales Network Design; PDND: Production Distribution Network Design.
+ MTC: Minimize Total Cost; MTP: Maximize Total Profit.
± NS: Number of suppliers served by new warehouse; BS-EA: Installed base size and error accuracy; TL: Time Limit; ATL: Allowed transportation links.
S: Simulation; M: Metaheuristics; IHS: In-house solver; CS: Commercial solver; HH: Hierarchical heuristics (tabu search, determination of approximate route distance and modified Clarke and Wright (1964) procedure)

2.2. Problem Definition and Mathematical Model

2.2.1. Problem Definition

This study is motivated by the purpose of introducing a new spare parts distribution system design problem through the inclusion of route selection for outbound shipments and vehicle size selection for both inbound to and outbound transportations from the regional depots. After-sales service systems provide an interface between the firms and customers in order to respond to customers' maintenance and repair requests. Through its regional depots and distribution systems, after-sales service systems are responsible of transporting of a high variety of parts that are procured from various suppliers to a high variety of service points. Although there is a variety of decisions involved in establishing and operating such systems, we focus on finding the locations of the regional depots from which the parts are sent to the service points. This higher level decision profoundly affect impact on the performance/effectiveness of the system. As well as specifying the location of the regional depots, we also consider other operational issues such as spare part flows, and selection of routes as well as sizes of vehicles for both inbound and outbound transportations.

We are inspired by the spare parts distribution system of a household appliance manufacturer in Turkey, which was studied previously in Aylı (2015). Although it is known that the responsiveness to the customers has an immense importance in terms of the competition in the market, in Altekin *et al.* (2017), it is noted that the spare parts service systems in Turkey are managed in a cost-oriented manner. The reviewed literature on spare parts distribution system design demonstrates the available content is limited. Therefore, in both practice and academia, more realistic approaches are necessary in order to design more effective and efficient spare parts distribution systems. Next, we will present the details on two features that differentiate our study from the available studies and enable the design of efficient and effective spare parts distribution systems.

Route Selection Decisions

The first extension on Altekin *et al.* (2017), is the inclusion of alternative approaches of route formation where a route is defined as a set of service points to be visited by the vehicle. Even though route optimization is beyond the scope of this study, alternative routes will be constructed for the given service points. In Altekin *et al.* (2017), 73 given routes are used to cover all of the 531 service points. The routes given by the company and used in Altekin *et al.* (2017) are examined and the following observations are made:

- All of the 531 service points are covered by a single regional depot (i.e. single-sourcing is enforced).
- Every service point is assigned exactly to one route.
- It is not certain if the company includes the vehicle size constraint while constructing the 73 routes.
- We think factors such as maximum driving speed, daily limit on driving hours, service time associated with unloading and delivering the spare parts have been used in addition to classifications based on congestion of the locations of the service points.

Altekin *et al.* (2017) have solved the problem with a more limited approach, where delivery routes are pre-specified. In our study, in order to observe the effect of the given alternative routes on the results of the mathematical model, alternative routes will be generated by three different algorithms.

Alternative Vehicle Types

We extend the work and the contribution in Aylı (2015) and Altekin *et al.* (2017) by also including the selection of vehicle sizes. The vehicle size dimension consists of three options: small, medium and large. As the volume of the vehicle increases, the fixed cost of using that truck also increases. The motivation behind this extension is the opportunity of creating a possible decrease on the total cost.

The solution to a spare part system design problem should satisfy the demands of the service points from the distribution center through regional depots. There are some assumptions that define the structure of the spare part distribution system design problem such as the following:

- There is only one distribution center in the system.
- There is no restriction on the number of opened and operated regional depots and the corresponding costs of opening and operating those regional depots are given.
- There is no restriction on the capacity of regional depots.
- The locations of the service points, regional depots and distribution center are given.
- The demands of the service points for different parts are known.
- The transportation costs are defined with an increasing staircase cost function.
- The transportation from the regional depots to the service points will be through the given routes.
- A service point can be assigned to more than one route. Thus, a service point can also be covered by more than one regional depot.
- The given routes are generated for each regional depot. Hence, the same route might be independently generated for more than one regional depot.
- Determining the inventory levels of the spare parts of the distribution center and the regional depots are beyond the scope of this study.

Figure 2.1. demonstrates the proposed spare parts distribution system. The main aim of the spare part distribution system design problem is to minimize the total cost while the main decisions are summarized as follows:

- the number and location of the regional depots to open,
- the amount of spare parts transported from distribution center to the regional depots,
- the route and the amount of spare parts to be transported from the regional depots to the service points,
- the size of the vehicles to be used for inbound transportation,
- the size of the vehicles to be used for outbound transportation.

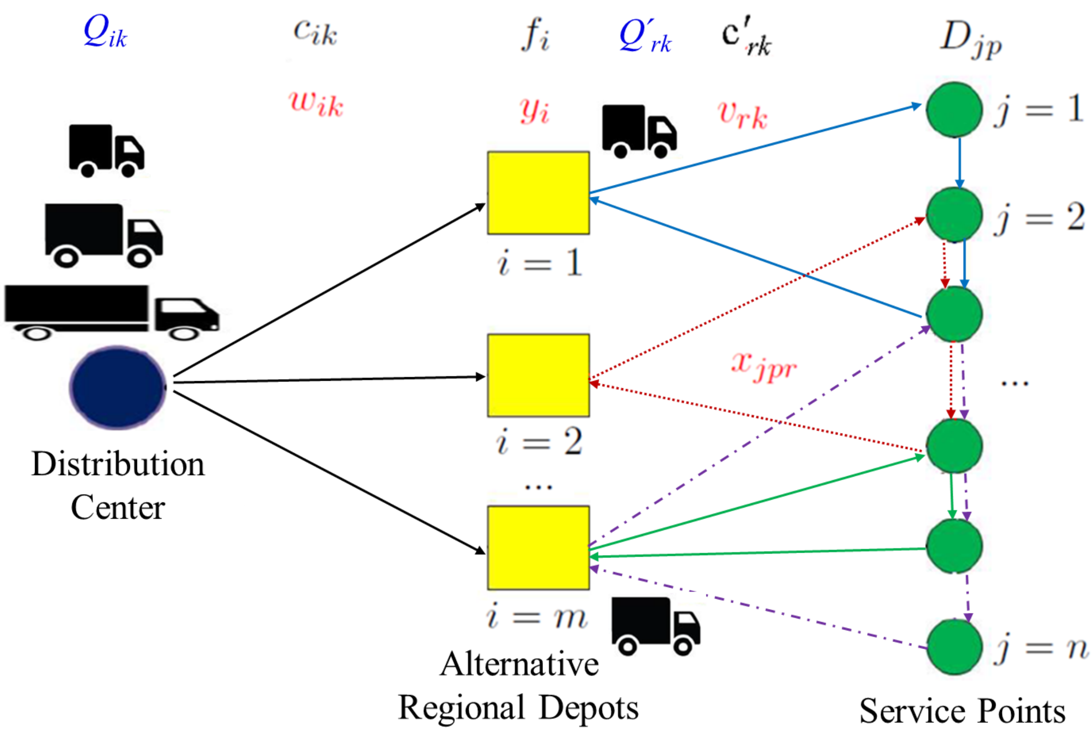

Figure 2.1 Proposed spare parts distribution system

2.2.2. Mathematical Model

In order to depict the mathematical model developed for the spare part distribution system design problem, we first present the sets, the parameters and the decision variables.

Sets:

I:	alternative regional depots
J:	service points
P:	part families
R:	all routes from potential regional depot locations to service points
R_i:	set of routes that are assigned to regional depot *i*
R_j:	set of routes that contain service point *j*
J_r:	service points covered in route *r*
$k \in K_r$:	volume breaks $(0 < Q_{r1} < Q_{r2} < \dots)$ for outbound transportation cost function for route *r*
$k \in K_i'$:	volume breaks $(0 < Q'_{i1} < Q'_{i2} < \dots)$ for inbound transportation cost function from distribution center to regional depot *i*

Parameters:

D_{jp}: demand of service point j for part p (in terms of volume)

f_i: fixed cost of opening a regional depot at location i

c_{rk}: outbound transportation cost for volumes less than or equal to Q_{rk} on route r

c'_{ik}: inbound transportation cost for volumes less than or equal to Q'_{ik} from distribution center to the regional depot i

Decision variables:

x_{jpr}: Amount (volume) of part p delivered to service point j through route r

$$y_i: \begin{cases} 1, \text{ if a regional depot is opened at location } i \\ 0, \text{ otherwise} \end{cases}$$

$$v_{rk}: \begin{cases} 1, \text{ if transportation option } k \text{ is utilized on route } r \\ 0, \text{ otherwise} \end{cases}$$

$$w_{ik}: \begin{cases} 1, \text{ if transportation option } k \text{ is utilized from distribution center to regional depot } i \\ 0, \text{ otherwise} \end{cases}$$

Accordingly, the mathematical model can be presented as follows:

$$\text{Minimize} \quad \sum_{i\in I} f_i\, y_i + \sum_{r\in R}\sum_{k\in K_r} c_{rk}\, v_{rk} + \sum_{i\in I}\sum_{k\in K'_i} c'_{ik}\, w_{ik} \tag{1}$$

$$\text{subject to} \quad \sum_{r\in R_j} x_{jpr} = D_{jp}\,, \forall\, (j,p) \in (J,P), \tag{2}$$

$$\sum_{j\in J_r}\sum_{p\in P} x_{jpr} \le \sum_{k\in K_r} Q_{rk}\, v_{rk}\,, \forall\ r \in R, \tag{3}$$

$$\sum_{r\in R_i}\sum_{j\in J_r}\sum_{p\in P} x_{jpr} \le \sum_{k\in K'_i} Q'_{ik}\, w_{ik}\,, \forall\ i \in I, \tag{4}$$

$$\sum_{k\in K_r} v_{rk} \le y_i\,, \forall\, (i,r) \in (I,R_i), \tag{5}$$

$$\sum_{k\in K'_i} w_{ik} \le y_i\,, \forall\ i \in I\,, \tag{6}$$

$$x_{jpr} \ge 0\,, \forall\ (j,p,r) \in \left(J,P,R_j\right), \tag{7}$$

$$y_i \in \{0,1\}\ \forall\ i \in I, \tag{8}$$

$$v_{rk} \in \{0,1\} \;\forall\; (r,k) \in (R, K_r), \tag{9}$$

$$w_{ik} \in \{0,1\} \;\forall\; (i,k) \in (I, K_i). \tag{10}$$

The objective function (1) minimizes the total cost of the network and consists of fixed opening and operating costs of the regional depots, inbound transportation costs from DC to regional depots as well as outbound transportation costs from regional depots to the service points. Constraint (2) ensures that the demand of each service point is satisfied for all part families. Constraints (3) and (4) are the outbound and inbound flow capacity constraints that warrant the transportation capacities for the deliveries depending on the selected vehicle size. The outbound flow capacity constraint includes the delivery from the regional depots to the service points where the inbound capacity constraint includes the delivery from the DC to the regional depots. Constraints (5) and (6) are the outbound and inbound truck selection constraints ensuring that only open regional depots are used for the possible deliveries and also that one volume break is used during these deliveries representing the vehicle size selection decision. Finally, constraints (7), (8), (9) and (10) are the domain constraints for the decision variables.

The provided mathematical model is also strengthened with the addition of the following three valid inequalities.

$$\sum_{r \in R_j} \sum_{k \in K_r} v_{rk} \geq 1, \forall j \in J^+ = \left\{j \in J : D_{jp} > 0, \exists p \in P\right\}, \tag{11}$$

$$\sum_{r \in R_i} \sum_{k \in K_r} v_{rk} \geq \; y_i \,, \forall\, i \in I, \tag{12}$$

$$\sum_{k \in K_i'} w_{ik} \geq \; y_i \,, \forall \; i \in I. \tag{13}$$

Valid inequality (11) ensures that a service point with any positive demand for the spare parts, will visited. If depot *i* is opened, valid inequalities (12) and (13) ensure the usage of inbound and outbound vehicles.

A solution to this static problem yields a set of opened regional depots, number and sizes of inbound vehicles to the regional depots from the distribution center, a set of selected routes, sizes of vehicles used on the selected routes for the outbound vehicles to the service points and quantities of the transported spare parts. Figure 2 demonstrates a simple solution with two regional depots and two routes assigned to each. A service point can be assigned to more than one depot. Moreover, a service point can be served using two different routes. Thus, it can be underlined that our model provides flexibility by not enforcing single sourcing which was the case in Altekin *et al*. (2017).

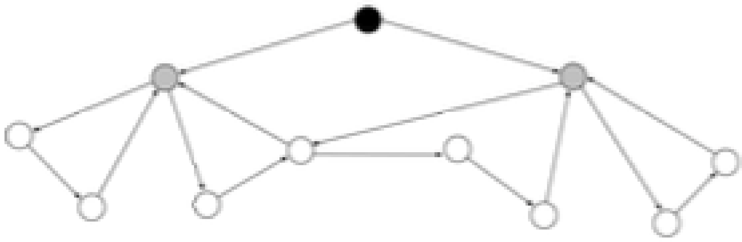

Figure 2.2 Demonstration of two regional depots and two routes assigned to each

3. Part Aggregation and Route Generation

In this chapter, alternative aggregation strategies are implemented on the past data regarding the commodity flows in the system obtained from the household appliances manufacturer in Altekin *et al.* (2017) in order to decrease the number of part families to be included so as to reduce the problem size with respect to type of commodities. After determining the number of part families, we focus on the route generation and provide both a brief review of the relevant literature and the details of the three heuristics used.

3.1. Part Aggregation

In large-scale distribution system design problems, an important issue is associated with the aggregation of commodity flow data as this process has direct impact on the problem size due to the number of parts included in the problem. Altekin *et al*. (2017)'s multi-level facility location problem for spare parts distribution system design studied an aggregation based on the suppliers. First, each supplier was assumed to provide one aggregated spare part with a demand equal to total demand (in volume) of all parts from the same supplier. Then, 93 supplier-based items were reduced to 16 using Pareto analysis. In our study, one of the main purposes is to develop alternative aggregation approaches to those in Altekin *et al.* (2017) in which more than 40,000 individual spare parts exist.

In the multi-level facility location problem representing our spare parts distribution system we have studied alternative aggregation strategies in order to determine the number of parts to be included. Among 1,801 spare parts, 94 parts have incomplete information. Hence, the aggregation strategies are applied to the remaining 1,707 spare parts whose volume and demand information are available and those that have demand greater than 1,000 units. Accordingly, the following three aggregation strategies are proposed:

- Supplier based strategies
- Part based strategies
- Code based strategies

3.1.1. Supplier Based Aggregation

We present two different supplier-based aggregation strategies. In the first one, each supplier is treated as an individual part family. Since there are 49 suppliers of those 1,707 parts, we have 49 different part families. Hence, for each part family, the parts are provided by the same supplier. Then, the number of parts supplied by these 49 suppliers are determined. If the number of parts that are supplied by the same supplier is less than ten, such suppliers are merged under one fictive supplier. With this approach, 16 part families are obtained.

In the second one, the suppliers that provide more than ten parts are investigated individually. For each supplier, the volumetric demand of all the parts they provide are sorted in an increasing order. Then a Pareto-based analysis is used to construct part families. Hence, instead of taking each supplier as a single part family, this strategy facilitates inclusion of multiple part families from big suppliers. For all of the suppliers that supply less than ten parts, the fictive supplier is assumed to provide a single part**.**

3.1.2. Part Based Aggregation

The corresponding volumetric demand information of every single part (independent from their supplier) are identified and sorted. Again, Pareto-based analysis is used to construct the part families. The same approach can be implemented by either using only the volume or only demand data.

3.1.3. Code Based Aggregation

In this strategy, part families are constructed by using only their code number. The first number of the part code and the number of digits in the code number are used for the identification of part families. Then, each part family (13) is investigated based on volumetric demand information and sorted accordingly. Again Pareto-based analysis of each part family is used to further divide it into several new part families. The number of part families that are constructed as a result of this strategy is 42. In order to further decrease the number of the part families, the summations of the volumetric demand values of each part family (42) are sorted. Application of similar Pareto-based analysis has yielded 7 part families.

As a result of the analysis of these three different part aggregation strategies, the obtained number of the part families ranges between 7 and 16. In the scope of our spare part distribution system design problem, we eventually study problems with 10 part families; this is not only consistent with the results of the aggregation strategies we test but also compatible with real life data of our example.

3.2. Route Generation

The efficiency and effectiveness of the proposed mathematical model depends on the given set of routes and involves a trade-off: providing a high number of routes increases both the solution time and quality while providing few number of routes decreases the solution time and might lead to inferior solutions in terms of the total cost. On the other hand, for big instances solutions with lower optimality gaps might be obtained when fewer routes are given. Hence, we study three different algorithms to generate routes to investigate their impact on the solution quality for the spare parts distribution system design problem and required computational effort.

We first provide a brief overview of literature on the facility location problem that includes routing decisions, and then, present the three alternative heuristic methods to generate routes in detail.

3.2.1. Literature Review

In the literature, production distribution system design problem focuses on two main issues which are determination of the facility locations and generation of the routes.

Elson (1972) presents the first mathematical modelling of the facility location problem which shows that mixed integer programming can be applicable to the solution of certain site location problems. Geoffrion and Graves (1974) study the optimal locations of distribution facilities between plants and customers. Solution technique of that distribution system design problem is based on Bender’s decomposition. They apply their solution approach to a real problem of a food company. In addition to their consideration of facility opening costs, Geoffrion and Graves (1974) propose the first route oriented formulation. With a similar model to Geoffrion and Graves (1974), Pirkul and Jayaraman (1996) focus on a plant and warehouse location problem where they employ Langrangian relaxation.

Most of the facility location problems consider that transportation alternatives are planned and uncapacitated. Moreover, majority of the studies assume that the approximate transportation cost between two points is a simple linear function of the amount transported. However, there are some studies that avoid these assumptions by including transportation capacity constraints (Yılmaz and Çatay (2006); Li *et al.* (2009); Carle *et al.* (2012) and Meisel *et al.* (2016)), transportation mode decisions (Carle *et al*. (2012); Sadjady and Davoudpour (2012) and Meisel *et al.* (2016)) and vehicle type decision (Eskigun *et al.* (2005) and Validi *et al.* (2015)).

Even though, many studies in the literature discuss issues such as capacitated transportation alternatives, transportation mode selection and vehicle type selection, these studies assume direct transportation between the facilities and customers instead of milk-run logistics structure. Milk-run is a delivery method in which a vehicle visits each supplier on a fixed route in order to meet customer needs instead of visiting each supplier separately. In their study, Brar and Saini (2011) state that milk-run system results in transportation cost reduction and vehicle utility maximization. Although milk-run is a procurement method that uses routing to deliver goods to the consumers, it excludes routing decisions. The first combination of facility location decisions and routing decisions are discussed in Maranzana (1964). In the 1990s, the number of studies that combine location-transportation problem with routing has increased and include: Min *et al.* (1998), Nagy and Salhi (2007), Lopes *et al.* (2013), Prodhon and Prins (2014) and Drexl and Schneider (2015).

Bookbinder and Reece (1988) enhance the study of Geoffrion and Graves (1974) by adding routing decisions and vehicle size selection. In location-routing literature, the most similar study to ours is the study of Bookbinder and Reece (1988) since it also focuses on a two-stage distribution system in which the transportation from factories to consumers is done via depots.

Jacobsen and Madsen (1980) and Madsen (1983) discuss the two-stage location-routing problem for the first time in the literature. Following Madsen (1983), Ambrosino and Scutella (2005) and Ambrosino *et al.* (2009) develop models that combine distribution system design and detailed routing. Through their study of two-stage location-routing problem, Lin and Lei (2009) categorize clients as big clients and other clients and only include the big clients to the first-level routing.

Route optimization is beyond the scope of our study. Hence, route optimization is included neither at the first-level nor at the second-level of the spare parts distribution system. Furthermore, routing decisions are not included in the first-level our system which involves transportation from DC to the regional depots. Therefore, the main focus of the first-level is determining the locations of the regional depots and inbound vehicle type size selection. However, the routing decisions in the second-level involve selecting the routes from opened regional depots to the service points. Consequently, our study is not a location-routing problem; route planning decisions are made heuristically by giving a set of generated routes as input. Similar to Nagy and Salhi (2007), our study is associated with location-transportation problem.

In our study, we aim to solve a spare part distribution system design problem inspired from a real-life household appliances manufacturer by using the proposed mathematical model. Recall that Klibi *et al.* (2010) was also incorporating routing decisions in a similar approach to ours. In order to generate the alternative routes, we reviewed the routing literature for existing routing heuristics which can be applied to our study such as Azi *et al.* (2014), Braysy and Gendreau (2005), Clarke and Wright (1964), Contardo and Martinelli (2014), Ioannou *et al.* (2001), Renaud and Boctor (2002) and Rubrico *et al.* (2004). Table 3.1 presents a comparison of these studies and the factors that must considered while generating routes for our problem. After assessing the relevant studies in terms of various features that are needed in our study, we have found Clarke and Wright (1964)'s savings algorithm along with the nearest neighbor algorithm applicable for heuristically generating good routes.

3.2.2. Heuristic Methods

In this study, alternative routes will be generated by using three heuristics in order to facilitate route planning decisions of the proposed mathematical model. The two of the heuristics are modifications of existing heuristics which are Clarke and Wright (1964)'s savings algorithm and nearest neighbor algorithm. Although the three algorithms differ from each other, they have common points, such as creating a candidate service point list for each depot. For a service point to be included in the candidate service point list of a regional depot, the distance from the service point to the corresponding depot should be less than or equal to a given threshold value; we call this value as the routing diameter.

Recall that in our study a route defines only the set of service points visited. Therefore, in all the three algorithms, for each regional depot, if two of the generated routes cover the same service points (regardless of their order) they are treated as the same route. Hence, our algorithm excludes the duplicates of the existing routes.

Table 3.1 The differences between our study and other route generation studies

	Azi *et al.* (2014)	Braysy & Gendreau (2005)	Clarke & Wright (1964)	Contardo & Martinelli (2014)	Ioannou *et al.* (2001)	Renaud & Boctor (2002)	Rubrico *et al.* (2004)	Our Needs
Objective #	Multi	Multi	Single	Single	Single	Single	Multi	Single
Objective function*	MNC-MTD	MNR-MTD	MTD	MTT	MTC	MTC	MNR-MTD	MTC
Number of depots	Single	Single	Single	Multi	Single	Single	Single	One at a time
Time windows	X	X			X			
Heterogeneous vehicles			X			X		X
Multi commodity								X
Split deliveries	X						X	X
Multiple visits	X						X	X
Service time of customers				X	X			X
UB on travelling time of the vehicle				X		X		X
LB on number of routes							X	
LB on number of vehicles				X				
UB on number of vehicles				X	X			

*MTC: Minimize Total Cost; MTD: Minimize Total Distance; MNR: Minimize Number of Routes, MNC: Minimize Number of Served Customers; MTT: Minimize Total Time

Savings Algorithm

One of the well-known and widely used route construction heuristics for routing problems is the savings algorithm; it has been developed by Clarke and Wright (1964). The savings algorithm is easy to understand and easy to implement. Initially, it begins with a solution that includes individual routes $(0, j, 0)$ for all nodes $j \in J$ (with 0 denoting the depot) in which every customer is connected and served directly from the depot. At any iteration, the algorithm progresses by merging two routes based on the notion of "savings". Cost savings of (j_1, j_2) are represented with $S_{j1,j2}$ and it is determined by merging (0, j_1 ,0) and

$(0, j_2, 0)$. By removing the arcs $(j_1, 0)$ and $(0, j_2)$ and adding the arc (j_1, j_2), the cost savings is calculated as $S_{j1,j2} = c_{j1,0} + c_{0,j2} - c_{j1,j2}$. Once all feasible route pair mergers' cost savings are calculated, the maximum of cost savings is chosen to determine the pair of routes to be merged. The algorithm is terminated when there is no positive cost saving left, i.e., there is no pair of routes that can be merged.

In our implementation, we consider a daily limit on driving hours and a maximum speed for the vehicles along with a service time associated with unloading the spare parts at each service point visited on the route. Therefore, the heuristic methods need to incorporta such issues that may require a bit of customization.

For each regional depot, our modified savings algorithms steps can be listed as follows:

Step 1: Construct initial routes where every service point is served individually by a route originating from the regional depot (RD). Add each to route to current routes set. Assuming each service point's demand will be singly sourced from the RD, calculate the current demand met. Determine the vehicle sizes given the current demand met on each individual route. Finally, by including the service time, calculate the distance of each individual route.

Step 2: Calculate the savings from merging all possible pairs of routes in current routes set. Savings will be calculated by considering vehicle costs and distances due to merging two routes.

Step 3: Calculate the total distance from merging all possible pairs of routes in current routes set. If the total distance is exceeding the allowed maximum driving distance, make the savings of that merger pair negative to prevent the selection of that merger due to exceeding the given maximum route length.

Step 4: Sort the savings in descending order. If there is no positive saving, terminate. Otherwise, go to Step 5.

Step 5: Select the greatest positive saving and merge the corresponding two routes. Update the current routes, current demand met, current vehicles and current distances by first removing the data of the two routes that will be merged. Then, add the corresponding entries for the new route that consist of the merged routes. Go to Step 2 until no positive savings can be found.

In our savings algorithm, a route length should not exceed the given maximum driving distance. In order to prevent exceeding the maximum driving distance, when a route length exceeds the maximum driving distance, the corresponding savings merge is ignored. The process repeats itself for each regional depot until no possible savings can be found by merging the formed routes.

Nearest Neighbor Heuristic

One of the first algorithms used to solve the traveling salesman problem is the nearest neighbor algorithm. In the traveling salesman problem, a traveling salesman starts from a customer and wants to visit each customer exactly once. In our case, the nearest neighbor heuristic starts from a given regional depot; it searches for the closest service point and selects that service point to be added to the route as the next destination, as long as the given maximum driving distance is not exceeded. At each iteration, the algorithm searches for the closest neighbor of the last service point to be added to the current route without exceeding the maximum distance. If the closest neighbor cannot be added to the current route, the current route is closed, and a new route is started from the regional depot. The heuristic ends when all the candidate service points are visited on the generated routes. For each regional depot, the implementation details of the nearest neighbor algorithm are provided below:

Step 1: Start a new route from the corresponding regional depot (RD).
Search for nearest service point to the current node in unassigned service points list.

Step 2: Select the nearest service point to the depot in unassigned service points set.
Remove the service point from unassigned service points list.
Calculate the current route distance by considering the service time as well as the distance.
If unassigned service points list is empty, go to step 4. Otherwise. go to step 3.

Step 3: Find the nearest service point to the current service point in the unassigned service points list using given distances.
If the current route distance is not exceeding the allowed maximum driving distance, update the current route distance and go to Step 2. Otherwise. go to Step 4.

Step 4 Close the route.

Add the route to the generated routes set.

If unassigned service points list is not empty, go to step 1. Otherwise, terminate.

Expanded Neighborhood Search

In a standard nearest neighbor algorithm, beginning from the starting point, the closest service point is chosen to be visited. After reaching that service point, the closest service point is chosen among the rest of the unassigned service points until all have been visited. Hence, each service point is included only in one of the generated routes. The reason why we name this algorithm as the expanded neighborhood search is due to starting a new route from each of the service points in the regional depot's candidate service points list. Hence, in this algorithm, one by one all of the service points in the candidate service point list are included as the first service point of a new route. However, for each route the other service points are added one by one similar to the nearest neighbor algorithm. Hence, service points are added until the given maximum driving distance is reached and that tour is closed. For each regional depot, the number of routes generated by this algorithm is equal to the number of service points in the candidate service points set. This algorithm also allows the assignment of a service point to more than one route. For each regional depot, the steps of the algorithm can be summarized as follows:

Step 1: Start a new route from the corresponding regional depot (RD).

Create an assignable service points list which includes covered service points of the corresponding regional depot.

Step 2: Let service point *k* in the unassigned service points list be the first service point on the route.

Remove *k* from unassigned service points list.

Add current service point *k* to the current route.

Calculate the current route distance by considering the service time as well as the distance.

If unassigned service points list is empty, go to step 4. Otherwise. go to step 3.

Step 3: Find the nearest service point to the current service point in the unassigned service points list using given distances.

If the current route distance is not exceeding the allowed maximum driving distance, update the current route distance and repeat Step 3. Otherwise. go to Step 4.

<u>*Step 4*</u> Close the route.

Add the route to the generated routes set.

If unassigned service points list is not empty, replace *k* with another service point in the unassigned service points list and go to step 1. Otherwise, terminate.

4. Computational Results

In this chapter, we first present the experimental design of our study. Then, we continue with analyzing the results of computational experiments which also incorporates a summary of generated routes and a comparison of the routing heuristic approaches.

4.1. Experimental Design

In the interest of observing the response, imposing a treatment on a group of subjects is called an experiment. Organizing the experiment properly has a key importance because the validity of experiment is directly associated with its construction and execution. An experimental design differs from an observational study which includes an analysis without changing the existing conditions.

In our study, it is assumed that in every problem the same ten spare parts are distributed. In order to observe the impact of the problem size to our mathematical formulation and routing approaches, we generate four different problems that contain different number of service points and regional depots:

- 30 service points and 10 alternative regional depots
- 50 service points and 15 alternative regional depots
- 100 service points and 30 alternative regional depots
- 250 service points and 75 alternative regional depots

While generating the random problem instances, for each problem size the distribution center is placed at the center of a 100 x 100 grid coordinate system. The locations of the service points in the coordinate system are determined randomly, whereas the locations of the regional depots are determined with the k-means approximation algorithm. With this approach, for each problem size ten different instances in terms of demands and locations of the service points and regional depots are created. In Figure 4.1, instance 1 with 30 service points and 10 regional depots is illustrated on the 100 x 100 grid coordinate system. The distances between the facilities are calculated using Euclidean distance.

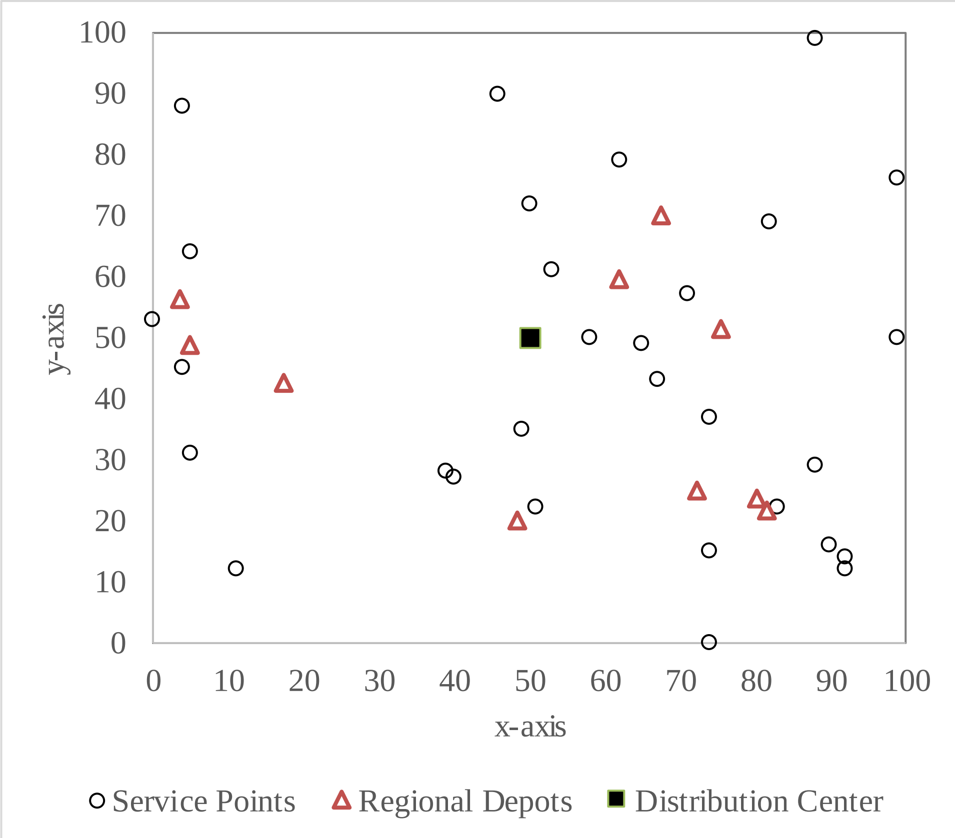

Figure 4.1 Instance 1 of 30 service points and 10 regional depots

The routing diameter is set as 40 distance units. The daily limit on driving hours is 8 hours and the maximum speed of the vehicles 10 distance units per hour; the maximum length of a route is considered as 80 distance units accordingly. The service time is assumed as 15 minutes, and it is converted into distance units using the maximum speed limit; 15 minutes of service time is represented as 2.5 distance units considering a maximum speed limit of 10 distance units per hour.

The regional depot opening and operating costs are randomly generated between 3000 and 6000. In our study, both the inbound transportation cost to the regional depots from the distribution center and the outbound transportation cost from the regional depots to the service points are represented with staircase cost structures considering three different vehicle sizes. The inbound transportation costs are a function of the vehicle size and the distance between the distribution center and given regional depots. The outbound transportation costs depend only on the selected vehicle type. The values used to represent the inbound and outbound transportation costs are given in Tables 4.1 and 4.2.

Table 4.1 Inbound transportation costs used

Volume Break (*k*)	Vehicle Size	Vehicle Capacity (Volume)	Cost per Unit Distance
1	Small	1000	100
2	Medium	2000	180
3	Large	5000	250

Table 4.2 Outbound transportation costs used

Volume Break (*k*)	Vehicle Size	Vehicle Capacity (Volume)	Cost per Vehicle
1	Small	500	2500
2	Medium	1000	4500
3	Large	2000	6500

4.2. Computational Experiments

4.2.1. Summary of Generated Routes

In the input preparation phase of our location-transportation problem, alternative routes are generated by using three different heuristics. The detailed results of the three heuristics for instance 1 with 30 service points and 10 regional depots are given in Appendices A, B and C.

The results of the expanded neighborhood search (ENS) heuristic can be found in Appendix A. For instance 1 with 30 service points and 10 regional depots, 91 alternative routes are generated. The first route (R1) is generated starting from the first regional depot to the service points 1, 2, 4 and 5 in this order. The total distance from the first regional depot to the last service point selected (5) is 60.80 distance units. The total demand covered on this route is 888 units. R6, R30, R41 and R43 are the routes that visit the minimum number of service points which is two. R7, R89 and R91 are the routes that visit the maximum number of service points which is seven. The minimum, average and maximum distances of the routes are 33.64, 53.95 and 88.57 distance units, respectively.

For all the 10 instances of the smallest problem size consıstıng of 30 service points and 10 regional depots, ENS has generated a total of 796 routes. The number of routes formed vary from one instance to another. The instance with minimum number of routes generated for 30 service points and 10 regional depots is instance 2 and incorporates 52 routes. Whereas the instance with maximum number of routes generated for 30 service points and 10 regional depots is instance 10 and has 116 routes. Table 4.3 provides a brief summary of the total number of routes, number of regional depots per service point's minimum, average and maximum, and number of routes per service point's minimum, average and maximum. For the sake of completeness, in Table 4.4 and 4.5 similar route summaries for nearest neighbor (NN) and savings algorithm (SAV) are given.

Table 4.3 Summary of ENS generated routes

Problem Size	Total # Routes	# of RD per SP			# of Route per SP		
		Min.	Avg.	Max.	Min.	Avg.	Max.
30 SP & 10 RD	796	6.00	8.85	10.00	2.50	3.06	3.75
50 SP & 15 RD	1684	10.00	11.75	12.50	3.12	3.76	4.17
100 SP & 30 RD	7664	16.67	19.67	20.00	4.35	4.55	5.00
250 SP & 75 RD	47569	17.86	20.05	20.83	5.21	5.73	6.10

Table 4.4 Summary of NN generated routes

Problem Size	Total # Routes	# of RD per SP			# of Route per SP		
		Min.	Avg.	Max.	Min.	Avg.	Max.
30 SP & 10 RD	345	6.00	7.85	10.00	2.73	3.05	3.33
50 SP & 15 RD	645	10.00	11.50	12.50	3.33	3.85	4.55
100 SP & 30 RD	2002	16.67	19.33	20.00	4.35	4.79	5.56
250 SP & 75 RD	8720	19.23	20.67	20.83	5.56	5.98	6.58

Table 4.5 Summary of savings algorithm generated routes

Problem Size	Total # Routes	# of RD per SP			# of Route per SP		
		Min.	Avg.	Max.	Min.	Avg.	Max.
30 SP & 10 RD	713	6.00	8.35	10.00	1.43	1.64	1.88
50 SP & 15 RD	1514	10.00	11.50	12.50	1.61	1.77	2.00
100 SP & 30 RD	6034	16.67	19.33	20.00	1.79	1.86	2.00
250 SP & 75 RD	37925	19.23	20.67	20.83	1.84	1.92	2.03

The given routes affect the size of our mathematical problem. For the sake of brevity, the number of routes, corresponding number of variables and binary variables for all the 40 instances using the ENS, NN and savings algorithm are given in Tables 4.6 and 4.7. The nearest neighbor algorithm yields the smallest route set for all the 40 instances. The number of routes generated by the savings algorithm are pretty close to that of the expanded neighborhood search. However, when the routes of instance 1 provided in Appendices A and C are compared, we see that the routes generated by the savings algorithm are significantly shorter due to visiting one or two service points (except R28 where three service points are visited).

Table 4.6 Number of routes and number of variables of the three heuristics

Pr.	Ins.	Number of Routes			Number of Variables		
		ENS	NN	SAV	ENS	NN	SAV
30 Service points & 10 RD	1	91	38	75	4183	1404	1515
	2	58	26	54	2444	1008	1092
	3	52	27	63	2346	1111	1219
	4	116	38	87	5708	1614	1761
	5	92	38	81	4546	1484	1613
	6	77	33	68	3721	1279	1384
	7	86	43	87	3878	1579	1711
	8	79	37	62	3617	1321	1396
	9	77	35	68	3311	1235	1334
	10	68	30	68	3214	1230	1344
50 Service points & 15 RD	1	171	64	137	8933	2872	3091
	2	140	60	148	7490	2600	2864
	3	155	62	141	9215	2896	3133
	4	198	75	192	10864	3245	3596
	5	155	61	150	7785	2703	2970
	6	198	66	164	10294	3158	3452
	7	192	71	168	10606	3103	3394
	8	145	58	131	7625	2534	2753
	9	180	70	156	10030	3020	3278
	10	150	58	127	7140	2434	2641
100 Service points & 30 RD	1	747	199	601	50711	11107	12313
	2	860	210	652	58780	12160	13486
	3	724	190	579	49462	11060	12227
	4	846	203	598	56508	11559	12744
	5	750	197	594	47750	11081	12272
	6	798	202	632	53744	11866	13156
	7	683	192	582	46609	10616	11786
	8	703	202	622	45369	11166	12426
	9	800	206	605	51530	11378	12575
	10	753	201	569	48399	10923	12027
250 Service points & 75 RD	1	5056	901	3850	442138	69463	78310
	2	4805	854	3890	424785	68172	77280
	3	4647	856	3661	407661	66538	74953
	4	4746	872	3785	422078	68586	77325
	5	5026	915	4049	430348	71025	80427
	6	4921	889	3793	433243	69447	78159
	7	4414	828	3587	390722	65074	73351
	8	4723	857	3590	408169	67061	75260
	9	4691	878	3830	411533	68294	77150
	10	4540	870	3890	390830	67380	76440

Table 4.7 Number of binary variables and number of constraints of the three heuristics

Pr.	Ins.	Number of Binary Variables			Number of Constraints		
		ENS	NN	SAV	ENS	NN	SAV
30 Service points & 10 RD	1	313	154	265	542	436	510
	2	214	118	202	476	412	468
	3	196	121	229	464	414	486
	4	388	154	301	592	436	534
	5	316	154	283	544	436	522
	6	271	139	244	514	426	496
	7	298	169	301	532	446	534
	8	277	151	226	518	434	484
	9	271	145	244	514	430	496
	10	244	130	244	496	420	496
50 Service points & 15 RD	1	573	252	471	937	723	869
	2	480	240	504	875	715	891
	3	525	246	483	905	719	877
	4	654	285	636	991	745	979
	5	525	243	510	905	717	895
	6	654	258	552	991	727	923
	7	636	273	564	979	737	931
	8	495	234	453	885	711	857
	9	600	270	528	955	735	907
	10	510	234	441	895	711	849
100 Service points & 30 RD	1	2361	717	1923	2684	1588	2392
	2	2700	750	2076	2910	1610	2494
	3	2292	690	1857	2638	1570	2348
	4	2658	729	1914	2882	1596	2386
	5	2370	711	1902	2690	1584	2378
	6	2514	726	2016	2786	1594	2454
	7	2169	696	1866	2556	1574	2354
	8	2229	726	1986	2596	1594	2434
	9	2520	738	1935	2790	1602	2400
	10	2379	723	1827	2696	1592	2328
250 Service points & 75 RD	1	15468	3003	11850	13087	4777	10675
	2	14715	2862	11970	12585	4683	10755
	3	14241	2868	11283	12269	4687	10297
	4	14538	2916	11655	12467	4719	10545
	5	15378	3045	12447	13027	4805	11073
	6	15063	2967	11679	12817	4753	10561
	7	13542	2784	11061	11803	4631	10149
	8	14469	2871	11070	12421	4689	10155
	9	14373	2934	11790	12357	4731	10635
	10	13920	2910	11970	12055	4715	10755

For instance 1 with 30 service points and 10 regional depots, expanded neighborhood search generated 91 routes, nearest neighbor generated 38 routes and savings heuristic generated 75 routes. The routes that have been commonly generated in all three heuristics are demonstrated with bold fonts in Appendices A, B and C. Also, the number of common routes generated by the three heuristics in this instance are given in Table 4.8.

Table 4.8 Number of common routes between heuristics

	Number of Common Routes
ENS-NN	21
ENS-SAV	1
NN-SAV	3

4.2.2. Results of Computational Experiments

In our experimental design, we have four problem sizes with ten instances for each. Considering the three heuristics used for generating the given routes, we will be reporting on a total of 120 instances solved with the proposed mathematical model. Each instance has been solved with a time limit of 4 hours on Sabancı University's High Power Computing system using GUROBI 8.0. All the coding for data reading, model preparation and output generation have been implemented using Python 3.6 and GUROBI through Anaconda's Spyder scientific environment.

The results of our computational analysis will be presented in two parts. In the first part, a detailed comparison will be provided using an example problem. In the second part, an overview of the results obtained over the entire experimentation will be presented.

4.2.2.1. Results for an Example Problem

Instance 1 of the 30 service points and 10 regional depots problem size has been selected to demonstrate the impact of the three different route sets over various performance measures.

The total cost revealed by optimally solving the proposed mathematical model using the expanded neighborhood search algorithm's routes is 69553.69, which involves total opening and operating costs of regional depots, total inbound transportation cost from distribution center to the regional depots, and total outbound transportation cost from regional depots to the service points. The breakdown of the total cost on each of the cost terms is given in Table 4.9.

98% of the ten parts of the 30 service points are assigned to a single route (see Appendix D). As the demand of spare part 9, for service points 5 and 9 are zero, they are not assigned to any route. Only four spare parts (spare part 1 for service points 2, 22 and 29; and spare part 3 for service point 23) are provided using two routes.

Table 4.10 illustrates the regional depots opened, the assigned routes and inbound (IB) vehicle sizes selected, IB truck utilizations and total demand met. Regional depots 2, 6 and 7 are opened and are sent medium, big and big vehicle sizes, respectively. The average vehicle utilization of the inbound vehicles is 60%. In total ten routes are selected for the outbound transportation. Table 4.11 presents details on the outbound (OB) shipments via selected routes. Medium and small sized vehicles have been assigned leading to 94% utilization of the outbound vehicles on average. 70% of the service points are served using a single route and remaining 30% are covered using two routes. Only service point 14, which is on both routes R33 and R45 is receiving spare parts from two regional depots (i.e. 6 and 7).

Table 4.9 Total cost breakdown of the solution using ENS algorithm's routes

	Fixed Cost	**IB Transportation Cost**	**OB Transportation Cost**	**Total Cost**
ENS	11381.67	23172.02	35000.00	69553.69

Table 4.10 Regional depots and IB shipment details using ENS algorithm's routes

Depots Opened	**IB Assigned Vehicle Size**	**IB Vehicle Utilization (%)**	**Total Demand Met**	**Assigned Routes**
2	Med (2000)	65.05	1301.00	R5, R8
6	Big (5000)	66.09	3304.52	R33, R34, R41, R42, R43
7	Big (5000)	48.76	2437.89	R45, R51, R52

Table 4.11 Selected routes and OB shipment details using ENS algorithm’s routes

Routes	Assigned Depot (# of SP)	OB Assigned Vehicle Size	OB Vehicle Utilization (%)	Demand Met	Number of Parts
R5	2 (4 SP)	Med (1000)	80.10	801.00	34
R8	2 (3 SP)	Small (500)	100.00	500.00	26
R33	6 (6 SP)	Med (1000)	96.33	963.34	43
R34	6 (4 SP)	Med (1000)	96.23	962.30	35
R41	6 (2 SP)	Small (500)	100.00	500.00	17
R42	6 (3 SP)	Small (500)	75.78	378.88	20
R43	6 (2 SP)	Small (500)	100.00	500.00	15
R45	7 (5 SP)	Med (1000)	94.27	942.69	40
R51	7 (4 SP)	Small (500)	99.04	495.20	28
R52	7 (6 SP)	Med (1000)	100.00	1000.00	44

The total cost obtained using the nearest neighbor algorithm’s routes is 72601.86, which is 4.4% higher than the total cost obtained using expanded neighborhood’s routes. Table 4.12 provides the breakdown of the total cost with respect to the three cost terms. When the cost terms are compared with those provided in Table 4.9, we can see that the first level decisions associated with the selection of the regional depots and inbound transportation costs are profoundly affected by the given routes.

In this solution, 98.7% of the spare parts are assigned to a single route and only two spare parts (spare part 1 for service point 18 and spare part 10 for service point 22) are provided using two routes (see Appendix E).

Table 4.13 summarizes the selected regional depots, IB truck sizes and their utilizations, total demand met and assigned routes in the optimal solution. Regional depots 2, 5, 6 and 10 are opened and all three vehicle sizes are used. In this solution, usage of more medium and small size vehicles has led to an increased vehicle utilization of 73%. Nine routes are selected for outbound transportation. The details regarding the OB shipments are given in Table 4.14. 90% of the service points are single sourced using one route originating from a single depot. Service points 9, 18 and 22 are served by two different routes originating from two different depots (i.e. 5 and 6 in all).

Table 4.12 Total cost breakdown of the solution using NN algorithm's routes

	Fixed Cost	IB Transportation Cost	OB Transportation Cost	Total Cost
NN	15791.66	22310.2	34500.00	72601.86

Table 4.13 Regional depots and IB shipment details using NN algorithm's routes

Depots Opened	IB Assigned Vehicle Size	IB Vehicle Utilization (%)	Total Demand Met	Assigned Routes
2	Med (2000)	65.05	1301.00	R3, R4
5	Big (5000)	67.89	3394.31	R12, R13, R14, R15
6	Small (1000)	85.48	854.75	R17, R18
10	Med (2000)	74.67	1493.36	R35

Table 4.14 Selected routes and OB shipment details using NN algorithm's routes

Routes	Assigned Depot (# of SP)	OB Assigned Vehicle Size	OB Vehicle Utilization (%)	Demand Met	Number of Parts
R3	2 (4 SP)	Med (1000)	86.55	865.54	39
R4	2 (2 SP)	Small (500)	87.09	435.45	20
R12	5 (4 SP)	Med (1000)	95.16	951.61	30
R13	5 (5 SP)	Med (1000)	100.00	1000.00	50
R14	5 (2 SP)	Small (500)	100.00	500.00	16
R15	5 (4 SP)	Med (1000)	94.27	942.70	40
R17	6 (3 SP)	Small (500)	80.51	402.53	16
R18	6 (2 SP)	Small (500)	90.44	452.22	19
R35	10 (7 SP)	Big (2000)	74.67	1493.36	70

The total cost is obtained using the saving algorithm's routes is 79553.69, which is 14.4% higher than the total cost obtained using expanded neighborhood's routes. Table 4.15 provides the breakdown of the total cost with respect to the three cost terms. When the cost terms are compared with those provided in Table 4.9, we can see that the first level decisions associated with the selection of the regional depots and inbound transportation costs are not affected by the given routes and are the same. Hence, due to the difference in the given route sets, the outbound transportation cost is 28.5% higher as 18 routes are selected and all are shipped using small vehicles. In this solution, each spare part is assigned to a single route (see Appendix F).

Table 4.15 Total cost breakdown of the solution using SAV algorithm's routes

	Fixed Cost	IB Transportation Cost	OB Transportation Cost	Total Cost
SAV	11381.67	23172.02	45000.00	79553.69

Table 4.16 Regional depots and IB shipment details using SAV algorithm's routes

Depots Opened	IB Assigned Vehicle Size	IB Vehicle Utilization (%)	Total Demand Met	Assigned Routes
2	Med (2000)	65.05	1301.00	R4, R5, R6, R7
5	Big (5000)	47.33	2366.52	R30, R31, R34, R37, R38, R39
6	Big (5000)	67.52	3375.90	R41, R42, R43, R44, R45, R46, R47, R48

Table 4.17 Selected routes and OB shipment details using SAV algorithm's routes

Routes	Assigned Depot (# of SP)	OB Assigned Vehicle Size	OB Vehicle Utilization (%)	Demand Met	Number of Parts
R4	2 (1 SP)	Small (500)	49.42	247.08	10
R5	2 (1 SP)	Small (500)	56.55	282.75	10
R6	2 (2 SP)	Small (500)	87.09	435.45	20
R7	2 (2 SP)	Small (500)	67.14	335.72	19
R30	6 (1 SP)	Small (500)	77.55	387.77	10
R31	6 (1 SP)	Small (500)	66.17	330.87	10
R34	6 (1 SP)	Small (500)	68.78	343.92	10
R37	6 (2 SP)	Small (500)	71.68	358.42	10
R38	6 (2 SP)	Small (500)	89.84	449.22	19
R39	6 (2 SP)	Small (500)	99.26	496.32	20
R41	7 (2 SP)	Small (500)	82.97	414.85	20
R42	7 (2 SP)	Small (500)	80.04	400.18	20
R43	7 (2 SP)	Small (500)	73.65	368.27	20
R44	7 (2 SP)	Small (500)	89.33	446.63	20
R45	7 (2 SP)	Small (500)	95.03	475.16	20
R46	7 (2 SP)	Small (500)	90.29	451.45	20
R47	7 (2 SP)	Small (500)	93.73	468.67	20
R48	7 (2 SP)	Small (500)	70.14	350.69	20

Table 4.16 summarizes the selected regional depots, IB vehicle sizes and their utilizations, total demand met and assigned routes in the optimal solution. Similar to the solution using the expanded neighborhood search's routes, regional depots 2, 6 and 7 are opened and are

sent medium, big and big vehicle sizes, respectively. Again, the average vehicle utilization of the inbound vehicles is 60%. Eighteen routes are used for outbound transportation. Only 5 of these 18 routes are delivering to a single service point, while the remaining 13 routes are distributing spare parts to two service points Due to the short routes given by the saving algorithm, only small size vehicles are used on all selected routes. Consequently, the outbound average vehicle utilization is 78%. The details regarding the OB shipments are given in Table 4.17. 97% of the service points are single sourced using one route originating from a single depot. The only exception being service point 16 as it served by routes R37 and R42 originating from regional depots 6 and 7, respectively.

A comparison of the number of vehicles used in the solutions obtained using the route sets provided by the three route generation algorithms is provided in Table 4.18. Due to the shorter routes generated by the savings algorithm, only small sized vehicles are used for outbound shipments. Overall, when using the routes generated by the savings algorithm generated route, the solution incorporates 61.5% more vehicles to serve the same service points.

Table 4.18 Number of vehicles of three heuristics

	Inbound			**Outbound**			
	Small	**Medium**	**Big**	**Small**	**Medium**	**Big**	**Total**
ENS	0	1	2	5	5	0	13
NN	1	2	1	4	4	1	13
SAV	0	1	2	18	0	0	21

4.2.2.2. Overall Results

The details of the solutions obtained for each instance of each problem size using the routes of the three heuristics are given in Appendix G. The objective function values and the objective bounds (for the given time limit of 4 hours) of the solutions obtained using the routes of the three heuristics are given in Table 4.19. Table 4.20 summarizes the number of best solutions found by each heuristic for each problem size. When the objective function values of different problem sizes are compared for the three route generation heuristics, we observe the following:

Table 4.19 Objective function values and bounds obtained using the three route sets

Pr.	Ins	Objective Function Value			Objective Bound		
		ENS	NN	SAV	ENS	NN	SAV
30 Service points & 10 RD	1	**69553.7**	72601.9	79553.7	69553.7	72601.9	79553.7
	2	**80580.8**	81080.8	96309.2	80580.8	81080.8	96309.2
	3	**93716.9**	97702.7	110678.1	93716.9	97702.7	110678.1
	4	**60874.9**	66874.9	71041.5	60874.9	66874.9	71041.5
	5	**66312.7**	76366.7	79312.7	66312.7	76366.7	79312.7
	6	**71687.1**	77312.2	83013.5	71687.1	77312.2	83013.5
	7	**70565.9**	75185.2	84185.2	70565.9	75185.2	84185.2
	8	**67334.8**	71656.9	76422.0	67334.8	71656.9	76422.0
	9	**76690.3**	81710.7	88190.3	76690.3	81710.7	88190.3
	10	**75241.9**	76394.5	87397.1	75241.9	76394.5	87397.1
50 Service points & 15 RD	1	**98185.3**	104908.7	116329.9	98185.3	104908.7	116329.9
	2	106417.7	**105892.3**	123908.0	106417.7	105892.3	123908.0
	3	**112572.3**	114596.0	133491.7	112572.3	114596.0	133491.7
	4	**102863.1**	108810.4	125064.8	102863.1	108810.4	125064.8
	5	**116257.1**	118494.7	135294.0	115504.3	118494.7	135294.0
	6	**95661.3**	101848.4	116781.5	95661.3	101848.4	116781.5
	7	**107280.8**	109361.5	129178.0	107280.8	109361.5	129178.0
	8	**113644.7**	118918.1	135684.6	113644.7	118918.1	135684.6
	9	**100662.2**	106880.2	124345.5	100662.2	106880.2	124345.5
	10	**112281.7**	116341.2	138013.0	112281.7	116341.2	138013.0
100 Service points & 30 RD	1	**164902.4**	174050.8	215814.3	159773.7	166235.6	215814.3
	2	161087.4	**158840.7**	200402.9	151444.4	157118.6	200402.9
	3	**150973.9**	156443.3	196610.4	144213.1	156443.3	196610.4
	4	**160373.2**	161647.0	198138.1	151506.8	156003.0	198138.1
	5	**154278.1**	159852.1	200860.8	149118.2	157801.7	200860.8
	6	**166306.5**	170017.6	207734.5	158107.4	163277.3	207734.5
	7	**169765.0**	173254.1	220096.5	160430.0	170338.9	220096.5
	8	**161679.2**	165179.2	208308.8	154861.0	165179.2	208308.8
	9	**162889.1**	168482.8	204466.3	152306.9	163440.1	204466.3
	10	**156503.4**	164876.4	201399.3	151846.3	164876.4	201399.3
250 Service points & 75 RD	1	340708.5	**334588.7**	448488.9	305650.4	307842.0	426278.9
	2	**342764.0**	343974.4	468583.7	308379.7	314602.1	440966.9
	3	368240.6	**351905.6**	466754.9	327974.3	330556.8	448705.2
	4	355298.1	**336951.0**	444024.8	304759.0	311854.6	430177.4
	5	364162.7	**349278.8**	462749.4	315667.9	321017.6	447351.2
	6	357075.9	**338731.7**	443100.6	295822.0	301467.5	422594.0
	7	358685.1	**352775.2**	452283.4	318378.4	318607.8	434064.5
	8	346909.4	**335822.5**	452083.9	310030.0	314722.6	436137.1
	9	**340119.5**	343642.9	460185.1	308785.3	317565.9	446325.8
	10	352628.8	**350153.9**	472639.1	319492.5	323646.0	454209.5

- Expanded neighborhood search gives the best solutions for all of the instances of 30 service points and 10 regional depots.
- In 50 service points and 15 regional depots instances, the minimum objective function value is found by expanded neighbor search heuristic in 9 of the instances and by the nearest neighbor heuristic in one instance only.
- Similarly, in 100 service points and 30 regional depots instances, the minimum objective function value is found by expanded neighbor search heuristic in 9 of the instances and by the nearest neighbor heuristic in a single instance.
- In contrast to the other problem sizes, in 250 service points and 75 regional depots instances, most of the best solutions are provided by the nearest neighbor heuristic. Only in two instances, the best solutions are provided by expanded neighbor search heuristic.

Table 4.20 Number of best solutions found by each route generation heuristic

	Number of best solutions found			
	30SP & 10RD	**50SP & 15RD**	**100SP & 30RD**	**250SP & 75RD**
ENS	10	9	9	2
NN	0	1	1	8
SAV	0	0	0	0

It is observed that, when the number of service points and regional depots increase, nearest neighbor heuristics can find better solutions within the given time limit, probably due to the smaller problem size. For all problem sizes and over all instances, none of the best solutions are obtained using the savings algorithm's routes. Table 4.21 presents the average of the percentage differences of each heuristic with the best solution representing the lowest total cost solution among the three heuristics.

Table 4.21 Average of percentage differences with the best heuristic

	Average of % difference of ENS with best solution	**Average of % difference of NN with best solution**	**Average of % difference of SAV with best solution**
30 SP & 10 RD	0.00	6.32	16.80
50 SP & 15 RD	0.05	3.92	20.04
100 SP & 30 RD	0.14	2.88	27.86
250 SP & 75 RD	2.73	0.14	33.16

When the three components of the total cost (fixed cost of opening and operating regional depots, inbound transportation cost and outbound transportation cost) are analyzed, it is seen that the difference between the total costs due to using savings algorithm and the other heuristics originates mainly from the difference of the outbound transportation costs. Table 4.22 shows the average of fixed, inbound transportation and outbound transportation costs of the three heuristics for each problem sizes. Consequently, for the smallest problem size, nearest neighbor algorithm's and savings algorithm's fixed costs are 11% and 7% higher than the expanded neighbor search algorithm, respectively. Similarly, for the 50 service points and 15 regional depots problem size, nearest neighbor algorithm's and savings algorithm's fixed costs are 2% and 4% higher than the expanded neighbor search algorithm, respectively. For the 100 service points and 30 regional depots problem size, both algorithms' fixed costs are 2% greater than the expanded neighbor search algorithm. However, for the largest problem size, savings algorithm has the minimum fixed cost. For the inbound transportation cost (IB Tcost), there is no discernible pattern regarding the superiority of the three heuristics as the best values obtained are also changing from one instance to another of each problem size. On the contrary, the outbound transportation cost (OB Tcost) is affected by both the problem size and the heuristics. For the first three problem sizes, expanded neighbor search algorithm yields the minimum outbound transportation costs on majority of the instances. For these three problems, on average, inbound transportation costs of the nearest neighbor algorithm and the savings algorithm are 6% and 39% greater than that of the expanded neighbor search algorithm, respectively. For the last problem size, savings algorithm's outbound transportation cost is 50% greater than the nearest neighbor algorithm which gives the minimum outbound transportation cost in 9 of the 10 instances.

Table 4.23 presents the average number of vehicles used for each problem size and routing heuristic. As expected, the number of vehicles yielded by the savings algorithm is significantly higher in all of the problem sizes due to the given shorter routes.

Table 4.22 Average of cost terms according to the problem sizes and heuristics

Average of	30SP&10RD	50SP&15RD	100SP&30RD	250SP&75RD
Fixed Cost ENS	16791.50	20954.58	24973.33	57760.67
Fixed Cost NN	18608.50	21382.63	25589.83	56338.17
Fixed Cost SAV	18023.50	21825.03	25458.17	55958.50
IB TCost ENS	21864.41	31928.03	38902.49	67248.60
IB TCost NN	21530.14	32472.52	40974.57	64694.32
IB TCost SAV	20786.83	31984.08	40225.03	67430.88
OB TCost ENS	34600.00	53700.00	97000.00	227650.00
OB TCost NN	37550.00	56750.00	98700.00	222750.00
OB TCost SAV	46800.00	74000.00	139700.00	333700.00

Table 4.23 Average of the number of vehicles used

	ENS	NN	SAV
30 SP & 10 RD	13.5	13.8	22.1
50 SP & 15 RD	17.7	17.5	32.8
100 SP & 30 RD	27.1	26.2	59.0
250 SP & 75 RD	56.2	54.0	142.3
Total	114.5	111.5	256.2

The average of both inbound and outbound vehicle utilizations can be found in Table 4.24. For each problem size, there is no significant effect of the routing heuristics on the inbound vehicle utilizations. However, 77.5% of the highest outbound vehicle utilizations are obtained using the routes of the expanded neighbor search algorithm. Due to the shorter routes given by the savings algorithm where significantly fewer service points are visited, the outbound vehicle utilizations are significantly lower.

Table 4.24 Average of inbound and outbound vehicle utilizations

Average of	30SP&10RD	50SP&15RD	100SP&30RD	250SP&75RD
IB Util. ENS	75.97	80.54	93.17	93.30
IB Util. NN	79.88	80.80	93.24	95.89
IB Util. SAV	78.42	84.08	94.94	96.87
OB Util. ENS	90.96	91.49	92.27	89.01
OB Util. NN	81.26	80.39	88.08	91.15
OB Util. SAV	74.04	78.88	81.47	85.92

Table 4.25 gives the average number of service points with multiple routes for each problem size and routing heuristic. We see split deliveries in each problem size and routing heuristic. On average, more than 80% of the service points are receiving split deliveries.

Table 4.25 Average number of service points with multiple routes

	ENS	NN	SAV
30 SP & 10 RD	25.3	26.1	25.8
50 SP & 15 RD	42.1	42.0	43.0
100 SP & 30 RD	84.2	82.8	83.1
250 SP & 75 RD	212.1	212.2	214.5

Table 4.26 illustrates the impact of the routing heuristics on the average number of selected routes. For all of the problem sizes, the nearest neighbor algorithm and expanded neighbor search algorithm give the smallest number of selected routes. Number of selected routes obtained by expanded neighborhood search algorithm deviates significantly from that by the nearest neighbor algorithm by at most 5% (for the 100 SP & 30 RD problem size) and at least 1% (for the 30 SP & 10 RD problem size). For the savings algorithm, as the problem size increases, the difference with the nearest neighbor algorithm also increases. For the smallest problem size the average number of selected routes in the savings algorithm is 86% higher than that of the nearest neighbor algorithm, whereas for the largest problem size the average difference is 210% higher.

Table 4.27 shows the average number of regional depots opened. There is no significant difference in terms of the number of opened regional depots by the three routing heuristics.

Table 4.26 Average number of selected routes

	ENS	NN	SAV
30 SP & 10 RD	10.0	9.9	18.4
50 SP & 15 RD	13.4	13.1	28.4
100 SP & 30 RD	22.0	21.0	53.8
250 SP & 75 RD	43.7	41.9	130.2

Table 4.27 Average number of regional depots opened

	ENS	NN	SAV
30 SP & 10 RD	3.5	3.9	3.7
50 SP & 15 RD	4.3	4.4	4.4
100 SP & 30 RD	5.1	5.2	5.2
250 SP & 75 RD	12.5	12.1	12.1

Table 4.28 presents the percentage gap and CPU times obtained by using the routes of each route generation for all solved problem sizes and instances. The smaller problem sizes are solved to optimality (except instance 5 of 50 service points and 15 regional depots problem using expanded neighbor search). Using the routes generated by the savings algorithm leads to lowest CPU times or smallest percentage gaps, although it has not yielded any of the best solutions. Table 4.29 presents the average. minimum and maximum percentage gaps for each problem size and route generation heuristic. In Table 4.20, we had seen that 75% best solutions were obtained using the expanded neighbor search routes and 25% using the nearest neighbor search. Being 4% and 2% around the optimum for the routes obtained by these two heuristics is good.

Table 4.28 Percentage gaps and CPU times of each route generation heuristic

Pr.	Ins.	Gap (%)			CPU Time (sec)		
		ENS	NN	SAV	ENS	NN	SAV
30 Service points & 10 RD	1	0	0	0	6.04	1.10	0.10
	2	0	0	0	15.84	0.56	0.34
	3	0	0	0	6.70	1.56	0.84
	4	0	0	0	223.35	0.90	0.11
	5	0	0	0	2.97	1.20	0.09
	6	0	0	0	5.57	1.60	0.49
	7	0	0	0	9.54	1.60	0.04
	8	0	0	0	25.04	4.36	0.15
	9	0	0	0	14.82	3.80	0.10
	10	0	0	0	27.81	0.94	1.43
50 Service points & 15 RD	1	0	0	0	722.87	13.23	5.21
	2	0	0	0	5945.72	8.20	1.97
	3	0	0	0	614.02	40.97	14.75
	4	0	0	0	3187.59	93.26	6.47
	5	0.65	0	0	**14400.01**	32.61	8.07
	6	0	0	0	63.66	19.68	2.26
	7	0	0	0	901.19	17.92	5.58
	8	0	0	0	334.38	8.59	2.17
	9	0	0	0	83.76	8.95	5.54
	10	0	0	0	1899.26	5.53	7.80
100 Service points & 30 RD	1	3.11	4.49	0	**14400.02**	**14400.01**	2297.81
	2	5.99	1.08	0	**14400.01**	**14400.01**	266.75
	3	4.48	0	0	**14400.04**	7901.68	1030.48
	4	5.53	3.49	0	**14400.04**	**14400.01**	1422.95
	5	3.34	1.28	0	**14400.02**	**14400.01**	992.01
	6	4.93	3.96	0	**14400.04**	**14400.01**	3841.12
	7	5.50	1.68	0	**14400.01**	**14400.01**	5042.64
	8	4.22	0	0	**14400.02**	4565.63	871.61
	9	6.50	2.99	0	**14400.01**	**14400.01**	724.91
	10	2.98	0	0	**14400.02**	12084.30	167.87
250 Service points & 75 RD	1	10.29	7.99	4.95	**14400.08**	**14400.01**	**14400.02**
	2	10.03	8.54	5.89	**14400.08**	**14400.01**	**14402.67**
	3	10.93	6.07	3.87	**14402.70**	**14400.01**	**14401.47**
	4	14.22	7.45	3.12	**14400.15**	**14400.01**	**14400.55**
	5	13.32	8.09	3.33	**14400.05**	**14400.01**	**14400.06**
	6	17.15	11.00	4.63	**14400.06**	**14400.01**	**14400.20**
	7	11.24	9.69	4.03	**14400.04**	**14400.01**	**14400.02**
	8	10.63	6.28	3.53	**14400.65**	**14400.01**	**14400.48**
	9	9.21	7.59	3.01	**14400.06**	**14400.01**	**14400.06**
	10	9.40	7.57	3.90	**14404.60**	**14400.01**	**14401.42**

Table 4.29 Summary of percentage gaps

Problem	Measure	ENS	NN	SAV
30 SP & 10 RD	Avg.	0.00	0.00	0.00
	Min.	0.00	0.00	0.00
	Max.	0.00	0.00	0.00
50 SP & 15 RD	Avg.	0.07	0.00	0.00
	Min.	0.00	0.00	0.00
	Max.	0.65	0.00	0.00
100 SP & 30 RD	Avg.	4.66	1.90	0.00
	Min.	2.98	0.00	0.00
	Max.	6.50	4.49	0.00
250 SP & 75 RD	Avg.	11.64	8.03	4.03
	Min.	9.21	6.07	3.01
	Max.	17.15	11.00	5.89
Overall	Avg.	4.09	2.48	1.01

5. Conclusion

In this study, we present a spare parts distribution system model, which in addition to facility locations and transshipment amounts includes other real-life aspects such as the selection of inbound and outbound vehicle sizes, and selection of routes. A mixed integer linear programming model defining define our static single period multi commodity system design problem is provided. The objective function is based on minimizing the total cost and involves opening and operating costs of the regional depots and both the inbound and outbound transportation costs. We also employ a series of data aggregation schemes in order to determine the number of part families to be used in this spare part system design problem. Also, three different route generation algorithms are used to observe the impact of different routes on the solution time and quality.

The results obtained using the proposed three different route generation algorithms on the four problem sizes of the mathematical model results are analyzed. The objective function values of the three algorithms are compared for the different problem sizes. All of the best solutions are found by the expanded neighbor search algorithm in the 30 service points and 10 regional depots problem size. For 50 service points and 15 regional depots and 100 service points and 30 regional depots, 9 of the best results are given by expanded neighbor search algorithm whereas 1 of the best results is found by the nearest neighbor algorithm. In contrast to other problem sizes, for 250 service points and 75 regional depots, 8 of the best solutions are found by nearest neighbor algorithm and 2 of the best solutions are found by the expanded neighbor search algorithm. As the number of service points and the number of regional depots increases, nearest neighbor algorithms tendency of finding a better solution than the other two algorithms increases. Contrary to other algorithms, savings algorithm finds no best solution in any of the problem sizes.

Our study should be considered as the early phase of a multi-period spare parts distribution system design problem. Hence, our single period spare parts distribution system design problem is an approximation. When the problem is considered in a multi-period setting, these routes may not necessarily be the best routes to be generated. In the multi-period problem, vehicles are expected to take on non-identical routes for each period as the service points are not necessarily visited with identical frequencies. Therefore, an approximation to a single-period setting provides upper bounds for the multi-period problem while it also delivers solution methods to solve the decomposed parts of the multi-period problem.

From a practical point of view, the single period setting can be considered as an important limitation. The immediate follow-up study will include a straight forward extension of the same setting to a multi-period one. In addition, a variety of service level constraints for different part families can be considered in the later studies.

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APPENDICES

In Appendices A, B and C the detailed information on the routes of the same instance for the same problem size are given. The exact same routes among the heuristics are indicated with bold fonts.

APPENDIX A: Detailed Information on Routes Generated by ENS Heuristic for problem Instance 1 in the set with 30 Service Points and 10 Regional Depots

Route	Origin	Route Detail	# SP	Distance	Demand
R1	1	**1-2-4-5**	4	60.80	888
R2	1	1-2-5-3	4	56.81	865.55
R3	1	1-5-3	3	40.92	582.8
R4	2	2-1-4-6	4	55.35	965.28
R5	2	**2-1-5-3**	4	48.97	865.55
R6	2	**5-3**	2	39.19	335.72
R7	2	2-1-5-4	4	57.95	888
R8	2	2-4-6	3	37.88	718.2
R9	3	2-1-4-6	4	65.09	965.28
R10	3	**2-1-5-4**	4	67.69	888
R11	3	2-4-6	3	47.62	718.2
R12	3	**7-8-10-12**	4	52.62	942.7
R13	4	8-7-6	3	44.60	731.69
R14	4	12-8-7-10-19	5	61.17	1231.5
R15	4	**12-8-7-10-14-16-17**	7	60.05	1507.99
R16	4	17-16-14-21	4	63.77	759.62
R17	4	17-16-21-23	4	68.58	718.18
R18	4	10-14-16-17	4	46.05	923.71
R19	4	19-23-21-17	4	64.28	888.32
R20	4	19-23-20	3	61.34	649.93
R21	5	**10-8-7-12**	4	54.76	942.7
R22	5	13-11-9	3	39.01	934.89
R23	5	13-11-14-16-17-21	6	66.60	1478.26
R24	5	**13-11-15-9**	4	53.88	1167.86
R25	5	**18-16-17-21-14**	5	55.47	1041.14
R26	5	13-11-15-14-16	5	70.81	1292.97
R27	5	13-11-14-16-17	5	57.38	1283.93
R28	5	13-14-16-17-21	5	43.87	1090.49
R29	5	18-16-17-21-22	5	67.84	1078.79
R30	5	**22-30**	2	47.51	517.47
R31	6	13-11-9	3	46.93	934.89
R32	6	16-14-10	3	45.90	699.78
R33	6	13-11-14-16-17-21	6	74.51	1478.26

R34	6	15-11-13-9	4	65.45	1167.86
R35	6	18-16-17-21-14	5	59.84	1041.14
R36	6	**15-11-13-14-16-17**	6	61.10	1516.9
R37	6	18-16-17-21	4	39.23	818.44
R38	6	13-11-14-16-17	5	65.29	1283.93
R39	6	16-17-21-14	4	57.50	759.62
R40	6	18-16-17-21-22	5	72.21	1078.79
R41	6	29-25	2	57.62	579.89
R42	6	**18-22-29**	3	48.35	885.79
R43	6	22-30	2	40.14	517.47
R44	7	**12-8-7-10**	4	47.20	942.7
R45	7	12-8-7-10-14	5	64.70	1165.4
R46	7	21-17-16-14	4	34.74	759.62
R47	7	23-24-21-17-16	5	51.39	1008.72
R48	7	**21-17-16-14-18**	5	49.50	1041.14
R49	7	21-17-16-18	4	37.67	818.44
R50	7	**19-23-24-26-27-28**	6	48.13	1313.49
R51	7	19-23-24-20	4	62.35	940.47
R52	7	23-24-26-27-28-21	6	68.51	1219.02
R53	7	23-24-30	3	43.43	728.92
R54	8	**10-12-19**	3	68.35	816.65
R55	8	16-14-13-11	4	41.32	1060
R56	8	14-10-12	3	48.20	750.55
R57	8	13-11-15	3	49.76	951.61
R58	8	16-17-21-24-23-14	6	88.58	1231.42
R59	8	**14-13-11-15**	4	54.93	1174.31
R60	8	16-17-21-24-23-26	6	60.26	1193.34
R61	8	16-17-14-13-11-15	6	65.87	1516.9
R62	8	**18-16-17-21-24-23**	6	57.46	1290.24
R63	8	24-23-26-19	4	59.50	945.22
R64	8	16-17-21-14-13-11	6	70.41	1478.26
R65	8	18-16-17-21-22	5	65.72	1078.79
R66	8	24-23-26	3	43.46	656.42
R67	8	18-22-29	3	41.86	885.79
R68	8	30-24-23-26	4	65.07	913.54
R69	9	19-12-10	3	47.92	816.65
R70	9	12-10-14-16	4	67.12	869.21
R71	9	21-17-16-14	4	37.41	759.62
R72	9	24-21-17-16	4	41.00	827.46
R73	9	17-16-14-18	4	51.68	846.81
R74	9	21-17-16-18	4	40.34	818.44
R75	9	**23-24-26-27-28-19**	6	47.94	1313.49
R76	9	23-24-19-20	4	46.51	940.47
R77	9	**21-17-16-14-18**	5	52.18	1041.14
R78	9	23-24-26-27-28-21	6	60.50	1219.02

R79	9	23-24-30	3	35.42	728.92
R80	10	19-12-10	3	47.40	816.65
R81	10	12-10-14-16	4	68.42	869.21
R82	10	21-17-16-14	4	39.74	759.62
R83	10	24-21-17-16	4	41.31	827.46
R84	10	17-16-14-18	4	54.04	846.81
R85	10	21-17-16-18	4	42.67	818.44
R86	10	23-24-26-27-28-19	6	46.17	1313.49
R87	10	23-24-19-20	4	44.74	940.47
R88	10	**21-17-16-14-18**	5	54.51	1041.14
R89	10	**23-24-26-27-28-19-20**	7	61.17	1493.36
R90	10	23-24-26-27-28-21-17	7	67.94	1442.95
R91	10	23-24-30	3	33.64	728.92

APPENDIX B: Detailed Information on Routes Generated by NN Heuristic for problem Instance 1 in the set with 30 Service Points and 10 Regional Depots

Route	Origin	Route Detail	# SP	Distance	Demand
R1	1	**1-2-4-5**	4	60.80	888
R2	1	3	1	31.80	96.16
R3	2	**2-1-5-3**	4	48.97	865.55
R4	2	**4-6**	2	37.76	435.45
R5	3	**2-1-5-4**	4	67.69	888
R6	3	**7-8-10-12**	4	52.62	942.7
R7	3	6	1	31.23	316.84
R8	4	**12-8-7-10-14-16-17**	7	60.05	1507.99
R9	4	19-23-21	3	55.06	664.39
R10	4	20	1	32.49	179.87
R11	4	**6**	1	38.11	316.84
R12	5	**13-11-15-9**	4	53.88	1167.86
R13	5	**18-16-17-21-14**	5	55.47	1041.14
R14	5	**22-30**	2	47.51	517.47
R15	5	**10-8-7-12**	4	54.76	942.7
R16	6	**15-11-13-14-16-17**	6	61.10	1516.9
R17	6	**18-22-29**	3	48.35	885.79
R18	6	9-25	2	72.11	452.22
R19	6	21-10	2	58.93	552.75
R20	6	**30**	1	37.50	257.12
R21	7	**19-23-24-26-27-28**	6	48.13	1313.49
R22	7	**21-17-16-14-18**	5	49.50	1041.14
R23	7	**12-8-7-10**	4	47.20	942.7
R24	7	20	1	25.06	179.87
R25	7	30	1	36.58	257.12
R26	8	**18-16-17-21-24-23**	6	57.46	1290.24
R27	8	**14-13-11-15**	4	54.93	1174.31
R28	8	22-29-30	3	63.16	861.39
R29	8	**10-12-19**	3	68.35	816.65
R30	8	26	1	38.25	184.62
R31	9	**23-24-26-27-28-19**	6	47.94	1313.49
R32	9	**21-17-16-14-18**	5	52.18	1041.14
R33	9	20-12-10	3	69.46	707.72
R34	9	30	1	32.28	257.12
R35	10	**23-24-26-27-28-19-20**	7	61.17	1493.36
R36	10	**21-17-16-14-18**	5	54.51	1041.14
R37	10	12-10	2	43.85	527.85
R38	10	30	1	33.17	257.12

APPENDIX C: Detailed Information on Routes Generated by SAV Heuristic for problem Instance 1 in the set with 30 Service Points and 10 Regional Depots

Route	Origin	Route Detail	# SP	Distance	Demand
R1	1	1	1	4.82	247.08
R2	1	2-4	2	25.24	401.36
R3	1	5-3	2	31.95	335.72
R4	2	1	1	6.38	247.08
R5	2	2	1	3.92	282.75
R6	2	**4-6**	2	37.76	435.45
R7	2	**5-3**	2	39.19	335.72
R8	3	2	1	13.66	282.75
R9	3	7	1	26.02	279.34
R10	3	10	1	32.45	358.42
R11	3	8-12	2	39.49	304.94
R12	3	1-5	2	32.41	486.64
R13	3	4-6	2	36.91	435.45
R14	4	**6**	1	38.11	316.84
R15	4	10	1	15.16	358.42
R16	4	14-16	2	38.74	341.36
R17	4	17-21	2	38.98	418.26
R18	4	19-23	2	37.57	470.06
R19	4	8-7	2	12.36	414.85
R20	4	12-20	2	35.28	349.3
R21	5	10	1	27.89	358.42
R22	5	11	1	17.28	387.77
R23	5	13	1	9.17	330.87
R24	5	18	1	9.31	281.52
R25	5	7-8	2	40.57	414.85
R26	5	15-9	2	38.78	449.22
R27	5	17-30	2	50.11	481.05
R28	5	16-21-12	3	53.50	482.42
R29	5	14-22	2	41.07	483.05
R30	6	11	1	17.49	387.77
R31	6	13	1	17.09	330.87
R32	6	14	1	22.28	222.7
R33	6	18	1	13.68	281.52
R34	6	29	1	32.13	343.92
R35	6	**30**	1	37.50	257.12
R36	6	17-21	2	36.42	418.26
R37	6	16-10	2	42.60	477.08
R38	6	15-9	2	29.74	449.22
R39	6	22-25	2	45.24	496.32

R40	7	10	1	25.35	358.42
R41	7	8-7	2	33.77	414.85
R42	7	16-18	2	35.08	400.18
R43	7	27-28	2	24.57	368.27
R44	7	17-14	2	30.16	446.63
R45	7	24-26	2	29.36	475.16
R46	7	21-30	2	40.30	451.45
R47	7	19-20	2	25.15	468.67
R48	7	23-12	2	43.12	350.69
R49	8	11	1	32.79	387.77
R50	8	13	1	24.47	330.87
R51	8	18	1	7.19	281.52
R52	8	24	1	25.64	290.54
R53	8	29	1	34.03	343.92
R54	8	23-26	2	39.55	365.88
R55	8	21-19	2	36.47	483.13
R56	8	14-12	2	46.42	392.13
R57	8	16-10	2	32.03	477.08
R58	8	22-15	2	41.13	493.32
R59	8	17-30	2	44.70	481.05
R60	9	10	1	33.35	358.42
R61	9	16-14	2	36.72	341.36
R62	9	27-28	2	17.11	368.27
R63	9	21-18	2	35.02	475.85
R64	9	17-12	2	49.92	393.36
R65	9	19-20	2	25.73	468.67
R66	9	26-30	2	47.47	441.74
R67	9	23-24	2	11.71	471.8
R68	10	10	1	35.30	358.42
R69	10	16-14	2	39.07	341.36
R70	10	21-18	2	37.35	475.85
R71	10	17-12	2	52.28	393.36
R72	10	27-28	2	14.86	368.27
R73	10	19-20	2	25.21	468.67
R74	10	26-30	2	45.24	441.74
R75	10	23-24	2	9.94	471.8

APPENDIX D: Service Points – Parts Assignment for ENS Heuristic

SP/Parts	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	1
2	2	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	0	1
6	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	0	1
10	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1
22	2	1	1	1	1	1	1	1	1	1
23	1	1	2	1	1	1	1	1	1	1
24	1	1	1	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1	1	1	1
26	1	1	1	1	1	1	1	1	1	1
27	1	1	1	1	1	1	1	1	1	1
28	1	1	1	1	1	1	1	1	1	1
29	2	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1

APPENDIX E: Service Points – Parts Assignment for NN Heuristic

SP/Parts	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	0	1
6	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	0	1
10	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	1	1	1	1
18	2	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1
22	1	1	1	1	1	1	1	1	1	2
23	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1	1	1	1
26	1	1	1	1	1	1	1	1	1	1
27	1	1	1	1	1	1	1	1	1	1
28	1	1	1	1	1	1	1	1	1	1
29	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1

APPENDIX F: Service Points – Parts Assignment for SAV Heuristic

SP/Parts	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	0	1
6	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	0	1
10	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	1	1	1	1
13	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1
21	1	1	1	1	1	1	1	1	1	1
22	1	1	1	1	1	1	1	1	1	1
23	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1	1	1	1
26	1	1	1	1	1	1	1	1	1	1
27	1	1	1	1	1	1	1	1	1	1
28	1	1	1	1	1	1	1	1	1	1
29	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1

APPENDIX G: Solution Details for the Three Heuristics

IB: Inbound, **OB:** Outbound.

Table G.1 Summary of solutions using ENS generated routes - for the first two problem sizes

Number of SP	Number of RD	Inst.	Number of Routes	Number of RD Opened	Number of Selected Routes	Number of Vehicles	Number of RD per SP	Number of Route per SP	Number of SP w/multiple Routes	Total Cost	Fixed Cost	Transportation Cost	
												IB	OB
30	10	1	91	3	10	13	10.00	3.00	27	69553.69	11381.67	23172.02	35000
30	10	2	58	4	8	12	7.50	3.75	25	80580.75	19570.00	25010.75	36000
30	10	3	52	5	10	15	6.00	3.00	22	93716.93	28653.33	28063.59	37000
30	10	4	116	3	9	12	10.00	3.33	25	60874.93	12488.33	15886.60	32500
30	10	5	92	3	9	12	10.00	3.33	27	66312.73	15011.67	16801.07	34500
30	10	6	77	3	11	14	10.00	2.73	25	71687.13	15456.67	20730.47	35500
30	10	7	86	3	12	15	10.00	2.50	26	70565.90	15830.00	18735.90	36000
30	10	8	79	4	11	15	7.50	2.73	26	67334.83	16940.00	18894.84	31500
30	10	9	77	4	12	16	7.50	2.50	26	76690.28	16286.67	24403.61	36000
30	10	10	68	3	8	11	10.00	3.75	24	75241.90	16296.67	26945.23	32000
50	15	1	171	4	12	16	12.50	4.17	45	98185.26	21942.50	26242.76	50000
50	15	2	140	4	12	16	12.50	4.17	40	106417.74	15881.67	34536.07	56000
50	15	3	155	5	14	19	10.00	3.57	45	112572.27	27061.67	34510.61	51000
50	15	4	198	5	14	19	10.00	3.57	41	102863.11	23336.67	24526.45	55000
50	15	5	155	5	12	17	10.00	4.17	37	116257.14	25976.67	32280.48	58000
50	15	6	198	4	14	18	12.50	3.57	42	95661.25	20471.67	22189.59	53000
50	15	7	192	4	12	16	12.50	4.17	42	107280.79	19608.33	33672.45	54000
50	15	8	145	4	14	18	12.50	3.57	48	113644.71	19915.00	38729.71	55000
50	15	9	180	4	14	18	12.50	3.57	41	100662.20	18366.67	31295.53	51000
50	15	10	150	4	16	20	12.50	3.12	40	112281.69	16985.00	41296.69	54000

Table G.1 Summary of solutions using ENS generated routes - for the first two problem sizes (continued)

			Number and Size of Vehicles														
			IB Vehicles			OB Vehicles			IB Vehicle Utilizations			OB Vehicle Utilizations			Selected Route Distances		
Number of SP	Number of RD	Inst.	Small (1000)	Medium (2000)	Big (5000)	Small (500)	Medium (1000)	Big (2000)	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
30	10	1	0	1	2	5	5	0	48.76	59.97	66.09	75.78	94.17	100.00	37.88	56.85	74.51
30	10	2	1	2	1	3	2	3	36.91	70.12	93.19	54.52	79.00	100.00	48.00	60.91	71.94
30	10	3	3	1	1	5	4	1	49.64	78.99	99.22	55.03	92.21	100.00	42.61	59.75	71.39
30	10	4	1	1	1	4	5	0	75.55	84.30	95.32	81.72	93.45	100.00	52.43	62.18	76.53
30	10	5	1	1	1	4	4	1	69.07	84.53	95.80	38.15	87.08	100.00	38.21	49.94	59.29
30	10	6	0	2	1	7	4	0	62.07	85.97	100.00	62.01	95.63	100.00	39.08	50.33	61.97
30	10	7	0	2	1	9	3	0	69.02	82.50	100.00	56.94	95.59	100.00	43.98	57.32	75.17
30	10	8	1	3	0	9	2	0	70.72	87.99	96.09	84.88	94.47	100.00	35.05	57.36	83.03
30	10	9	1	2	1	9	3	0	49.72	78.86	99.04	41.04	91.46	100.00	36.63	49.84	60.49
30	10	10	0	0	3	4	2	2	42.90	46.49	51.74	68.03	86.51	100.00	37.98	56.18	85.98
50	15	1	1	1	2	5	4	3	73.85	87.80	99.35	69.25	90.02	100.00	36.87	59.33	75.64
50	15	2	1	0	3	1	9	2	50.00	71.41	93.05	64.99	90.42	100.00	46.24	58.49	69.18
50	15	3	1	2	2	9	2	3	71.16	80.34	100.00	54.48	90.06	100.00	37.88	52.66	76.19
50	15	4	2	1	2	7	4	3	50.00	84.26	100.00	52.41	86.32	100.00	52.00	63.97	77.46
50	15	5	1	2	2	2	6	4	51.62	88.31	100.00	61.24	84.54	100.00	49.34	56.50	66.37
50	15	6	1	1	2	8	3	3	78.15	92.91	100.00	75.46	93.38	100.00	36.74	54.24	82.50
50	15	7	1	0	3	1	10	1	58.25	74.60	91.71	79.46	94.25	100.00	35.52	56.32	66.80
50	15	8	0	1	3	6	6	2	57.61	77.73	100.00	78.13	95.60	100.00	46.90	59.99	74.24
50	15	9	1	1	2	8	4	2	78.21	88.65	98.29	46.68	92.50	100.00	34.48	57.75	74.31
50	15	10	0	0	4	11	3	2	50.00	59.36	64.73	82.24	97.78	100.00	37.92	56.38	67.74

Table G.2 Summary of solutions using ENS generated routes - for the last two problem sizes

Number of SP	Number of RD	Inst.	Number of Routes	Number of RD Opened	Number of Selected Routes	Number of Vehicles	Number of RD per SP	Number of Route per SP	Number of SP w/multiple Routes	Total Cost	Fixed Cost	Transportation Cost	
												IB	OB
100	30	1	747	5	22	27	20.00	4.55	77	164902.37	24355.00	47547.37	93000
100	30	2	860	5	22	27	20.00	4.55	81	161087.39	24966.67	35120.72	101000
100	30	3	724	5	23	28	20.00	4.35	88	150973.91	26086.67	31387.25	93500
100	30	4	846	5	22	27	20.00	4.55	81	160373.17	25173.33	40199.83	95000
100	30	5	750	5	22	27	20.00	4.55	85	154278.05	21493.33	35784.72	97000
100	30	6	798	5	22	27	20.00	4.55	83	166306.52	24538.33	44768.18	97000
100	30	7	683	5	20	25	20.00	5.00	92	169765.05	25555.00	46210.05	98000
100	30	8	703	5	23	28	20.00	4.35	92	161679.19	25785.00	34394.20	101500
100	30	9	800	6	21	27	16.67	4.76	86	162889.11	25963.33	40425.78	96500
100	30	10	753	5	23	28	20.00	4.35	77	156503.44	25816.67	33186.78	97500
250	75	1	5056	12	43	55	20.83	5.81	205	340708.45	58240.00	60968.46	221500
250	75	2	4805	12	41	53	20.83	6.10	209	342764.00	55775.00	58489.00	228500
250	75	3	4647	12	41	53	20.83	6.10	212	368240.63	60635.00	75105.63	232500
250	75	4	4746	13	48	61	19.23	5.21	223	355298.09	52303.33	70994.76	232000
250	75	5	5026	13	45	58	19.23	5.56	206	364162.72	54836.67	72826.05	236500
250	75	6	4921	14	43	57	17.86	5.81	208	357075.94	65063.33	70512.61	221500
250	75	7	4414	12	43	55	20.83	5.81	211	358685.13	55973.33	77211.80	225500
250	75	8	4723	12	44	56	20.83	5.68	210	346909.42	53935.00	66974.42	226000
250	75	9	4691	13	42	55	19.23	5.95	227	340119.49	53415.00	65704.49	221000
250	75	10	4540	12	47	59	20.83	5.32	210	352628.81	67430.00	53698.81	231500

Table G.2 Summary of solutions using ENS generated routes - for the last two problem sizes (continued)

			Number and Size of Vehicles														
			IB Vehicles			OB Vehicles			IB Vehicle Utilizations			OB Vehicle Utilizations			Selected Route Distances		
Number of SP	Number of RD	Inst.	Small (1000)	Medium (2000)	Big (5000)	Small (500)	Medium (1000)	Big (2000)	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
100	30	1	0	0	5	11	3	8	68.22	91.95	99.97	71.74	95.98	100.00	35.53	59.42	82.73
100	30	2	0	0	5	9	3	10	85.21	94.45	100.00	56.36	89.37	100.00	37.35	53.53	72.28
100	30	3	0	1	4	11	6	6	96.22	99.16	100.00	64.08	92.79	100.00	40.62	57.91	73.30
100	30	4	0	0	5	9	6	7	68.42	87.70	100.00	34.07	87.49	100.00	44.63	58.27	76.72
100	30	5	0	0	5	5	13	4	55.48	90.57	100.00	40.53	94.56	100.00	45.24	58.28	77.56
100	30	6	0	0	5	10	3	9	71.41	92.76	100.00	67.92	91.89	100.00	48.10	59.41	79.81
100	30	7	0	0	5	5	6	9	88.38	95.29	100.00	62.56	91.42	100.00	47.40	58.88	75.40
100	30	8	0	0	5	9	6	8	75.94	94.36	100.00	64.45	93.14	100.00	42.10	57.64	83.41
100	30	9	1	0	5	6	8	7	56.54	90.65	100.00	70.93	92.73	100.00	43.47	54.69	66.12
100	30	10	0	0	5	11	4	8	84.66	94.79	100.00	62.72	93.33	100.00	44.70	55.14	73.06
250	75	1	0	0	12	12	5	26	78.43	93.69	100.00	28.77	89.02	100.00	39.31	53.79	68.20
250	75	2	0	0	12	6	7	28	74.81	96.54	100.00	17.61	87.38	100.00	42.55	52.91	64.95
250	75	3	0	0	12	7	3	31	87.48	97.27	100.00	56.57	87.17	100.00	39.82	53.28	64.59
250	75	4	1	0	12	17	6	25	50.00	92.01	100.00	48.17	90.12	100.00	40.81	54.63	84.63
250	75	5	0	0	13	13	2	30	68.09	92.05	100.00	57.00	87.86	100.00	42.41	54.63	69.92
250	75	6	0	0	14	13	3	27	50.00	81.03	100.00	56.38	91.67	100.00	36.66	53.04	67.26
250	75	7	0	0	12	12	3	28	71.94	94.86	100.00	53.67	87.87	100.00	35.68	52.36	65.83
250	75	8	0	0	12	15	0	29	79.85	96.38	100.00	20.79	87.37	100.00	36.93	54.19	70.85
250	75	9	0	0	13	13	0	29	74.11	91.81	100.00	25.98	91.89	100.00	35.39	55.02	71.02
250	75	10	0	0	12	17	3	27	89.15	97.40	100.00	34.03	89.70	100.00	43.51	56.31	69.37

Table G.3 Summary of solutions using NN generated routes - for the first two problem sizes

Number of SP	Number of RD	Inst.	Number of Routes	Number of RD Opened	Number of Selected Routes	Number of Vehicles	Number of RD per SP	Number of Route per SP	Number of SP w/multiple Routes	Total Cost	Fixed Cost	Transportation Cost IB	Transportation Cost OB
30	10	1	38	4	9	13	7.50	3.33	29	72601.87	15791.67	22310.20	34500
30	10	2	26	4	9	13	7.50	3.33	23	81080.75	19570.00	25010.75	36500
30	10	3	27	5	11	16	6.00	2.73	25	97702.68	28613.33	29589.35	39500
30	10	4	38	3	9	12	10.00	3.33	26	66874.93	12488.33	15886.60	38500
30	10	5	38	4	11	15	7.50	2.73	29	76366.71	18625.00	20241.71	37500
30	10	6	33	4	10	14	7.50	3.00	27	77312.24	20293.33	18018.91	39000
30	10	7	43	3	10	13	10.00	3.00	27	75185.20	15830.00	18355.20	41000
30	10	8	37	4	10	14	7.50	3.00	28	71656.89	16808.33	19848.55	35000
30	10	9	35	4	11	15	7.50	2.73	26	81710.70	17898.33	26312.36	37500
30	10	10	30	4	9	13	7.50	3.33	21	76394.48	20166.67	19727.82	36500
50	15	1	64	4	12	16	12.50	4.17	44	104908.73	21086.33	29822.40	54000
50	15	2	60	4	13	17	12.50	3.85	40	105892.27	15868.33	35523.93	54500
50	15	3	62	5	13	18	10.00	3.85	46	114595.97	27158.33	32937.64	54500
50	15	4	75	4	14	18	12.50	3.57	41	108810.44	19853.33	27957.11	61000
50	15	5	61	5	11	16	10.00	4.55	41	118494.74	25976.67	35018.08	57500
50	15	6	66	4	12	16	12.50	4.17	44	101848.36	19045.00	28803.36	54000
50	15	7	71	5	14	19	10.00	3.57	44	109361.50	24685.00	29676.50	55000
50	15	8	58	5	15	20	10.00	3.33	40	118918.10	24681.67	34736.43	59500
50	15	9	70	4	13	17	12.50	3.85	41	106880.23	18486.67	31893.56	56500
50	15	10	58	4	14	18	12.50	3.57	39	116341.19	16985.00	38356.19	61000

Table G.3 Summary of solutions using NN generated routes - for the first two problem sizes (continued)

			Number and Size of Vehicles															
			IB Vehicles			OB Vehicles			IB Vehicle Utilizations			OB Vehicle Utilizations			Selected Route Distances		
Number of SP	Number of RD	Inst.	Small (1000)	Medium (2000)	Big (5000)	Small (500)	Medium (1000)	Big (2000)	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
30	10	1	1	2	1	4	4	1	65.05	73.27	85.48	74.67	89.85	100.00	37.76	53.33	72.11
30	10	2	1	2	1	4	3	2	50.00	70.61	81.59	54.93	84.56	100.00	26.20	55.56	69.89
30	10	3	2	3	0	5	6	0	73.67	90.57	100.00	65.63	89.23	100.00	42.61	51.99	66.32
30	10	4	1	1	1	3	4	2	81.08	81.53	82.02	48.82	71.28	99.12	27.91	54.77	63.83
30	10	5	2	1	1	7	3	1	64.21	80.34	92.34	38.46	82.38	100.00	36.34	51.30	71.52
30	10	6	2	1	1	5	3	2	67.16	84.38	100.00	48.94	77.83	100.00	29.61	49.06	66.76
30	10	7	1	0	2	4	4	2	57.35	69.13	83.73	34.14	72.41	100.00	26.14	44.46	68.44
30	10	8	1	3	0	6	3	1	70.68	88.50	98.58	51.54	83.32	100.00	46.36	54.72	66.42
30	10	9	1	2	1	6	5	0	50.71	76.54	99.16	35.17	83.21	100.00	28.70	51.42	65.51
30	10	10	2	1	1	3	5	1	65.62	83.94	99.55	41.61	78.50	100.00	28.56	53.50	68.51
50	15	1	0	2	2	3	6	3	69.21	80.96	90.74	39.99	81.23	100.00	35.26	57.70	73.13
50	15	2	1	0	3	7	1	5	62.95	80.76	96.75	63.15	88.72	100.00	34.61	57.52	73.10
50	15	3	1	2	2	6	3	4	61.49	77.81	98.56	30.65	81.15	100.00	28.94	51.75	65.38
50	15	4	1	0	3	5	5	4	60.35	81.23	100.00	16.46	77.41	100.00	33.26	55.13	64.14
50	15	5	1	1	3	2	3	6	49.95	74.47	96.66	22.45	73.28	100.00	27.17	55.23	70.03
50	15	6	1	0	3	4	4	4	48.71	78.71	100.00	47.42	83.85	100.00	38.57	55.73	69.01
50	15	7	1	2	2	6	6	2	46.80	81.33	100.00	68.15	88.61	100.00	37.36	55.21	65.88
50	15	8	2	1	2	9	1	5	80.20	91.68	100.00	40.18	80.54	100.00	26.63	52.63	66.61
50	15	9	1	1	2	6	2	5	83.05	86.67	95.26	44.33	72.99	97.95	34.48	49.86	60.07
50	15	10	0	1	3	5	5	4	63.22	74.36	100.00	28.72	76.11	100.00	39.53	53.48	68.59

Table G.4 Summary of solutions using NN generated routes - for the last two problem sizes

Number of SP	Number of RD	Inst.	Number of Routes	Number of RD Opened	Number of Selected Routes	Number of Vehicles	Number of RD per SP	Number of Route per SP	Number of SP w/multiple Routes	Total Cost	Fixed Cost	Transportation Cost	
												IB	OB
100	30	1	199	6	22	28	16.67	4.55	80	174050.80	29110.00	47940.80	97000
100	30	2	210	5	20	25	20.00	5.00	78	158840.67	24131.67	36709.01	98000
100	30	3	190	5	23	28	20.00	4.35	82	156443.32	22885.00	38058.32	95500
100	30	4	203	5	20	25	20.00	5.00	83	161647.00	25265.00	42382.00	94000
100	30	5	197	5	18	23	20.00	5.56	88	159852.13	22721.67	38130.47	99000
100	30	6	202	5	20	25	20.00	5.00	81	170017.58	26418.33	45599.24	98000
100	30	7	192	5	21	26	20.00	4.76	88	173254.11	25675.00	47079.11	100500
100	30	8	202	5	22	27	20.00	4.55	83	165179.20	25785.00	34394.20	105000
100	30	9	206	6	21	27	16.67	4.76	85	168482.85	26971.67	45011.18	96500
100	30	10	201	5	23	28	20.00	4.35	80	164876.40	26935.00	34441.40	103500
250	75	1	901	12	40	52	20.83	6.25	204	334588.74	55066.67	67522.08	212000
250	75	2	854	12	41	53	20.83	6.10	214	343974.44	59631.67	55842.78	228500
250	75	3	856	12	38	50	20.83	6.58	215	351905.62	60868.33	74037.29	217000
250	75	4	872	12	45	57	20.83	5.56	215	336950.98	51560.00	54890.98	230500
250	75	5	915	12	40	52	20.83	6.25	213	349278.83	52030.00	63248.83	234000
250	75	6	889	13	41	54	19.23	6.10	209	338731.73	56446.67	65785.06	216500
250	75	7	828	12	42	54	20.83	5.95	203	352775.21	57661.67	80113.54	215000
250	75	8	857	12	43	55	20.83	5.81	214	335822.48	53771.67	62550.82	219500
250	75	9	878	12	44	56	20.83	5.68	227	343642.91	51110.00	62532.92	230000
250	75	10	870	12	45	57	20.83	5.56	208	350153.90	65235.00	60418.90	224500

Table G.4 Summary of solutions using NN generated routes - for the last two problem sizes (continued)

			Number and Size of Vehicles														
			IB Vehicles			OB Vehicles			IB Vehicle Utilizations			OB Vehicle Utilizations			Selected Route Distances		
Number of SP	Number of RD	Inst.	Small (1000)	Medium (2000)	Big (5000)	Small (500)	Medium (1000)	Big (2000)	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
100	30	1	0	2	4	9	5	8	79.35	94.11	99.58	33.34	87.07	100.00	27.27	55.37	68.49
100	30	2	0	0	5	5	6	9	83.04	94.45	100.00	50.10	88.04	100.00	48.82	56.27	68.28
100	30	3	0	1	4	11	5	7	97.80	99.16	100.00	67.61	92.54	100.00	40.59	55.81	66.04
100	30	4	0	0	5	6	6	8	64.35	87.70	100.00	35.28	88.32	100.00	39.23	55.78	66.41
100	30	5	0	0	5	2	5	11	71.57	90.57	100.00	53.51	83.98	100.00	42.46	54.42	67.22
100	30	6	0	0	5	5	6	9	83.84	92.76	100.00	57.36	89.63	100.00	37.95	55.13	68.13
100	30	7	0	0	5	6	6	9	78.58	95.29	100.00	62.08	90.73	100.00	40.35	55.39	65.07
100	30	8	0	0	5	6	7	9	87.77	94.36	100.00	33.76	85.75	100.00	34.23	53.30	68.99
100	30	9	1	0	5	7	6	8	77.06	89.18	100.00	23.99	87.20	100.00	41.50	55.02	63.21
100	30	10	0	0	5	8	7	8	84.53	94.79	100.00	60.12	87.58	100.00	32.10	52.45	67.07
250	75	1	0	0	12	10	4	26	79.98	93.69	100.00	37.15	91.24	100.00	39.00	52.93	70.26
250	75	2	0	0	12	6	7	28	85.95	96.54	100.00	52.27	88.49	100.00	41.76	52.04	62.23
250	75	3	0	0	12	5	5	28	89.51	97.27	100.00	71.50	92.36	100.00	39.59	51.44	60.21
250	75	4	0	0	12	12	7	26	77.01	96.34	100.00	60.19	88.88	100.00	40.58	53.82	69.23
250	75	5	0	0	12	3	7	30	96.71	99.73	100.00	33.24	86.41	100.00	43.92	53.10	64.44
250	75	6	0	0	13	9	7	25	58.19	87.26	100.00	37.49	92.24	100.00	40.05	51.75	63.69
250	75	7	0	0	12	12	5	25	66.66	94.86	100.00	56.96	93.66	100.00	39.73	52.08	62.46
250	75	8	0	0	12	11	8	24	88.12	96.38	100.00	57.40	94.37	100.00	38.52	53.67	66.95
250	75	9	0	0	12	13	2	29	95.27	99.46	100.00	48.26	90.24	100.00	36.27	51.30	60.75
250	75	10	0	0	12	13	8	24	90.00	97.40	100.00	61.35	93.57	100.00	39.52	52.75	66.79

Table G.5 Summary of solutions using SAV generated routes - for the first two problem sizes

Number of SP	Number of RD	Inst.	Number of Routes	Number of RD Opened	Number of Selected Routes	Number of Vehicles	Number of RD per SP	Number of Route per SP	Number of SP w/multiple Routes	Total Cost	Fixed Cost	Transportation Cost	
												IB	OB
30	10	1	75	3	18	21	10.00	1.67	28	79553.69	11381.67	23172.02	45000
30	10	2	54	4	19	23	7.50	1.58	24	96309.16	19618.33	27190.82	49500
30	10	3	63	5	21	26	6.00	1.43	23	110678.14	28613.33	27564.81	54500
30	10	4	87	3	17	20	10.00	1.76	25	71041.47	13720.00	14821.47	42500
30	10	5	81	3	19	22	10.00	1.58	27	79312.73	15011.67	16801.07	47500
30	10	6	68	4	18	22	7.50	1.67	26	83013.49	20715.00	17298.49	45000
30	10	7	87	3	20	23	10.00	1.50	27	84185.20	15830.00	18355.20	50000
30	10	8	62	4	16	20	7.50	1.88	27	76422.04	18891.67	17530.38	40000
30	10	9	68	4	19	23	7.50	1.58	27	88190.28	16286.67	24403.61	47500
30	10	10	68	4	17	21	7.50	1.76	24	87397.05	20166.67	20730.39	46500
50	15	1	137	4	25	29	12.50	2.00	44	116329.89	21102.00	26727.89	68500
50	15	2	148	4	29	33	12.50	1.72	40	123908.01	17648.33	31759.68	74500
50	15	3	141	5	27	32	10.00	1.85	46	133491.71	26768.33	35223.37	71500
50	15	4	192	4	30	34	12.50	1.67	40	125064.80	19881.67	28183.13	77000
50	15	5	150	5	29	34	10.00	1.72	40	135294.00	27463.33	33330.67	74500
50	15	6	164	4	28	32	12.50	1.79	45	116781.50	20471.67	24309.83	72000
50	15	7	168	4	28	32	12.50	1.79	45	129178.03	20353.33	34824.70	74000
50	15	8	131	4	29	33	12.50	1.72	45	135684.63	19965.00	39219.63	76500
50	15	9	156	5	28	33	10.00	1.79	44	124345.52	24646.67	27698.85	72000
50	15	10	127	5	31	36	10.00	1.61	41	138013.04	19950.00	38563.04	79500

Table G.5 Summary of solutions using SAV generated routes - for the first two problem sizes (continued)

			Number and Size of Vehicles														
			IB Vehicles			OB Vehicles			IB Vehicle Utilizations			OB Vehicle Utilizations			Selected Route Distances		
Number of SP	Number of RD	Inst.	Small (1000)	Medium (2000)	Big (5000)	Small (500)	Medium (1000)	Big (2000)	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
30	10	1	0	1	2	18	0	0	47.33	59.97	67.52	49.42	78.26	99.26	3.92	29.61	45.24
30	10	2	1	2	1	18	1	0	64.39	79.06	95.32	47.41	73.55	99.78	2.89	32.08	63.68
30	10	3	3	1	1	20	1	0	53.26	85.18	93.86	19.26	66.53	100.00	0.00	26.64	44.71
30	10	4	1	1	1	17	0	0	75.92	84.11	94.38	54.91	76.52	92.11	10.21	30.73	59.11
30	10	5	1	1	1	19	0	0	73.84	83.89	100.00	38.46	76.37	99.18	5.62	29.68	82.22
30	10	6	2	1	1	18	0	0	73.02	78.86	94.21	47.02	78.00	99.89	4.69	33.27	46.07
30	10	7	1	0	2	20	0	0	55.53	69.13	83.73	48.68	70.20	97.18	8.82	29.31	60.89
30	10	8	2	1	1	16	0	0	58.81	74.38	84.88	28.09	76.65	99.53	18.86	34.58	48.86
30	10	9	1	2	1	19	0	0	46.34	70.07	96.32	43.10	72.30	96.57	0.45	30.14	51.77
30	10	10	1	3	0	15	2	0	99.12	99.59	100.00	31.66	72.01	93.49	8.72	29.16	38.81
50	15	1	1	1	2	22	3	0	70.01	83.18	100.00	55.98	78.07	98.55	11.36	30.06	64.05
50	15	2	1	1	2	28	1	0	89.70	94.33	99.76	29.13	81.80	99.69	8.79	33.90	75.65
50	15	3	1	2	2	25	2	0	54.99	81.35	93.66	37.09	77.88	98.43	2.55	24.03	45.50
50	15	4	0	2	2	29	1	0	67.19	90.77	100.00	53.96	79.11	100.00	1.30	30.83	70.78
50	15	5	2	1	2	28	1	0	74.30	89.88	100.00	43.78	81.16	99.00	8.16	32.49	64.45
50	15	6	1	0	3	27	1	0	65.45	73.97	83.47	52.07	80.47	99.96	12.89	35.72	66.23
50	15	7	0	2	2	26	2	0	61.80	87.69	98.01	37.83	79.06	98.10	2.00	27.29	58.48
50	15	8	0	1	3	27	2	0	57.89	76.32	95.42	63.19	80.81	99.14	9.37	26.18	48.88
50	15	9	3	0	2	27	1	0	81.20	90.17	100.00	35.51	75.70	96.18	7.91	30.31	67.35
50	15	10	2	0	3	30	1	0	53.86	73.09	82.35	26.95	74.71	100.00	9.69	32.21	56.33

Table G.6 Summary of solutions using SAV generated routes - for the last two problem sizes

Number of SP	Number of RD	Inst.	Number of Routes	Number of RD Opened	Number of Selected Routes	Number of Vehicles	Number of RD per SP	Number of Route per SP	Number of SP w/multiple Routes	Total Cost	Fixed Cost	Transportation Cost	
												IB	OB
100	30	1	601	6	55	61	16.67	1.82	77	215814.32	29126.67	43187.66	143500
100	30	2	652	5	52	57	20.00	1.92	77	200402.90	24093.33	40309.57	136000
100	30	3	579	5	53	58	20.00	1.89	83	196610.38	25268.33	34842.04	136500
100	30	4	598	6	50	56	16.67	2.00	81	198138.13	31056.67	38081.47	129000
100	30	5	594	5	56	61	20.00	1.79	89	200860.81	21558.33	35302.47	144000
100	30	6	632	5	52	57	20.00	1.92	82	207734.45	25710.00	46024.45	136000
100	30	7	582	5	56	61	20.00	1.79	91	220096.54	25578.33	46518.21	148000
100	30	8	622	5	54	59	20.00	1.85	85	208308.79	24803.33	40505.46	143000
100	30	9	605	5	54	59	20.00	1.85	85	204466.28	21420.00	44046.28	139000
100	30	10	569	5	56	61	20.00	1.79	81	201399.33	25966.67	33432.67	142000
250	75	1	3850	12	128	140	20.83	1.95	208	448488.93	57673.33	66815.60	324000
250	75	2	3890	12	131	143	20.83	1.91	216	468583.67	57980.00	73103.67	337500
250	75	3	3661	12	130	142	20.83	1.92	215	466754.89	61426.67	72328.22	333000
250	75	4	3785	12	130	142	20.83	1.92	216	444024.78	52045.00	60979.78	331000
250	75	5	4049	12	135	147	20.83	1.85	210	462749.35	50325.00	66924.36	345500
250	75	6	3793	12	130	142	20.83	1.92	211	443100.63	50921.67	61178.97	331000
250	75	7	3587	12	123	135	20.83	2.03	210	452283.45	54760.00	78023.45	319500
250	75	8	3590	12	126	138	20.83	1.98	215	452083.86	54386.67	68697.19	329000
250	75	9	3830	13	133	146	19.23	1.88	233	460185.11	53128.33	66556.77	340500
250	75	10	3890	12	136	148	20.83	1.84	211	472639.13	66938.33	59700.80	346000

Table G.6 Summary of solutions using SAV generated routes - for the last two problem sizes (continued)

			Number and Size of Vehicles														
			IB Vehicles			OB Vehicles			IB Vehicle Utilizations			OB Vehicle Utilizations			Selected Route Distances		
Number of SP	Number of RD	Inst.	Small (1000)	Medium (2000)	Big (5000)	Small (500)	Medium (1000)	Big (2000)	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.
100	30	1	1	1	4	52	3	0	99.83	99.96	100.00	39.89	79.36	99.50	0.35	31.06	63.77
100	30	2	0	0	5	50	1	1	88.09	94.45	99.13	46.66	83.96	99.79	4.32	32.80	48.40
100	30	3	0	1	4	51	2	0	97.26	99.13	100.00	37.40	79.03	99.79	4.69	32.28	57.11
100	30	4	1	1	4	48	2	0	88.04	94.97	98.65	41.53	84.28	99.75	13.36	33.35	52.81
100	30	5	0	0	5	54	2	0	59.97	90.57	100.00	23.57	77.45	99.96	4.93	31.26	58.54
100	30	6	0	0	5	49	3	0	71.41	92.76	99.78	32.09	84.49	99.90	4.03	31.76	59.92
100	30	7	0	0	5	52	4	0	80.51	95.29	100.00	44.25	79.12	100.00	8.30	34.23	64.00
100	30	8	0	0	5	50	4	0	84.32	94.36	99.75	41.64	81.27	100.00	10.14	34.03	69.48
100	30	9	0	0	5	52	2	0	83.52	93.07	100.00	46.63	82.81	99.70	3.78	27.15	52.67
100	30	10	0	0	5	55	1	0	88.00	94.79	98.32	33.49	82.92	99.95	4.73	33.32	54.96
250	75	1	0	1	11	126	2	0	88.21	98.10	100.00	38.44	86.65	100.00	5.24	33.49	59.43
250	75	2	0	0	12	126	5	0	70.39	96.54	100.00	37.46	85.17	100.00	9.83	32.63	60.93
250	75	3	0	0	12	127	2	1	75.15	97.27	100.00	42.05	86.33	100.00	1.55	33.48	69.64
250	75	4	0	0	12	127	3	0	83.87	96.34	100.00	36.67	86.84	100.00	3.86	33.05	64.37
250	75	5	0	0	12	132	2	1	98.93	99.73	100.00	29.69	85.17	100.00	9.72	33.32	61.07
250	75	6	0	0	12	127	3	0	72.99	94.54	100.00	43.89	85.19	100.00	13.49	34.30	56.68
250	75	7	0	0	12	119	2	2	71.84	94.86	100.00	35.32	86.71	100.00	7.95	32.25	57.95
250	75	8	0	0	12	120	5	1	87.77	96.38	100.00	41.62	85.99	100.00	6.31	33.91	68.21
250	75	9	1	0	12	129	4	0	89.40	97.58	100.00	45.20	87.08	100.00	9.98	35.41	74.29
250	75	10	0	0	12	133	3	0	83.83	97.40	100.00	40.14	84.03	100.00	2.80	34.52	59.30