

**EXACT SOLUTIONS
FOR LOCATION-ROUTING PROBLEMS
WITH TIME WINDOWS
USING BRANCH-AND-PRICE METHOD**

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PREFACE

This Ph.D. dissertation consists of the research effort and results of the following journal and conference papers.

Journal Papers

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Conference Papers

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ABSTRACT

The distribution network design is one of the most important strategic decision that need to be optimized for the efficient long-term operation of whole supply chain. Integrated logistics systems to optimize a product support and customer service have become a primary necessity of private and public firms. The decisions made for network design determine the number and locations of facility (i.e. factory, warehouse, or depot), select the distribution channel to customers, and identify the transportation volume among distributed facilities for an extended time horizon. Determining a suitable location of the business center is considered one of the essential steps in supply chain management. It involves the process to locate a set of facilities to minimize the cost of satisfying a set of demands with respect to a set of constraints. Thus, the facility location is required at several points throughout the supply chain.

This problem usually involves making tradeoffs the cost components include the costs of setting up and operating the facility, and the transportation costs. These two cost components must be balanced. The use of warehouses provides a flexibility to respond to changes in the demand and customer services and can result in significant cost savings due to economies of scale in transportation costs. An increasing number of facilities decreases total transportation cost. However, if the number of facilities increased to a point where there is a significant loss of economies of scale in inbound transportation, increasing the number of facilities increases total transportation cost.

Traditionally, the facility location and vehicle routing has been determined and carried out at the different levels. While the routing can be solved more frequently at the short term operational stage, the facility must be located earlier in the long term strategic planning. Some argue that an integration of these two problems is impractical since they are in the different planning framework, which makes it inappropriate to calculate them together. Eventually, it was proved that the combination of Location-Routing Problem (LRP) reduces the cost over the long-term horizon. Solving them together early in the planning horizon provides benefits and positive impacts for both operators and society.

Moreover, to improve the customers' satisfaction, just in time scheduling has become a key element in the modern distribution management. Since the customers often request the service time and deadlines, the future LRP studies should be extended to consider the presence of time windows. Despite its importance, from our best knowledge of literature, all of the LRP studies that considered time windows bases on heuristic approaches, none of them attempted at the optimal solution using the exact algorithm. This study, therefore, proposes the integrated approach to determine the exact solution of the Location-Routing Problem with Time Windows (LRPTW) using branch-and-price algorithm.

Branch-and-price algorithm follows the idea of the Dantzig-Wolfe decomposition by splitting original formulation into two problems: a master problem and a subproblem. The master problem considers only a subset of variables from the original while the subproblem identifies the new variables. The objective function of the subproblem considers the reduced cost of the new variables with respect to the current dual variables. The master problem uses a simplex algorithm, and the subproblem uses an Elementary Shortest Path Problem with Resource Constraints (ESPPRC) as the main tools. The master problem is solved using an initial solution that can be any feasible solution that meets all constraints. From this step, the dual prices of each constraint in the master problem are obtained. Then, the reduced cost is calculated and utilized in the objective function of the subproblem. After that, the variables in the master problem with negative reduced cost must be identified. Then, these variables are added to the master problem in a form of columns and resolved iteratively. The process is repeated until the subproblem solution has only non-negative reduced costs columns. Theoretically, in that particular incidence, the solution of the master problem is the optimal solution.

The new test instances are generated from the VRPTW Solomon benchmark instances, with the first 10- and 25-customer, to evaluate the performance of our algorithm. The original depot is replaced by the new three potential depot sites together with other parameters used in the LRPTW formulations. It is proved that the new exact algorithm proposed in this research can solve the LRPTW instances to optimality within an acceptable time. Moreover, the exact solutions of the LRPTW can reduce the required number of vehicles as well as the distance traveled as compared to the exact VRPTW solutions. Therefore, further emphasizes the importance of the LRPTW and the advantage of an exact solution approach for this variation. Also, the characteristics of the

time window constraints affecting the location and routing processes in the LRPTW are also intensively explored.

The first application of LRPTW is examined in Osaka distribution network. It is proposed to evaluate the cost structure on different factors of LRPTW which is rarely observed by the exact algorithm. The distribution network is extracted from the real operation of logistics firm while the travel time is collected by the GPS and the traffic census data of the Osaka city. The main decision factors for LRPTW are the location of the depot, depot size, and vehicle size. It is found that the large size depot together with the large size vehicle is among the best scheme in our case study. The depot located in Minato-ku is the best location for the large size depot scenario by the fact that it is located in the low-price area. Furthermore, the large size vehicle of three-ton trucks is proved to be the best choice. Regardless of the highest vehicle fixed cost, the number of the vehicle can be reduced to only seven vehicles, but remain the high truckload, making the lowest delivered cost option.

Another application is proposed for humanitarian relief operations in Ishinomaki. The city was attacked by the tsunami triggered from the great Japanese earthquake on March 11, 2011. 3,417 people were killed, 53,742 houses were destroyed and left 30,930 people displaced. The LRPTW tabu search is adapted to determine the location of refugee centers or depots to inventory food and important commodities for the victims. Apart from the two depot locations used in the real operation, we propose eight additional locations all over the city and determine the optimal locations in four different scenarios. The results are expected to provide the broader perspective on how mathematical models can support the humanitarian logistics in disaster relief operation.

Nevertheless, it is observed that to implement the LRPTW scheme into the real world supply chain operation, it requires more comprehensive data to achieve the goal. These testing instances and application limit only a portion of selected customers and demand points. Furthermore, it is found that the exact algorithms are usually computationally expensive. To handle the larger problems, the approximate method or the combination of exact and metaheuristic approach as a hybrid algorithm is proposed for the further research. It is a promising approach to accelerate the process without losing much on the exact optimal solution.

LIST OF ABBREVIATIONS

CLRP	Capacitated Location-Routing Problem
CVRP	Capacitated Vehicle-Routing Problem
ESPPRC	Elementary Shortest Path Problem with Resource Constraints
GDP	Gross Domestic Product
GPS	Global Positioning System
IP	Integer Programming
JSDF	Japan Self Defense Force
LP	Linear Programming
LPI	Logistics Performance Index
LRP	Location-Routing Problem
LRPTW	Location-Routing Problem with Time Windows
MLIT	Ministry of Land, Infrastructure, Transport and Tourism
NP-Hard	Non-Deterministic Polynomial-Time Hard
RMP	Restricted Master Problem
RPP	Rural Postman Problem
SPPRC	Shortest Path Problem with Resource Constraints
VRP	Vehicle-Routing Problem
VRPTW	Vehicle-Routing Problem with Time Windows

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Chapter 1

Introduction

- 1.1 Background
- 1.2 Research Motivation
- 1.3 Research Purpose and Objectives
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1.1 Background

Logistics is the process of planning, implementing, and controlling the right materials in the right amount to the right places at the right time with the right cost while the given performance measures are optimized. It was originated as a branch of military science to describe the army's procedure with food, clothing, ammunition, spare parts, or the transportation of troops themselves. For many decades, the term logistics had been always the subject of war affairs. Until the early '60s where the regulation, competitive, information technology, or globalization motivated the logistics science in the modern business form as presented today.

Nowadays, the development of global economic led to the creation of borderless supply chain, complex business network, and goods flow movement. The traditional industrial, where the raw materials, end products, and customers are locally neighbored, replaces by a globalized economy. It also helps in economic transactions, serving as a major enabler of the growth of trade and commerce. There is a strict relationship between economic development and logistics expenditure (Bowersox, et al., 2003). Improving logistics facilities prove to level up the countries' economic (FHWA, 2005; Shepherd, 2011; Gilmore, 2014). While logistics costs represent about less than 10% of GDP in developed countries, it costs more than 20% of GDP in developing countries as shown in Figure 1.1. The World Bank states "*high logistic costs (especially in developing countries) cause a serious impediment to the country's economic growth*" (Bahagia, et al., 2013).

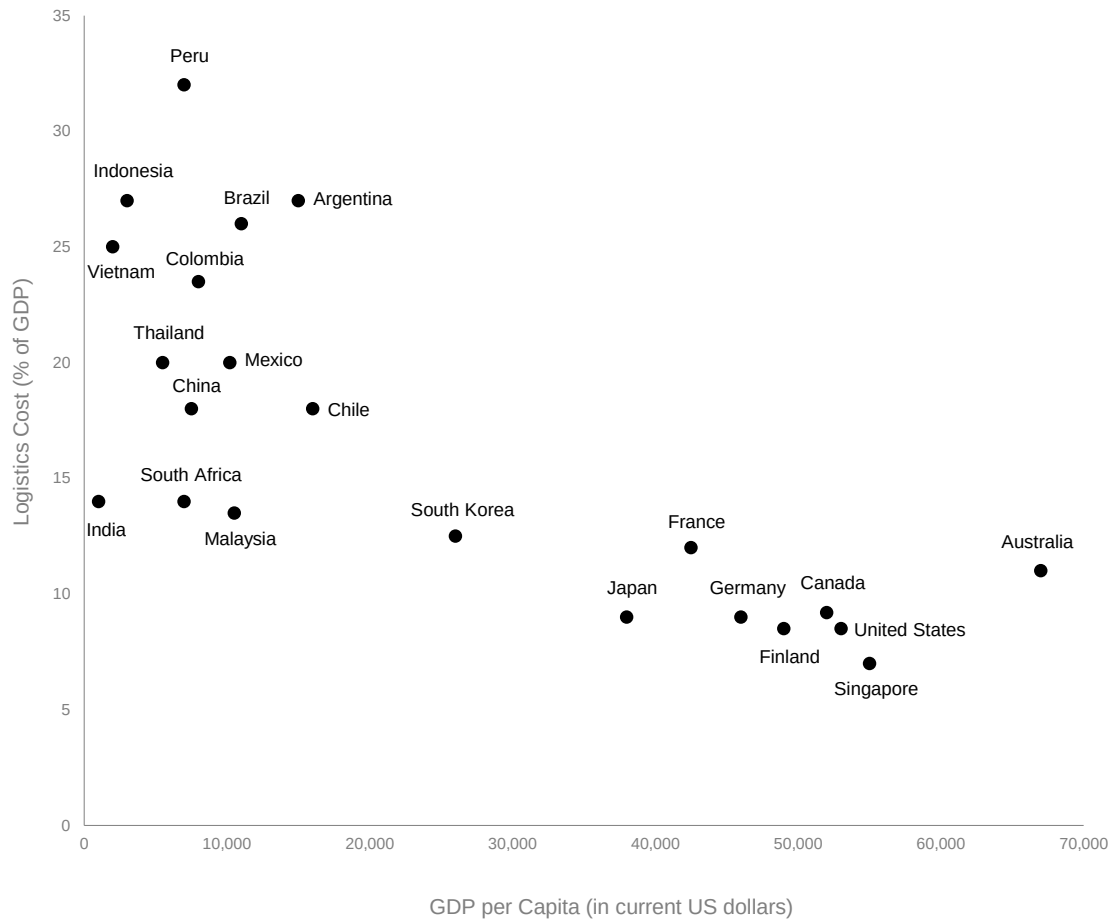


Figure 1.1 Relationship between Country GDP and Logistics Cost (Rodrigue, et al., 2013)

To improve the logistics performance at a country level, the World Bank develops the “Logistics Performance Index (LPI)” to help countries address the challenges and opportunities they face in trade logistics. It guides what countries can do to improve their performance (World Bank, 2015). The results based on the worldwide survey of operators in every country and reflected both qualitative and quantitative measures. Six key dimensions are weighted and represented the country’s LPI, including;

1. Efficiency of the clearance process by border control agencies, including the Customs
2. Quality of trade and transport related infrastructure
3. Ease of arranging competitively priced shipments
4. Competence and quality of logistics services
5. Ability to track and trace consignments

6. Timeliness of shipments in reaching the destination within the scheduled or expected delivery time.

More results of the latest LPI including international LPI (i.e. global ranking and country score card) and domestic LPI (i.e. environment and institutions, and performance) present at www.lpi.worldbank.org.

Considering the domestic level, the key activities of logistics that contribute to the total cost include customer service, transportation, warehouse, inventory management, and other processes (Figure 1.2). Transportation costs consist of inbound traveling costs from the plants or suppliers to the warehouses/depots, and the outbound traveling costs from the warehouses/depots to the customers. Warehousing costs are the fixed and operating costs. The former is the combination of land acquisition, building, machinery, maintenance, and administrative costs. The latter include labor, ordering, and material handling (Srivastava, 1986). They are also essential to the effective coordinate and completion of logistics task. The proportion of logistics cost depends on countries and their economic. The logistics costs in the countries where economic rely on the natural resource will generate higher logistic cost than the countries focusing on advanced services (Rodrigue, et al., 2013). Three logistics strategies have to be fully addressed and interrelated to achieve the customer service goal including location, inventory, and transport decisions. Since there is a strong relationship among these logistics components, reducing transportation cost might not only be achieved by improving transportation features themselves (Ghiani, et al., 2013).

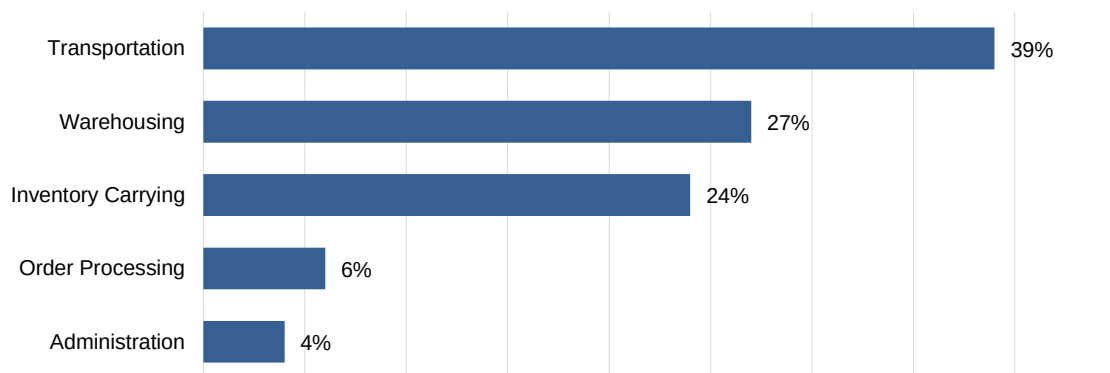


Figure 1.2 Worldwide Logistics Cost (Rodrigue, et al., 2013)

The distribution network design is one of the most important strategic decision that need to be optimized for the efficient long-term operation of whole supply chain. It mostly involves all of the integrated decisions. The decisions made for network design determine the number and locations of facility (i.e. factory, warehouse, or depot), select the distribution channel to customers, and identify the transportation volume among distributed facilities for an extended time horizon (Selim & Ozkarahan, 2008). This problem usually involves making tradeoffs the cost components include the costs of opening and operating the facility, and the transportation costs. These two cost components must be balanced. Theoretically, increasing the number of facilities decreases total transportation cost. However, if the number of facilities increased to a point where there is a significant loss of economies of scale in inbound transportation, increasing the number of facilities will increase the total transportation cost (Chopra, 2003) as shown in Figure 1.3. The use of warehouses provides a flexibility to respond to changes in the demand and customer services and can result in significant cost savings due to economies of scale in transportation costs (Amiri, 2006).

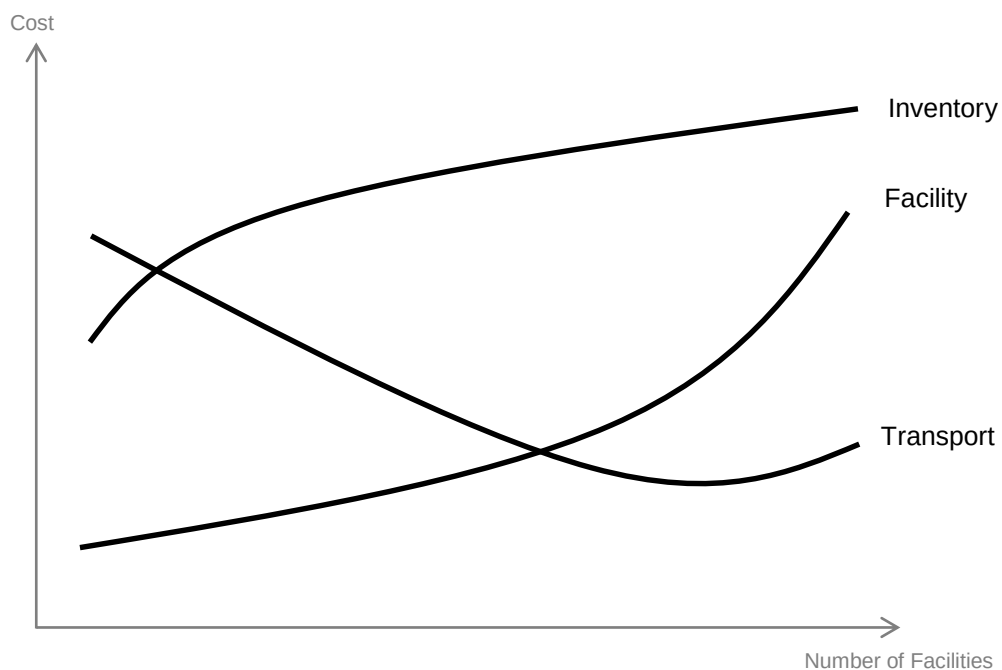


Figure 1.3 Relationship between Number of Facilities and Logistics Cost

Considering only a cost minimization is probably a risky approach for the real-world competitive market. If a company wants to save the response time to its customers, it may have to increase the number of warehouses beyond the point that minimizes

logistics costs. Opening the new facilities that exceed the cost-minimizing point might be required if such response increase in profit because of better responsiveness is greater than the increase in costs of the additional facilities. For example, Amazon who offers the customers to deliver the books within a week has only five stores. On the other hand, Borders provided the books to their customers on that day needs to locate more than 400 stores throughout the United States (Chopra, 2003).

Another important finding related to the location analysis in the business point of view showing that there is a correlation between the distances and market share. It happens on the basis hypothesis; if all things (e.g. price, service, etc.) being equal, people prefer to go to closest service points (Mercer, 1970). This phenomena happens where the competition can be regarded as a homogeneous mass by the number of competitors (e.g. gas station or repair services), or where the competition is well defined by their location (e.g. food shop or supermarket) (Rand, 1976; Beckmann, 1999). The good example of this hypothesis is the lesson on hospital planning and strategy by Lambdin (2013). The market share of four hospitals was recorded and analyzed base on the patient address. It shows the tight relationship between the distance from the hospitals and market share, as shown in Figure 1.4.

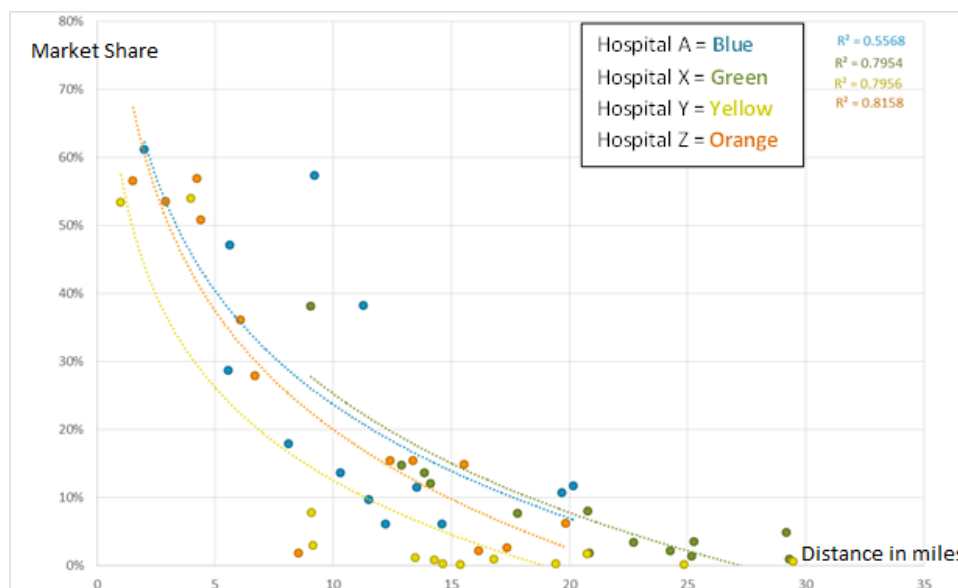


Figure 1.4 Relationship between Distance and Market Share (Lambdin, 2013)

From the reasons mentioned above, it can be observed that integrated logistics systems to optimize a product support and customer service have become a primary necessity

for private and public firms in the modern distribution management. Determining a suitable location of the business center is one of the essential steps in supply chain management. It involves in setting up factory, warehouse, retail store, or public services, i.e. hospital, police station, fire station, etc. (Hassanzadeh, et al., 2009). It involves the process to locate a set of facilities to minimize the cost of satisfying a set of demands with respect to a set of constraints.

1.2 Research Motivation

The facility location problem determines the place(s) where the total cost of satisfying customer's demand is minimum with a set of constraints. Those costs include fixed cost to establish facility and distribution cost. There are two types of distribution to be considered; direct trip and tour trip. The direct trip requires the vehicle to visit only one customer and return base like a fire service. On the other hand, the tour trip requires the vehicle to visit more than one customer before return to base such as a postman (Hassanzadeh, et al., 2009). If the service is a direct trip, it is considered a location-allocation problem. If the service is a tour trip, it becomes a location-routing problem (LRP) as shown in Figure 1.5.

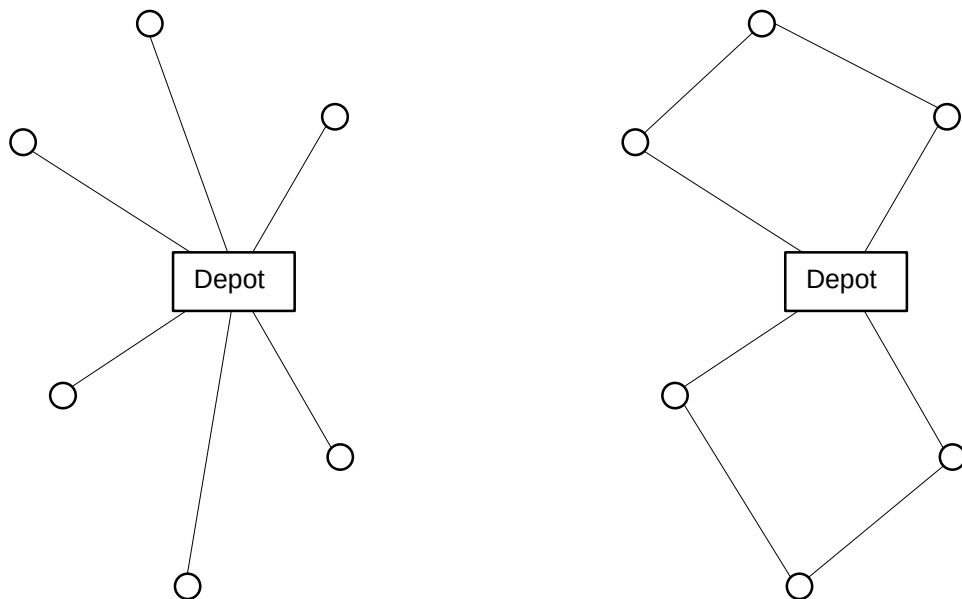


Figure 1.5 Location-Allocation Problem (Left) and Location-Routing Problem (Right)
Traditionally, the facility location and vehicle routing has been determined and carried out at the different levels. While the routing can be solved more frequently at the short

term operational stage, the facility must be located earlier in the long term strategic planning. Some argue that an integration of these two problems, location and routing, is impractical since they are in the different planning framework, which makes it inappropriate to calculate them together.

Nagy and Salhi (2007) states three possible reasons why academics and practitioners often ignore this interrelation and contribute to slow progress on the LRP. First, there are many situations where the locational problems do not require a routing aspect. Second, both decisions are in the different planning horizon. While the location is strategic, the routing is a tactical problem. In other words, routes can be re-calculated and re-drawn frequently, but depot locations are normally for a much longer period. Thus, it is inappropriate to combine location and routing in the same planning framework. Third, the LRP is conceptually more difficult than the classical location problem. In the classical problems, the facility must be located by considering distances to individual demand points. However, in LRP, the facility must be central about the ensemble of the demand points as ordered by the (unknown) tour through all of them (Berman, et al., 1995). Adding the routing into location problem adds difficulty in solving these problems since there are far more decisions that need to be made by the model.

These criticisms led the authors to investigate this issue. Eventually, it was proved that the combination of location and routing problems reduces the cost over the long-term horizon. Solving them together, early in the planning horizon provides benefits and positive impacts for both operators and society (Rand, 1976; Salhi & Rand, 1989; Salhi & Nagy, 1999). These decisions include (Marinakis, 2009):

- How many facilities to locate?
- Where is the location of facilities?
- Which customers to assign to which depots?
- Which customers to assign to which routes?
- In what order of the customers should be on each route?

Moreover, in the context of logistics management, much attention has been paid to improve the service quality by increasing customer satisfaction. It is recommended by

Min et al. (1998) that the future LRP studies should extend to consider the presence of time windows since the customers often impose service deadlines and earliest service time constraints. Some might argue that the delivery time is relatively small compared to the time horizon of the facility location process. However, the technology improvement enables the growth of a new market which responsive to customers' behavior and their needs. One of them is the importance of "just in time" policies (Gonzalez-Feliu, et al., 2012). The time windows are now almost essential to different businesses such as bank deliveries, postal deliveries, industrial refuse collection, school bus routing and scheduling, or the modern e-commerce (Solomon & Desrosiers, 1988).

According to the latest comprehensive surveys (Nagy & Salhi, 2007; Drexler & Schneider, 2013; Prodhon & Prins, 2014), the LRP-related research are growing in number. However, few of literature on location problem have been applied to specific applications or case studies. The application-based publications are amount only less than one-fifth (Nagy & Salhi, 2007). Current et al. (2002) summarized the reasons behind this phenomenon. First, the application of location problem practices the existing model and solution technique. It does not provide a scientific approach to research literature. Second, the real world business and industries handle this task by consultants or professional firms. They are not interested or motivated in sharing such experiences. Third, the private sectors treat their valuable knowledge in this area secretly. Nonetheless, it is still important to advance the modeling together with the specific application in real world problem.

By adding the complexity of time window constraint into the LRP problem, a proper and effective method must be developed to deal with its NP-hard (Dror, 1994). Despite its importance, from our best knowledge of literature, all of the LRP studies that considered time windows base on heuristic approaches. None of them attempted at the optimal solution using the exact algorithm. Therefore, this study proposes the integrated approach to determine the exact solution of the Location-Routing Problem with Time Windows (LRPTW) using branch-and-price algorithm.

1.3 Research Purpose and Objectives

This study provides a broad scope for distribution network design to improve the effectiveness of logistics processes. The main propose is to develop the integrated model to consider the ordinary facility location problem (FLP) and vehicle routing problem (VRP) simultaneously as the location-routing problem (LRP). The time windows corresponding to the customer services is comprehensively considered as an additional variant, lead the problem into the location-routing problem with time windows (LRPTW) class. The objectives of this research are;

1. To formulate the mathematic models for LRPTW to minimize the total logistics costs that consist of facility cost, vehicle cost, and transportation cost.
2. To set the new benchmarks of LRPTW and offers the optimal solutions.
3. To modify the supplementary heuristic approach to handling the large-scale problems that extend the limitation of exact algorithms.
4. To demonstrate the application of developed models into the real world problems. Distribution network and humanitarian logistics are selected as the cases studies.

1.4 Research Contributions

- This study is the first to solve the LRPTW to optimality using an exact algorithm. We propose a branch-and-price approach with the fundamentals of column generation together with the Elementary Shortest Path Problem with Resource Constraint as a pricing problem.
- The acceleration processes are developed to reduce the search space and improve computational time and resources.
- The new test instances of the LRPTW are formulated from the original VRPTW Solomon benchmark instances to evaluate the performance of our algorithm. To this end, additional depot locations are generated by using the k-medoids algorithm. The resulting instances are expected to be the new benchmarks for other researchers.

- The computational results and the corresponding discussion to understand the effects and characteristics of time window constraints in the LRPTW is another scientific contribution.
- The impact of the main parameters in logistics costs is evaluated from freight carrier with different depot location, depot size, and vehicle size.
- The LRPTW model is applied to the humanitarian logistics to determine the locations of the depots as the centers for disaster relief operation. The city of Ishinomaki which attacked by the tsunami triggered by the great Japanese earthquake on March 11, 2011, is selected as a case study.

1.5 Research Outlines

This chapter describes the broad introduction about the situation of supply chain and logistics management systems. The cost components of transportation, warehousing, inventory, order processing, and administration are explored. The research motivation for location analysis is introduced. It leads to the purpose and objectives of this research, together with the lists of research contributions.

Chapter 2 reviews the literature related to this research. Two types of location problems are described which are a location on a continuous plane and location on a network. The integration between location and routing problems is comprehensively described with the exact solution methods. The details related to time windows and benchmark instances give are also provided.

Chapter 3 presents the main formulation of LRPTW. The objective function and eleven constraints are described in details. The branch-and-price algorithm is as a main tool to solve LRPTW. It consists of a master problem, subproblem, accelerating processes, and branching strategies. The results and effects of time windows on testing instances, developed from VRPTW Solomon benchmarks, are shown in Chapter 4. It describes the cost components including the depot, vehicle, distance, load, and computational time.

The application of LRPTW is applied in Osaka distribution network and Ishinomaki humanitarian logistics, as presented in Chapter 5 and Chapter 6, respectively. Although the background of these two problems is different, the main purpose remains the same. The model determines the best locations for the depots, the number of vehicles, the sequence of the demand points, and the best routes to deliver goods. Numbers of scenarios are evaluated based on the different cost components and other constraints.

Finally, the conclusions of this research are summarized, and extensions to this research presents in Chapter 7.

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Chapter 2

Literature Review

- 2.1 Facility Location Problem
 - 2.1.1 Location on a Continuous Plane
 - 2.1.2 Location on a Network
- 2.2 Location-Routing Problem
- 2.3 Exact Methods in LRP
- 2.4 Column Generation
- 2.5 Time Windows
- 2.6 Benchmark Instances
- References

2.1 Facility Location Problem

The facility location problem is a branch of operation research on location analysis. The aim is to determine the optimal location of the facility to minimize transport cost. In general, there are two types of main structural categories (Eilon, et al., 1971). The first approach is an infinite set approach or location on a continuous plane. It allows no restrictions as to where are the location of the depots. The objective is to find the location of facilities that minimize the sum of weighted distances of customers from these locations. The second approach is a feasible set approach or location on a network. This type of problem considers a finite solution space that consist of points on the network and specify a list of possible depot locations.

In transportation and logistics modeling, one of the most fundamental data used in the design, analysis, and operation is the distance. One might think that the most accuracy distance is the actual road distance driven by the actual vehicle. However, the approximated distance is still required in the recent algorithm since the actual road distance is too expensive or even unknown (Goetschalckx, 2011). Nowadays, three types of distances are still widely used to compute the distance between points in a plane which are Euclidean, Rectilinear, and Chebyshev (Figure 2.1). The Euclidean distance is also called the straight line distance, frequently used in a global or national level where approximate distances are acceptable. It is widely used in the communications industry. The Rectilinear Distance is primarily used in transportation and logistics firms where the distance measures on perpendicular and cross lines, represented the grid roads in the cities. Lastly, the Chebyshev distance is also called the simultaneous travel distance, used in material handling process where vertical movement is involved.

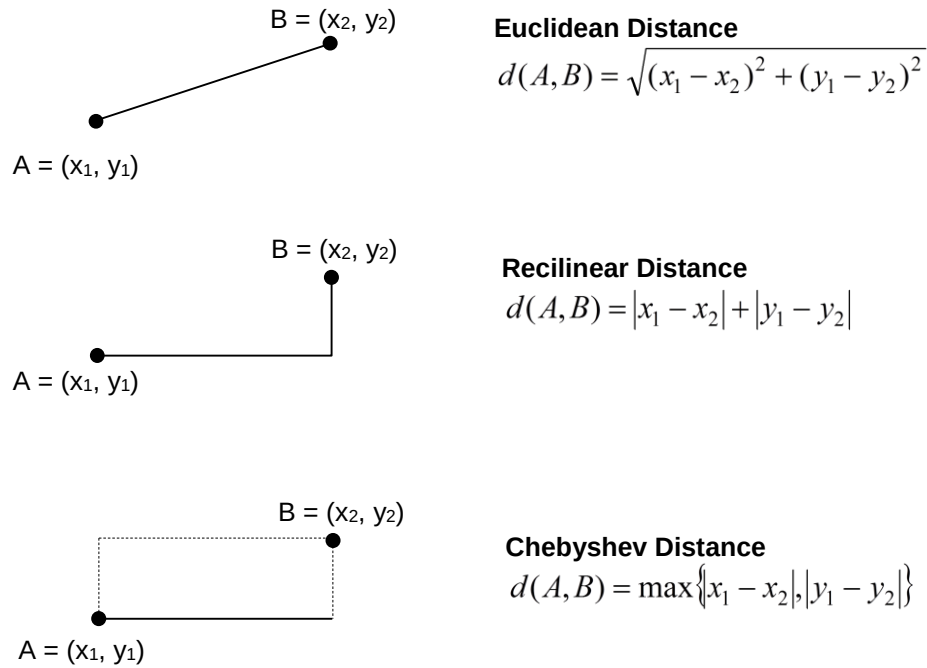


Figure 2.1 Distance Measures

The following section describes the details of two different location model approaches.

2.1.1 Location on a Continuous Plane

Eilon et al. (1971) list the main features of the infinite set approach as follows.

1. It does not require the locations that are selected to be prior attractive.
2. It is flexible in that it examines a monotonic function.
3. Alternative solutions are available in multi-site selection problems.
4. It is possible that the solution will involve a non-feasible location, e.g. a site on a mountain range.
5. Transport costs must be a monotonic function distance.

The first theoretical study on a location on a continuous plane problem is back to 1909. Weber identified the optimal location and minimum cost of manufacturing plants by considering freight rates and the production function (Friedric, 1929). One of the most famous problems in location theory is Weber problem. It requires locating a single point where the sum of transport cost from this point to n destination points is minimized (Tellier, 1972). It is sometimes referred to Fermat-Weber problem since it computes the geometric median of three points in triangle cases called Fermet (Hansen & Thisse,

1983). The classical problems in location analysis are set covering location problem (Toregas, et al., 1971), the maximum covering location problem (Church & ReVelle, 1974), p -median and p -center problems (Hakimi, 1964), and uncapacitated facility location problem (Kuehn & Hamburger, 1963). The more complex problem in this discipline is the multi-facility location problem. Two techniques that are widely used in location theory are minisum and minimax. Minisum facility location determines the minimizing the sum of the weighted distance between the new facility and the other existing facilities. Minimax location problem calculates the minimizing the maximum distance between the new facility and any existing facility.

From the parameter involving in location analysis, Figure 2.2 shows the classification of planar facility location problems with different types of technique and distance.

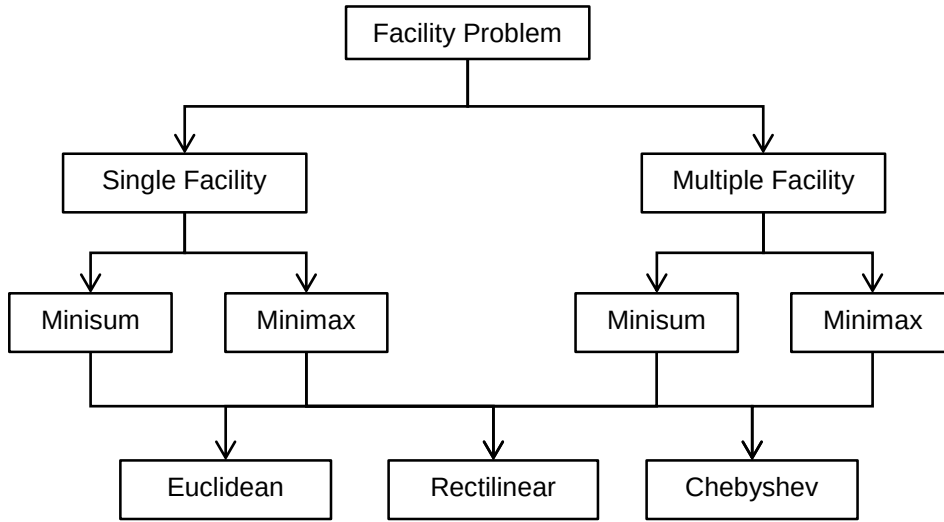


Figure 2.2 Classification of Facility Location Problems

The formulation of minisum and minimax location problems are shown as follows.

Minisum Single Facility Location Problem

$$\min f(x) = \sum_{i=1}^m w_i d(X, P_i) \quad (2.1)$$

Minimax Single Facility Location Problem

$$\min f(x) = \max\{w_i d(X, P_i), i = \{1, 2, \dots, m\}\} \quad (2.2)$$

where

$X = (x,y)$	Location of new facility
$P = (a_i,b_i)$	Location of existing facilities
w_i	Weight associated with travel between the new facility and existing facility i
$d(X,P_i)$	Distance between the new facility and existing facility i

Minisum Multifactory Location Problem

$$\min f(x) = \sum_{1 \leq j < k \leq n} v_{jk} d(X_j, X_k) + \sum_{j=1}^n \sum_{i=1}^m w_{ji} d(X_j, P_i) \quad (2.3)$$

Minimax Multifactory Location Problem

$$\min f(x) = \max \{v_{jk} d(X_j, X_k), w_{ji} d(X_j, P_i)\} \quad (2.4)$$

where

n	Number of new facilities
m	Number of existing facilities
w_{ij}	Weight associated with travel between new facility i and existing facility j
v_{ik}	Weight associated with travel between new facility i and k
$d(X_j, P_i)$	Distance between new facility j and existing facility i
$d(X_j, X_k)$	Distance between new facility j and k
$P_j = (a_j, b_j)$	Location of existing facility j

The infinite set approach has numbers of advantage in many ways. However, it has some limitations for multi-site selection (Rand, 1976). First, there is no method guarantee to find the optimal solution. It is necessary to regenerate many solutions with different starting points and then choose the best sites from that particular findings. Second, it might obtain a solution giving non-feasible sites. Thirdly, there is no protocol to determine the number of depots. It is only approximate algorithms available. On the other hand, the discrete location problems involve the integer programming optimization to determine zero/one variable in the location problems on networks.

2.1.2 Location on a Network

Eilon et al. (1971) list the main features of the feasible set approach as follows.

1. It incorporates costs that relate to specific geographic locations.
2. It does not require transport costs to be any function of distance.
3. It requires a set of sites that are known to be feasible and for which all cost data are available.
4. The number of locations must be finite and sufficiently small for computational efficiency.
5. The set of feasible sites may not include the optimum solution.

The comprehensive study on network-based location problem started in the middle of 1960s. Hakimi (1964) and Hakimi (1965) investigated the minimum weighted distance location of p facilities on a network of n demand nodes and named the p -median problem. His works were similar to the linear programming proposed by Dantzig by reducing the set of optimal solutions from infinite set to a finite set. ReVelle and Swain (1970) were the first to formulate the p -median problem into the zero-one integer programming. The original formulation is;

$$\text{Min } \sum_{i \in I} \sum_{j \in J} w_i d_{ij} x_{ij} \quad (2.5)$$

subject to

$$\sum_{j \in J} x_{ij} = 1 \quad \forall i \in I \quad (2.6)$$

$$x_{ij} \leq y_j \quad \forall i \in I, \forall j \in J \quad (2.7)$$

$$\sum_{j \in J} y_j = p \quad (2.8)$$

$$x_{ij} = 0,1 \quad \forall i \in I, \forall j \in J \quad (2.9)$$

$$y_j = 0,1 \quad \forall j \in J \quad (2.10)$$

The location variables y_j are one if a facility is located at node j and zero otherwise. The allocation variables x_{ij} denote the proportion of the demand of the customer at node i that assigned to a facility at node j . p denotes the number of facilities to be located. Church

and ReVelle (1976) reported one of the important way to measure the effectiveness of facility location is to determine the average distance traveled by vehicles. Later, Kariv and Hakimi (1979) proved that the general p -median problem is NP-Hard.

The first heuristic solution to apply in the p -median problem called location-allocation heuristics, introduced by Maranzana (1964) and following by the more powerful vertex substitution technique of Teitz and Bart (1968). They are the earliest simultaneously exchanged algorithms that lately called 1-opt heuristics. Although the simplex algorithm of 1-opt lead to the optimal solution, this work does not always produce the global optimum since the solution space of p -median is not necessary convex. Galvão (1993) employed the exact solution by applying Lagrangian relaxation and the linear programming relaxation. The heuristics concentration is introduced by Rosing and ReVelle (1997) incorporated the exchange heuristics in metaheuristics. Lately, it was proved by Schilling et al. (2000) that the performance of both exact and heuristic solutions of p -median problem depends on the extent of the triangle inequality is determined underlying the problem.

Considering another class of facility location problem, one of the simplest is the single-commodity, uncapacitated, zero echelons, and linear costs. This model has the following formulation;

$$\text{Min } \sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij} + \sum_{i \in I} f_i z_i \quad (2.11)$$

$$\text{subject to } \sum_{i \in I} x_{ij} = 1 \quad j \in J \quad (2.12)$$

$$z_i - x_{ij} \geq 0 \quad i \in I, j \in J \quad (2.13)$$

$$x_{ij} \geq 0 \quad (2.14)$$

$$z_i \in \{0,1\} \quad (2.15)$$

where

x_{ij}	Proportion of customer j 's demand satisfied by facility i
z_i	1 if facility i is established, 0 otherwise
c_{ij}	Total production and distribution costs for supplying all of customer j 's demand from facility i

f_i	Fixed cost of establishing facility i
I, J	Sets of candidate facility sites and customer zones, respectively

Constraints (2.12) ensure that each customer's demand is satisfied exactly and Constraints (2.13) confirm that customers visits by vehicles from open facilities only.

More complex location problem are developed lately. The placement of upper limits on supplies changes the uncapacitated into the capacitated problem. The formulation of capacitated location problem is shown as follow;

$$\text{Min } \sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij} + \sum_{i \in I} f_i z_i \quad (2.16)$$

$$\text{subject to } \sum_{j \in J} D_j x_{ij} \leq S_i z_i \quad i \in I \quad (2.17)$$

$$\sum_{i \in I} x_{ij} = 1 \quad j \in J \quad (2.18)$$

$$x_{ij} \in \{0,1\} \quad i \in I, j \in J \quad (2.19)$$

$$z_i \in \{0,1\} \quad (2.20)$$

where

D_j	Demand of customer j
S_i	Capacity of facility i

Constraints (2.17) prevent upper bound violations of supply for open facilities and require that demand is satisfied.

In summary, a recent survey study by Klose and Drexler (2005) summarized the types of facility location models that can be classified as follows:

1. The shape or topography of the set of potential facilities effects models in the plane, network location models, and a discrete location or mixed-integer programming models, respectively.
2. Objectives may be either of the minisum or the minimax type.
3. Models without capacity constraints do not restrict demand allocation. If capacity constraints for the potential sites have to be assigned, the demand has to be allocated carefully.

4. Single-stage models focus on distribution systems covering only one stage explicitly. In multi-stage models, the flow of goods comprising several hierarchical stages has to be examined.
5. Single-product models can be considered by the fact that demand, cost, and capacity for several products can be aggregated to a single homogeneous product.
6. Location models base on the assumption that demand is inelastic, meaning that demand is independent of spatial decisions.
7. Static models try to optimize the objective function for one representative period. By contrast, dynamic models reflect data varying over time within a given planning horizon.
8. In practice, data are based on forecasts and are likely to be uncertain. As a consequence, we have either deterministic models if the input is known with certainty or probabilistic models if the input is subject to uncertainty.
9. In classical models, the quality of demand allocation is measured in isolation for each pair of supply and demand points. Unfortunately, if demand is satisfied through delivery tours, the delivery cost cannot be calculated for each pair of supply and demand points separately. The combination of location and routing models elaborate on this interrelationship.

2.2 Location-Routing Problem

The definition of location-routing problem (LRP) given by Srivastava and Benton (1990) states as:

“Given a feasible set of potential depot sites and customer sites, find the location of the depots and the routes to customers from the depots such that the overall cost is minimized. The overall cost is the sum of the location and distribution costs.”

From the previous topic, the facility location problem does not require a routing determination, similar to the p -median problems. Likewise, the multi-depot vehicle routing problem does not solve the facility location since it is implicitly determined. However, in the LRP, two decisions are considered interdependently, how many and which facilities should be opened and which routes should be built to meet customer

demand. The former is based on ordinary location problem while the latter is developed with the fundamentals of the vehicle-routing problem (VRP) seeking to serve a set of customers with a fleet of vehicles with minimum distribution cost.

One of the first study that pointed out the important of routing in location problem referred to Maranzana (1964). This study stated that “*the location of factories, warehouses and supply points in general ... is often influenced by transport costs*”. Lately, Rand (1976) observed “*many practitioners are aware of the danger of sub-optimizing by separating depot location and vehicle routing.*” Watson-Gandy and Dohrn (1973) is probably one of the first studies to consider the tour of the vehicle routes within the location-transportation framework. Until then, the consideration to integrate the routing in location analysis became more popular among researchers. It includes Or and Pierskalla (1979), Jacobsen and Madsen (1978), Harrison (1979), Jacobsen and Madsen (1980), Nambiar et al. (1981), Laporte and Nobert (1981), and Madsen (1983).

One of the early works published by Rand (1976). He pointed out that the practitioners should be aware of the danger of sub-optimizing by separating depot location and vehicle routing since the best vehicle routes are not necessarily the one that minimize the distance traveled. However, it is difficult to incorporate routing in depot locations analysis at that time because of the shortage of computational resources. Lately, Salhi and Rand (1989) evaluated the effect of ignoring routing when locating the depots by using a two stage process. This study proved that the best solution after the location stage does not necessarily produce the lowest transport cost after the routing stages. This result was found both when compare the best locations obtained from various methods, and when evaluate a single method for different numbers of depots. Salhi and Nagy (1999) developed the work on location-routing heuristics using location-first routing-second methods. Their work proved that the combined models consistently produce a solution of higher quality than sequential methods.

Larporte and Nobert (1981) is among the first authors to formulate the simple uncapacitated LRP model by a global integer programming that require opening only one single depot. No vehicle costs are considered. Later on, most authors address the LRP with capacity constraints on depots and vehicles and vehicle cost which called

capacitated LRP (CLRP). Following notations are used in the CLRP formation addressed by Prodhon and Prins (2014).

Set

V	set of nodes, $V = I \cup J$
I	set of potential depot nodes $I = \{1, 2, \dots, m\}$
J	set of customers to be served $J = \{1, 2, \dots, m\}$

Parameter

O_i	Opening cost of depot i
W_i	capacity of depot i
d_j	demand of customer j
K	number of available vehicle (fleet size)
Q	capacity of each vehicle
F	fixed cost per vehicle used
c_{ij}	traveling cost for edge (i, j)

Decision Variables

y_i	1 if depot i is opened or 0 otherwise
x_{ij}	1 if edge (i, j) is traversed from i to j by a vehicle

Objective Function

Minimize sum of the depots cost, vehicles fixed cost, and routes cost

$$\min \sum_{i \in I} O_i y_i + F \sum_{i \in I} \sum_{j \in J} x_{ij} + \sum_{i \in V} \sum_{j \in V} c_{ij} x_{ij}$$

Constraints

- (i) The total demand of customers assigned to one depot must not exceed its capacity
- (ii) Each route begins and ends at the same depot
- (iii) Each vehicle performs at most one trip
- (iv) Each customer is served by one single vehicle (no split delivery)
- (v) The total demand of customers visited by one vehicle fits vehicle capacity

After that, there are numbers of study on LRP with various perspectives and schemes. Min et al. (1998) and Nagi and Salhi (2007) developed a taxonomy and classification schemes to categorize LRP studies to provide a more integrated view of the LRP as listed in Table 2.1. It is noticed that most of the papers using heuristic methods. More details on heuristic solutions for LRP can be found in the survey papers (Min, et al., 1998; Nagy & Salhi, 2007; Drexl & Schneider, 2013; Prodhon & Prins, 2014). The details of the solution methods using the exact algorithm are described in the following topic.

Table 2.1 Classification of LRP (Min, et al., 1998)

Topic	Subcategories
Hierarchical level	Single stage Two stages
Nature of demand/supply	Deterministic Stochastics
Number of facilities	Single facility Multiple facility
Size of vehicle fleets	Single vehicle Multiple vehicles
Vehicle capacity	Uncapacitated Capacitated
Facility capacity	Uncapacitated Capacitated
Facility layer	Primary Secondary/intermediate
Planning horizon	Single period (static) Multiple periods (dynamic)
Time windows	Unspecified time with no deadline Soft time windows with loose deadlines Hard time windows with strict deadlines
Objective function	Single objective Multiple objectives
Type of model data	Hypothetical Real-world
Solution method	Exact algorithm Heuristic algorithm

2.3 Exact Method in LRP

In LRP, exact solution approaches are successful for more specific cases and provide substantial insights into problems comparing with the heuristic approach. Table 2.2 summarize the literature on LRP using exact methods and their details.

Table 2.2 Summary of Publications on LRP using Exact Methods

Year	Authors	Title	Nature of Demand and Supply	Number of Facilities	Size of vehicle fleets	Vehicle Capacity	Facility Capacity	Solution Method
1981	Ghosh, J. K. Sinha, S. B. Acharya, D.	A generalized reduced gradient based approach to round-trip location problem	Deterministic	Single	Single	Uncapacitated	Uncapacitated	Non-linear programming
1981	Laporte, G. Nobert, Y.	An exact algorithm for minimizing routing and operating costs in depot location	Deterministic	Single	Multiple	Uncapacitated	Uncapacitated	Two branching strategies
1983	Laporte, G. Nobert, Y. Pelletier, P.	Hamiltonian location problems	Deterministic	Multiple	Multiple	Uncapacitated	Uncapacitated	Cutting planes
1986	Laporte, G. Nobert, Y. Arpin, D.	An exact algorithm for solving a capacitated location-routing problem	Deterministic	Multiple	Multiple	Capacitated	Capacitated	Integer programming
1988	Laporte, G. Nobert, Y. Tallefer, S.	Solving a family of multi-depot vehicle routing and location-routing problems	Deterministic	Multiple	Multiple	Capacitated	Capacitated	Modified branch-and-bound method
1989	Zografos, K. G. Samara, S.	Combined location-routing model for hazardous waste transportation and disposal	Deterministic	Multiple	Single	Uncapacitated	Capacitated	Mixed-integer programming
1989	Laporte, G. Dejax, P. J.	Dynamic location-routing problems	Deterministic	Multiple	Multiple	Uncapacitated	Uncapacitated	Integer programming
1989	Laporte, G. Louveau, F. Mercure, H.	Models and exact solutions for a class of stochastic location-routing problems	Stochastic	Multiple	Multiple	Capacitated	Uncapacitated	Branch-and-bound
1991	List, G. Mirchandani, P.	An integrated network/planar multiobjective model for routing and siting for hazardous materials and wastes	Deterministic	Multiple	Multiple	Uncapacitated	Uncapacitated	Multiobjective route generation method
1991	ReVelle, C. Cohon, J. Shobrys, D.	Simultaneous siting and routing in the disposal of hazardous wastes	Deterministic	Multiple	Multiple	Uncapacitated	Uncapacitated	Integer programming, shortest paths, and weighting method
1993	Stowers, C. L. Palekar, U. S.	Location models with routing considerations for a single obnoxious facility	Deterministic	Single	Single	Uncapacitated	Uncapacitated	Non-linear programming

Year	Authors	Title	Nature of Demand and Supply	Number of Facilities	Size of vehicle fleets	Vehicle Capacity	Facility Capacity	Solution Method
1994	Averbakh, I. Berman, O.	Routing and location-routing p-delivery men problems on a path	Deterministic	Single	Multiple	Uncapacitated	Uncapacitated	Dynamic programming
1995	Averbakh, I. Berman, O.	Probabilistic sales-delivery man and sales-delivery facility location problems on a tree	Stochastic	Single	Multiple	Uncapacitated	Uncapacitated	Non-linear programming
1999	Ghiani, G. Larporte, G.	Eulerian location problems	Deterministic	Multiple	Multiple	Uncapacitated	Uncapacitated	Branch-and-cut
2002	Averbakh, I. Berman, O.	Minmax p-traveling salesmen location problems on a tree	Deterministic	Single	Multiple	Uncapacitated	Uncapacitated	Polynomial algorithm
2007	Berger, R. T. Coullard, C. R. Daskin, M. S.	Location-routing problems with distance constraints	Deterministic	Multiple	Multiple	Uncapacitated	Uncapacitated	Branch-and-price
2009	Akca, Z. Berger, R. T. Ralphs, T. K.	A Branch-and-Price Algorithm for Combined Location and Routing Problems under Capacity Restrictions	Deterministic	Multiple	Multiple	Capacitated	Capacitated	Branch-and-price
2011	Baldacci, R. Mingozzi, A. Wolfler Calvo, R.	An exact method for the capacitated location-routing problem	Deterministic	Multiple	Multiple	Capacitated	Capacitated	Branch-and-price
2011	Belenguer, J. M. Benavent, E. Prins, C.	A branch-and-cut method for the capacitated location-routing problem	Deterministic	Multiple	Multiple	Capacitated	Capacitated	Branch-and-cut
2013a	Contardo, C. Cordeau, J. F. Gendron, B.	A computational comparison of flow formulations for the capacitated location-routing problem	Deterministic	Multiple	Multiple	Capacitated	Capacitated	Branch-and-cut
2013b	Contardo, C. Cordeau, J. F. Gendron, B.	An exact algorithm based on cut-and-column generation for the capacitated location-routing problem	Deterministic	Multiple	Multiple	Capacitated	Capacitated	Branch-and-cut-and-price

In the early year, many studies focus on a single primary facility with uncapacitated LRP. A classical branch-and-bound algorithm consisted of systematic of all candidate solutions is firstly used by Laporte and Nobert (1981) to solve uncapacitated LRP. The algorithm determines simultaneously both the best depot location and the optimal m -travelling salesmen problem (m -TSP). The model is solved by relaxing most of its constraints and by introducing them only when they are violated. Ghosh et al. (1981) use non-linear programming algorithms to solve the uncapacitated facility location and routing problems. A specific focus of this study is on the non-rectilinear round-trip distance location. Stowers and Palekar (1993) develop bi-objective problems as a minimization of both location and transportation risks using non-linear programming. When considering the location risks and the population is concentrated at nodes, the problem unveils a finite dominating set. With uniform population distribution on arcs and nodes, it is possible to partition the arcs of the network and search for the global optimum solution. Averbakh and Berman (1994) propose an $O(n^2)$ algorithm to find service tours so as to minimize the total waiting time of all customers. It is further used in polynomial time algorithms that are developed for routing and location-routing problems with p servers. Another complex problem with multiple facilities uncapacitated LRP is reviewed by Zografos and Samara (1989) to combine location and routing models for hazardous waste transportation and disposal. The multiple objectives for this work include minimizing disposal risk, minimize routing risk, and minimize travel time. This developed model is proposed to implement by hazardous waste management agencies for planning and policy evaluation. Averbakh and Berman (2002) present the exact polynomial algorithms with a linear order of complexity for location versions of the problem. The objective is to minimize the length of the longest vehicle tour. The solution is found by reducing the main problem into the minimal γ -dividing set problem.

For multiple facilities/vehicles uncapacitated LRP, Laporte et al. (1983) present the subtour elimination constraints and Gomory cuts to achieve integrality more efficient. These algorithms present the double advantage of being highly efficient for the solution of some difficult combinatorial problems while offering flexibility with a good lower bound on the optimal solution. To improve the model applying for stochastic LRP, Laporte and Dejax (1989) develop branch-and-bound algorithms with integrality constraints and reintroduction of violated constraints solving two solution approaches. The first exact method appropriated for small-scale problems. In the second, some of the system costs are approximated, and a global solution

is then obtained by determining a shortest path in a directed graph. List and Mirchandani (1991) present the multiobjectives model for making a decision on routing for either material or waste shipments. These objectives include minimizing of risk, cost, and risk equity. Costs here are treated as link attributes while risks are zonal attributes, about non-overlapping geographic areas spread out over the plane. Equity is measured as the maximum zonal risk per unit population. The results are helpful for government agencies to regulate the routing and locating hazardous material and waste stations. Another application papers related to hazardous and wastes is conducted by ReVelle et al. (1991). Multi objectives are set to minimize transportation burden and perceived risk. The solution approach consists of integer programming, shortest paths, and weighting method. It proposes to use to locate storage facilities for spent fuel rods from commercial nuclear reactors, distribute reactors to those facilities, and find the routes for the shipment of the spent fuel. Ghiani and Laporte (1999) solves Eulerian location problem in arc routing context using the branch-and-cut algorithm. The problem can be transformed into a rural postman problem (RPP). Berger et al. (2007) use branch-and-price algorithm to solve uncapacitated facilities/vehicles with maximal route length constraints. The subproblem to generate new paths is an elementary shortest path problem with route length constraints.

Stochastics LRP shares only a fraction proportion of research comparing to deterministic. The term stochastic here refers to customer demand as the only stochastic variables. Laporte et al. (1989) use branch-and-bound to design two stages LRP by making a decision on location and routing prior knowing some supplies in the first stage. If the vehicles failed to deliver the goods by the capacity constraints, the penalties would be made, and the vehicle must return to the depot and empties its load before resuming its trip in the second stage. The objective function is to minimize depot and prior route costs. Averbakh and Berman (1995) applies the polynomial algorithms to find an optimal home location for the server and an optimal basic sequence to minimize the total expected waiting time or the expected maximal waiting time of customers.

For more generic multiple facilities/vehicles capacitated LRP, Laporte et al. (1986) extent his previous work by applying branching procedures and modifying the formulation incorporates the degree constraints, generalized subtour elimination constraints, and chain barring constraints. Later on, Laporte et al. (1988) applies a branch-and-bound algorithm that consists of constrained assignment problem in the search trees. By using an appropriate graph representation to create a graph extension, the problems are transformed into equivalent

constrained assignment problems. Akca et al. (2009) models three exact and one heuristic branch-and-price approaches. The subproblem uses elementary shortest path problem with resource constraint corresponds to the labeling algorithm. Five classes of valid inequalities are also added to the relaxed master problem to strengthen it. Base in the formulation of this study, Baldacci et al. (2011) also describe a new exact method based on a set partitioning like the formulation. The original problem is decomposed into a limited set of multi-capacitated depot vehicle routing problems. It improves the quality of lower bounds and the number of the dimensions of the instances. Belenguer et al. (2011) develop a branch-and-cut algorithm and introduce some valid equalities. Some of them derived from capacitated vehicle routing problem (CVRP), some of them derived from mixed-integer programming. Two new exact polynomial algorithms are developed to separate path elimination and w -subtour elimination constraints, and some heuristic separation procedures have been designed for all the families of constraints. This work is extended by Contardo et al. (2013a) to compare three different flow formulations, namely a two-index two-commodity flow formulation, a three-index vehicle-flow formulation, and a three-index two-commodity flow formulation. The existing two-index vehicle-flow formulation is also modified by introducing new families of valid inequalities and separation algorithms. Contardo et al. (2013b) apply the similar approach to Akca et al. (2009) and Baldacci et al. (2011) by using cut-and-column algorithms. The problem is solved by column generation where the subproblem using a shortest path of minimum reduced cost under capacity constraints. Five new families of inequalities are introduced that are shown to dominate some of the cuts from the two-index formulation. All of these studies have solved instances with 50 customers and 5-10 depots.

2.4 Column Generation

Column generation is the algorithm for solving the large integer of mixed integer problems. The reason behind the issue on the large problem is that many linear programs are too large to consider all the variables explicitly. Since most of the variables are going to be non-basic and assume a value of zero in the optimal solution, we do not need to include all variables in the model. Only a subset of variables needs to be included when solving the problem. The algorithm generates only particular variables that have the potential to improve the objective function by looking for the variables with negative reduced cost.

The reduced cost here is the amount of change needed in the corresponding coefficient for the variable to enter the basis. Its sign does not necessarily give any information. At the point where the optimal solution exists, two phenomena happen;

1. All non-basic variables have a poor reduced cost since they cannot produce a better solution.
2. All basic variables have a zero negative cost since they are already in the basis.

For general problem P , the regular form to model a column generation is;

$$\min \sum_{p \in P} c_p x_p \quad (2.21)$$

$$\text{subject to} \quad \sum_{p \in P} a_p x_p \geq b \quad (2.22)$$

$$x_p \geq 0 \quad p \in P \quad (2.23)$$

In each iteration, it looks for a non-basic variable to price out and enter the basis. In the subproblem, given the vector $\pi \geq 0$ as dual variables, the cost is replaced as;

$$\bar{c}_p = c_p - \pi^T a_p, \quad p \in P \quad (2.24)$$

An explicit search of P may be computationally impossible when $|P|$ is huge. Therefore, it is more practical to determine only a subset $P' \subseteq P$ of columns, with restricted master problem (RMP).

The purpose of RMP is to determine the dual variables, transfer to the subproblem, and control the stopping criterion. Primal methods maintain primal feasibility and work towards dual feasibility. It is therefore only natural to monitor the dual solution in the course of the algorithm. A dual solution to the RMP needs not be unique, e.g., if the primal is degenerate. It is significant in as much the dual solution directly influences the selection of new columns. Because a dual basic solution corresponds to an extreme point of the optimal face, it may be a bad representative of all the dual solutions obtainable (Lübbecke & Desrosiers, 2005).

The application of column generation in VRP and LRP is described in Chapter 3 of this dissertation. More details on the survey papers of column generation can be found in Barnhart et al. (1998), Wilhelm (2001), Lübbecke & Desrosiers (2005), and Desaulniers et al. (2005).

2.5 Time Windows

In the context of logistics management, improve the service quality and reliability by increasing customer satisfaction has been paying much attention. House and Karrenbauer (1982) observed that the greater speed has decreased the significance in logistics systems. Some might argue that time windows are relatively smaller time horizon than facility location and discouraged researchers considering this aspect. However, Min et al. (1998) suggested that customers often request service time and deadlines, the future LRP studies should be extended to consider the presence of time windows. The technology improvement gives benefits to growing a new market responded to customer behavior and their needs, especially the importance of “just in time” policies (Gonzalez-Feliu, et al., 2012). Furthermore, the growing of business competition and financial crisis require a readjustment on the logistics strategy decision that must include the main logistics tactical as well. Hence, it is most important for logistics distribution to maintain the efficiency while the service quality such as time windows or other parameters is satisfied. Even though the higher on the quality causes the higher of the cost, but this relation is very significant. These two factors are considered differently among other stakeholders (Danielis, et al., 2005).

The time window in logistics requires services to be delivered to the customer within desired period, represented by notation a_i and b_i (Taniguchi, et al., 2001). If a vehicle arrives early, it will induce waiting time and probably parking costs. If a vehicle made a delay, it diminishes customer satisfaction, even breaks the contract in the worst case. These additional costs of early arrival and delay are called the penalty costs. In the case of the hard time window, the late arrival is strictly prohibited setting the penalty cost equal to infinity while the early arrival is allowed with no extra charge (Figure 2.3). However, it is important to note that service still cannot start earlier than a_i .

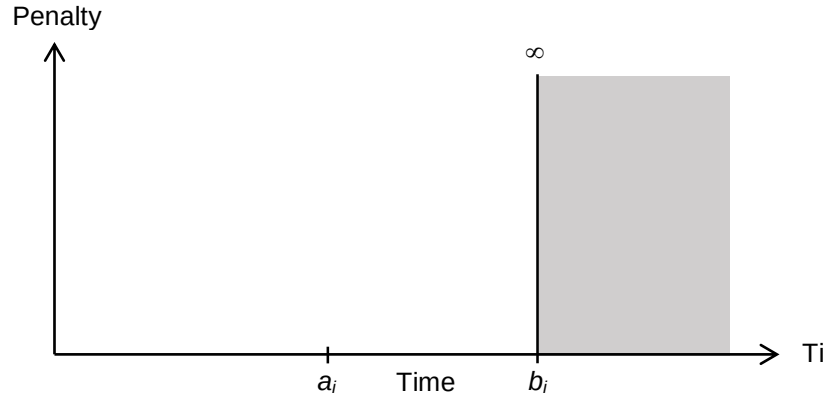


Figure 2.3 Penalty Function for Early Arrival and Delay

By adding the time windows, it adds the complexity of allowable service times, either earliest service time or service deadline, into the problem. The time windows are strictly considered in different business include bank deliveries, postal deliveries, industrial refuse collection, school bus routing and scheduling, or the modern e-commerce (Solomon & Desrosiers, 1988). From our best knowledge, LRP articles mostly considered hard time windows solved the problem based on heuristic approaches, as shown in Table 2.3.

All methodologies decompose the problem into ordinary location, allocation, and routing problems, and find the solution of each part repeatedly, iteratively, or simultaneously (Toyoglu, et al., 2012). Nagy and Salhi (2007) categorize those techniques into four methods, namely sequential, clustering-base, iterative, and hierarchical methods. Additional analysis is required to ensure and yield a good quality solution, such as robustness and debility analysis (Salhi & Nagy, 1999). Nevertheless, none of them set the lower bound to the problem using the exact algorithm.

Table 2.3 Summary of LRPTW using Heuristic Methods

Year	Authors	Title	Time Windows	Solution Method	Specific Method
1978	Jacobsen, S. K. Madsen, O. B.	On the location of transfer points in a two-level newspaper delivery system - A case study	Hard time windows	Heuristics	Location-allocation-first, route-second
1980	Jacobsen, S. K. Madsen, O. B.	A comparative study of heuristics for a two-level routing-location problem	Hard time windows	Heuristics	Location-allocation-first, route-second
1981	Nambiar, J. M. Gelders, L. F. Van Wassenhove, L. N.	A large scale location-allocation problem in the natural rubber industry	Hard time windows	Heuristics	Location-allocation-first, route-second
1990	Srivastava, R. Benton, W. C.	The location-routing problem: Consideration in physical distribution system design	Hard time windows	Heuristics	Savings method and clustering
1993	Semet, F. Taillard, E.	Solving real-life vehicle routing problems efficiently using tabu search	Hard time windows	Metaheuristics	Tabu search
2004	Wasner, M. Zapfner, G.	An integrated multi-depot hub-location vehicle routing model for network planning of parcel service	Hard time windows	Heuristics	Hierarchical method (Local search)
2006	Burks, R.	An Adaptive Tabu Search Heuristic for the Location Routing Pickup and Delivery Problem with Time Windows with a Theater Distribution Application	Hard time windows	Metaheuristics	Tabu search
2007	Crainic, T. G. Ricciardi, N. Storchi, G.	Models for evaluating and planning city logistics transportation systems	Hard time windows	Heuristics	Hierarchical decomposition
2008	Aksen, D. Altinkemer, K.	A location-routing problem for the conversion to the "click-and-mortar" retailing: The static case	Single-sided hard time windows	Heuristics	Add-drop heuristic
2009	Schittekat, P. Sorensen, K.	Or practice - supporting 3PL decisions in the automotive industry by generating diverse solutions to a large-scale location-routing problem	Hard time windows	Metaheuristics	Tabu search
2010	Nikbakhsh, E. Zegordi, S.	A heuristic algorithm and a lower bound for the two-echelon location-routing problem with soft time window constraints	Soft time windows	Heuristics	Neighborhood search and or-opt heuristic
2011	Gündüz, H. I.	The Single-Stage Location-Routing Problem with Time Windows	Hard time windows	Metaheuristics	Tabu search

2.6 Benchmark Instances

Unlike other routing and scheduling problems, the benchmarks or instances for LRPTW have not been generated and shared by other researchers publicly. The existing well-known VRPTW benchmark developed by Solomon (1987) is used in this study. It consists of three main categories, R-Type (random), C-Type (clustered), and RC-Type (mixed random/clustered) (Figure 2.4). Each category is designed to several factors that affect the behavior of routing and scheduling algorithms, including

- Geographical data
- Number of customers serviced by a vehicle
- Percent of time-constrained customers
- Tightness and positioning of the time windows

The largest problems are 100 customer problems where travel times equal the corresponding Euclidean distances. In each category, the customer coordinates are identical for all problems within one type. The problems differ with respect to the width of the time windows. Some have very tight time windows while others have time windows that are hardly constraining. In terms of time window density or the percentage of customers with time windows, they are created with 25, 50, 75 and 100% time windows. Also, the problem sets R1, C1 and RC1 have a short scheduling horizon and allow only a few customers per route (approximately 5 to 10). In contrast, the sets R2, C2 and RC2 have a long scheduling horizon permitting many customers (more than 30) to be served by the same vehicle. For each such problem, smaller problems have been created by considering only the first 25 or 50 customers. Figure 2.5 shows the details of the small problem of R101 with 25 customers. The label of each customer represents customer number, demand, and time windows $[a,b]$.

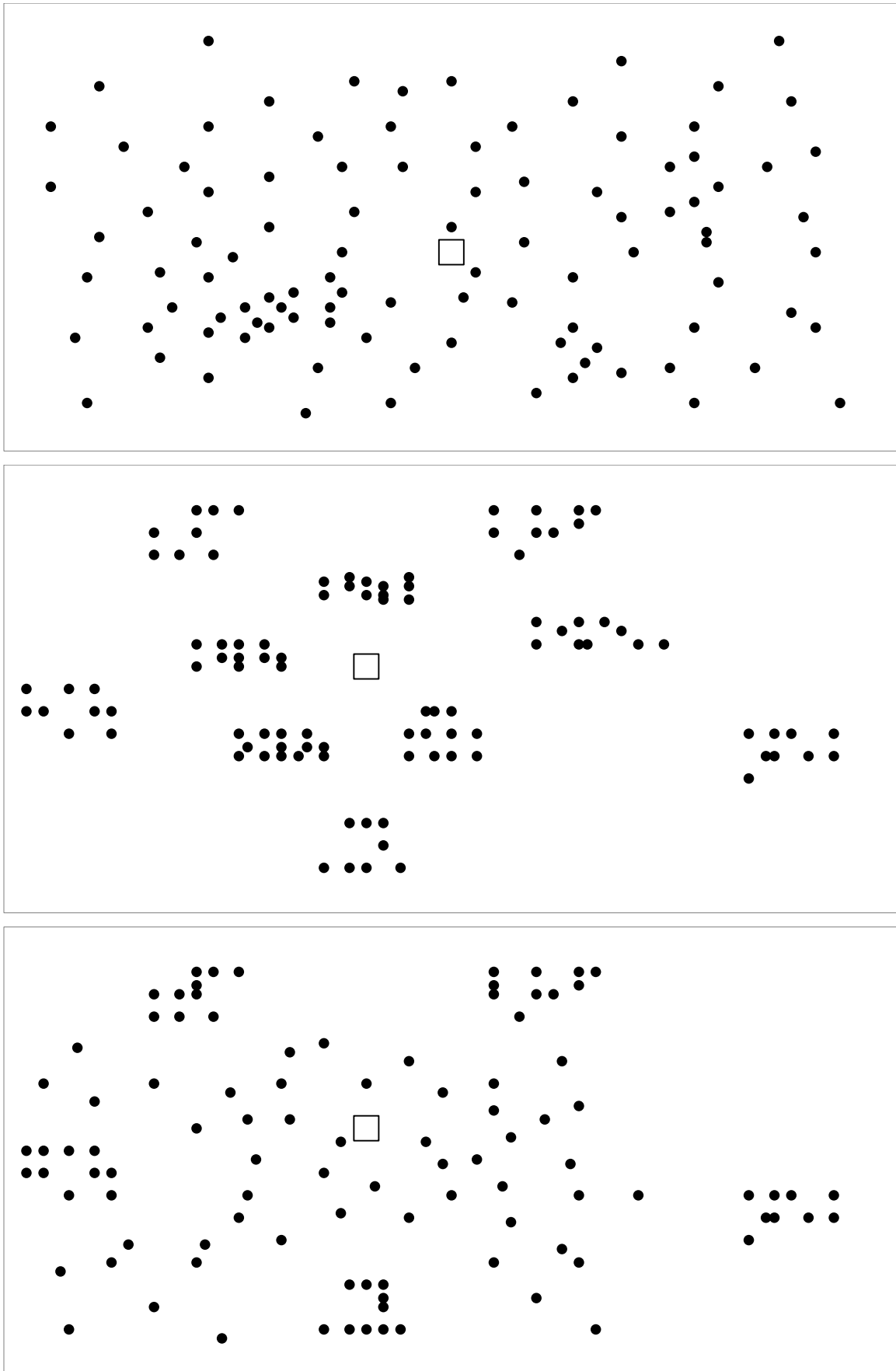


Figure 2.4 Locations of Depot and Customers in R (top), C (middle), and RC (below)

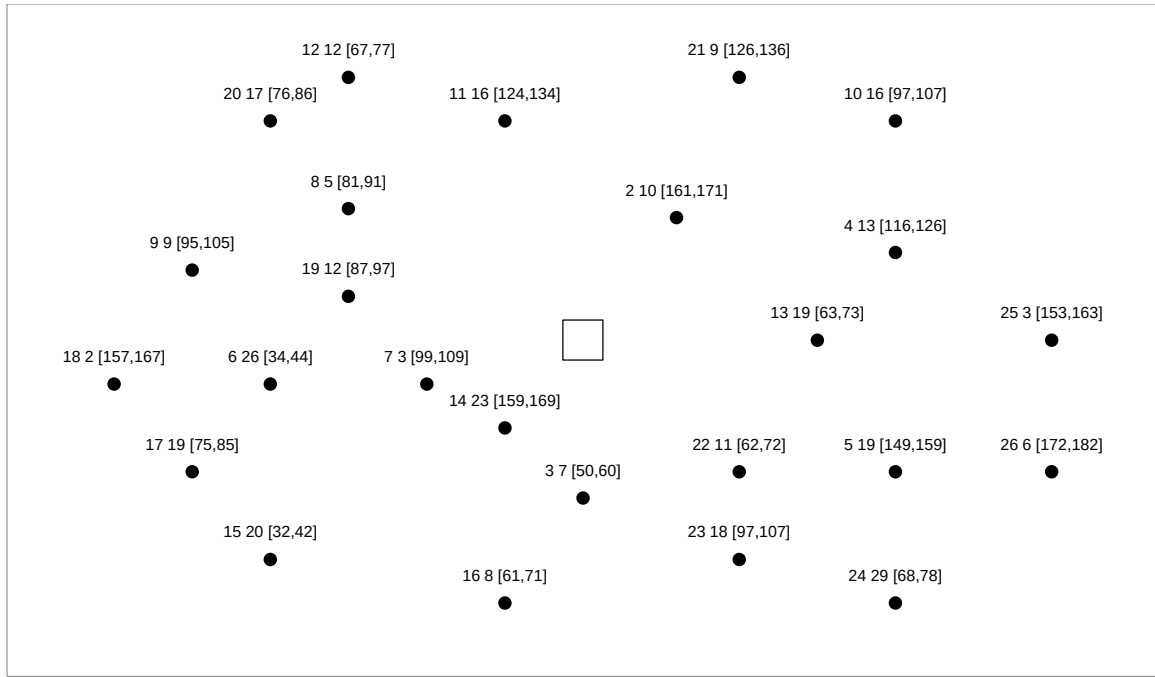


Figure 2.5 Example of R101 with 25 Customers Instance

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Chapter 3

Methodology

3.1 Formulation

3.2 Branch-and-Price Algorithm

3.2.1 The Master Problem

3.2.2 The Subproblem (Pricing Problem)

3.2.3 Accelerating Processes

3.2.4 Branching Strategies

3.3 Example of Branch-and-Price algorithm for LRPTW

References

3.1 Formulation

The description of sets, parameters, and decision variables are described below.

Sets

M	potential depots
C	customers
K_m	homogeneous vehicles, which belong to each depot m

Parameters

f_m	cost of setting up the depot at site m , $\forall m \in M$
Q_m	depot capacity, $\forall m \in M$
O_k	vehicle cost, $k \in K_m$
d_i	customers' demand, $\forall i \in C$
$[a_i, b_i]$	time windows, $\forall i \in C$
q	vehicle capacity
c_{ij}	operating cost between pairs of depots and customers, $\forall (i, j) \in C$
c_{mj}	vehicle fixed cost on the starting vertices, $\forall m \in M$ and $\forall j \in C$
t_{ij}	travel time on arc (i, j) and the service time at vertex i , $\forall (i, j) \in C$

Decision Variables

y_m	1 if depot m is opened or 0 otherwise (Constraints (3.11))
x_{ijk}	1 if arc (i, j) is used by vehicle k or 0 otherwise (Constraints (3.12))
s_{ik}	time when vehicle k starts to service customer i (Constraints (3.10))

The LRPTW can be defined in the graph $G = (V, A)$ where V consists of set M and set C while A is the set of all arcs (i, j) , $i, j \in V$. The standard formulation for the LRPTW is shown below:

$$\min \sum_{m \in M} f_m y_m + \sum_{m \in M} \sum_{j \in A} \sum_{k \in K} O_k x_{mjk} + \sum_{i \in A} \sum_{j \in A} \sum_{k \in K} c_{ij} x_{ijk} \quad (3.1)$$

$$\text{subject to} \quad \sum_{m \in M} \sum_{k \in K_m} \sum_{j \in V} x_{ijk} = 1 \quad \forall i \in C \quad (3.2)$$

$$\sum_{j \in V} x_{mjk} = 1 \quad \forall m \in M, \forall k \in K_m \quad (3.3)$$

$$\sum_{i \in V} x_{imk} = 1 \quad \forall m \in M, \forall k \in K_m \quad (3.4)$$

$$\sum_{i \in V} x_{ihk} - \sum_{j \in V} x_{hjk} = 0 \quad \forall h \in C, \forall k \in K \quad (3.5)$$

$$\sum_{i \in C} d_i \sum_{j \in V} x_{ijk} \leq q \quad \forall k \in K \quad (3.6)$$

$$\sum_{k \in K_m} \sum_{i \in C} d_i \sum_{j \in V} x_{ijk} \leq Q_m y_m \quad \forall m \in M \quad (3.7)$$

$$\sum_{m \in M} \sum_{j \in A} \sum_{k \in K} x_{mjk} - V = 0 \quad (3.8)$$

$$x_{ijk} (s_{ik} + t_{ij} - s_{jk}) \leq 0 \quad \forall (i, j) \in A, \forall k \in K_m \quad (3.9)$$

$$a_i \leq s_{ik} \leq b_i \quad \forall i \in V, \forall k \in K_m \quad (3.10)$$

$$y_m \in \{0, 1\} \quad \forall m \in M \quad (3.11)$$

$$x_{ijk} \in \{0, 1\} \quad \forall (i, j) \in A, \forall k \in K_m \quad (3.12)$$

The LRPTW objective (3.1) is to find a set of open depots and a set of arcs of minimal total cost composing the routes to meet customers' demand.

The decision variable y_m in constraints (3.11) is equal to 1 if depot m is opened and 0 otherwise. x_{ijk} in constraints (3.12) is equal to 1 if arc (i, j) is used by vehicle k and 0 otherwise. The variable s_{ik} denotes the time when vehicle k starts to service customer i .

Constraint (3.2) indicates each customer must be visited exactly once. Constraints (3.3) and (3.4) are flow conservation constraints, meaning that if the vehicle start from a depot m , it must return to the same depot. Constraint (3.5) is also a flow conservation constraint requiring the vehicle to leave the customer h after visiting. Constraints (3.6) and (3.7) are vehicle and depot capacity constraints, respectively. Constraint (3.8) limits the number of vehicle V used in the solution. Constraints (3.9) and (3.10) are time windows constraints implying that if the vehicle goes from i to j , it must serve customer i before j within its specified time windows.

3.2 Branch-and-Price Algorithm

The branch-and-price algorithm is the embedded algorithm between column generation techniques within a linear programming based and branch-and-bound framework (Lübbecke & Desrosiers, 2005). It is first introduced by Desrosiers et al. (1984) for solving the vehicle routing problem with time windows. Column generation follows the idea of the Dantzig-Wolfe decomposition (Dantzig & Wolfe, 1960) by splitting original formulation into two problems: the master and the subproblems. The master problem considers only a subset of variables from the original while the subproblem identifies the new variables. The objective function of the subproblem considers the reduced cost of the new variables with respect to the current dual variables. The outline of branch-and-price algorithm is illustrated in Figure 3.1.

The process works as follows: the master problem is solved using an initial solution. It can be any feasible solution that meets all constraints (Perrot, 2005). In this case, we start with the *depot-i-depot* routes. From this step, the dual prices of each constraint in the master problem are obtained. Then, the reduced cost is calculated and utilized in the objective function of the subproblem. After solving the subproblem, the variables called columns in the master problem with negative reduced cost must be identified. Then, these variables are added to the master problem and resolved iteratively. The process is repeated until the subproblem solution has only non-negative reduced costs columns. Theoretically, at that instance, the solution of the master problem is the optimal solution.

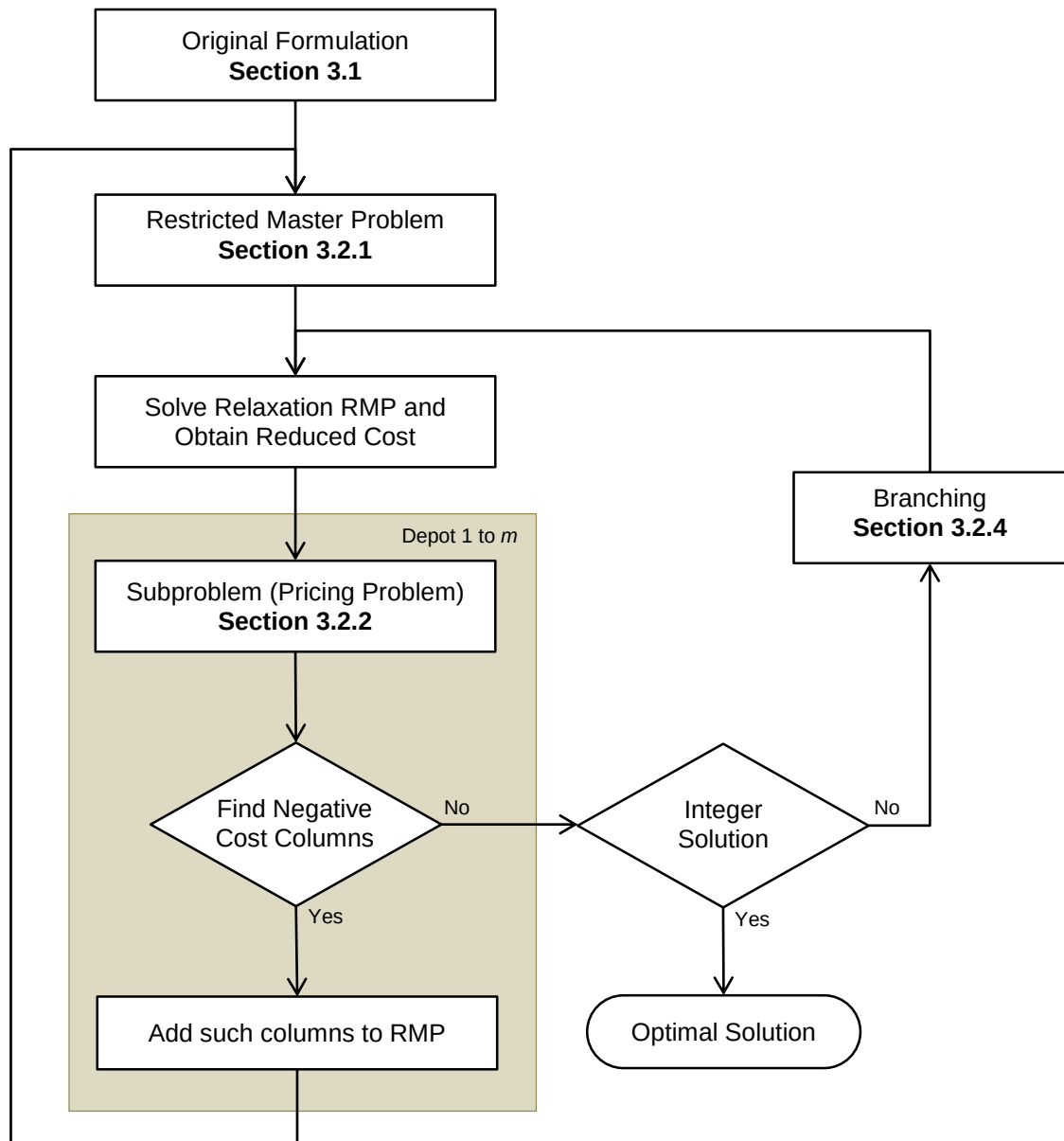


Figure 3.1 Framework of Branch-and-Price Algorithm for the LRPTW

3.2.1 The Master Problem

The set, parameters, and decision variables in the master problem are;

Set

P all feasible single vehicle routes with respect to vehicle capacity that start and end at the same depot

Parameter

d_p cumulative demand, $\forall p \in P$
 c_p operating cost of the route, $\forall p \in P$
 a_{ip} number of times that route p serves customer i , $\forall p \in P$ and $\forall i \in C$

Decision Variables

y_m 1 if depot m is opened or 0 otherwise (Constraints (17))
 z_p 1 if route p is selected or 0 otherwise (Constraints (18))
 v_{pk} 1 if vehicle $k \in K_m$ is assigned the route $p \in P$ and 0 otherwise

The master problem can be formulated as;

$$\min \sum_{m \in M} f_m y_m + \sum_{p \in P} c_p z_p \quad (3.13)$$

$$\text{subject to } \sum_{p \in P} a_{ip} z_p \geq 1 \quad \forall i \in C \quad (3.14)$$

$$\sum_{k \in K_m} \sum_{p \in P} d_p v_{pk} \leq Q_m y_m \quad \forall m \in M \quad (3.15)$$

$$\sum_{p \in P} z_p - V = 0 \quad (3.16)$$

$$y_m \in \{0,1\} \quad \forall m \in M \quad (3.17)$$

$$z_p \in \{0,1\} \quad \forall p \in P \quad (3.18)$$

The objective function of the master problem (3.13) is to find a set of opened depots and a set of routes with minimal total cost (starting and ending at the open depots) and meet the customers' demand.

The decision variable y_m in constraints (3.17) is equal to 1 if depot m is opened and 0 otherwise. z_p at constraints (3.18) is equal to 1 if route p is selected or 0 otherwise.

Constraints (3.14) ensure that each customer must be visited exactly once while constraints (3.15) indicate the total demand of the customers on routes originating and ending at a particular depot does not exceed its capacity. Constraints (3.16) limit the number of the vehicle used in the solution.

3.2.2 The Subproblem (Pricing Problem)

The pricing problem attempts to generate feasible routes with negative reduced costs to add to the master problem. It can be solved by dynamic programming. The Dijkstra's algorithm solving the shortest path problems is one of the simplest way to use in subproblem as long as all arc costs are non-negative (Dijkstra, 1959). Basically, the shortest path problem is cycling. If there are no restrictions on path length, it will cycle forever in any cycle with negative cost. However in our case, the restriction is vehicle capacity. A positive integer demand d_i is associated with each vertex $i \in I$ and a positive integer vehicle capacity q is given. The summation of the demands of the nodes visited by the same vehicle cannot exceed q (Toth & Vigo, 2002). Nevertheless, the vehicle capacity constraints limit the cycling, but they do not remove cycling completely. A node is not allowed to be visited more than once on a path. It is called elementary paths.

The Elementary Shortest Path Problem with Resource Constraints (ESPPRC) is used in the pricing problem to determine the shortest path between two vertices of a graph, origin and destination depot. It ensures that each intermediate node is visited exactly once, i.e. a feasible route. As the capacity of the vehicles is assumed to be the same for all vehicles stationed at each depot, therefore, m different subproblems need to be solved one for each $\forall m \in M$.

The explicit formulation of the subproblem to be considered is given as follows:

$$\min \sum_{i \in A} \sum_{j \in A} \bar{c}_{ijm} x_{ij} \quad (3.19)$$

$$\text{subject to} \quad \sum_{j \in V} x_{mj} = 1 \quad (3.20)$$

$$\sum_{i \in V} x_{im} = 1 \quad (3.21)$$

$$\sum_{i \in V} x_{ih} - \sum_{j \in V} x_{hj} = 0 \quad (3.22)$$

$$\sum_{i \in C} d_i \sum_{j \in V} x_{ij} \leq q \quad (3.23)$$

$$x_{ij}(s_i + t_{ij} - s_j) \leq 0 \quad \forall (i, j) \in A \quad (3.24)$$

$$a_i \leq s_i \leq b_i \quad \forall i \in V \quad (3.25)$$

$$x_{ij} \in \{0,1\} \quad \forall (i, j) \in A \quad (3.26)$$

The cost shown in the objective function (3.19) $\bar{c}_{ijm}$, called reduced cost is given by:

$$\bar{c}_{ijm} = c_{ij} - \pi_i + d_i \mu_m - \eta_m \quad (3.27)$$

Here π_i , μ_m , and η_m are dual variables from constraints (3.14), (3.15), and (3.16) corresponding to the customer i and depot m , respectively. The aim of the subproblem is to find the routes with a minimal reduced cost. The column generation process ends when the optimal objective of the subproblem is either a non-negative value or zero.

An effective method for solving the ordinary shortest path problem with resource constraints (SPPRC) is the labeling algorithm introduced by Desrochers (1988). In this method, a label is assigned to each node throughout the algorithm indicating the consumption of time and resources along a partial path that starts at the depot and ends at the particular node. The algorithm determines the possible optimal partial paths, eliminating labels using some dominance rules. Iteratively, all non-dominated labels are extended toward possible successor nodes until no new labels are created. Feillet et al. (2004) modified Desrochers's algorithm by adding new resources to enforce the elementary path constraint.

a) Label Definition

A label (L_i^m) associates a set of information for a partial path starting from a particular depot m and ending at customer vertex i . It contains eight identities throughout the problem. These identities include;

$res(L_i^m)$	Resident node
$t(L_i^m)$	Time resource
$q(L_i^m)$	Demand resource
$c(L_i^m)$	Cost
$vis(L_i^m)$	Visited vertex resource vector
$pred(L_i^m)$	Immediate predecessor node
$S(L_i^m)$	Total number of unreachable vertices
Label No.	A label counter

The identities are assigned with the values in numerical units except $vis(L_i^m)$ that is assigned with the value equal to 1 for unreachable nodes and 0 for reachable vertices. The initial label L_0^m comprises of zero cost $c(L_0^m)$, zero demand resource $q(L_0^m)$, and no unreachable vertices in $vis(L_0^m)$. The labeling structure is extended in this paper from the earlier research (Qureshi, et al., 2009; Bhusiri, et al., 2014) to encompass the multi-depot characteristics of the LRPTW.

b) Label Extension

This process is the most important for the effectiveness of the overall algorithm in the subproblem. Additional labels are explored from the current vertices. All vertices are cyclically visited and for each vertex the algorithm extends all states that have not yet been extended. Labels associated with the same vertex can be sorted according to a secondary criterion, for instance, according to the cost or the consumption of a certain resource (Righini & Salani, 2008). The label extension process starts by selecting the label at depot m with minimum $t(L_i^m)$. At this point, the label associated with the partial

path must be updated by adding time, cost, and resource that of the successor node. If the vehicle is traveling from node i to node j , the label L_j^m is obtained by updating L_i^m as follows;

$$t(L_j^m) = \max[t(L_i^m) + t_{ij}, a_j] \quad (3.28)$$

$$q(L_j^m) = q(L_i^m) + d_j \quad (3.29)$$

$$c(L_j^m) = c(L_i^m) + \bar{c}_{ij} \quad (3.30)$$

This current label inherits $vis(L_i^m)$, which is further updated by assigning the j^{th} to 1 in the visited vertex resource $vis(L_j^m)$, indicates that it will not be visited again by this partial path. Furthermore, other nodes $h \in C$ must also be determined simultaneously, whether they remain reachable or not, calculating the additional time and capacity resource. If $t(L_j^m) + t_{jh} > b_h$ or $q(L_j^m) + d_h > q$, $vis(L_j^m)$ is set to 1 at the h^{th} position. Otherwise, it is left as a reachable node. Finally, other parameters are updated by assigning the sum of $vis(L_j^m)$ to $S(L_j^m)$ and *Label No.*(L_i^m) as the immediate predecessor $pred(L_j^m)$.

3.2.3 Accelerating Processes

Fundamentally, the basic idea of an exact algorithm for a routing problem is that all possible routes must be explored. However, it is computationally expensive to generate all possible routes, which will be either non-basic variables or infeasible routes in the end. Therefore, two accelerating processes are incorporated into the algorithm to eliminate redundant steps, but still ensuring that the optimal solution is not lost.

a) Dominance Rules

In the label extension step, as many labels are extended to all of the reachable nodes, a huge proliferation of labels is created. It creates a full enumeration of feasible paths. Therefore, the dominance rules are introduced here to avoid the generation of too many unprofitable labels, which will not lead to the optimal solution. Such labels, which are

easily dominated by others, must be ignored in the early stage (Baker & Trietsch, 2009).

Let the labels L_1^m and L_2^m have the same resident node (i.e. $res(L_1^m) = res(L_2^m)$). If all the five conditions described below are verified, they ensure that L_1^m dominates L_2^m . We can neglect L_2^m since any of its future extensions will not produce a better partial path than the ones produced by extensions of L_1^m (Feillet, et al., 2004; Qureshi, et al., 2009; Jouglet & Carlier, 2011).

- | | |
|--|---------------------------|
| i) Less total number of unreachable vertices | $S(L_1^m) \leq S(L_2^m)$ |
| ii) Less time consumption | $t(L_1^m) \leq t(L_2^m)$ |
| iii) Less resource consumption | $q(L_1^m) \leq q(L_2^m)$ |
| iv) Less cost | $c(L_1^m) \leq c(L_2^m)$ |
| v) Feasible extensions of L_1^m | $vis(L_1^m) < vis(L_2^m)$ |

b) Tailing-Off Effect

One of the main issues to solve optimization problems using column generation is the tailing-off effect (Gilmore & Gomory, 1963). This phenomenon happens when the column generation suffers from poor convergence. In the early iterations, the column generation results in the high value of dual prices causing a rapid reduction in the objective value. However, at the later stages of the iterations, when the dual prices reduce gradually, the convergence slows down. Thus, it requires many iterations without much improvement in the objective function. It must be noted that the main objective of solving the LP is to determine a lower bound of the subproblem at the current node. Therefore, no further iterations are needed if this objective is met.

Du Merle, et al. (1999) proposed a stabilization and acceleration process by combining the perturbation of primal problem and exact penalty method. The dual prices are restricted to boxes and adjusted iteratively if the subproblem fails to return the negative reduced cost column. Figure 3.2 (Top) demonstrates the poor convergence due to the tailing-off effect on the LRPTW problem while Figure 3.2 (Below) shows the reduction in the iterations when the stabilization process is added.

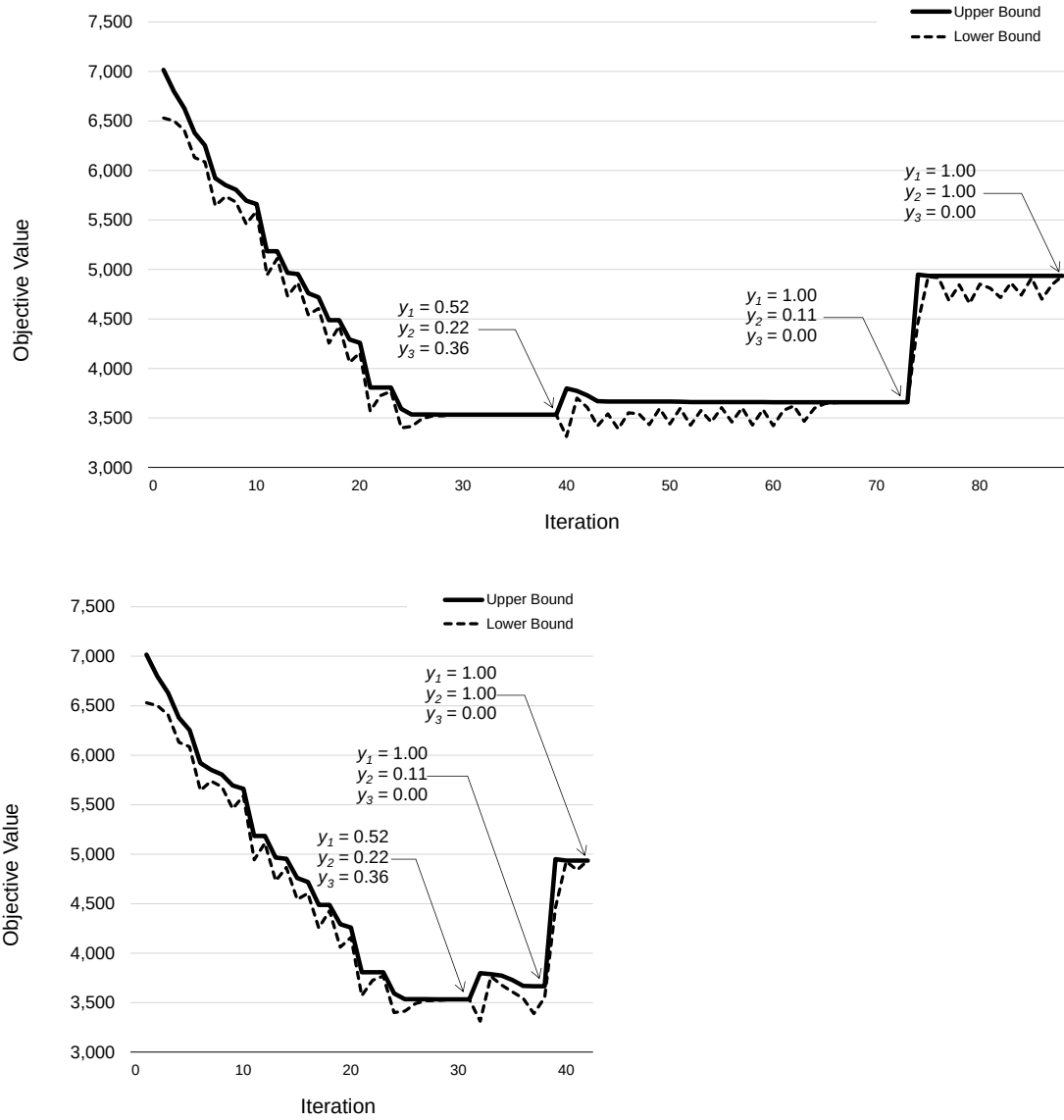


Figure 3.2 Comparison between Without (Top) and With (Below) Tailing-Off Effect Stabilization on the LRPTW-R103 Instance

c) Column Management

One of the main issues of the subproblem is that solving an ESPPRC is costly. It must be run a full problem to be sure that no more good columns exist. It is probably a good idea to keep columns once they are generated (Qureshi, et al., 2009; Oppen, et al., 2010; Bhusiri, et al., 2014). The reduced cost will change for every iteration, so a poor column with a positive reduced cost in the current iteration might become a good column with a negative reduced cost in the next iteration. It is the matter of some

aspects to consider about generating new columns, keeping old ones, and how many to add to the restricted master.

3.2.4 Branching Strategies

The major issue with integer problems is that the feasible region is not a convex set, which is an important feature of an LP and the key to the good performance of the simplex algorithm. The feasible region of an IP is a set of points, and the number of points or solutions for a bounded IP is finite. However, integer problems are nevertheless much harder than LPs. There is no integer version of the simplex algorithm that leads us towards the optimal solution by visiting a series of feasible solutions with increasingly good objective function values (Oppen, et al., 2010). To avoid ends up with that enumeration, therefore, the branch-and-bound algorithm is introduced in this step.

The branch-and-bound was first proposed by Land and Doig (1960) for discrete programming and has become the most commonly used tool for solving NP-hard optimization problems (Clausen, 1999). The algorithm explores branches of this tree, which represent subsets of the solution set. Before enumerating the candidate solutions of a branch, the branch is checked against upper and lower estimated bounds on the optimal solution. It is discarded if it cannot produce a better solution than the best one found so far by the algorithm. While the subproblem is solved, one of the following situation occur as the branching rules (Oppen, et al., 2010);

1. If the solution is fractional with a better objective value than the current candidate solution, choose a variable with a fractional value to branch on, and create two (or more) subproblems.
2. If the solution has a poorer or equal value than the current candidate solution, the node is fathomed.
3. If the solution is an integer with a better objective value than the candidate solution, the solution becomes the new candidate solution, and the node is fathomed.
4. If no feasible solution, the node is fathomed.

In our case, when subproblem does not generate any more negative reduced cost columns, the master problem provides the optimal solution of the set covering type formulation. If all decision variables, y_m , x_{ijk} , are an integer, the solution is also optimum. However, if any of those variables have fractional values or some customers may be visited more than once, the branch-and-bound tree must be explored.

The branching strategies is very importance in a branch-and-price algorithm because branching decisions are taken regarding the fractional solutions of the generated columns. These decisions must be compatible with the structure of the subproblem for generating the new columns (Desrochers, et al., 1992). The depth-first, branch and bound algorithm is used if the LP solution is fractional. Three branching schemes are applied in the branch-and-price algorithm for solving the LRPTW.

a) Facility Variables

If at least one of the facility variable y_m presents fractional value, it simply forces corresponding depot to be closed or open by assigning the value 0 or 1, respectively. The pricing problem remains the same since y_m is not present in any constraints of the subproblem where each depot is considered independently.

b) Number of Vehicles

Let k_m is the number of vehicles stationed at facility m . If the solution contains a fractional number of these vehicles, let's say l , it can be either round up or round down by adding the covering constraints $k_m \geq \lceil l \rceil$ or $k_m \leq \lfloor l \rfloor$ in constraint (3.16). This process is repeated everywhere if it is needed in the branch-and-bound tree.

c) Flow Variables

The branching on flow variables (x_{ijk}) is used if both the number of open facilities and the number of vehicles are integers, but the flow variables are still fractional (Kallenhauge, et al., 2005). Equation (3.29) is used to make a decision for the branching arc.

$$\max c_{ij} [\min(x_{ijk}, 1 - x_{ijk})] \quad (3.31)$$

If $x_{ijk} = 0$, it must ensure that no columns including this arc are added to the master problem. If the columns generated earlier are reused, the columns that use this arc have to be removed from our column pool. If $x_{ijk} = 1$, it must ensure that no columns containing an arc $(i, k: k \neq j)$ or an arc $(k, j: k \neq i)$ are added to the master problem.

It must be noted here that it is possible to fix a fractional variable x_{ijk} at one. This information is easily transferred to the subproblem by fixing the value of the flow on each arc of the route at one by removing from the network the other arcs incident to the nodes visited by route r . However, it is impossible to fix variable x_{ijk} at zero directly. Rather, it is necessary to explore many combinations of the flow values of the arcs of the route.

3.3 Example of Branch-and-Price algorithm for LRPTW

The small distribution network of 2-depot $M = \{1, 2\}$ and 3-customer $C = \{1, 2, 3\}$, as shown in Figure 3.3, represents an example to demonstrate the branch-and-price algorithm. The objective is to find a set of open depot(s) and a set of arcs of minimal total cost. To do that, five questions have to be answered;

- How many facilities to locate?
- Where is the location of facilities?
- Which customers to assign to which depots?
- Which customers to assign to which routes?
- In what order of the customers should be on each route?

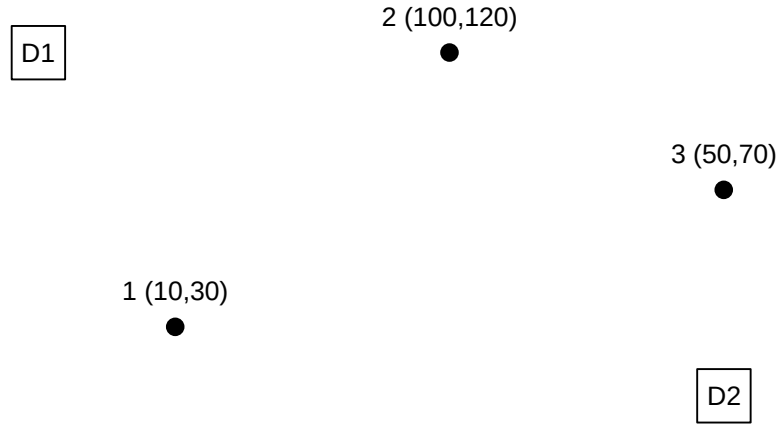


Figure 3.3 Example Network of LRPTW

The values below are assigned to each parameter.

f	= 5,000	cost of setting up the depot at every sites
Q	= 200	depot capacity
O	= 225	vehicle cost
d	= 20	customers' demand
q	= 200	vehicle capacity
t		travel time on arc (Figure 3.4) and service time at the vertex
$[a,b]$	= [10,30]	time windows of customer no.1
	= [100,120]	time windows of customer no.2
	= [50,70]	time windows of customer no.3

	D1	C1	C2	C3		D2	C1	C2	C3
D1	Inf	20	15	26	D2	Inf	20	26	15
C1	30	Inf	32	32	C1	30	Inf	32	32
C2	25	32	Inf	24	C2	36	32	Inf	24
C3	36	32	24	Inf	C3	25	32	24	Inf

Figure 3.4 Travel Time on Arcs between Depots to Customers

a) General Format of RMP

Figure 3.5 illustrates the general format of RMP for solving LRPTW. The objective function consists of two rows. The top row is the cost of setting up the depots and

operating cost of routes. The second row is the list of decision variables on depot y_m and route z_p . The constraints consist of four sets. First is the flow conservation constraints ensuring that each customer must be visited exactly once. Second is capacity constraints. Third and fourth are depot and vehicle control parameters. They will be used in the branch-and-bound if the decision variables cannot produce the integer solutions.

Cost	f_1	f_2	c_p at D1	c_p at D2		
Decision Variables	y_1	y_2	z_p at D1	z_p at D2		
Constraints			Visited customers at D1	Visited customers at D2	$\geq$	1
	Q_1		Negative route demand at D1		$\geq$	0
		Q_2		Negative route demand at D2	$\geq$	0
	1				$\leq$	1
		1			$\leq$	1
			Number of vehicle (k) at D1	Number of vehicle (k) at D2	$\geq$	0
					$\geq$	0

Figure 3.5 General RMP of LRPTW

b) Initial Solution

The problem starts with an initial solution. As mentioned, it can be any feasible solution that meets all constraints, and we start with *depot-i-depot* routes. Therefore, six routes are built in this step, including D1-C1-D1, D1-C2-D1, D1-C3-D1, D2-C1-D2, D2-C2-D2, and D2-C3-D2 (Figure 3.6). The RMP of this initial solution is shown in Figure 3.7.

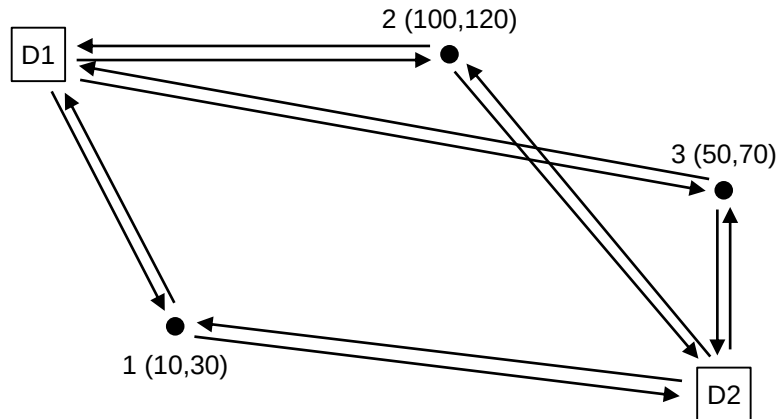


Figure 3.6 Initial Solution

	5,000	5,000	265	255	277	265	277	255			
	0	0	1	0	0	1	0	0	=	1	
	0	0	0	1	0	0	1	0	=	1	
	0	0	0	0	1	0	0	1	=	1	
200	0	0	-20	-20	-20	0	0	0	≥	0	
0	200	0	0	0	0	-20	-20	-20	≥	0	
1	0	0	0	0	0	0	0	0	≤	1	
0	1	0	0	0	0	0	0	0	≤	1	
0	0	1	1	1	0	0	0	0	≥	0	
0	0	0	0	0	0	1	1	1	≥	0	

Figure 3.7 RMP at Initial Solution

After performing simplex algorithm using Gurobi Optimization, the solution of the initial solution is shown in Figure 3.8 with the result of 10,775.

	5,000	5,000	265	255	277	265	277	255			
Decision Variables	$y_1 = 1$	$y_2 = 1$	$z_1 = 1$	$z_2 = 1$	$z_3 = 0$	$z_4 = 0$	$z_5 = 0$	$z_6 = 1$			Dual Price
	0	0	1	0	0	1	0	0	=	1	$\pi_1 = 265$
	0	0	0	1	0	0	1	0	=	1	$\pi_2 = 255$
	0	0	0	0	1	0	0	1	=	1	$\pi_3 = 255$
200	0	0	-20	-20	-20	0	0	0	≥	0	$\mu_1 = 0$
0	200	0	0	0	0	-20	-20	-20	≥	0	$\mu_2 = 0$
1	0	0	0	0	0	0	0	0	≤	1	5,000
0	1	0	0	0	0	0	0	0	≤	1	5,000
0	0	1	1	1	0	0	0	0	≥	0	$\eta_1 = 0$
0	0	0	0	0	0	1	1	1	≥	0	$\eta_2 = 0$

$Z = 10,775$

Figure 3.8 Results of RMP at Initial Solution

These initial solutions imply that both depots are open with three constructed routes, D1-C1-D1, D1-C2-D1, and D2-C3-D2 (Figure 3.9). It creates the “worst feasible solution” and set to be the upper bound.

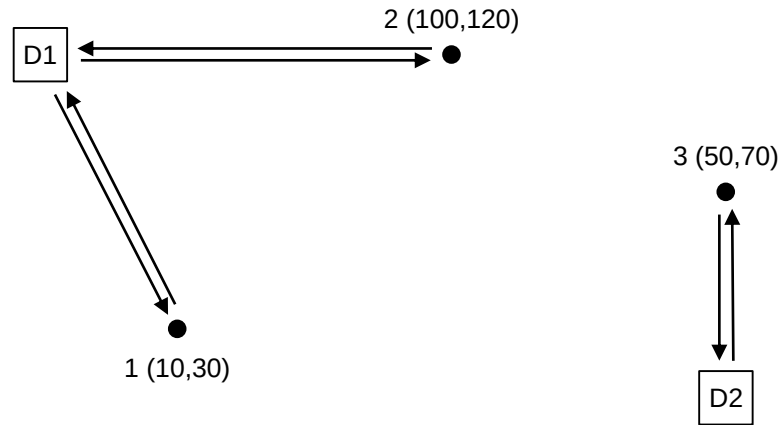


Figure 3.9 Initial Solution

c) Linear Programming (LP) Solution

Next, we need to determine the linear programming (LP) solutions or the lower bound. At this stage, the costs used in the subproblem must be the reduced cost. It can be calculated by using Equation 3.27 as shown in Figure 3.10.

	D1	C1	C2	C3
D1	Inf	20	15	26
C1	-235	Inf	-233	-233
C2	-230	-223	Inf	-231
C3	-219	-223	-231	Inf

	D2	C1	C2	C3
D2	Inf	20	26	15
C1	-235	Inf	-233	-233
C2	-219	-223	Inf	-231
C3	-230	-223	-231	Inf

Figure 3.10 Reduced Cost

The ESPPRC is called at the subproblem. It uses the labeling algorithm to create the routes. Table 3.1 shows the intermediate process while labeling algorithm starts and extends to determine the negative reduced cost columns to be added in the RMP.

Table 3.1 Example of Labeling Algorithm used in ESPPRC

Depot	Resident node	Time Resource	Demand Resource	Reduced Cost	Visited Node				Immediate predecessor or node	Label Number	Unreachable vertices
<i>M</i>	<i>res</i>	<i>t</i>	<i>d</i>	<i>c</i>	<i>vis</i>				<i>pred</i>	<i>Label No.</i>	<i>S</i>
D1	1	0	0	0.00	1	1	1	1	0	0	1
	2	20	20	245.00	0	1	0	0	0	1	1
	1	50	20	0.00	1	1	0	0	2	4	1
	4	50	20	251.00	0	1	0	1	0	3	2
	4	52	40	2.00	0	1	0	1	2	6	2
	1	86	20	22.00	1	1	0	1	4	7	2
	1	88	40	-227.00	1	1	0	1	4	9	2
	3	100	20	240.00	0	1	1	1	0	2	3
	3	100	40	2.00	0	1	1	1	2	5	3
	3	100	60	-239.00	0	1	1	1	4	10	3
	1	125	20	0.00	1	1	1	1	3	11	3
	1	125	40	-238.00	1	1	1	1	3	12	3
	1	125	60	-479.00	1	1	1	1	3	13	3
D2	1	0	0	0.00	1	1	1	1	0	0	1
	2	20	20	245.00	0	1	0	0	0	1	1
	1	50	20	0.00	1	1	0	0	2	4	1
	4	50	20	240.00	0	1	0	1	0	3	2
	4	52	40	2.00	0	1	0	1	2	6	2
	1	75	20	0.00	1	1	0	1	4	7	2
	1	77	40	-238.00	1	1	0	1	4	9	2
	3	100	20	251.00	0	1	1	1	0	2	3
	3	100	40	-1.00	0	1	1	1	4	8	3
	3	100	60	-239.00	0	1	1	1	4	10	3
	1	136	20	22.00	1	1	1	1	3	11	3
	1	136	40	-230.00	1	1	1	1	3	12	3
	1	136	60	-468.00	1	1	1	1	3	13	3

At this step, the subproblem returns 12 routes (columns):

Route 1	D1-C1-D1	Route 7	D2-C1-D2
Route 2	D1-C2-D1	Route 8	D2-C2-D2
Route 3	D1-C3-D1	Route 9	D2-C3-D2
Route 4	D1-C1-C3-D1	Route 10	D2-C1-C3-D2
Route 5	D1-C1-C2-D1	Route 11	D2-C3-C2-D2
Route 6	D1-C1-C3-C2-D1	Route 12	D2-C1-C3-C2-D2

These routes are added as the new columns in the RMP after calculating their original cost based on the initial cost (Figure 3.4). The master problem is re-optimized again as shown in Figure 3.11.

5,000	5,000	265	255	277	293	282	296	265	277	255	282	280	307		
$y_1 = 0.3$	0	0	0	0	0	0	$z_6 = 1$	0	0	0	0	0	0		
0	0	1	0	0	1	1	1	1	0	0	1	0	1	=	1
0	0	0	1	0	0	1	1	0	1	0	0	1	1	=	1
0	0	0	0	1	1	0	1	0	0	1	1	1	1	=	1
200	0	-20	-20	-20	-40	-40	-60	0	0	0	0	0	0	≥	0
0	200	0	0	0	0	0	0	-20	-20	-20	-40	-40	-60	≥	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	≤	1
0	1	0	0	0	0	0	0	0	0	0	0	0	0	≤	1
0	0	1	1	1	1	1	1	0	0	0	0	0	0	≥	0
0	0	0	0	0	0	0	0	1	1	1	1	1	1	≥	0

$z = 1,796$

Figure 3.11 Results of Linear Programming

The solutions shown in Figure 3.11 is the LP solution and represent the lower bound of the problem. However, the variable y_1 equals 0.3 which is a fractional value. As mentioned in the formulation, the variable must be an integer representing the opening of the depot. Therefore, the branch-and-bound algorithm is called to find the integer solution.

d) Integer Programming (IP) Solution

At this stage, the previous solution represents the “root node” of the branch-and-bound tree. Next, we extend two branches at a time, both round up and round down. In our case, y_1 has to be rounded up $y_1 = 1$ and round down $y_1 = 0$. In order to do that, we manipulate the equation on the sixth row, changing from $\leq$ to be $=$, and change the value on the right side of the equation to be either 1 or 0. After that, the calculation restarts again from the master problem and subproblem. The process ended if four branch-and-bound criterion mentioned in topic 3.2.4 is satisfied. Figure 3.12 illustrates the branch-and-bound solution in our example.

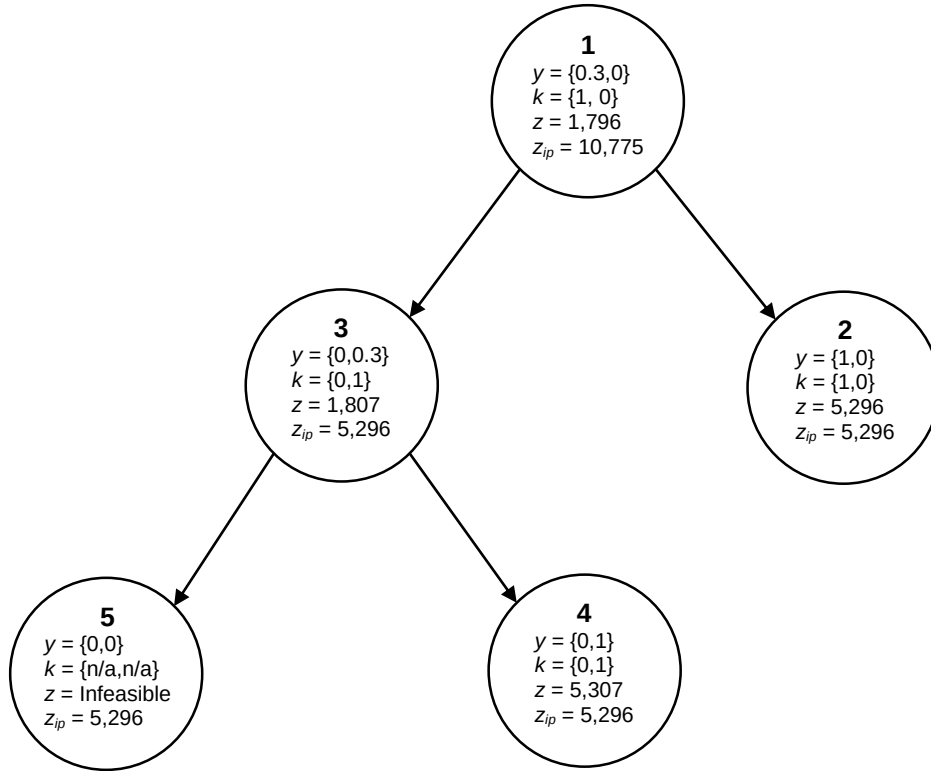


Figure 3.12 Branch-and-Bound Tree

The steps in branch-and-bound can be interpreted as follow:

1. From the previous process, the root node (Node 1) indicates the LP solution. It cannot be the IP solution since one of the variable (y_1) has a fractional value.
2. At Node 2, y_1 is mandatory set equal to 1. After reoptimizing, it creates the integer solutions $y_1 = 1$ and $k_1 = 1$ indicated that D1 is open, and only one vehicle used at that depot. Moreover, the solution in this step (5,296) is better than the predecessor node (10,775). Hence, this solution becomes a new candidate solution, and this node is fathomed by rule number 3. Nevertheless, we cannot ensure that this solution will be the optimal solution unless every node are explored.
3. At Node 3, y_1 is set equal to 0. The result shows that D2 is selected to be open. Although the solution (1,807) is better than the previous (5,296), the variable y_2 is a fractional value (0.3). Further branching step is required.
4. At Node 4, y_1 is set equal to 0 (from Node 3), and y_2 is set equal to 1. The solution shows that all variables present the integer values. However, this

solution (5,307) is poorer than the previous (5,296). Hence, this node is fathomed by branching rule number 2.

5. At Node 5, y_1 is set equal to 0 (from Node 3), and y_2 is set equal to 0. However, this scenario cannot process further since the criteria are not feasible. Therefore, this node is fathomed by branching rule no. 4.

From this completed branch-and-bound tree, it can be concluded that the result at Node 2 is the optimal solution. From the questions we raised in the beginning, they can be answered as follows;

- How many facilities to locate?
Ans One facility
- Where is the location of facilities?
Ans D1
- Which customers to assign to which depots?
Ans C1, C2, and C3 are assigned to D1
- Which customers to assign to which routes?
Ans All customers are assigned to the same route
- In what order of the customers should be on each route
Ans D1-C1-C3-C2-D1 as presented in Figure 3.13

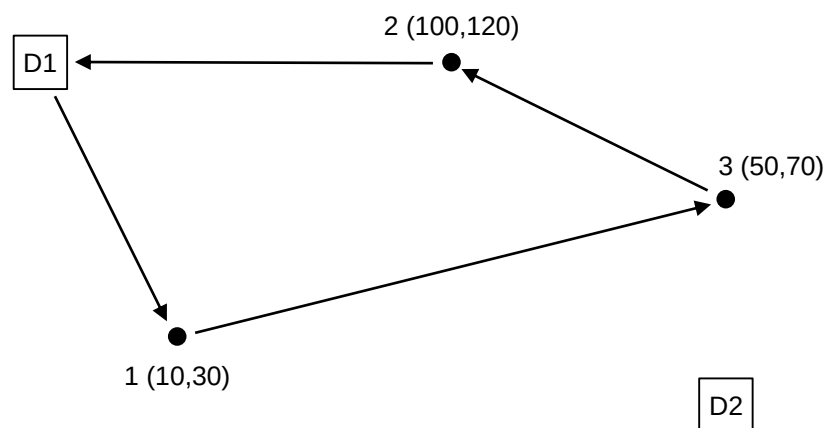


Figure 3.13 Optimal Solution

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Chapter 4

Model Evaluation

4.1 Modified Solomon Benchmark

4.2 Result and Discussion

4.2.1 Computational Time

4.2.2 Cost Components

References

4.1 Modified Solomon Benchmark

The branch-and-price algorithm is tested and compared with existing class 3 LRP instances available at http://prodhonc.free.fr/Instances/instances_us.htm (Prins, et al., 2006; Prins, et al., 2007). Since the original instances do not consider the time windows, we added the "well fit" time windows on the top of the routes found in the LRP solution. These "well fit" time windows would ensure that the same feasible optimal solution (as LRP) can be produced while solving the resulting LRPTW thereby providing a validation to our solution algorithm. Table 4.1 shows the results obtained by the branch-and-price algorithm of the modified LRP. It can be seen that our exact optimization algorithm for the LRPTW can identify the same optimal solution as is reported in the literature for the corresponding LRP instances. More details of the optimal solutions are presented in Appendix A.

Table 4.1 Results of Branch-and-Price on modified LRP

Instance	LP Solution	IP Solution	Branching Node	Time (Second)	
				LP	IP
Perl83-12x2 TW	181.48	204.00	2	0.58	0.72
Gaskell67-21x5 TW	383.89	424.90	5	0.53	1.23
Gaskell67-22x5 TW	523.24	585.11	10	5.29	14.32
Gaskell67-29x5 TW	454.60	512.10	3	5.71	6.94
Gaskell67-32x5(2) TW	491.02	504.33	2	74.27	79.75
Gaskell67-36x5 TW	388.75	460.37	16	3.85	28.27
Min92-27x5 TW	2,679.28	3,062.02	6	1.88	3.81

Since there are no LRPTW benchmark problems available, the new problem set is created in this study from the randomly generated problems (R1) of the VRPTW Solomon benchmark instances. The original VRPTW instances are modified to incorporate characteristics and effects of the LRPTW.

As the exact optimization of the LRPTW is computationally expensive, the first 10- and 25-customer of the Solomon benchmark instances are selected to create test instances for the LRPTW. Few test instances with 40-customer, the maximum size, which can be solved within reasonable computation time, are also created to evaluate the performance on medium size instances. The average width of time windows kept the

same as the original instance (Table 4.2). The LRPTW instances are named in a fashion such that the last part of the name shows the original Solomon benchmark instances, from which the LRPTW instance has been derived. New potential depot sites replace the original depot at coordinates (35,35). To determine the location of these depot sites, the k-medoids method introduced by Kaufman & Rousseeuw (1987) is used. It groups the customers as clusters and chooses the data point at a center and attempts to minimize the distance between customers in a cluster. The center of that cluster is taken as the possible depot location. We generate three new depots' location (Table 4.3). Finally, other parameters used in the LRPTW formulations are also generated. The capacity of each depot is set to 200. Facility and fixed vehicle costs are based on the cost values reported in Akca, et al. (2008), which are equal to 1,500 and 225 monetary units, respectively. The travel cost is the same as the travel distance, matched to the Euclidian distance and round down to nearest integer.

Table 4.2 Average Width of Time Windows

Instance	10-customer	25-customer
LRP-R100	-	-
LRPTW-R101	10.00	10.00
LRPTW-R102	105.00	63.44
LRPTW-R103	105.00	106.88
LRPTW-R104	143.20	136.64
LRPTW-R105	30.00	28.80
LRPTW-R106	115.00	77.84
LRPTW-R107	115.00	116.48
LRPTW-R108	149.20	143.04
LRPTW-R109	56.00	58.36
LRPTW-R110	74.70	83.28
LRPTW-R111	101.50	93.72
LRPTW-R112	112.10	116.44

Table 4.3 Location of the Potential Depots

Depot	Location (x,y coordinates)	Capacity
1	(16,29)	200
2	(35,57)	200
3	(49,19)	200

Figure.4.1 illustrates the location of the depots and customers for the newly created instances for the LRPTW. The numbers in the parenthesis represent the time windows

a_i and b_i , whereas the single number outside the parenthesis shows the customer's number.

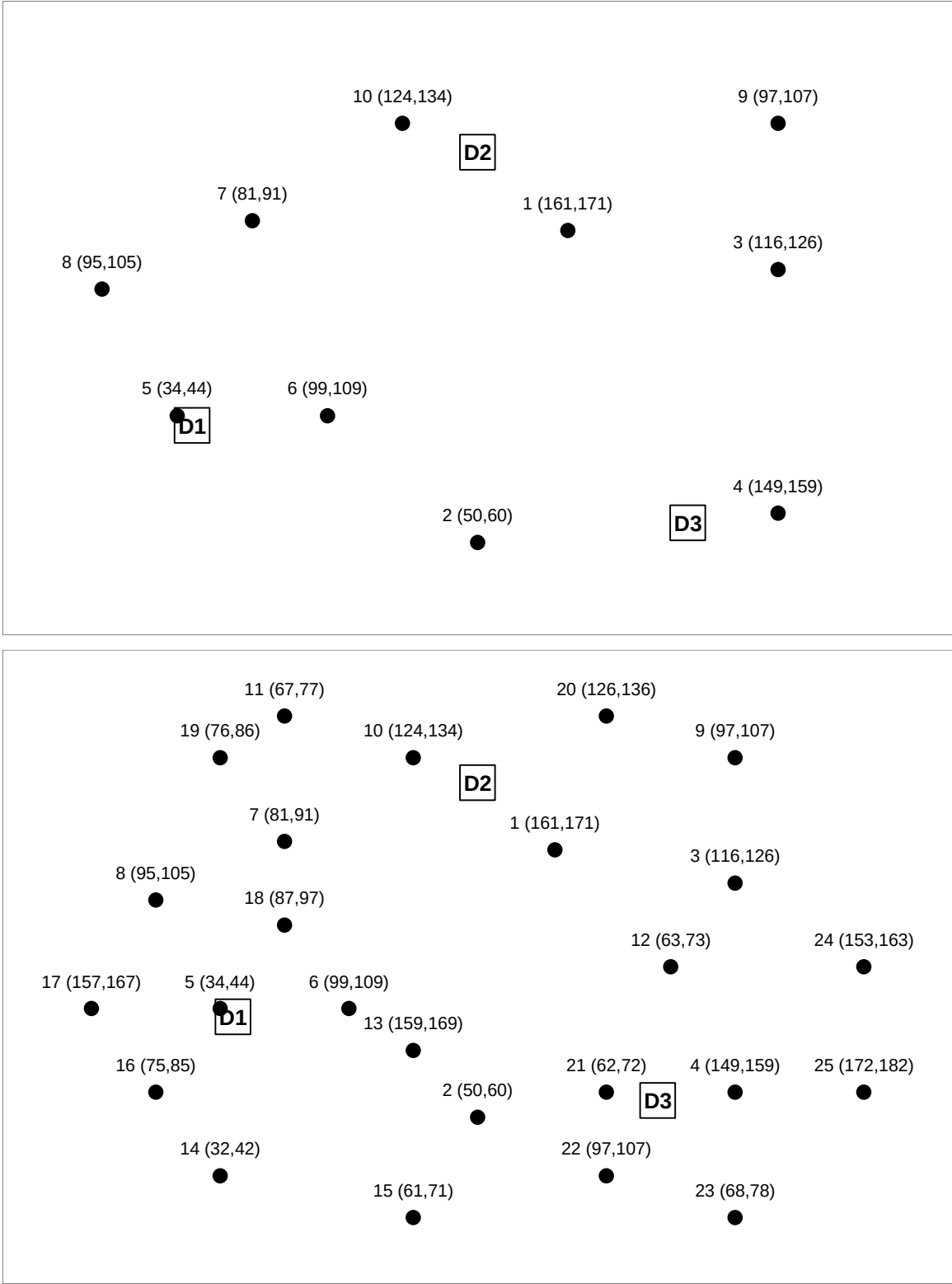


Figure 4.1 LRPTW-R101 Instances with 10-customer (Top) and 25-customer (Below)

4.2 Results and Discussion

Computational tests of the algorithm are performed on a computer with Intel® Core™ i7-3930K 3.20 GHz processor, and 32 GB of RAM. The algorithm is programmed in MATLAB with Gurobi Optimizer 5.6 as the LP solver.

The results are shown in Table 4.4. The column “*LP Solution*” refers to the linear programming solution at the root node while column “*IP Solution*” is the optimal integer solution. Column “*Branching Node*” means the number of nodes in the branch-and-bound tree from the root node to reach the optimal solution. “*Time*” shows the computational time. In “*Selected Depot*” column, the check mark means that the depot is selected. “*Number of Vehicles*” refers to the number of vehicles used in each selected depot and “*Number of Customers*” equals to the number of customers served by the particular depot.

Furthermore, “*Total Distance*” refers to the total traveling distance starting from the depot to visit all of the customers and return to the depot again and “*Average Distances*” means the average distances traveled by each vehicle. “*Total Load*” represents the total units of the commodity delivered by vehicles. In other words, this value equals to customers’ demand along the vehicle route. “*Average Load*” is the average units of a commodity containing by each vehicle. “*Load Factor*” equals to total load divide by vehicle capacity. Finally, the last three columns, i.e. depot, vehicle, and transport costs are the fragments of the total cost. Their summation is equal to the IP solution.

The results show that our algorithm is successful in solving LRPTW in all instances optimally with acceptable times. Moreover, three instances with 40-customer are also successfully solved under eight-hour limitation time. More details of the optimal solutions are presented in Appendix B.

Table 4.4 Computational Results

Instance	LP Solution	IP Solution	Branching Node	Time (hh:mm:ss)	
				LP	IP
LRP-R100-10	1,312.00	1,882.00	5	0:49	0:50
LRPTW-R101-10	1,922.00	2,691.00	29	0:00	0:01
LRPTW-R102-10	1,788.00	2,434.00	12	0:01	0:02
LRPTW-R103-10	1,788.00	2,434.00	12	0:01	0:02
LRPTW-R104-10	1,568.00	2,162.00	2	0:03	0:03
LRPTW-R105-10	1,719.00	2,438.00	15	0:00	0:01
LRPTW-R106-10	1,580.00	2,194.00	2	0:02	0:02
LRPTW-R107-10	1,580.00	2,194.00	2	0:02	0:02
LRPTW-R108-10	1,566.00	2,162.00	2	0:02	0:02
LRPTW-R109-10	1,588.00	2,429.00	39	0:01	0:02
LRPTW-R110-10	1,554.73	2,160.00	12	0:01	0:02
LRPTW-R111-10	2,855.50	2,184.00	28	0:00	0:08
LRPTW-R112-10	1,496.50	2,159.00	17	0:04	0:08
LRP-R100-25	3,586.63	3,776.00	19	1:10:01	2:36:26
LRPTW-R101-25	4,739.00	5,308.00	3	0:01	0:01
LRPTW-R102-25	3,533.00	5,027.00	5	0:10	0:18
LRPTW-R103-25	2,954.00	4,294.00	3	1:51	2:59
LRPTW-R104-25	2,888.00	4,251.00	3	4:52	5:55
LRPTW-R105-25	3,965.25	4,587.00	666	0:04	2:23
LRPTW-R106-25	3,843.86	4,438.00	39	0:42	2:07
LRPTW-R107-25	3,663.36	4,266.00	5	6:23	8:05
LRPTW-R108-25	3,514.00	4,077.00	587	25:19	1:49:09
LRPTW-R109-25	3,779.83	4,299.00	7	0:28	0:37
LRPTW-R110-25	3,658.74	4,285.00	153	1:32	11:34
LRPTW-R111-25	3,660.88	4,289.00	8	2:27	4:06
LRPTW-R112-25	3,557.11	4,250.00	5	6:39	9:00
LRPTW-R101-40	7,636.25	7,645.00	1,270	0:07	1:52:29
LRPTW-R102-40	6,752.30	7,150.00	3,759	6:00	7:49:51
LRPTW-R105-40	6,452.85	6,919.00	4,555	0:49	1:16:15

Table 4.4 (Cont.) Computational Results

Instance	Selected Depot			Number of Vehicles			Number of Customers			Total Distance			Average Distance		
	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3	D1	D2	D3
LRP-R100-10	-	-	✓	-	-	1	-	10	-	-	-	157	-	-	157
LRPTW-R101-10	-	✓	-	-	4	-	-	10	-	-	291	-	-	72.75	-
LRPTW-R102-10	✓	-	-	3	-	-	10	-	-	259	-	-	86.33	-	-
LRPTW-R103-10	✓	-	-	3	-	-	10	-	-	259	-	-	86.33	-	-
LRPTW-R104-10	-	-	✓	-	-	2	-	-	10	-	-	212	-	-	106
LRPTW-R105-10	-	✓	-	-	3	-	-	10	-	-	263	-	-	87.67	-
LRPTW-R106-10	-	-	✓	-	-	2	-	-	10	-	-	244	-	-	122
LRPTW-R107-10	-	-	✓	-	-	2	-	-	10	-	-	244	-	-	122
LRPTW-R108-10	-	-	✓	-	-	2	-	-	10	-	-	212	-	-	106
LRPTW-R109-10	✓	-	-	3	-	-	10	-	-	254	-	-	84.67	-	-
LRPTW-R110-10	✓	-	-	2	-	-	10	-	-	210	-	-	105	-	-
LRPTW-R111-10	✓	-	-	2	-	-	10	-	-	234	-	-	117	-	-
LRPTW-R112-10	-	✓	-	-	2	-	-	10	-	-	209	-	-	104.5	-
LRP-R100-25	✓	-	✓	1	-	1	10	-	15	351	-	425	351	-	425
LRPTW-R101-25	✓	-	✓	5	-	3	13	-	12	268	-	240	53.6	-	80
LRPTW-R102-25	✓	-	✓	4	-	3	12	-	13	213	-	239	53.25	-	79.67
LRPTW-R103-25	✓	-	✓	2	-	2	12	-	13	169	-	225	84.5	-	112.5
LRPTW-R104-25	✓	-	✓	2	-	2	13	-	12	161	-	190	80.5	-	95
LRPTW-R105-25	✓	-	✓	3	-	2	15	-	9	297	-	165	99	-	82.5
LRPTW-R106-25	✓	✓	-	2	2	-	14	11	-	250	288	-	125	144	-
LRPTW-R107-25	✓	-	✓	2	-	2	13	-	12	170	-	196	85	-	98
LRPTW-R108-25	✓	✓	-	1	2	-	8	17	-	115	287	-	115	143.5	-
LRPTW-R109-25	✓	-	✓	2	-	2	13	-	12	198	-	201	99	-	100.5
LRPTW-R110-25	-	✓	✓	-	2	2	-	11	14	-	175	210	-	88	105
LRPTW-R111-25	✓	-	✓	2	-	2	13	-	12	185	-	204	92.5	-	102
LRPTW-R112-25	✓	-	✓	2	-	2	13	-	12	159	-	191	79.5	-	95.5
LRPTW-R101-40	✓	✓	✓	5	3	3	14	13	13	253	234	183	50.6	78	61
LRPTW-R102-40	✓	✓	✓	4	3	2	14	14	12	242	222	161	60.5	74	80.5
LRPTW-R105-40	✓	✓	✓	2	2	3	12	13	15	220	240	384	110	120	128

Table 4.4 (Cont.) Computational Results

Instance	Total Load			Average Load			Average Load Factor			Depot Cost	Vehicle Fixed Cost	Transport Cost
	D1	D2	D3	D1	D2	D3	D1	D2	D3			
LRP-R100-10	-	-	124	-	-	124	-	-	0.62	1,500	225	157
LRPTW-R101-10	-	124	-	-	31	-	-	0.16	-	1,500	900	291
LRPTW-R102-10	124	-	-	41.33	-	-	0.21	-	-	1,500	675	259
LRPTW-R103-10	124	-	-	41.33	-	-	0.21	-	-	1,500	675	259
LRPTW-R104-10	-	-	124	-	-	62	-	-	0.31	1,500	450	212
LRPTW-R105-10	-	124	-	-	41.33	-	-	0.21	-	1,500	675	263
LRPTW-R106-10	-	-	124	-	-	62	-	-	0.31	1,500	450	244
LRPTW-R107-10	-	-	124	-	-	62	-	-	0.31	1,500	450	244
LRPTW-R108-10	-	-	124	-	-	62	-	-	0.31	1,500	450	212
LRPTW-R109-10	124	-	-	41.33	-	-	0.21	-	-	1,500	675	254
LRPTW-R110-10	124	-	-	62	-	-	0.31	-	-	1,500	450	210
LRPTW-R111-10	124	-	-	62	-	-	0.31	-	-	1,500	450	234
LRPTW-R112-10	-	124	-	-	62	-	-	0.31	-	1,500	450	209
LRP-R100-25	138	-	194	138	-	194	0.69	-	0.97	3,000	450	332
LRPTW-R101-25	172	-	160	34.4	-	53.33	0.17	-	0.27	3,000	1,800	508
LRPTW-R102-25	164	-	168	41	-	56	0.21	-	0.28	3,000	1,575	452
LRPTW-R103-25	156	-	176	78	-	88	0.39	-	0.44	3,000	900	394
LRPTW-R104-25	163	-	169	81.5	-	84.5	0.41	-	0.42	3,000	900	351
LRPTW-R105-25	191	-	135	63.67	-	67.5	0.32	-	0.34	3,000	1,125	462
LRPTW-R106-25	199	133	-	99.5	66.5	-	0.5	0.33	-	3,000	900	538
LRPTW-R107-25	163	-	169	81.5	-	84.5	0.41	-	0.42	3,000	900	366
LRPTW-R108-25	142	190	-	142	95	-	0.71	0.48	-	3,000	675	402
LRPTW-R109-25	174	-	158	87	-	79	0.44	-	0.4	3,000	900	399
LRPTW-R110-25	-	138	194	-	69	97	-	0.35	0.49	3,000	900	385
LRPTW-R111-25	163	-	169	81.5	-	84.5	0.41	-	0.42	3,000	900	389
LRPTW-R112-25	163	-	169	81.5	-	84.5	0.41	-	0.42	3,000	900	350
LRPTW-R101-40	194	171	198	38.8	57	66	0.19	0.29	0.33	4,500	2,475	670
LRPTW-R102-40	191	195	177	47.75	65	88.5	0.24	0.33	0.44	4,500	2,025	625
LRPTW-R105-40	191	172	200	95.5	86	66.67	0.48	0.43	0.33	4,500	1,575	844

4.2.1 Computational Time

Two computational times are evaluated in this section; the time spends to calculate the LP solution at a root node and the time to obtain the IP optimal solution (Figure 4.2). The difference between these times can be considered as the branching time. Typical to other column generation applications, in our algorithm as well, most of the computational time and resources are consumed by the pricing problem.

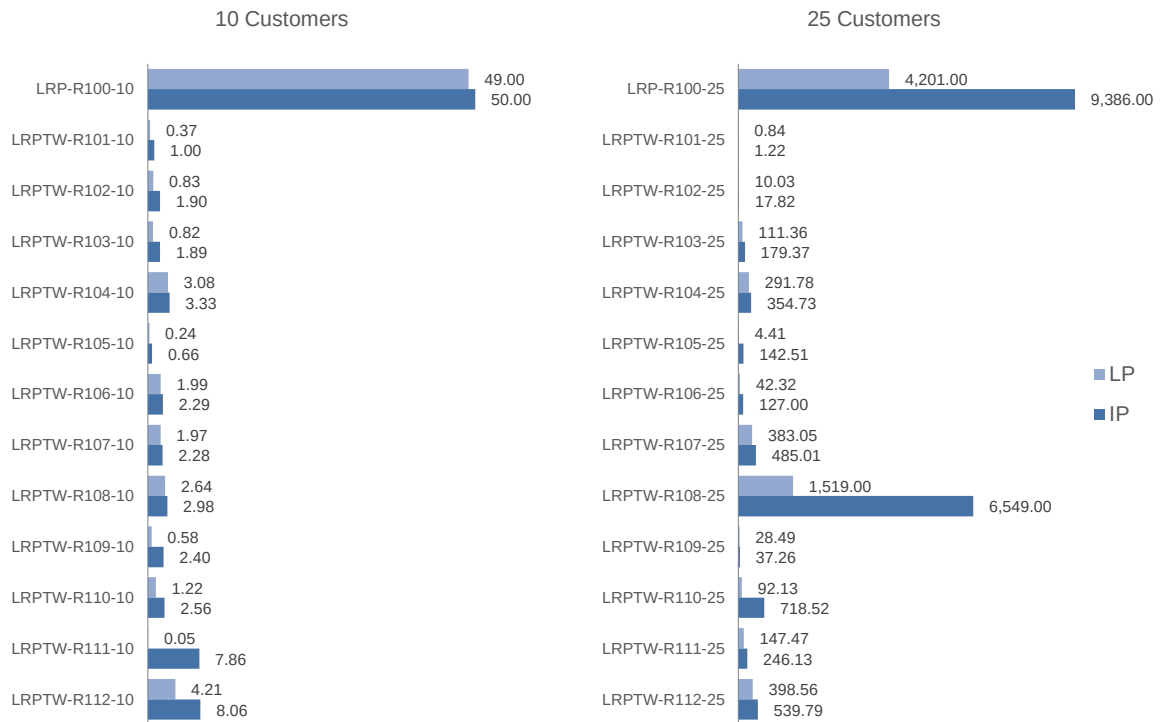


Figure 4.2 Computational Time in Second

Due to a higher number of possible paths, the computational time for LRP with relaxed time windows (R100) are relatively high. When the time windows are considered, the computational time is dramatically increased, especially when the density of time windows decreases, which allows longer feasible partial paths to be generated. For 10-customer, the computational time is relatively fast. 11 out of 12 instances are solved within 5 seconds of CPU time. Only one instance, LRPTW-R108, required the significant amount of time (40 seconds). However, for 25-customer, it required considerably longer computational time, as expected. There are seven instances that could be solved within 5 minutes while the other four instances computation time rose to 12 minutes. Here again the LRPTW-R108 instance

proved to be the most computationally expensive, and it required 1 hour and 49 minutes to be solved to the optimality.

4.2.2 Cost Components

Four topics related to LRPTW are discussed in the following section, including the depot, vehicle, distance, and load.

a) Depot

Based on the depot capacity and the total demand of the customers, at least one depot to be open for 10-customer and two depots are required to be open for 25-customer instances. For 25-customer, it can be seen that the combination of D1 and D3 is the most preferred pair, which dominated the other combinations in 9 out of 12 instances. Given the design constraint that at least two depots are required, different depots have been selected in the 25-customer case as compared to the 10-customer case (where one depot is sufficient). For example, in the three 25-customer instances where D2 has been selected, it has replaced the depot that is selected in the 10-customers instances of the same benchmark. Similarly, a completely new set of depots has been selected (leaving D2 out) in the exact solutions of the LRPTW-R101-25, LRPTW-R105-25, and LRPTW-R1012-25, as compared to their 10-customer version.

b) Vehicle

The number of vehicles used mostly depends on the density of the time windows (Figure 4.3). The tighter the time windows require the larger number of vehicles used. For 10-customer, there are four instances that required more than two vehicles, i.e. LRPTW-R101, LRPTW-R102, LRPTW-R103, and LRPTW-R105 while the other instances used only two vehicles. For 25-customer, the vehicles used in LRPTW-R101 is among the highest (8 vehicles) because of the tight time windows. The number of vehicles is reduced when the time windows are a bit relaxed. In LRPTW-R108, there are only three vehicles needed since the time window constraint is almost dormant.

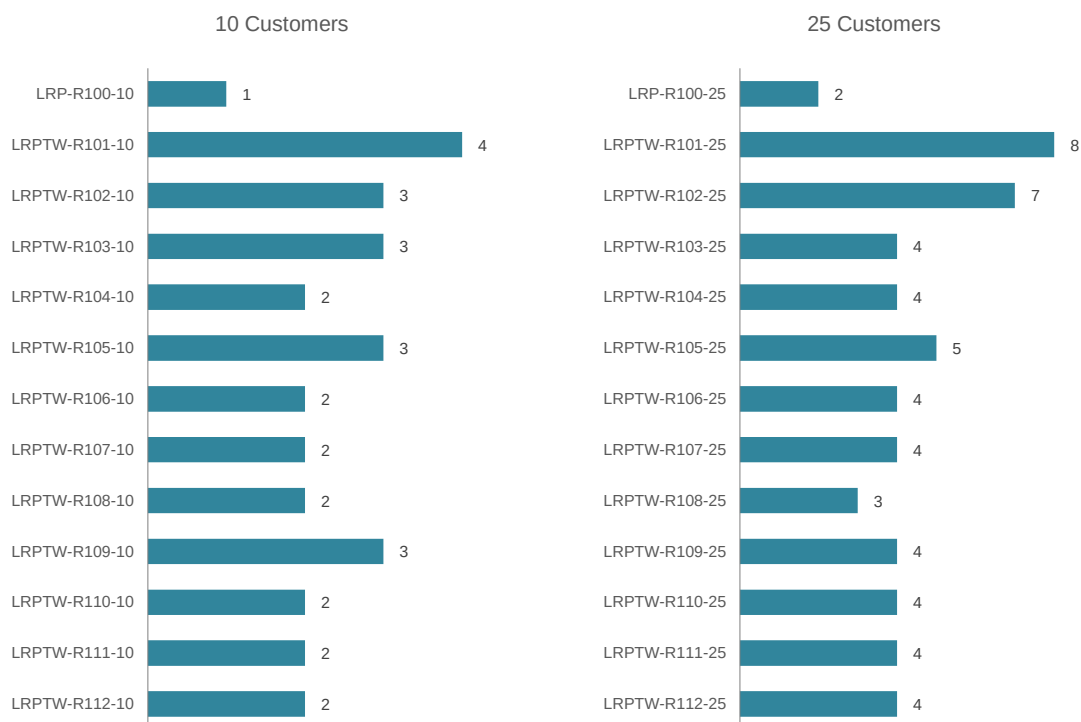


Figure 4.3 Number of Vehicles Used

c) Distance

Unlike other components, it is found that there is no relationship between width or density of time windows and traveling distance (Figure 4.4). One cannot easily differentiate the effect of time windows, especially when it is less tightly constrained. When they lose the tightness, the time windows are dominated by the location of the customers and the results become closer to an ordinary location-routing problem. Figure 4.5 illustrated the example of optimal solutions comparing between LRPTW-R102-10 and LRPTW-R102-25. As we expected, once the opening of new depot (D3) became viable, the customers located nearby (2,3,4,5,10) are shifted and served by that new depot. This result explains the comparison of the traveling distance between 10- and 25-customer instances. Even though the 25-customer problem has 2.5 times higher number of customers, the distance traveled per customer is decreased from 25.9 to 18.08, showing a decrease of 30.2 % in distance traveled per customers. Overall similar results are obtained in other problems and the average reduction in distance traveled per customer is 30.7 % for all 12 test instances, when the size of the problem increases from 10- to 25-customer.

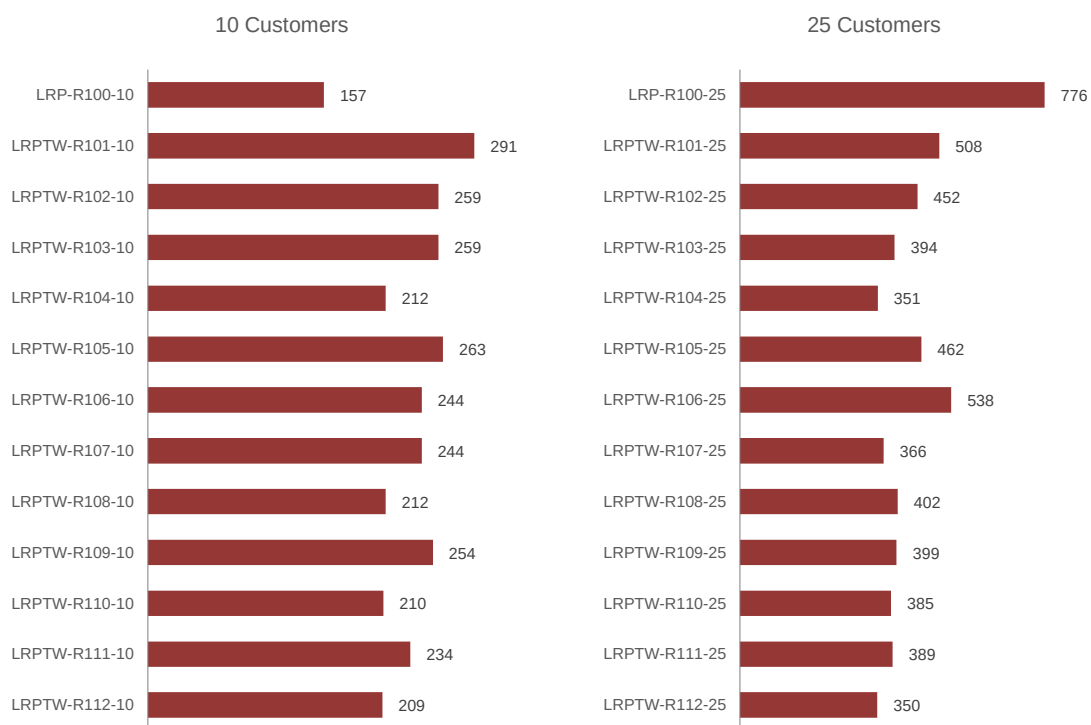


Figure 4.4 Total Travelled Distance

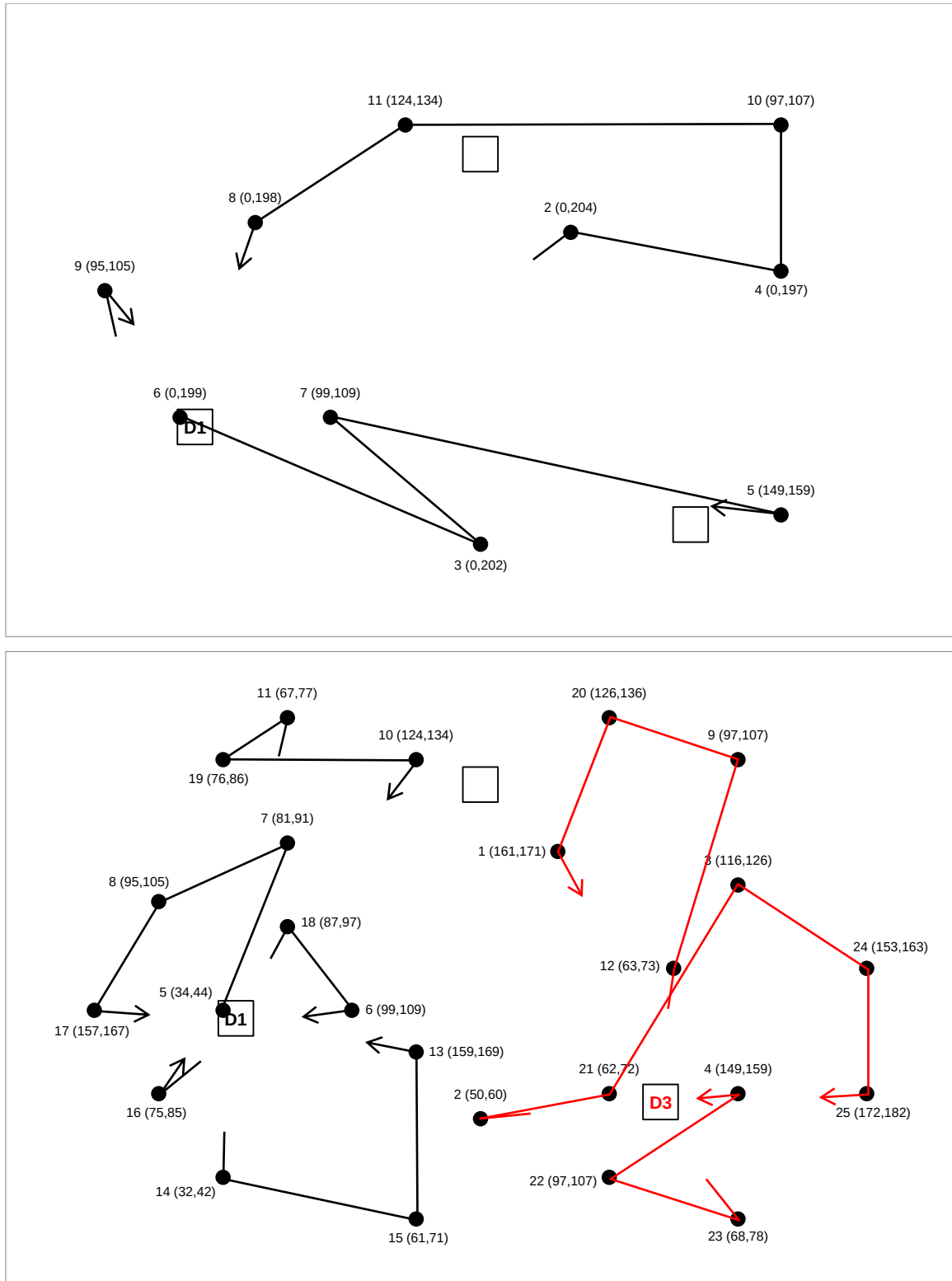


Figure 4.5 Optimal Solutions of LRPTW-R102 with
10-customer (Top) and 25-customer (Below)

d) Load

As mentioned in vehicle component, instances with tighter time windows demand more vehicles. As a result, each vehicle visited only a few customers and contained a few commodities. It can be seen in Figure 4.6 that in some instances, the load factor is fairly low due to the high density of time windows. In almost all instances, the load factors are calculated under 0.5 since only a small number of customers can be visited. The LRPTW-R108 with 25-customer resulted in the highest value of 0.71, which have relatively larger time windows. However, it must be noted here again that the value of vehicle capacity remains the same as original problems (200 units). For the practical purposes, the results can be improved by changing the vehicle size, lower the vehicle capacity, or using the soft time windows (Qureshi, et al., 2009; Bhusiri, et al., 2014).

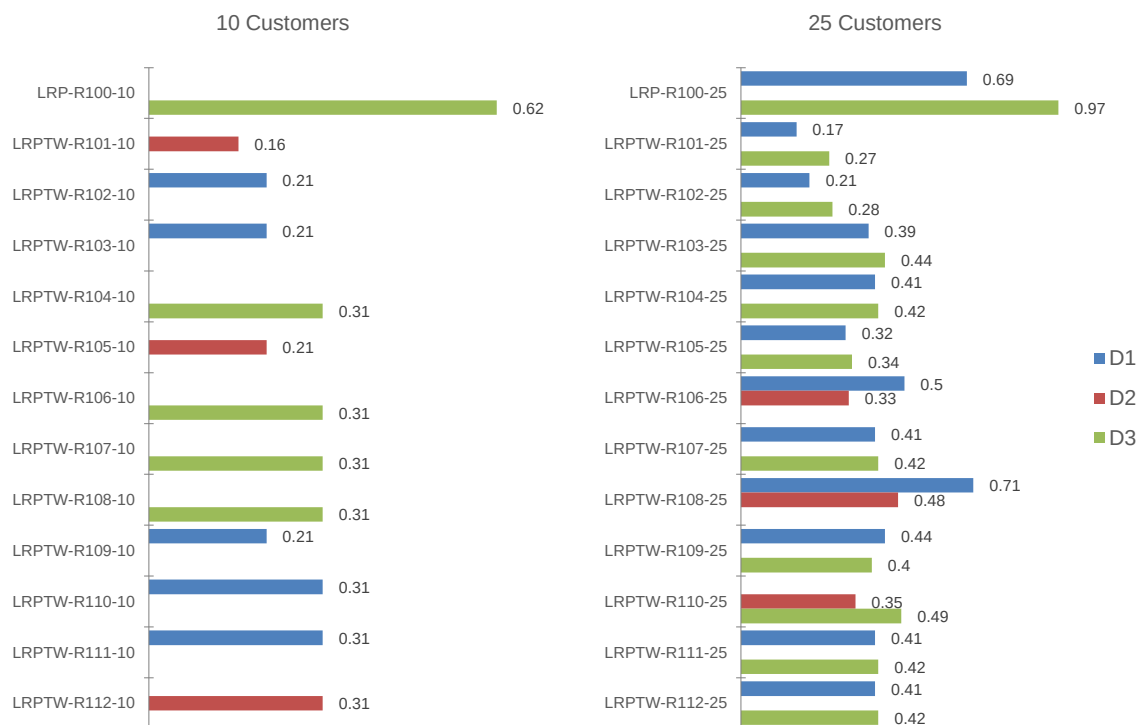


Figure 4.6 Average Load Factor

Furthermore, a comparison between exact solutions of the LRPTW and the original VRPTW has also been summarized in Table 4.5. By introducing the choices for depot selection in the LRPTW, it is clearly shown that the number of vehicles and the total distances is reduced as compared to the VRPTW. The number of vehicles is saved from 62 to 55 vehicles while the

total distance decreased from 5,477 to 4,996 units. Although it can be argued that additional depots in LRPTW costs more than savings in the distance traveled and number of vehicles, however, in long terms, these savings may easily subsidize the additional depot costs. This comparison clearly shows the advantage of simultaneously optimizing the mathematical problem set at both strategic and operational levels (i.e. in the form of the LRPTW) as compared to the classic VRPTW.

Table 4.5 Comparison of the Results between LRPTW and Original VRPTW of 25-customer Problems

Instance	Number of Vehicles					VRPTW	Difference
	LRPTW						
	D1	D2	D3	Total			
R101-25	5	-	3	8	8	0	
R102-25	4	-	3	7	7	0	
R103-25	2	-	2	4	5	-1	
R104-25	2	-	2	4	4	0	
R105-25	3	-	2	5	6	-1	
R106-25	2	2	-	4	5	-1	
R107-25	2	-	2	4	4	0	
R108-25	1	2	-	3	4	-1	
R109-25	2	-	2	4	5	-1	
R110-25	-	2	2	4	5	-1	
R111-25	2	-	2	4	5	-1	
R112-25	2	-	2	4	4	0	
Total				55	62	-7	

Table 4.5 (Cont.) Comparison of the Results between LRPTW and Original VRPTW of 25-customer Problems

Instance	Total Distance					% Different
	LRPTW				VRPTW	
	D1	D2	D3	Total		
R101-25	268	-	240	508	608	-16%
R102-25	213	-	239	452	540	-16%
R103-25	169	-	225	394	449	-12%
R104-25	161	-	190	351	412	-15%
R105-25	297	-	165	462	524	-12%
R106-25	250	288	-	538	460	17%
R107-25	170	-	196	366	418	-12%
R108-25	115	287	-	402	393	2%
R109-25	198	-	201	399	436	-8%
R110-25	-	175	210	385	424	-9%
R111-25	185	-	204	389	424	-8%
R112-25	159	-	191	350	389	-10%
Total				4,996	5,477	-9%

Lastly, the IP solutions are the combination of the depot, vehicle, and transport costs for 10-customer (Figure 4.7) and 25-customer (Figure 4.8). Among them, the depot cost has the highest proportion of our testing instances, 80% for 10-customer and 68% for 25-customer, approximately. Since the depot cost is relatively high, it is likely to be affected by capacity/demand constraints. On the other hand, the vehicle and transport costs more directly reflect the time windows effects.

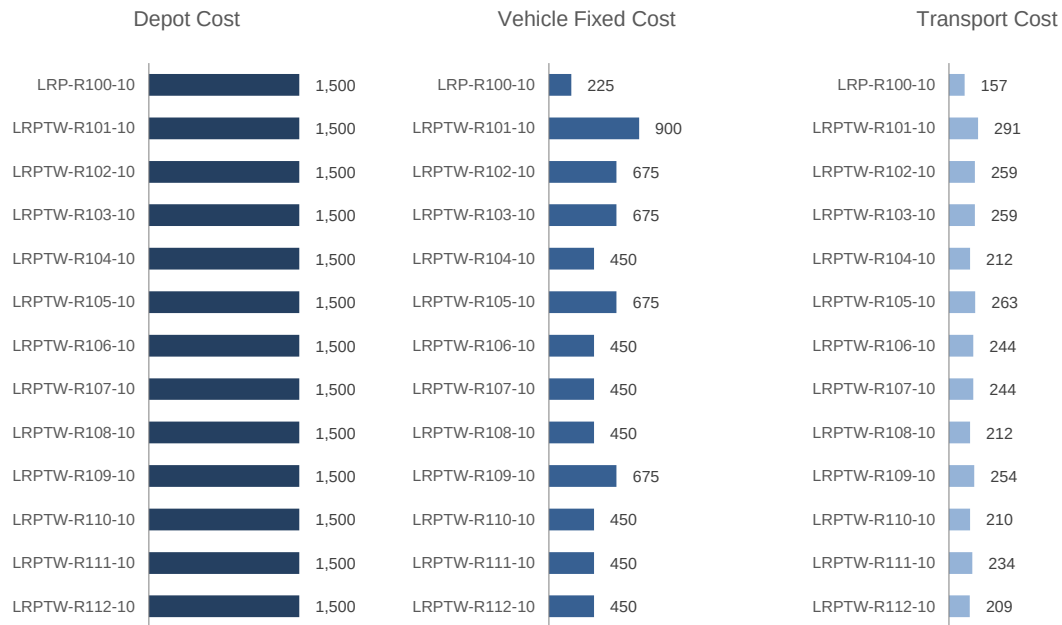


Figure 4.7 Cost Components for 10-customer

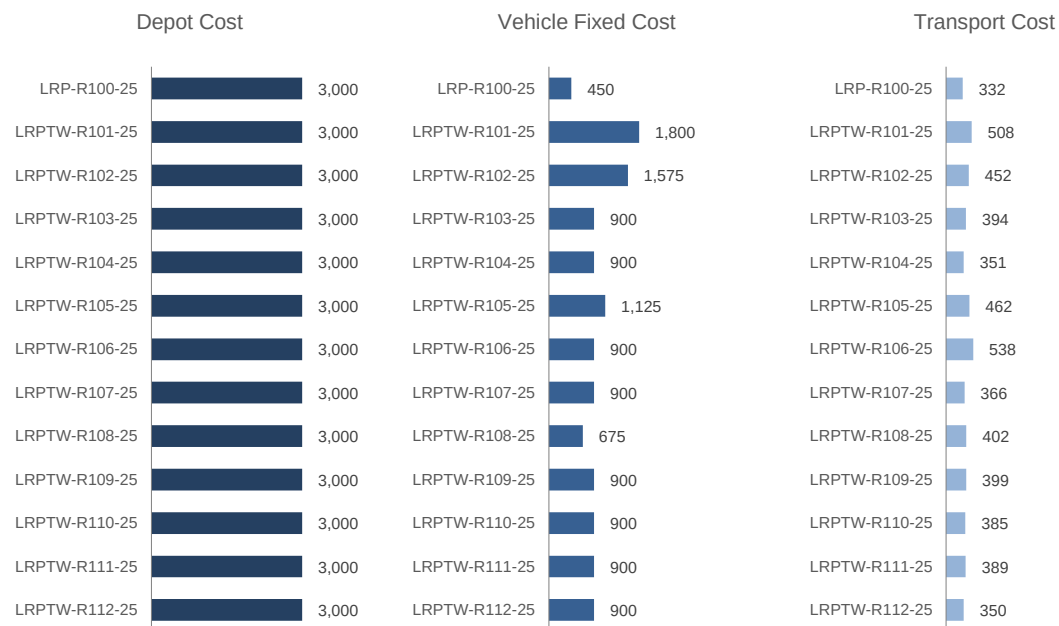


Figure 4.8 Cost Components for 25-customer

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Chapter 5

LRPTW in

Osaka Distribution Network

5.1 Introduction

5.2 Methodology

5.3 Results and Discussion

References

5.1 Introduction

While the early LRP studies provide the framework and algorithm development with hypothesis testing instances, the evaluation and investigation of specific applications is still being questioned. In LRP model, two cost components, i.e. location and routing, influence the calculation process and tradeoffs must be made between them. The ratio between these two components varies among different business. For example, the cost ratio of pharmaceuticals business is 0.26, the paper business is 0.85, and the consumer merchandising business is 1.56 (Srivastava, 1986). Understanding the different environment and apply to the real world problem provide not only a broader understanding of location-routing options, but also convincing evidence of its efficiency and practicality. This problem is motivated by the observation of LRPTW in Chapter 4 that in some contexts, the cost saving might not be influenced by only depot location, route length, and time windows. It may be more economical to change the configuration of the underlying parameter instead of open new facilities. Therefore, a full understanding of that observation is examined in this study. In other words, the main purpose of this study helps us to make decisions on;

- How many and which depots to be operated?
- Which customers to be assigned to which depots?
- What are the sequences of the customers?
- What are the truck routes?
- How is the difference between opening the new depot and enlarging the old depot?
- What is the effect on the size of the vehicle?

The impact of external characteristics is assessed and evaluated by various factors. The factors that influence the distribution system include depot location, depot and vehicle capacities, their fixed costs, and time windows.

5.2 Methodology

The distribution data from freight carrier have been tested with the branch-and-price algorithm to evaluate the cost structure and environmental impact on the location-routing problem. The selected logistic company provides a variety of services including warehousing, storage and inventory management, and door to door delivery. Fresh food, medical specimens, and large items are among the commodities to be delivered on the daily basis (Teo, et al., 2015). The transportation information is collected by the global positioning system (GPS) during the real time operation. It provides the customers' location, delivery routes, and traveling speed. Moreover, the additional travel times on the road networks, which have never been collected by the GPS are collected from the traffic census data from Osaka city (MLIT, 2010). Figure 5.1 and 5.2 shows the location of depots and selected customers in the city of Osaka. The depots are located at Toyonaka-shi, Minato-ku, and Nishinari-ku. The travel times between depot to the customer and customer to the customer are converted and calculated the shortest path using Dijkstra's algorithm. It must be noted here that the carrier specifically classifies some private information. Therefore, the logistics data including customers' demand are randomly hypothetical. The time window width ($b_i - a_i$) and service time are constantly set equal to 30 and 10 minutes, respectively.

Three influence factors to be evaluated in the test instance are depot and vehicle configuration, i.e. location, size, and cost. Three sizes of depots and vehicles, i.e. small, medium, and large, make a combination of nine scenarios. It is quite obvious that the size and cost are interdependence since the larger depot space is costly. However, the warehousing cost varies by their locations. We estimated the depots' cost (f_m) and capacity (Q_m) based on the data available from commercial real estate service firm (JLRE, 2015). For the vehicle, the capacity (q) of 1,340 kg, 2 ton, and 3 ton trucks represent the small, medium, large vehicles. The vehicle fixed costs (c_{mj}) are 5,209, 7,441, and 10,418 yen per vehicle, respectively. The vehicle operating cost (c_{ij}) is 14.02 yen per minute (Qureshi, et al., 2014; Toyota, 2015). The morning and afternoon services are assumed to be exactly the same. Table 5.1 and 5.2 show the parameters used in our calculation.

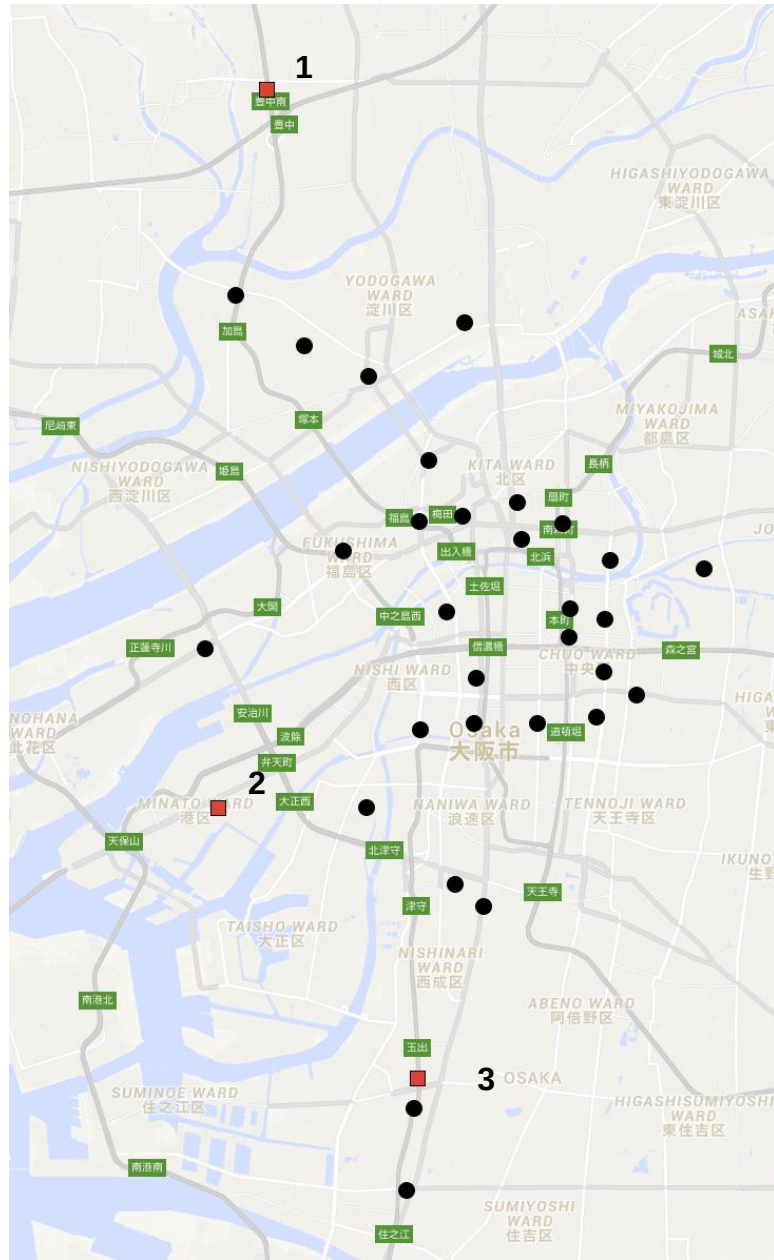


Figure 5.1 Location of Depots and Customers in Osaka Road Network



Figure 5.2 Location of the Depots in Osaka Distribution Network

Source: Google Maps®

Table 5.1 Parameters Used in Each Scenario

Scenario	Depot (m)		Vehicle	
	Capacity (Q_m)	Cost (f_m) in JPY	Capacity (q)	Cost (c_{mj}) in JPY
1	8,000	22,801	1,340	5,209
2		14,334	2,000	7,441
3		21,357	3,000	10,418
4	12,000	34,202	1,340	5,209
5		21,501	2,000	7,441
6		32,036	3,000	10,418
7	24,000	68,403	1,340	5,209
8		43,002	2,000	7,441
9		64,071	3,000	10,418

Table 5.2 Customers' Demand and Time Windows

Customer (i)	Demand (d_i)	Time Windows		Service Time (minute)
		a_i	b_i	
1	730	70	100	10
2	540	30	60	10
3	700	120	150	10
4	610	60	90	10
5	680	100	130	10
6	700	80	110	10
7	570	40	70	10
8	800	70	100	10
9	620	30	60	10
10	500	50	80	10
11	680	70	100	10
12	780	40	70	10
13	500	50	80	10
14	670	20	50	10
15	800	80	110	10
16	800	120	150	10
17	580	10	40	10
18	650	10	40	10
19	540	30	60	10
20	500	90	120	10
21	720	40	70	10
22	740	30	60	10
23	640	50	80	10
24	660	80	110	10
25	550	30	60	10
26	780	120	150	10
27	630	120	150	10
28	630	110	140	10
29	780	70	100	10
30	710	80	110	10

5.3 Result and Discussion

Computational tests of the algorithm are performed on a computer with AMD Phenom™ II X6 1100 T 3.20 GHz processor, and 16 GB of RAM. The algorithm is programmed in MATLAB and using Gurobi Optimizer 5.6 as the LP solver. Table 5.3 to 5.5 show the details of the solution on LRPTW performed on the test problem represented the depot, vehicle, and transport information respectively.

Table 5.3 Depot Information

Scenario	Depot Cost (JPY)	Opened Depot			Customer Demand			Depot Load		
		D1	D2	D3	D1	D2	D3	D1	D2	D3
1	58,492	O	O	O	6,620	5,270	7,900	0.83	0.66	0.99
2	58,492	O	O	O	7,940	3,960	7,890	0.99	0.50	0.99
3	58,492	O	O	O	7,880	5,990	5,920	0.99	0.75	0.74
4	53,537	X	O	O	-	7,860	11,930	-	0.66	0.99
5	53,537	X	O	O	-	7,960	11,830	-	0.66	0.99
6	53,537	X	O	O	-	8,660	11,130	-	0.72	0.93
7	43,002	X	O	X	-	19,790	-	-	0.82	-
8	43,002	X	O	X	-	19,790	-	-	0.82	-
9	43,002	X	O	X	-	19,790	-	-	0.82	-

Table 5.4 Vehicle Information

Scenario	Vehicle Cost (JPY)	Vehicle Used				Average Load			Average Truckload		
		D1	D2	D3	Total	D1	D2	D3	D1	D2	D3
1	78,135	5	4	6	15	1,324.00	1,317.50	1,316.67	0.99	0.98	0.98
2	74,410	4	2	4	10	1,985.00	1,980.00	1,972.50	0.99	0.99	0.99
3	72,926	3	2	2	7	2,626.67	2,995.00	2,960.00	0.88	0.99	0.99
4	78,135	-	6	9	15	-	1,310.00	1,325.56	-	0.98	0.99
5	74,410	-	4	6	10	-	1,990.00	1,971.67	-	0.99	0.99
6	72,926	-	3	4	7	-	2,886.67	2,782.50	-	0.96	0.93
7	78,135	-	15	-	15	-	1,319.33	-	-	0.98	-
8	74,410	-	10	-	10	-	1,979.00	-	-	0.99	-
9	72,926	-	7	-	7	-	2,827.14	-	-	0.94	-

Table 5.5 Transportation Information

Scenario	Transport Cost (JPY)	Total Travel Time				Travel Time per Vehicle		
		D1	D2	D3	Total	D1	D2	D3
1	13,223.40	350.71	243.21	349.25	943.18	35.07	30.40	29.10
2	9,047.89	267.23	125.59	252.54	645.36	33.40	31.40	31.57
3	7,623.90	219.55	183.30	140.94	543.79	36.59	45.82	35.24
4	14,060.09	-	421.08	581.78	1,002.86	-	35.09	32.32
5	9,706.51	-	302.84	389.49	692.33	-	37.86	32.46
6	7,557.83	-	276.49	262.59	539.08	-	46.08	32.82
7	15,082.30	-	1075.77	-	1,075.77	-	35.86	-
8	10,418.26	-	743.10	-	743.10	-	37.15	-
9	8,300.97	-	592.08	-	592.08	-	42.29	-

In Table 5.3, the “O” mark in column “*Opened Depot*” represents the depot to be opened while “X” mark means the unselected depot. The capacity restriction causes all three depots (small size depots) to be opened in scenario 1-3, two depots (medium size depots) in scenario 4-5, and one depot (large size depot) in scenario 7-9. “*Customer Demand*” column refers to the total demand of customers that belong to each depot while the figures in “*Depot Load*” column are the demand/capacity ratio. It can be observed that in the small and medium size depot scenarios (scenario 1-6), Depot 2 is dominated by other depots. While the depot load of depot 1 and 2 are reported up to 0.83-0.99, the demand on Depot 2 consumes only 0.50-0.66. The main reason is that depot 2 locates in an industrial area in Minato-ku, which far from the city center compared to the others. It can serve only a fractional portion to the customers. Nevertheless, the benefit of locating in that area makes depot 2 accounts the lowest depot fixed cost (37% and 33% lower than depot 1 and 3, respectively). Therefore, considering together with vehicle and transportation costs, it is only one depot to be selected for larger size depot scenarios (scenario 7-9).

Although the portion of depot cost varies on the scenarios, the vehicle cost remains constant as shown in Figure 5.3 since the customers’ demand does not change. Fifteen small size vehicle, ten medium size vehicle, and seven large size vehicle are used regardless of the depot size. Clearly, the number of vehicles used at Depot 2 (shown in column “*Vehicle Used*”) are less than another depot because of the same reason mentioned earlier.

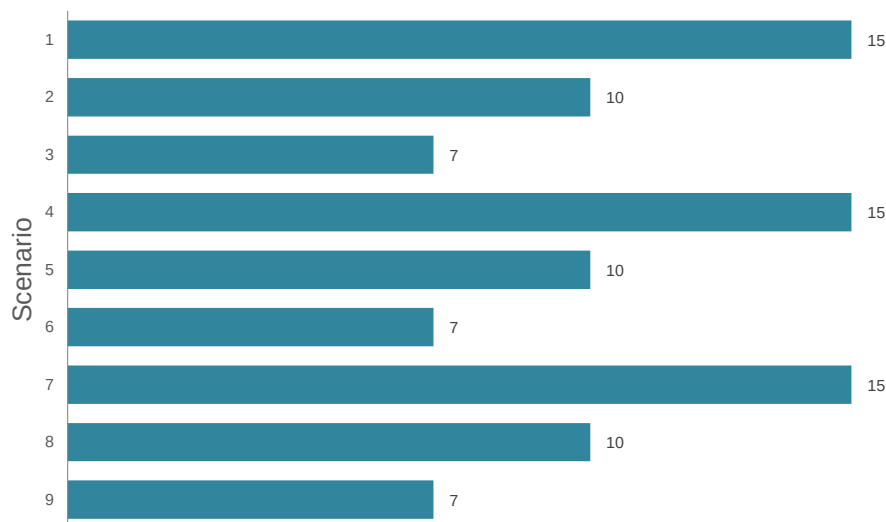


Figure 5.3 Number of Vehicles Used

In general, when the time windows constraints are taken into account on the routing problem, the truckload is significantly low comparing with ordinary VRP or LRP. It happens because the time restriction does not allow the vehicle to visit too many numbers of customers. Nevertheless, the truckload in our network is relatively high in all scenarios, presented 0.94-0.99 as shown in “Average Truck Load” column and Figure 5.4. It can be concluded that the 30-minute time window width ($b_i - a_i$) in this network is wide enough for each vehicle to deliver the goods in an effective manner.

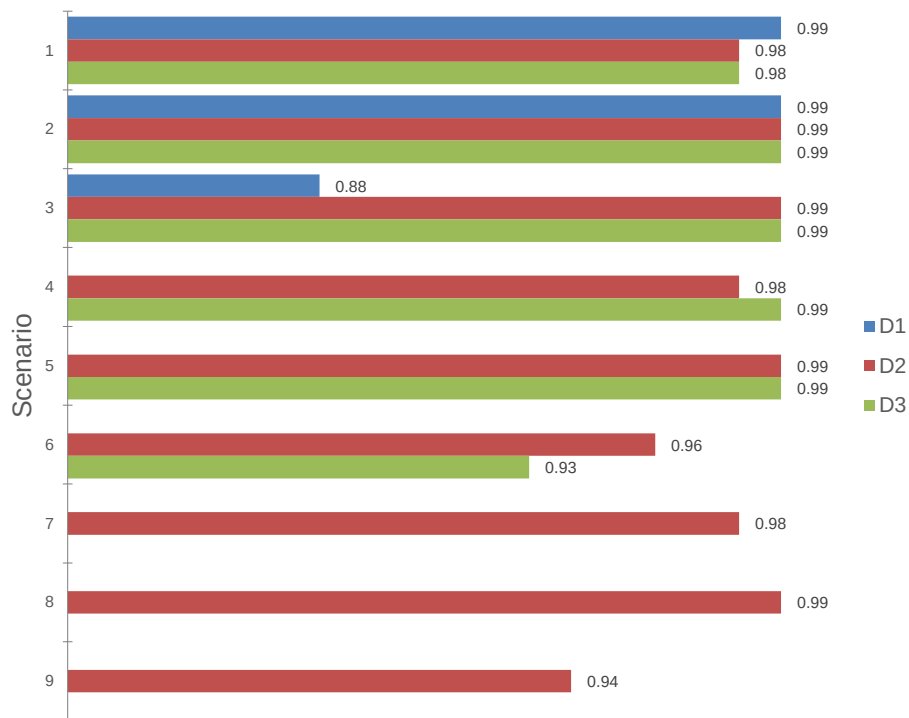


Figure 5.4 Average Truck Load

For the routing part, if the depot size did not change, it is undoubtedly true that the travel time reduced when the vehicle size increased (Figure 5.5). The numbers of customers that can be visited by small, medium, and large vehicles are 2, 3, and 4.28 customers on average. One of the main benefits of using larger size vehicle over the small size vehicle is that the non-profit empty truck on the return trips has been reduced dramatically, 34% of the medium vehicle and 58% of the large vehicle. In total, the medium and large size vehicles can save the distribution cost, i.e. vehicle plus transport costs, 9% and 12%, respectively.

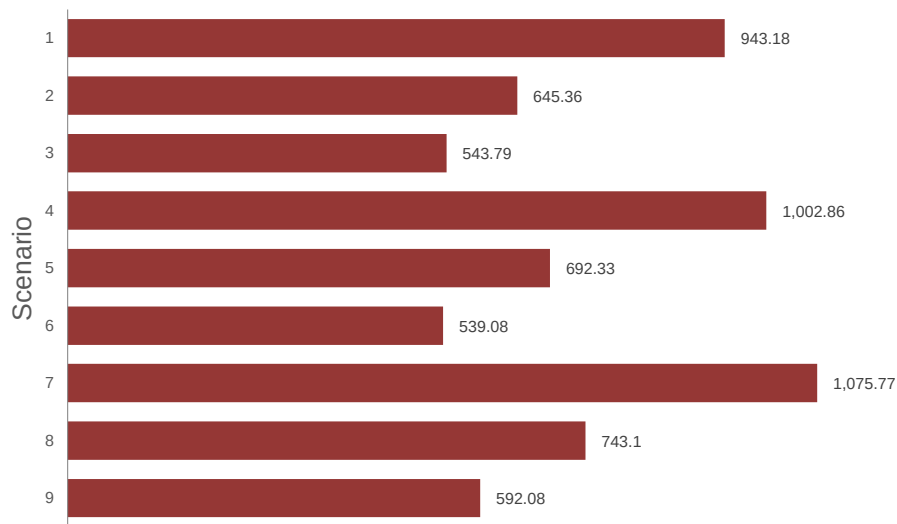


Figure 5.5 Total Travelled Time

Finally, the results of the overall cost prove that the large size depot serving by large size vehicles in scenario 9 satisfy the LRPTW in our distribution network as shown in Figure 5.6. Although the depot 2 located in Minato-ku seems not to be an appropriate location in small and medium size depot scenario, it proves to be the best location for the large size depot scenario. Figure 5.7 illustrates the optimal routes of scenario nine which represents the best solution of all scenarios.

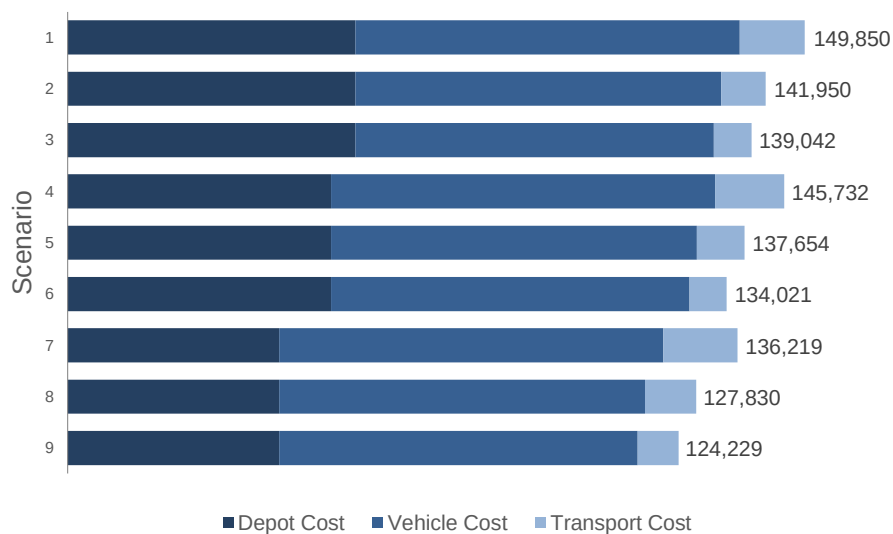
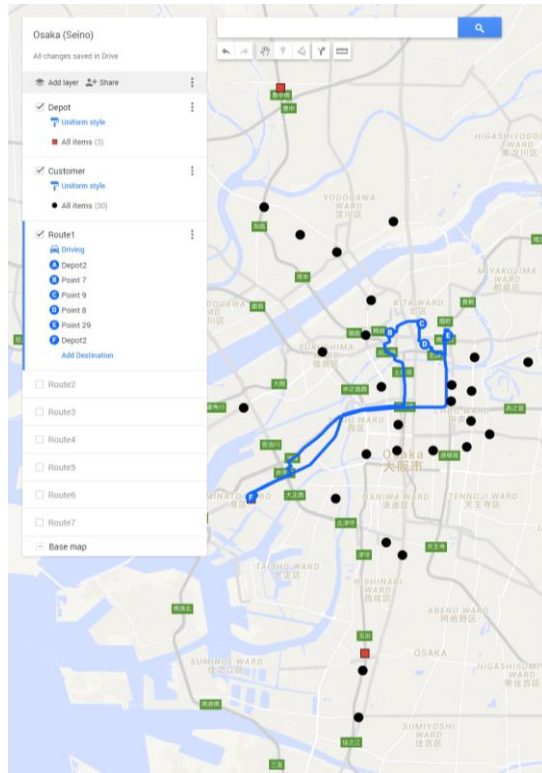
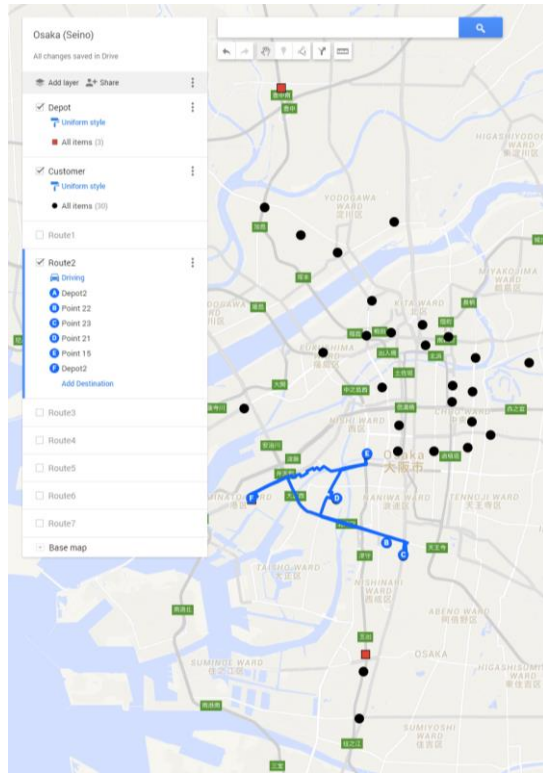


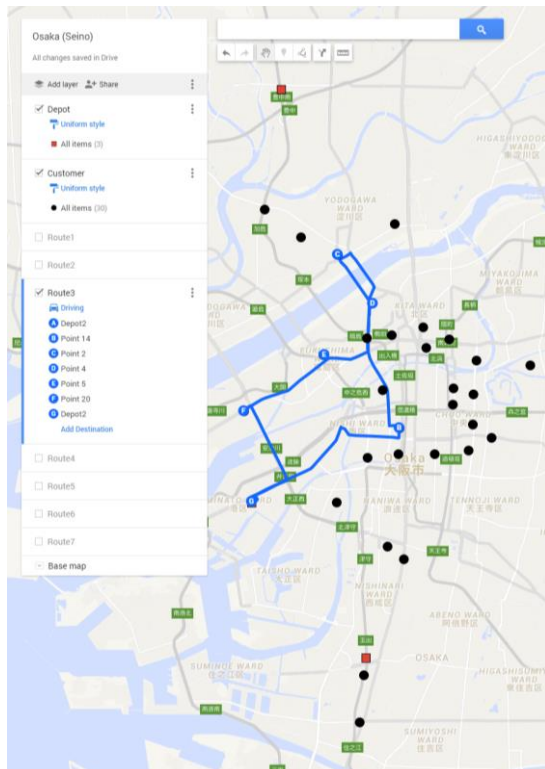
Figure 5.6 LRPTW Results on Testing Distribution Network



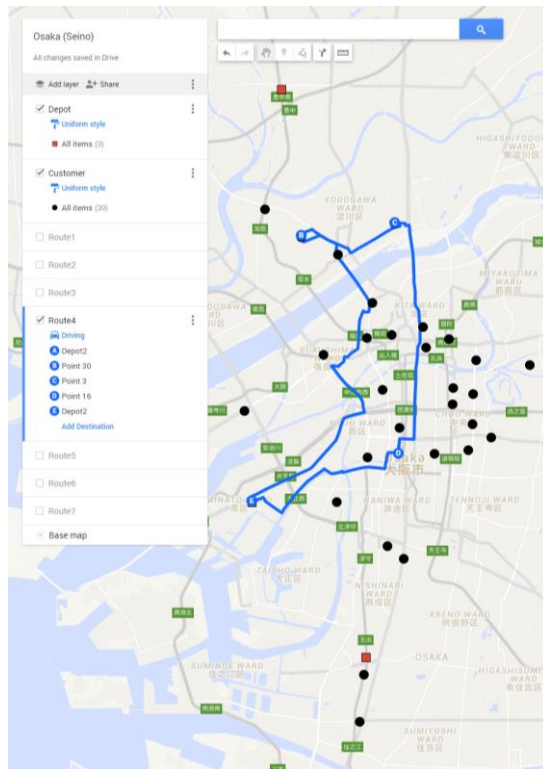
a)



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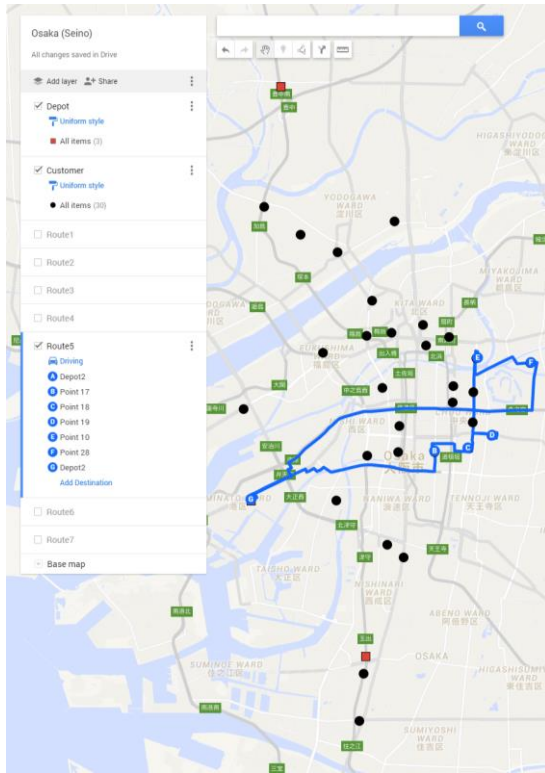


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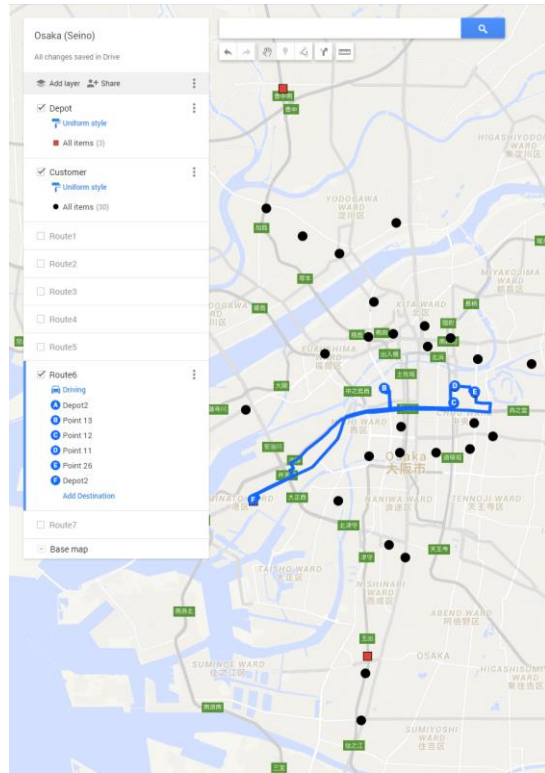


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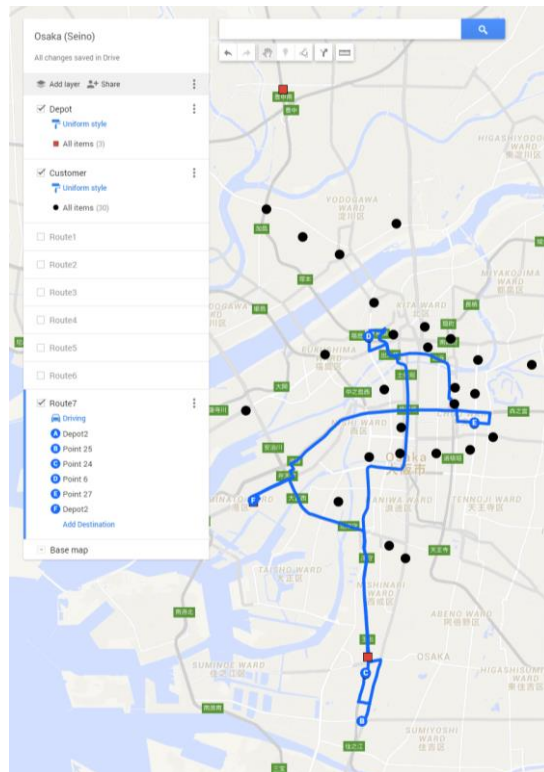
Figure 5.7 Optimal Routes of Scenario 9



e)



f)



g)

Figure 5.7 (cont.) Optimal Routes of Scenario 9

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Chapter 6

LRPTW in

Ishinomaki Humanitarian Logistics

6.1 Introduction

6.2 Scenarios

6.3 Tabu Search Heuristic

6.3.1 Route Construction

6.3.2 Route Improvement

6.3.3 Model Validation

6.4 Results and Discussions

References

6.1 Introduction

The city of Ishinomaki is located in the northeastern Miyagi Prefecture in a lowland area at the mouth of the Kitakami River (Figure 6.1). On February 2011, the total population was 162,822. During the great earthquake and tsunami, the maximum height of the tsunami in Ishinomaki was 8.6 m and these waves inundated about 30% of the coastal plains. As many as 3,417 people were killed, and 535 people are still officially missing (as of January 2013) (Nakanishi, et al., 2013). About 53,742 houses were affected, of which 22,357 houses were completely destroyed, 11,021 houses were severely damaged, and 20,364 houses were partially damaged (Taniguchi & Thompson, 2013).



Figure 6.1 Location of Ishinomaki and Epicenter

The official figures of the number of evacuees were reported as on April 11, 2011, a month after the disaster, to be 30,930 people, who were distributed to 152 shelters. Two depots were selected to store and manage the inventory. The sports park located in the north of the city was used by Japan Self Defense Force (JSDF) and private freight carriers in real operation after the earthquake. The market located on the west of the city was also used after closing down the sports park in September 2011 (Taniguchi & Thompson, 2013).

6.2 Scenarios

To model our algorithm in the Ishinomaki case, we needed to generalize the parameters and specific constraints as per the real-world problem. The specific needs of the victims after a disaster may vary depending on the desirability, time, and places. We considered food as our main priority. Based on Taniguchi and Thompson (2013), the daily meals, the rice balls (“onigiri” in Japanese) and bread for three meals per day, are considered the main demand of the people. This demand is formulated as a single commodity. Also, we recognize that there was a number of volunteers available to work without pay. In some cases, the expenses of relief operation were covered by the government or non-governmental organizations. The actual costs were implicitly added inside. It is interesting to see what changes in the relief planning occur if the depot opening cost, the vehicles, and the operating costs such as fuel are considered. The details in Table 6.1 show the five scenarios framed in this research to evaluate the location-routing problem in disaster relief operation.

Table 6.1 Scenarios of Location-Routing in Ishinomaki Case Study

Scenario	Number of Depot	Depot and Vehicle Cost	Time Windows
1 (Real Operation)	2	-	-
2	10	-	-
3	10	-	✓
4	10	✓	-
5	10	✓	✓

In scenario 1, the real operation is recalculated. Only two depots are operated located at the sports park and the market. We assumed that both depots had enough capacity for the total demand and the vehicle cost and operating cost are not taken into account.

In scenario 2, eight new depots are proposed. We determined the potential sites by considering their location, available spaces, and essential facilities. The capacity of each depot is estimated by its type and size. Figure 6.2 and Table 6.2 present the proposed depot locations corresponding to the operating centers.

In scenario 3, based on the lessons learned from the disaster that the volunteers or staffs from relief organization have a variety of functions to manage on the hourly basis and

also there may be desirable visiting times at shelters. Therefore, the hypothetical time windows (a_i and b_i) are assigned to each shelter randomly. The average time window width is kept equal to 132-time units.

In scenario 4, the operating costs are introduced into the operation. As mentioned previously, some might argue that the monetary term should not measure the relief operation in humanitarian logistics. However, in disaster cases, the available resources such as vehicles and staffs are always limited. The figures used in this scenario are expected to provide the effectiveness of the operation in the broader perspective. The depot opening cost (f_m) and vehicle cost (c_{ij}) are assigned equally to 50,000 and 25,000 monetary units.

Finally, in scenario 5, both operating cost and time windows are considered simultaneously. In every case, we used the homogeneous trucks with the capacity to carry 6,500 units. More details of the depot, vehicle, and shelter are represented in Appendix C.

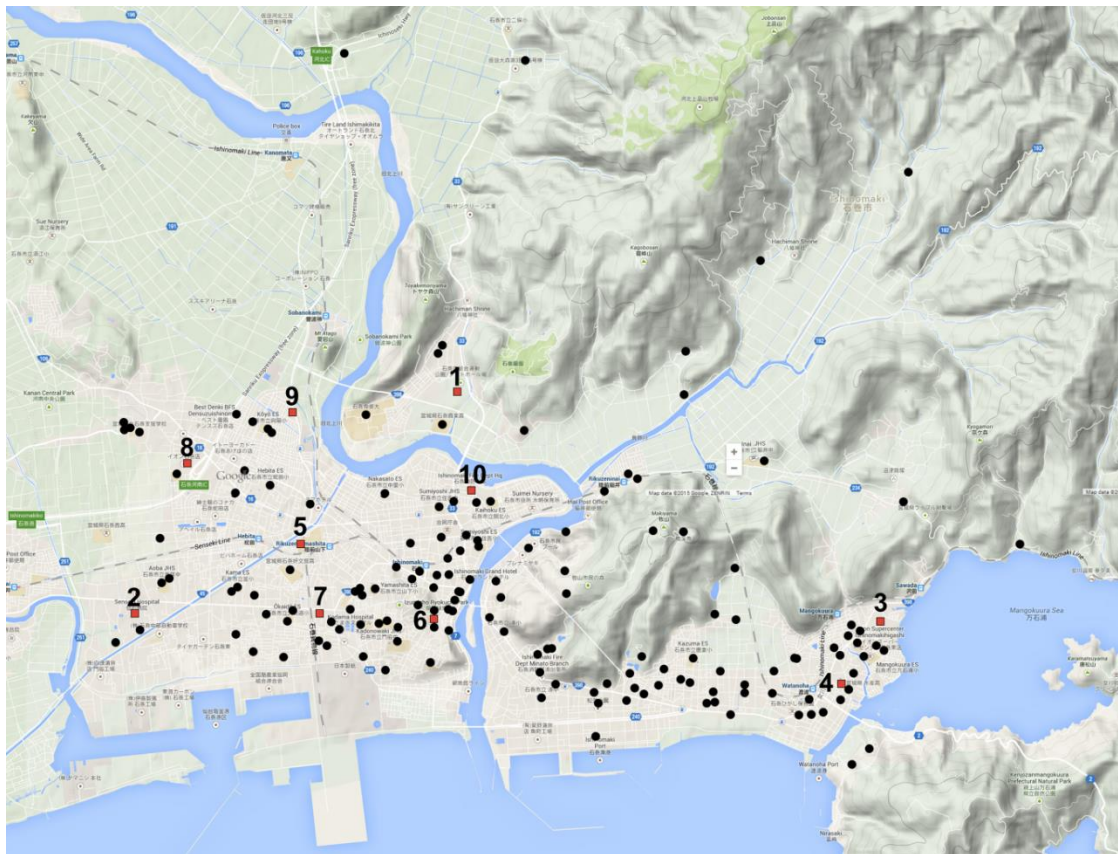


Figure 6.2 Location of 10 Proposed Depots and 152 Shelters in the City of Ishinomaki

Table 6.2 Proposed Depot Location in the City of Ishinomaki

Depot Number	Location	Coordinate		Capacity
		X	Y	
1	Sports Park (Real Operation)	38.45778	141.30933	50,000
2	Market (Real Operation)	38.42923	141.25772	20,000
3	Aeon Supercenter	38.42454	141.37451	40,000
4	Miyagi Prefectural Fisheries High School	38.42056	141.36965	20,000
5	Yamashita Junior High School	38.43799	141.28487	20,000
6	Ishinomaki Elementary School	38.42894	141.30500	20,000
7	York-Benimaru Okaido	38.42874	141.28680	20,000
8	Aeon Supercenter	38.44765	141.26542	40,000
9	Sakura Amusement	38.45419	141.28249	20,000
10	Ishinomaki Fire Department	38.44454	141.31077	20,000

6.3 Tabu Search Heuristic

Tabu search is a local search metaheuristic initially proposed by Glover (1977) as a metaheuristic for solving combinatorial optimization problems. It is a form of local search or local neighbor search by moving from a solution to its best neighbor. The term “neighbor” here means a solution obtained from a given solution using single allowable move (Desaulniers, et al., 2008). Each solution S has an associated set of neighbors $N(S)$. This iterative technique explores a set of solutions by repeatedly making moves using different “operators” from one solution S to a neighbor solution S' that located in the neighborhood $N(S)$ of S (Glover & Laguna, 1997). The tabu search allows the search space to be further explored even if the result is deterioration of the current objective function, to escape from local optima and avoid cycling. To avoid cycling, the previous solutions declares “tabu” (forbidden), not allowed for a specific number of iterations and stores in the tabu list in a short-term memory. The tabu status of a solution is overridden when certain criteria (aspiration criteria) are satisfied. Details about tabu search can be found in Glover (1989), Glover (1990), Hertz et al. (1997), Glover and Laguna (1999) and Gendreau (2003). The literature about tabu search in VRPTW and LRPTW is summarized as shown in Table 6.3.

Table 6.3 Summary of Publications on VRPTW and LRPTW using Tabu Search

Year	Authors	Problem	Title	Initial solution	Neighborhood operators
1993	Semet, F. and Taillard, E.	LRPTW	Solving real-life vehicle routing problems efficiently using tabu search	A generalized assignment heuristic	2-opt
1994	Garcia, B. L., Potvin, J. Y. and Rousseau, J. M.	VRPTW	A parallel implementation of the tabu search heuristic for vehicle routing problems with time window constraints	Solomon's I1 heuristic	2-opt*, Or -opt
1995	Rochat, Y. and Taillard, E.	VRPTW	Probabilistic diversification and intensification in local search for vehicle routing	Modification of Solomon's I1, 2-opt	2-opt, relocate
1995	Carlton, W. B.	VRPTW	A tabu search approach to the general vehicle routing problem	Insertion heuristic	Relocate
1996	Potvin, J. Y. and Bengio, S.	VRPTW	The vehicle routing problem with time windows, Part II: Genetic search	Solomon's I1 heuristic	2-opt*, Or -opt
1997	Taillard, E., Badeau, P., Gendreau, M., Guertin, F. and Potvin, J. Y.	VRPTW	A tabu search heuristic for the vehicle routing problem with soft time windows	Solomon's I1 heuristic	CROSS
1997	Badeau, P., Gendreau, M., Guertin, F., Potvin, J. Y. and Taillard, E.	VRPTW	A parallel tabu search heuristic for the vehicle routing problem with time windows	Solomon's I1 heuristic	CROSS
1997	Chiang, W. C. and Russell, R. A.	VRPTW	A reactive tabu search metaheuristic for the vehicle routing problem with time windows	Modification of Russell (1995)	l-interchange
1997	De Backer, B. and Furnon, V.	VRPTW	Meta-heuristics in constraint programming experiments with tabu search on the vehicle routing problem	Savings heuristic	Exchange, relocate, 2-opt *, 2-opt, Or -opt
1999	Brandão, J.	VRPTW	Metaheuristic for the vehicle routing problem with time windows	Insertion heuristics	Relocate, exchange, GENI
1999	Schulze, J. and Fahle, T.	VRPTW	A parallel algorithm for the vehicle routing problem with time window constraints	Solomon's I1, parallel I1 and savings heuristics	Ejection chains, Or -opt
2000	Tan, K. C., Lee, L. H. and Zhu, K. Q.	VRPTW	Heuristic methods for vehicle routing problem with time windows	Insertion heuristic of Thangiah et al. (1994)	l-interchange, 2-opt *
2001	Lau, H. C., Lim, Y. F. and Liu, Q.	VRPTW	Diversification of neighborhood via constraint-based local search and its application to VRPTW	Insertion heuristic	Exchange, relocate
2001	Cordeau, J. F., Laporte, G. and Mercier, A.	VRPTW	A unified tabu search heuristic for vehicle routing problems with time windows	Modification of sweep heuristics	Relocate, GENI
2003	Lau, H. C., Sim, M. and Teo, K. M.	VRPTW	Vehicle routing problem with time windows and a limited number of vehicles	Relocation from a holding list	Exchange, relocate

Year	Authors	Problem	Title	Initial solution	Neighborhood operators
2006	Burks, R.	LRPTW	An Adaptive Tabu Search Heuristic for the Location Routing Pickup and Delivery Problem with Time Windows with a Theater Distribution Application	Distance based greedy heuristic	Cycle swap, route insert, reallocation insert, and extraction insert
2009	Schittekat, P. and Sorensen, K.	LRPTW	Or practice - supporting 3PL decisions in the automotive industry by generating diverse solutions to a large-scale location-routing problem	Random chosen	Add, drop, swap
2011	Gündüz, H. I.	LRPTW	The Single-Stage Location-Routing Problem with Time Windows	Savings heuristic	2-opt, 2-opt*, Or-opt, relocate, exchange, and cross-exchange

Our tabu search algorithm consists of two parts. It includes route construction and route improvement.

6.3.1 Route Construction

The route construction selects nodes sequentially until a feasible solution is created. Nodes are selected based on the cost minimization criterion, and meet vehicle capacity and time window constraints (Bräysy & Gendreau, 2005).

To build an initial solution, three sub-stages including depot selection, customer allocation, and route construction are examined in this section. Since the depot cost is relatively high comparing with transportation cost, the depot(s) $m \in M$ that has a lowest depot cost is/are selected as an initial *opendepot* regardless of its location. At this point, two or more depots might be assigned whenever the customers' demand does not exceed the open depots' capacity. Next, each customer $c \in C$ is assigned to the nearest open depot. If the total demand exceeds depot capacity, the customer located near to another depot will be moved to that particular depot. Finally, the routes are constructed using insertion heuristics. An intuitive approach to the LRPTW is to assign all customers as *unroute*. Then, the tour is build by inserting the remaining "cheapest insertion" customers one after another with minimizing the cost to *route* (r) until all nodes have been inserted. At each insertion, new route r is initially constructed if the vehicle capacity and time windows constraints are violated. The algorithm ends when no customer in *unroute* remains.

The fundamental of insertion heuristics is to start with a tour of a subset of all customers, and then extend this tour by inserting the rest one after the other until all nodes have been inserted. Three decisions have to be made before implementing, 1) how to construct the initial tour? 2) how to choose next node to be inserted? And 3) where to insert chosen node? (Mertens, 1999)

Let the last customer on the current partial route be customer i , let j be any unrouted customer to be visited next, and c_{ij} is the distance between two customers. The starting tour is usually some tour on three nodes. In our case, the least arrival time windows (minimum a_i) is selected as the first customer to be inserted. After that, two criteria of $c_1(i, u, j)$ and $c_2(i, u, j)$ are used at every iteration to insert a new customer u into the current partial route. Let $(i_0, i_1, i_2, \dots, i_m)$

be the current route where $i_0 = i_m$ is the depot. To insert the customer u , the best feasible insertion position between i_{p-1} and i_p has to be calculated as shown in Equation (6.1)

$$c_1(i(u), u, j(u)) = \min[c_1(i_{p-1}, u, i_p)], \quad p = 1, 2, \dots, m \quad (6.1)$$

It must be noted here that inserting new customer into a partial route can potentially alter the visiting time to all customers. Therefore, the time windows constraints must be feasibility proved prior insertion. Next, the best customer u is selected by using Equation (6.2)

$$c_2(i(u^*), u^*, j(u^*)) = \text{optimum}[c_2(i(u), u, j(u))], \quad u \text{ unrouted and feasible} \quad (6.2)$$

From that process, customer u^* is inserted into the route between $i(u^*)$ and $j(u^*)$. If no more customers can be feasibly added to the route, the algorithm starts the new route until no unrouted customers exist.

6.3.2 Route Improvement

The initial solution in the previous section provides only moderate quality. The route improvement developed in this section is mainly the core of the algorithm. To apply the vehicle-routing route improvement in location-routing, Tuzun and Burke (1999) presented a two-phase approach that offers an efficient strategy integrating facility location and routing decision. Although this method has drawbacks by treating both subproblems equally, it produces better solutions than sequential methods (Nagy & Salhi, 1996). Four criterions are needed to design an efficient improvement algorithm (Bräysy & Gendreau, 2005);

1. How an initial feasible solution is generated?
2. What move-generation mechanism to use?
3. The acceptance criterion.
4. The stopping test.

In location phase, we apply *Swap* and *Add* moves. Both moves look for the neighbor depot to be open, but only *Swap* move requires to close the opening depot simultaneously. In routing phase, two basic operators, *Exchange* and *Relocate* neighborhoods, are used iteratively throughout the search space in three stages, i.e. intra-route, intra-depot, and inter-depot. The

substitutions of the neighborhoods on these two operators are introduced between the set of links to be removed from the current route and the set of links to replace the removed links. The lists of individual customers are scanned from the route and try to insert them into each possible position. Let us define vertex i and vertex j as the arc from the origin and destination route, respectively. After that, we set pre_i , suc_i , pre_j , and suc_j as its predecessor and successor of origin and destination route, respectively. Therefore, *Exchange* is the move of two vertices from different routes or different depots, and a try to insert into the other routes (Figure 6.3). On the other hand, *Relocate* is the move to insert a vertex from on route into another (Figure 6.4) (Savelsbergh, 1992).

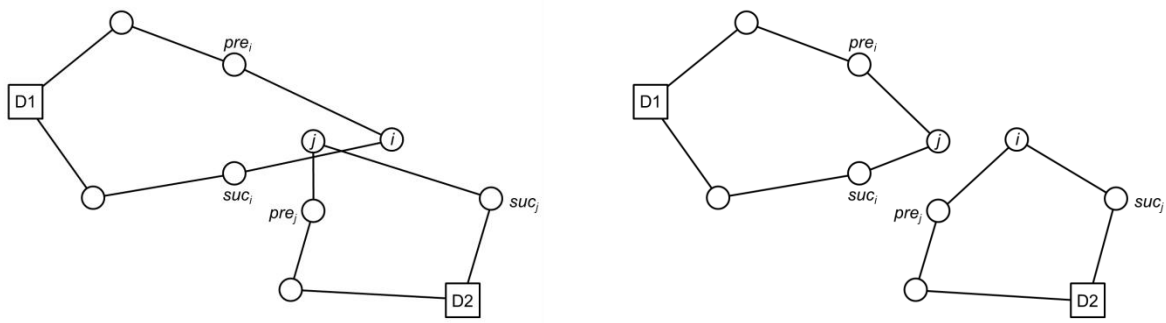


Figure 6.3 Exchange Neighborhood

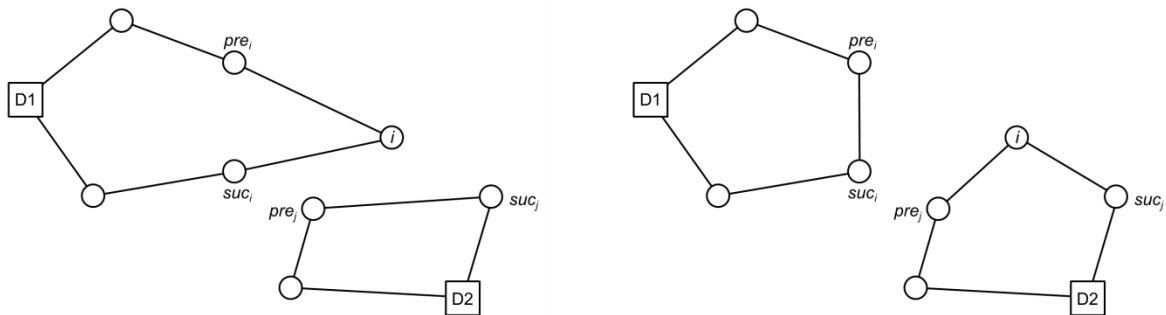


Figure 6.4 Relocate Neighborhood

Two acceptance strategies are commonly used in the VRPTW context, namely first-accept and best-accept. The first-accept strategy selects the first neighbor that satisfies the pre-defined acceptance criterion. The best-accept strategy examines all neighbors satisfying the criteria and selects the best among them (Bräysy & Gendreau, 2005). In our case, the best-accept strategy is used in every moved throughout the algorithms.

When the best move is explored, the parameters are collected in the tabu list for some iteration, called tabu tenure. We assigned the tenure equal to 5, meaning that they are forbidden during the next five moves. To escape from a local minima, we set the aspiration criteria allowing a move (even if it is tabu) if it produces a better solution (Gendreau & Potvin, 2010).

One of the drawbacks of local search approaches is that they try to search only the local space as the name implies (Gendreau & Potvin, 2010). Even a good solution is found; one cannot ensure whether the other search space can produce a better solution. To encounter this issue, we introduce one of the diversification techniques, called “restart diversification” forcing the search to escape from the best-known solution and examining the area that has not yet been explored. It can be achieved by restarting the searches in location phase and look for the unopened depots and continue the routing phase simultaneously.

6.3.3 Model Validation

The comparison between branch-and-price exact solution from Chapter 4 and tabu search heuristics solution presents in Table 6.4. The optimal solutions of Tabu search are sub-optimal as expected. The total cost of Tabu search on average is 2.8% higher than the branch-and-price. However, it saves up to 98.8% of the computational time. Therefore, it can be said that the Tabu search algorithm proposed in this research is a promising tool to solve LRPTW instances, especially with the large size problem.

Table 6.4 Comparison between Branch-and-Price and Tabu Search LRPTW

Instance	Branch-and-Price		Tabu Search	
	Solution	Time	Solution	Time
LRPTW-R101-10	2,955	1.00	2,955	0.90
LRPTW-R102-10	2,434	1.90	2,438	0.07
LRPTW-R103-10	2,434	1.89	2,438	0.07
LRPTW-R104-10	2,162	3.33	2,168	1.49
LRPTW-R105-10	2,438	0.66	2,438	0.82
LRPTW-R106-10	2,194	2.29	2,414	0.06
LRPTW-R107-10	2,194	2.28	2,414	0.06
LRPTW-R108-10	2,162	2.98	2,162	1.46
LRPTW-R109-10	2,429	2.40	2,431	0.71
LRPTW-R110-10	2,160	2.56	2,160	0.08
LRPTW-R111-10	2,184	7.86	2,413	0.75
LRPTW-R112-10	2,159	8.06	2,177	0.80
LRPTW-R101-25	5,308	1.16	5,317	8.66
LRPTW-R102-25	5,027	17.82	5,029	8.27
LRPTW-R103-25	4,294	179.37	4,583	10.50
LRPTW-R104-25	4,251	354.73	4,511	6.28
LRPTW-R105-25	4,587	6.43	4,782	4.78
LRPTW-R106-25	4,438	127.00	4,536	7.77
LRPTW-R107-25	4,266	468.41	4,292	7.94
LRPTW-R108-25	4,077	5,097.76	4,277	6.07
LRPTW-R109-25	4,299	28.96	4,530	9.37
LRPTW-R110-25	4,285	718.52	4,310	0.26
LRPTW-R111-25	4,289	246.13	4,523	10.18
LRPTW-R112-25	4,250	539.79	4,271	5.65
Total	81,276	7,823.29	83,569	92.98

6.4 Results and Discussions

Table 6.5 and Figure 6.5 shows the results of the location-routing in disaster relief operation in the city of Ishinomaki. It can be seen that apart from scenario one as our based case, scenario 2 required the highest number of depot (8 depots), followed by scenario 3 (7 depots). Scenario 4 and 5 required to open only three depots. This figures had a similarity to the number of trucks since scenario 2 and 3 required a higher number of trucks (18 and 20) comparing with scenario 4 and 5 (15 and 15). In contrast, the average truckload, average distance, and a total distance of scenario 2 and 3 were lower than the case of scenario 4 and 5. Figure 6.6 illustrates the example of traveling routes, according to the results.

Table 6.5 Results of the Location-Routing in Ishinomaki Case Study

Scenario	Number of Potential Depot	Depot and Vehicle Cost	Time Windows	Number of Open Depot	Open Depot	Number of Truck at each Depot	Total Number of Truck
1 (Real Operation)	2	-	-	2	1,2	13,3	16
2	10	-	-	8	2,3,4,5,6,7,9,10	1,2,4,1,4,2,1,3	18
3	10	-	✓	7	1,4,6,7,8,9,10	1,6,4,3,2,1,3	20
4	10	✓	-	3	1,3,8	6,6,3	15
5	10	✓	✓	3	1,3,8	7,5,3	15

Table 6.5 (Cont.) Results of the Location-Routing in Ishinomaki Case Study

Scenario	Average Truck Load	Average Distance (km)	Total Distance (km)	Computational Time (hh:mm:ss)
1 (Real Operation)	0.92	15.88	254.03	14:10
2	0.81	8.11	146.01	54:17:03
3	0.73	9.17	183.38	43:02:26
4	0.98	13.60	203.95	13:31
5	0.98	17.06	255.87	11:55

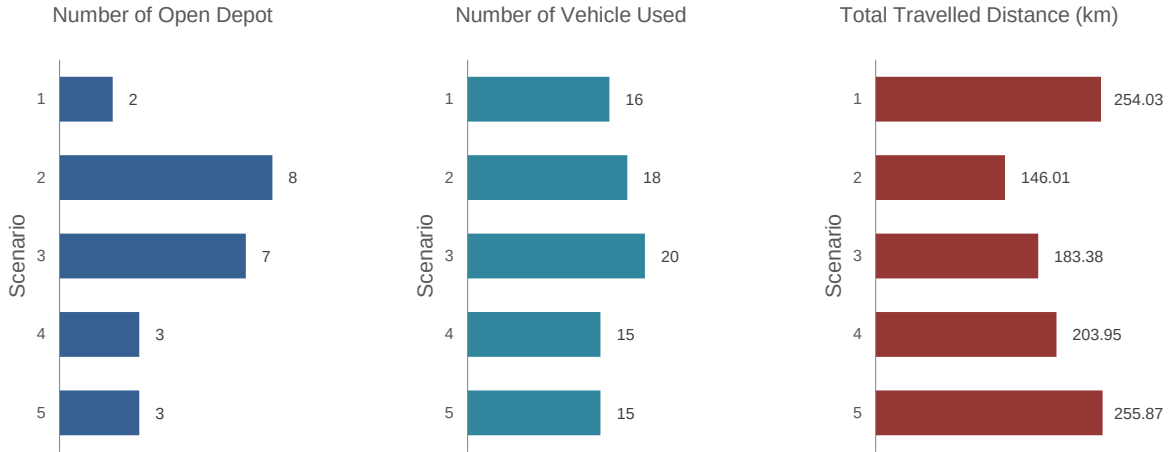
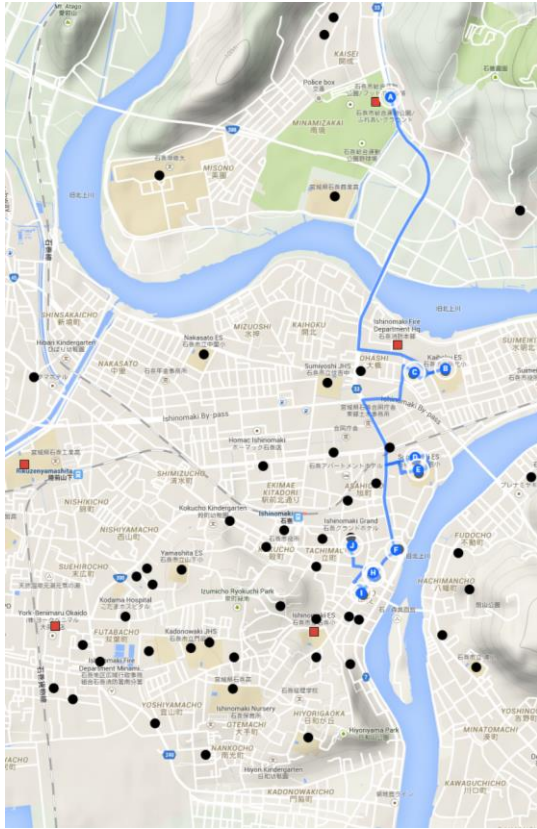


Figure 6.5 Results of the Location-Routing in Ishinomaki Case Study

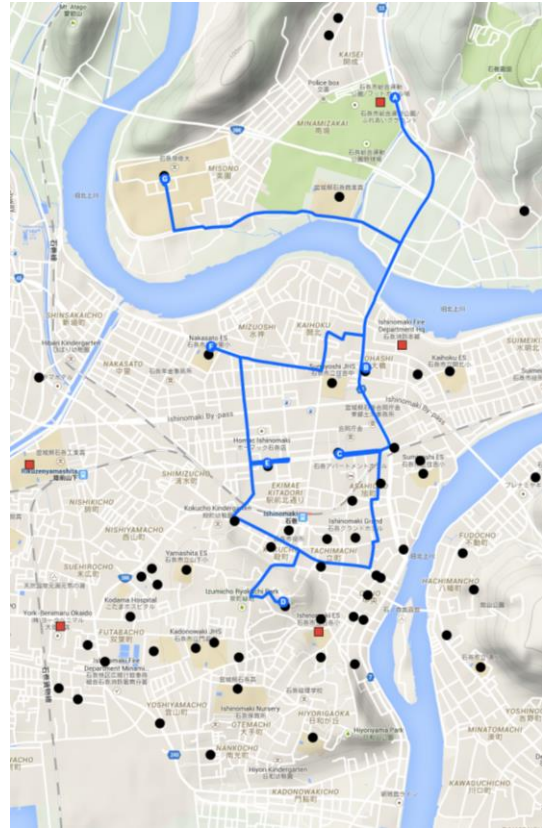
Not surprisingly, comparing between scenario 1 and scenario 2 when considering only the routing part, the algorithm had a preference to open as many depots as long as the capacity constraints are satisfied, i.e. depot and vehicle capacities are not violated. As we expected, since the number of depots and number of vehicles has increased, the lower value of truckload and total distance are found. It happened because each shelter had the privilege to be assigned to the nearest depot. Therefore, each truck was traveling on the shorter routes.

In scenario 3 when the time windows are assigned, although the number of depots is reduced to only seven depots; the number of trucks and traveling distance have both increased. This effect and phenomenon are unique for LRP and LRPTW as described in Chapter 4 since time window constraints limit the predecessor nodes (or possible move). It also has lower truckload as well. When the depot opening cost is engaged in scenario 4, the depot location part dominated the calculation process. Predictably, since the algorithm tried to open the least possible number of depots, only three depots are selected. Also, the vehicle cost played an important role in the routing, and the algorithm tried to lower the number of trucks to only 15 trucks. It caused the truckload to increase accordingly. Finally, the traveling distances are slightly increased when the time windows are considered as shown in scenario 5.

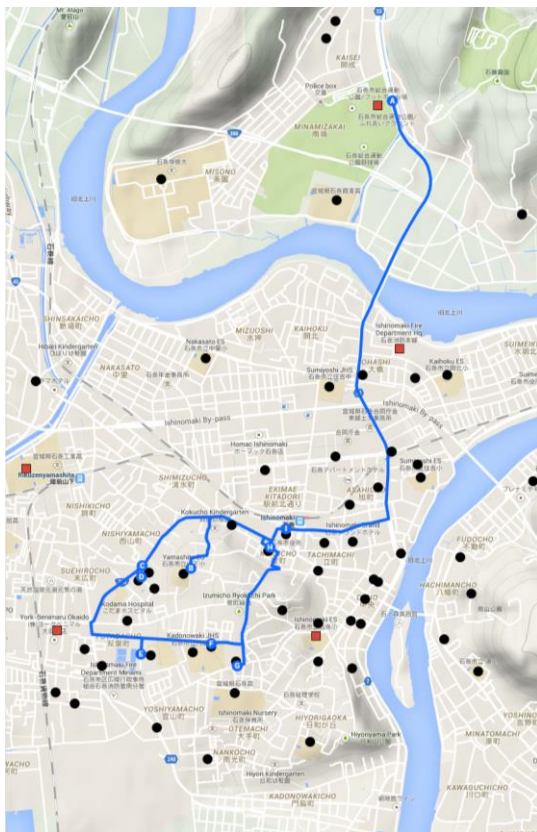
The computational times are varied between the scenarios. The higher number of open depots requires higher computational times. Every time a depot has to be moved in either *Swap* or *Add*, the routing phase has to restart and recalculate from the beginning, which requires a huge amount of time.



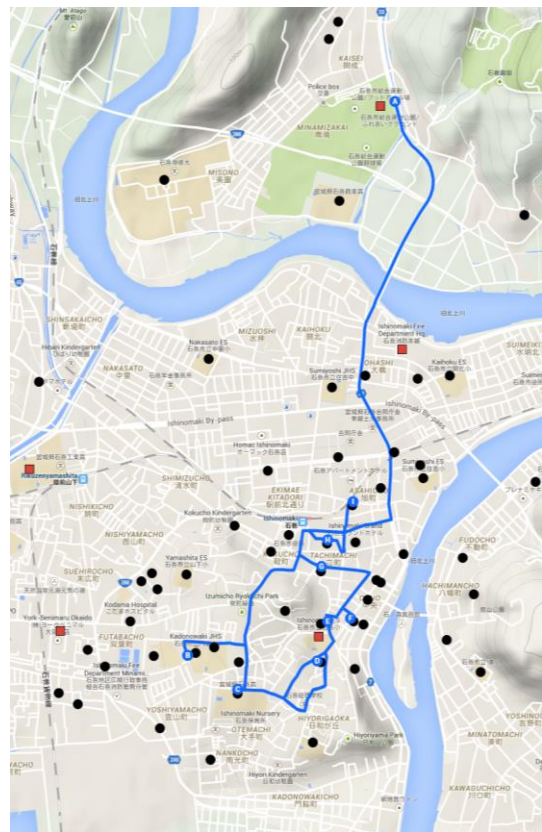
a)



b)



c)



d)

Figure 6.6 Examples of the Routes on Relief Operations

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Chapter 7

Conclusion and Recommendation

7.1 Conclusions

7.1.1 Branch-and-Price Algorithm for LRPTW

7.1.2 LRPTW in Osaka Distribution Network

7.1.3 LRPTW in Ishinomaki Humanitarian Logistics

7.2 Future Works

7.1 Conclusions

7.1.1 Branch-and-Price Algorithm for LRPTW

This paper presents the framework to integrate the facility location and the vehicle routing problems with time windows. The location-routing problem (LRP) is attracting many researchers and practitioners since it allows manipulating the mathematical problem in both strategic and operational levels. The combination of location-routing and time windows (LRPTW) has never been attempted before using an exact algorithm. This study proposes the method of decomposing the complex integer programming formulation of the LRPTW into master and subproblems and contributes the new column generation based algorithm to solve it.

New test instances for the LRPTW are generated from the VRPTW Solomon benchmark instances to evaluate the performance, with the first 10- and 25-customer. The original depot is replaced by the new three potential depot sites together with other parameters used in the LRPTW formulations. It proves that the new exact algorithm proposed in this research can solve the LRPTW instances to optimality within an acceptable time. It shows in the previous section that the exact solutions of the LRPTW can reduce the required number of trucks as well as the distance traveled as compared to the exact VRPTW solutions. Therefore, further emphasizes the importance of the LRPTW and the advantage of an exact solution approach for this variation. Also, the characteristics of the time window constraints affecting the location and routing processes in the LRPTW are also intensively explored and reported.

7.1.2 LRPTW in Osaka Distribution Network

This topic presents the evaluation of cost structure of different environmental factors of LRPTW, which is rarely examined by the exact algorithm. The branch-and-price algorithm is implemented to ensure that the quality of the solution is reliable. The distribution network is extracted from the real operation of logistics firm in Osaka while the travel time is collected by the GPS and the traffic census data of the Osaka city. The main decision factors for LRPTW are the location of the depot, depot size,

and vehicle size. It is found that the large size depot together with the large size vehicle scenario is among the best scheme in our case study. The depot located in Minato-ku is the best location for the large size depot scenario by the fact that it is located in the low-price area. Furthermore, the large size vehicle of the 3-ton vehicle is proved to be the best choice. Regardless of the highest vehicle fixed cost, the number of the vehicle can be reduced to only seven vehicles, but remain the high truckload, making the lowest delivered cost option.

7.1.3 LRPTW in Ishinomaki Humanitarian Logistics

This study presented two computational algorithms to solve the location-routing problem with time windows for disaster relief operations. The algorithm bases on the tabu search heuristics. The location and routing phases are separately considered using simple but effective operators. The process ends when no other beneficial moves are detected. We obtain the results from the branch-and-price algorithm as a benchmark for tabu search algorithm. After that, we use the latter for solving the large size real-world problems.

The city of Ishinomaki is a case study. It is attacked by the tsunami triggered from the great Japanese earthquake on March 11, 2011. 3,417 people were killed. 53,742 houses were destroyed and left 30,930 people displace. The developed Tabu search is used to determine the refugee center or depots to store food and important commodities for the people. Apart from the two depot locations used in the real operation, we propose eight more potential locations throughout the city and determine the optimal locations in four different scenarios. The results are expected to provide the broader perspective on how mathematical models can support the humanitarian logistics in disaster relief operation.

7.2 Future Works

The exact algorithms are usually computationally expensive comparing with approximate methods. Same is the case with our proposed algorithm, and it becomes much harder to solve the larger problems, especially with wider time windows. The combination of exact and metaheuristic approaches as a hybrid algorithm is, therefore,

needed to be explored to accelerate the process without losing much on the exact optimal solution.

To implement the location-routing scheme into the real supply chain operation, however, it requires more comprehensive information to achieve the goal. This tested distribution network limits only the portion of selected customers. To handle the large network instances, the approximate approach or the combination of exact and metaheuristic approach as a hybrid algorithm is needed to be explored in the future. It supposes to accelerate the process without losing much on the exact optimal solution.

Moreover, the integration approach in logistics and distribution problems is not only restricted to the location-routing problem. Combination approaches are becoming more popular, and both the location and the routing problems can be integrated with other logistical problems. Nagy and Salhi (2007) summarizes the promising combination with locational and routing based problem as follows.

Location-Based Integration

- Queueing-location problem
- Location-assignment problem
- Location-capacity-acquisition problem
- Location-network-design problem
- Inventory-location problem
- Location-scheduling problem

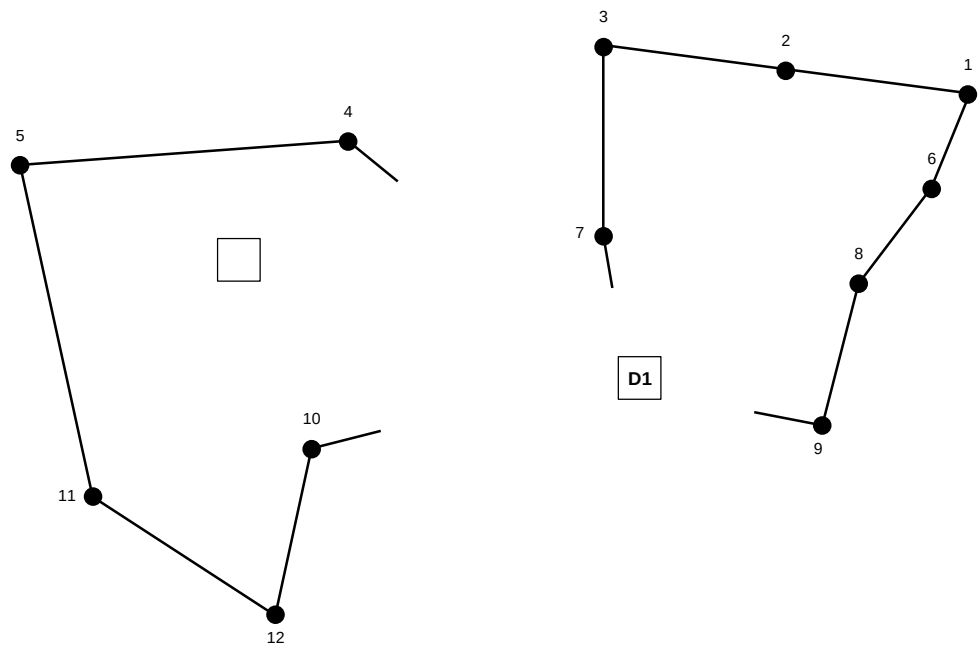
Routing-Based Integration

- Inventory-routing problem
- Routing-scheduling problem
- Routing-packing problem

Appendix A

Optimal Solutions of Modified LRP

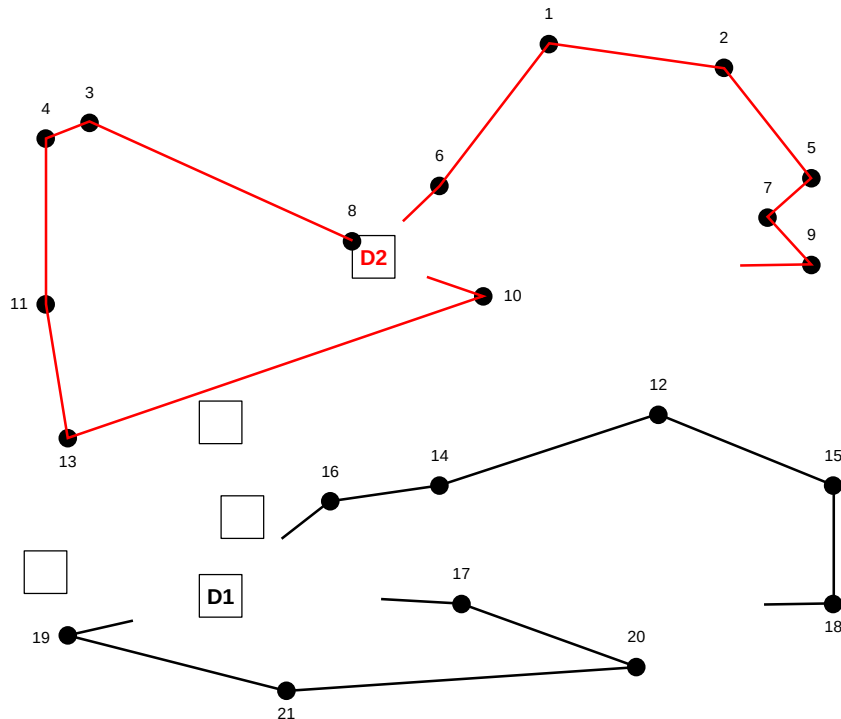
Perl83-12x2 TW



D1 7 3 2 1 6 8 9
4 5 11 12 10

Optimal solution = 204.00

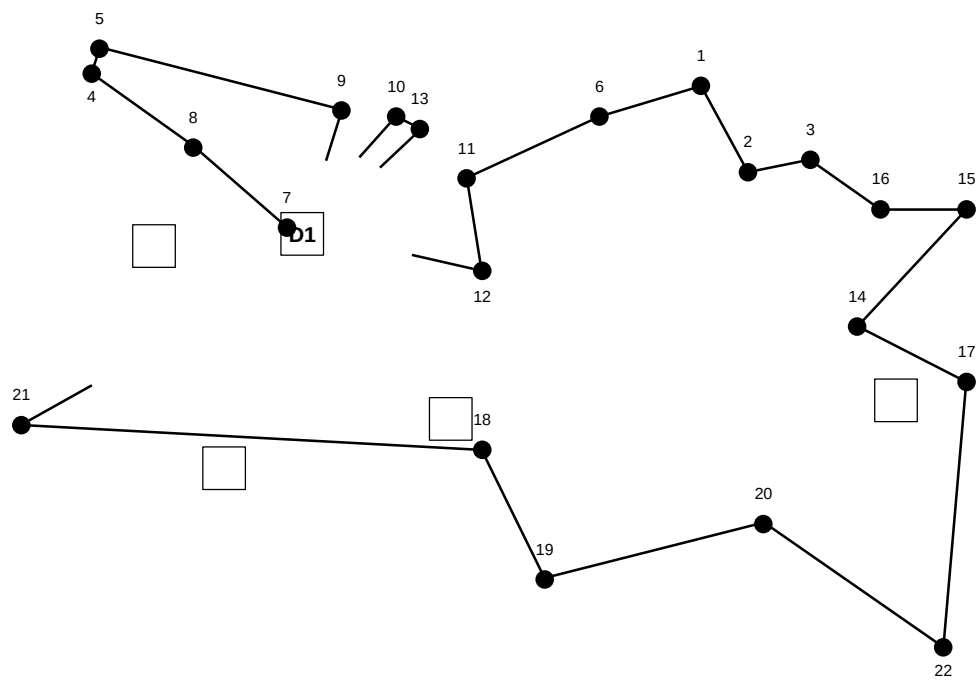
Gaskell67-21x5 TW



D1	17	20	21	19		
	18	15	12	14	16	
D2	9	7	5	2	1	6
	8	3	4	11	13	10

Optimal solution = 424.90

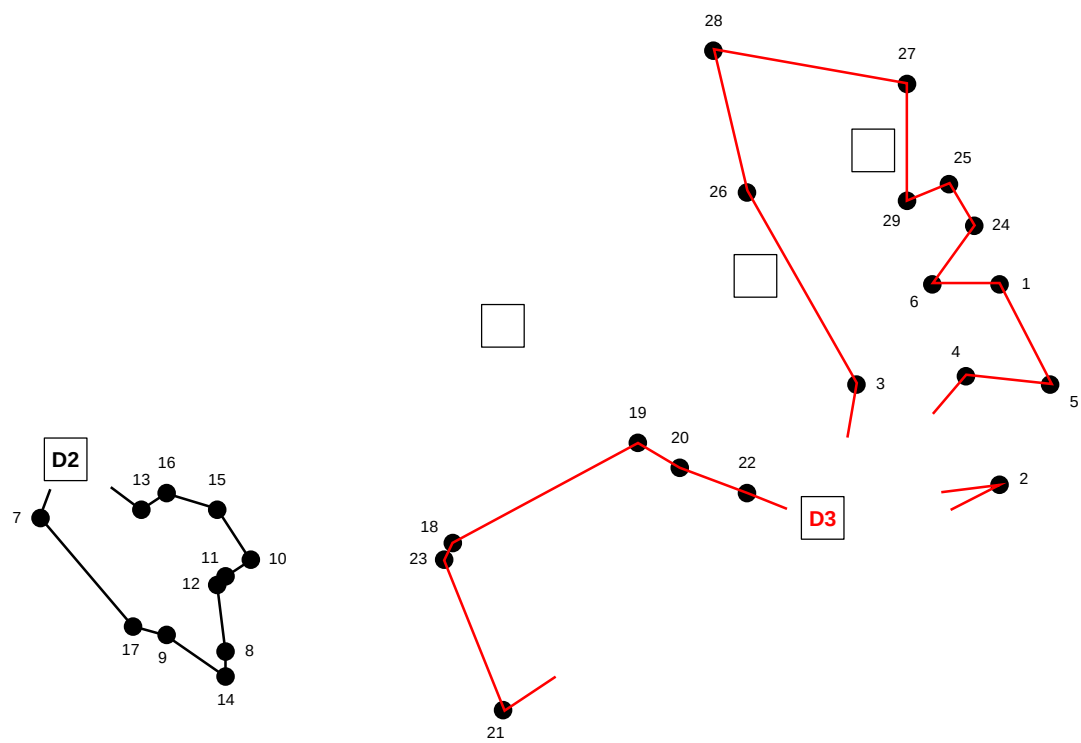
Gaskell67-22x5 TW



D1 10 13
7 8 4 5 9
12 11 6 1 2 3 16 15 14 17 22 20 19 18 21

Optimal solution = 585.11

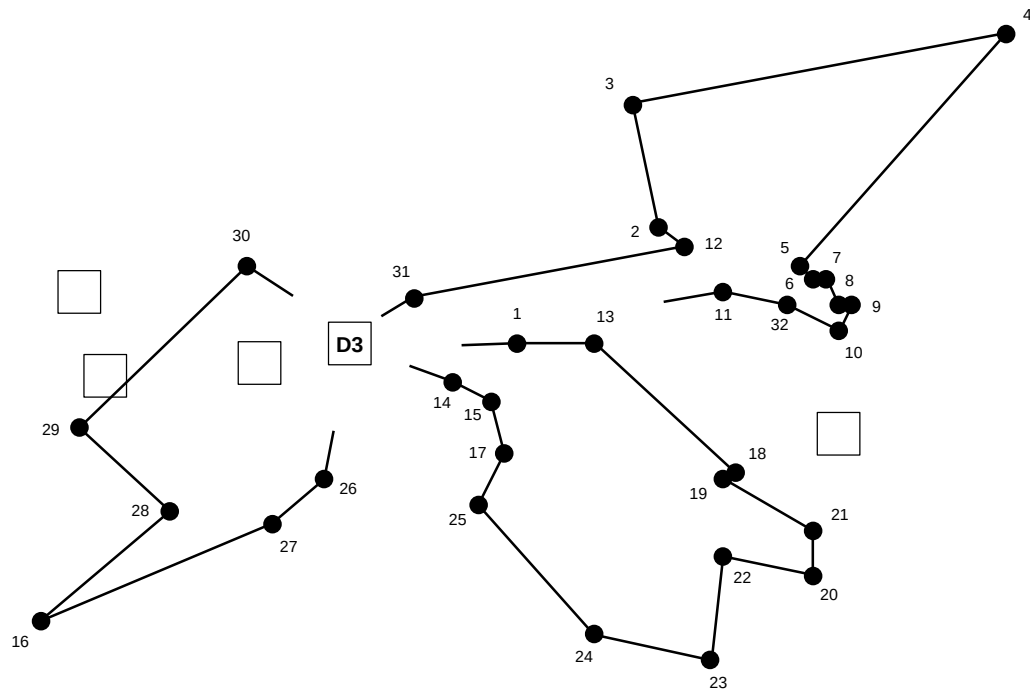
Gaskell67-29x5 TW



D2 7 17 9 14 8 12 11 10 15 16 13
D3 2
21 23 18 19 20 22
3 26 28 27 29 25 24 6 1 5 4

Optimal solution = 512.10

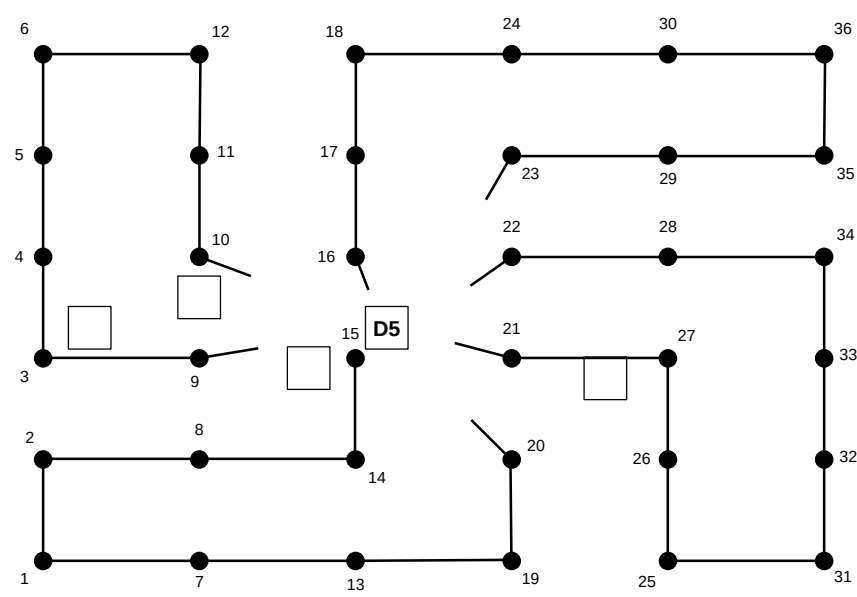
Gaskell67-32x5(2) TW



D3	1	13	18	19	21	20	22	23	24	25	17	15	14
	26	27	16	28	29	30							
	11	32	10	9	8	7	6	5	4	3	2	12	31

Optimal solution = 504.33

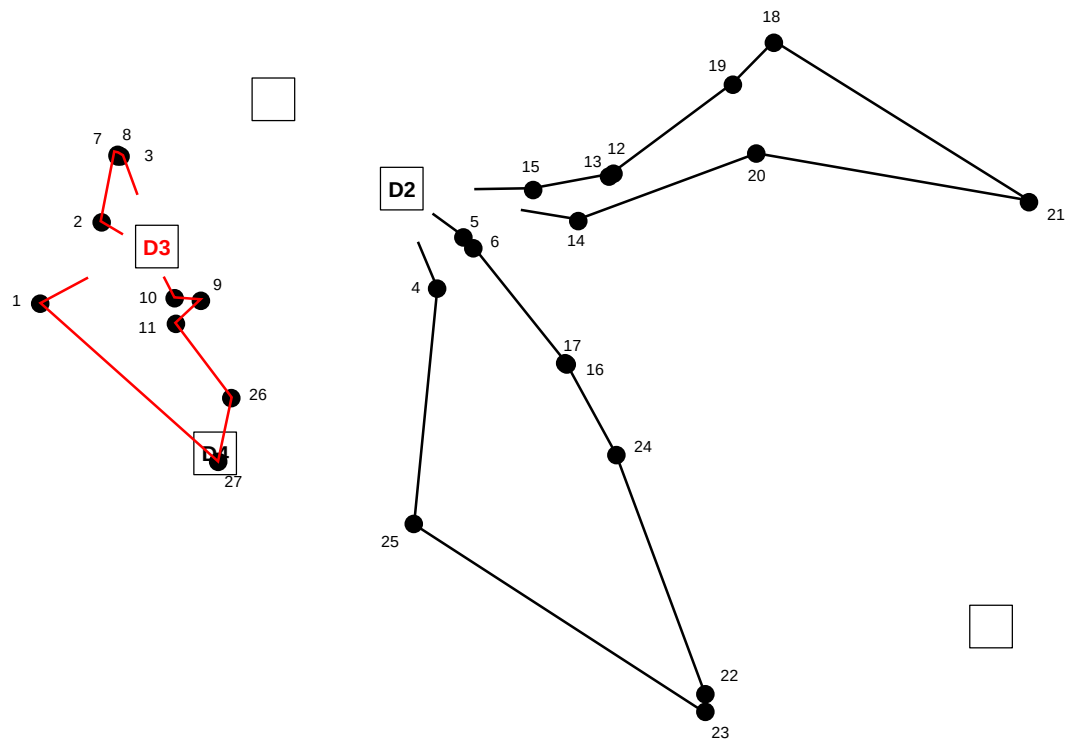
Gaskell67-36x5 TW



D5	15	14	8	2	1	7	13	19	20	
	16	17	18	24	30	36	35	29	23	
	21	27	26	25	31	32	33	34	28	22
	9	3	4	5	6	12	11	10		

Optimal solution = 460.37

Min92-27x5 TW



D2	14	20	21	18	19	12	13	15	
	4	25	23	22	24	16	17	6	5
D3	2	7	8	3					
	1	27	26	11	9	10			

Optimal solution = 3,062.02

Appendix B

Optimal Solutions of Modified Solomon's Benchmarks

Depot Information

Depot No.	x	y	Capacity	Cost
D1	16	29	200	1,500
D2	35	57	200	1,500
D3	49	19	200	1,500

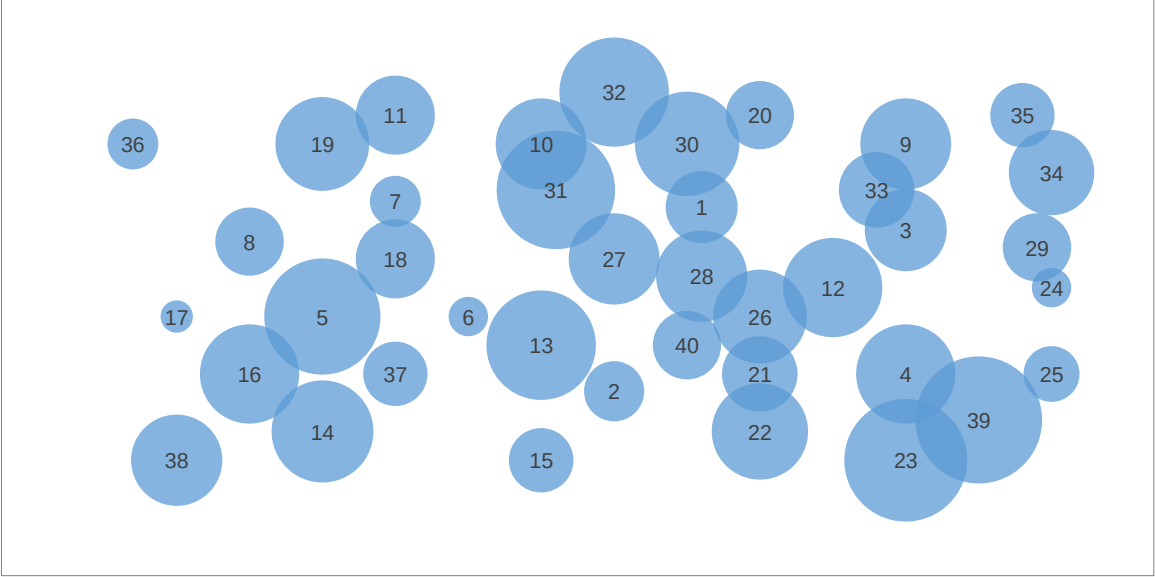
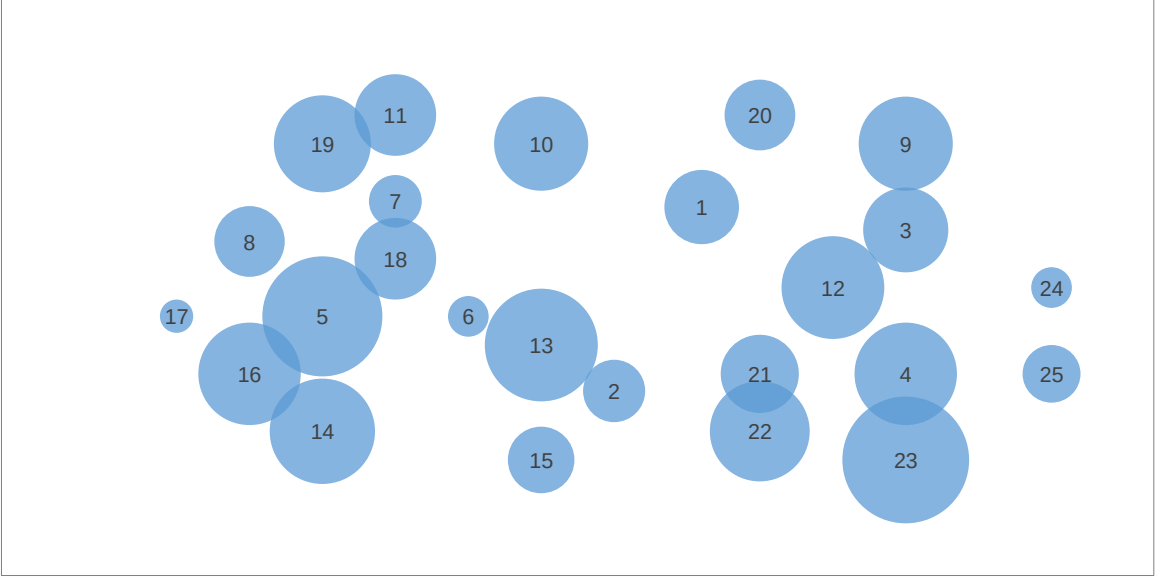
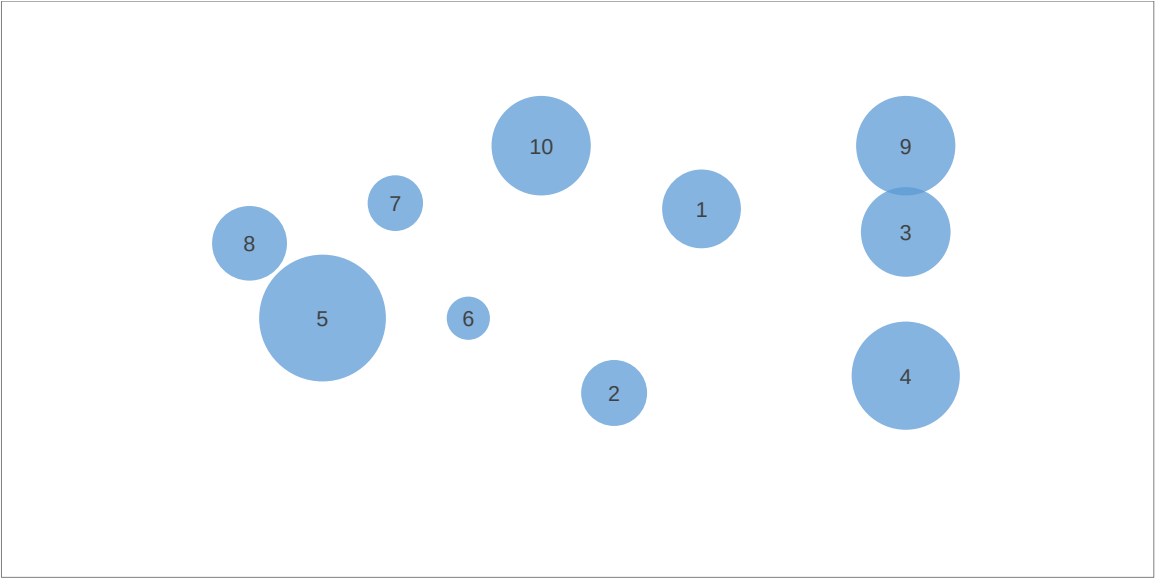
Vehicle Information

Capacity	Cost
200	225

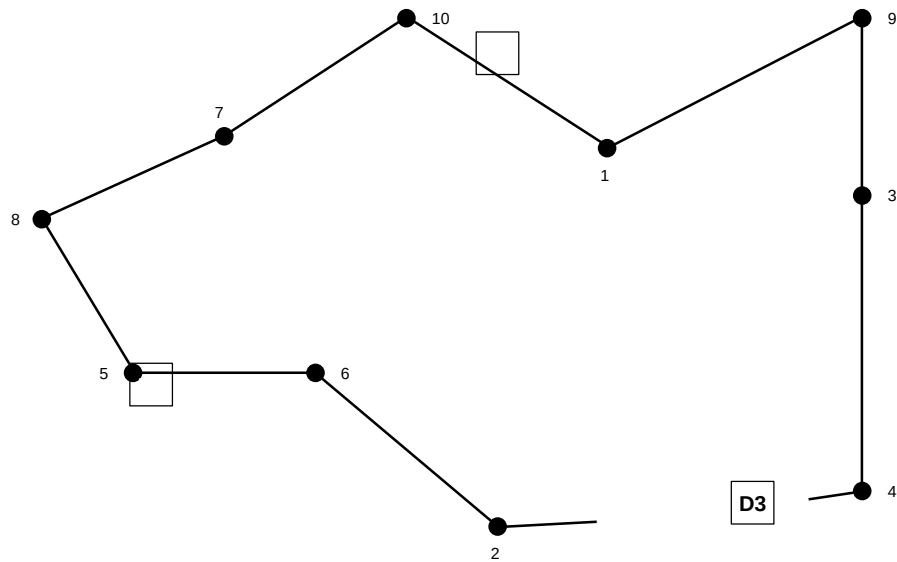
Customer Information

Customer No.	x	y	Demand	a	b	Service Time
1	41	49	10			10
2	35	17	7			10
3	55	45	13			10
4	55	20	19			10
5	15	30	26			10
6	25	30	3			10
7	20	50	5			10
8	10	43	9			10
9	55	60	16			10
10	30	60	16			10
11	20	65	12			10
12	50	35	19			10
13	30	25	23			10
14	15	10	20			10
15	30	5	8			10
16	10	20	19			10
17	5	30	2			10
18	20	40	12			10
19	15	60	17			10
20	45	65	9			10
21	45	20	11			10
22	45	10	18			10
23	55	5	29			10
24	65	35	3			10
25	65	20	6			10
26	45	30	17			10
27	35	40	16			10
28	41	37	16			10
29	64	42	9			10
30	40	60	21			10
31	31	52	27			10
32	35	69	23			10
33	53	52	11			10
34	65	55	14			10
35	63	65	8			10
36	2	60	5			10
37	20	20	8			10
38	5	5	16			10
39	60	12	31			10
40	40	25	9			10

Customers' Location and Size of Demand



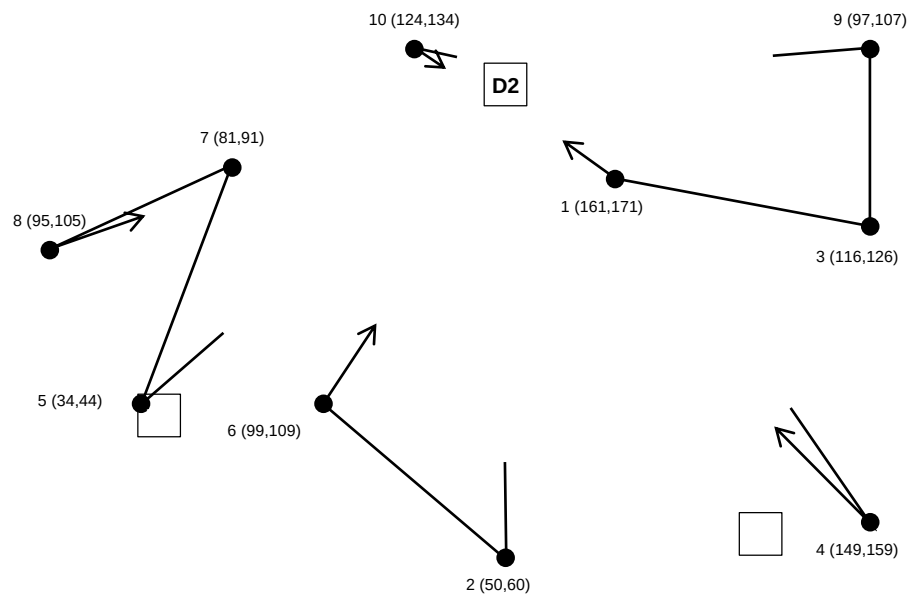
LRP-R100-10



D3 2 6 5 8 7 10 1 9 3 4

Optimal solution = 1,882

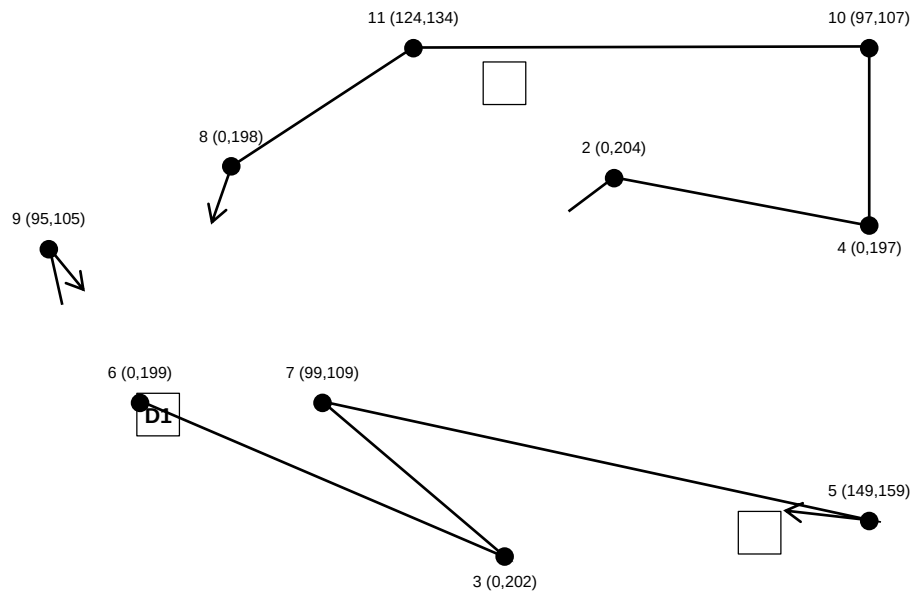
LRPTW-R101-10



D2	4			
	10			
	5	7	8	
	2	6		
	9	3	1	

Optimal solution = 2,955

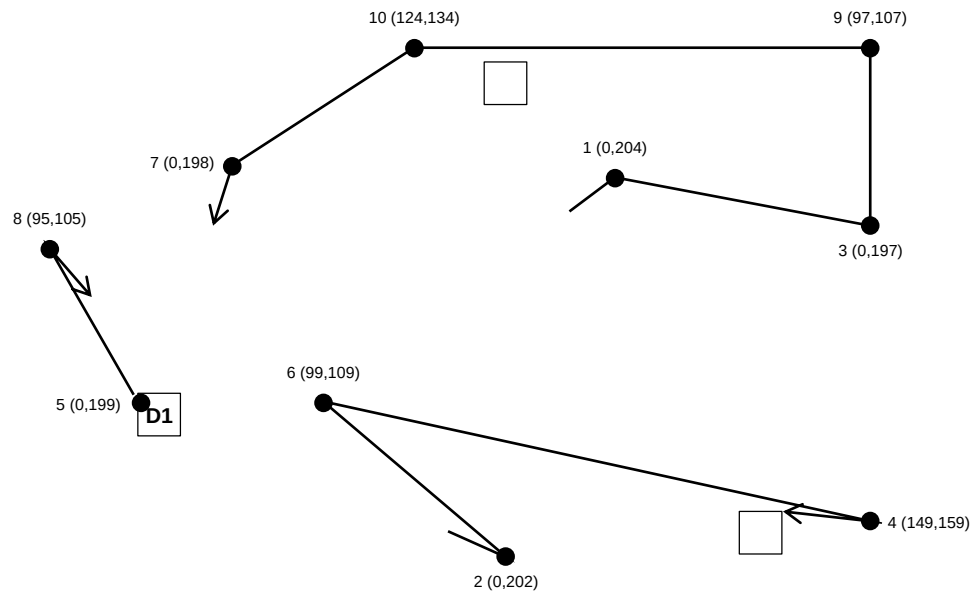
LRPTW-R102-10



D1	8				
1	3	9	10	7	
5	2	6	4		

Optimal solution = 2,434

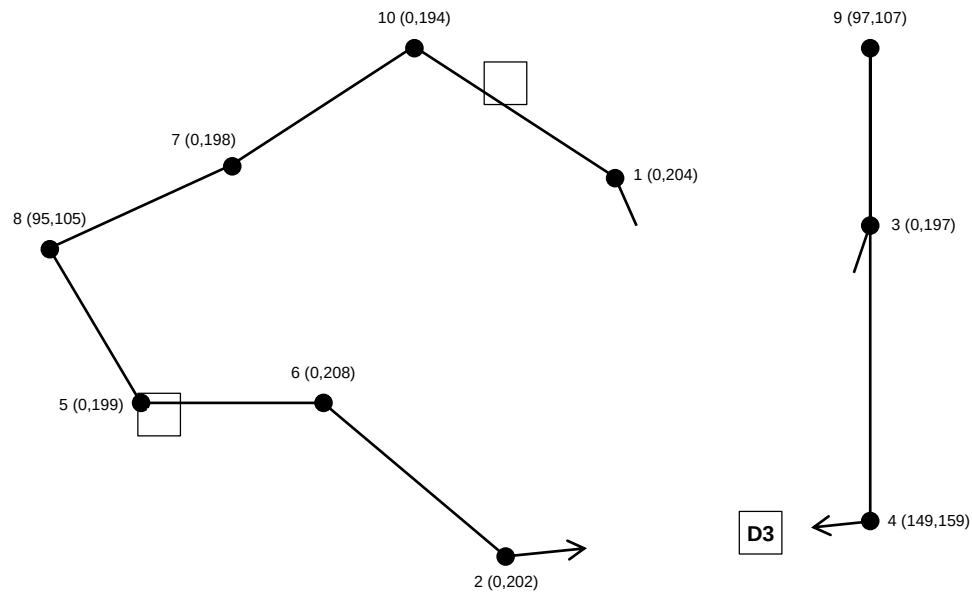
LRPTW-R103-10



D1 5 8
1 3 9 10 7
2 6 4

Optimal solution = 2,434

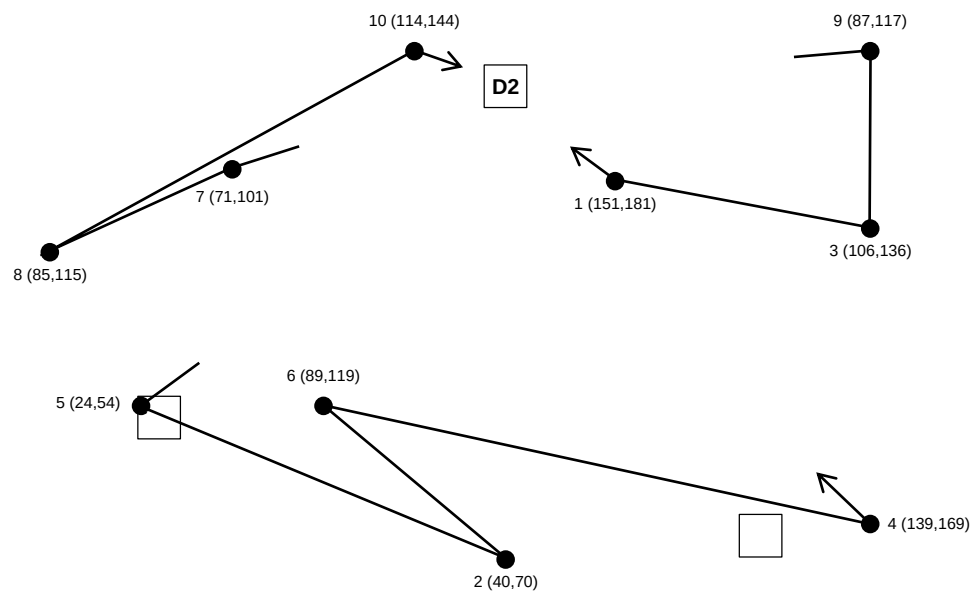
LRPTW-R104-10



D3 3 9 4
1 10 7 8 5 6 2

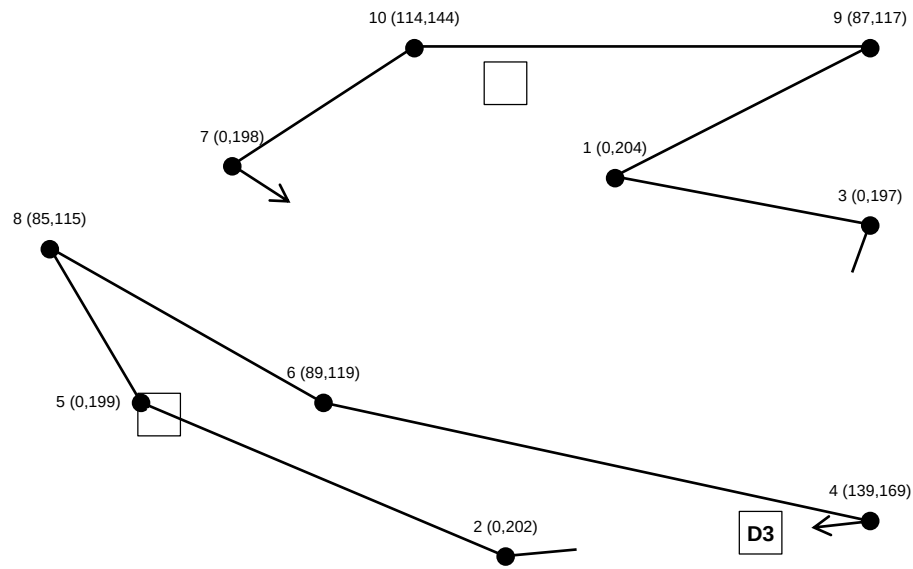
Optimal solution = 2,162

LRPTW-R105-10



D2	7	8	10
	5	2	6
	9	3	1

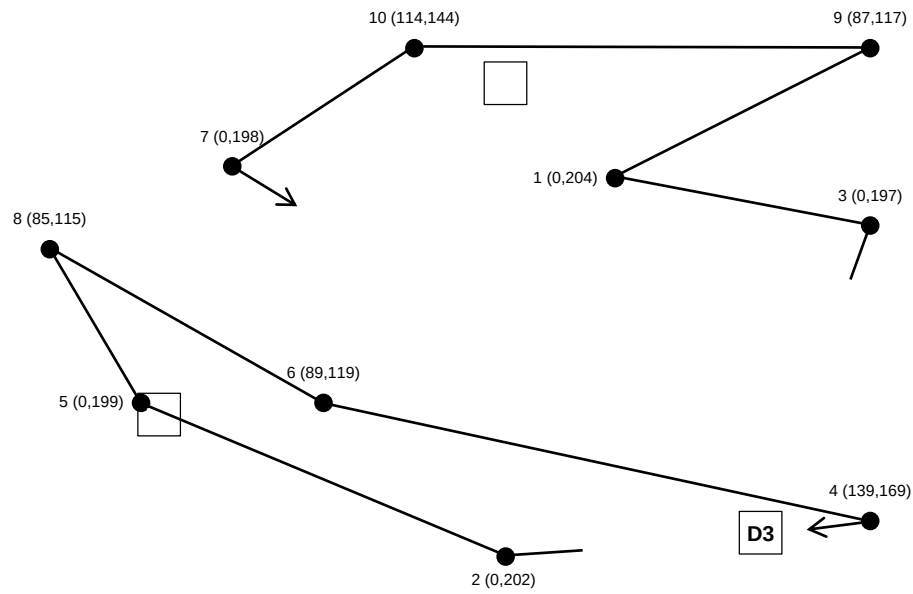
Optimal solution = 2,438



D3 3 1 9 10 7
2 5 8 6 4

Optimal solution = 2,194

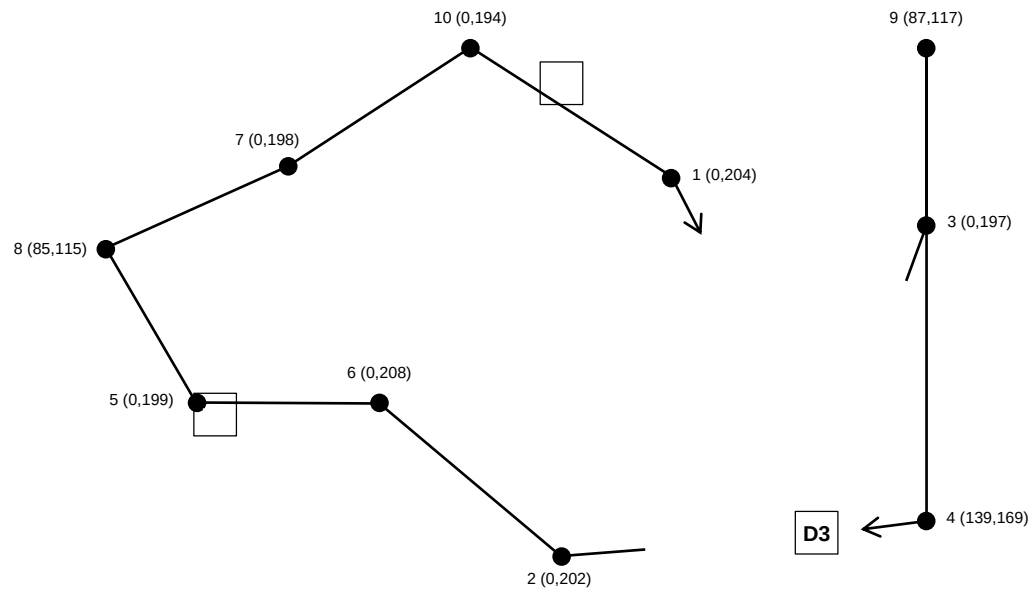
LRPTW-R107-10



D3 3 1 9 10 7
2 5 8 6 4

Optimal solution = 2,194

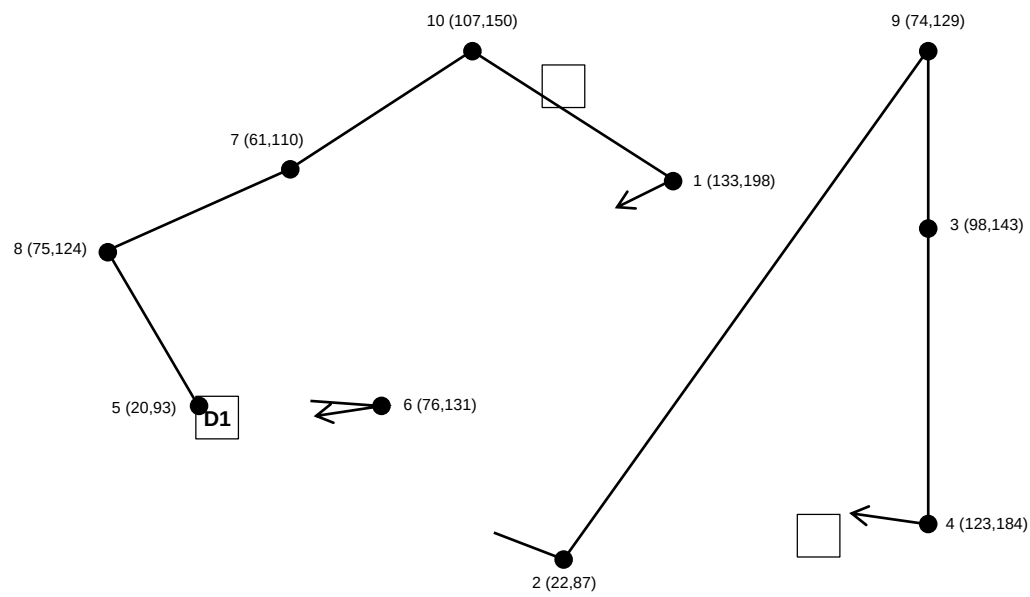
LRPTW-R108-10



D3 3 9 4
2 6 5 8 7 10 1

Optimal solution = 2,162

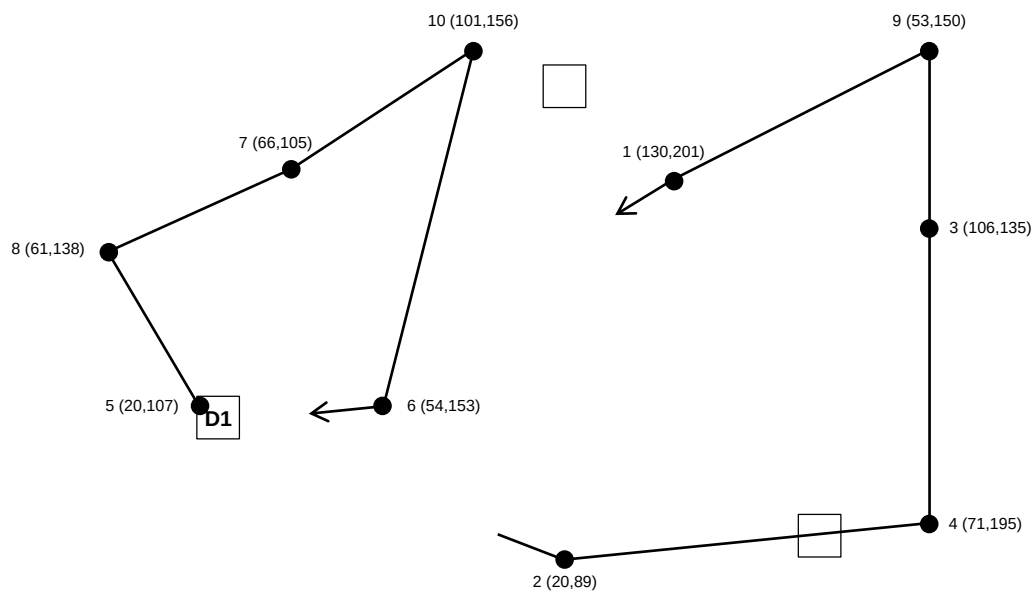
LRPTW-R109-10



D1 6
2 9 3 4
5 8 7 10 1

Optimal solution = 2,429

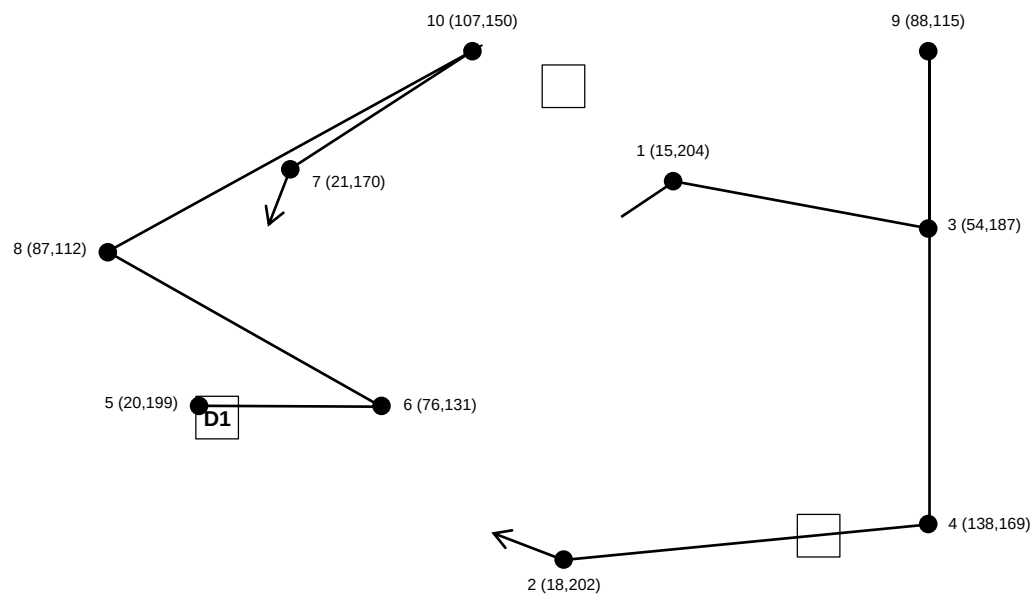
LRPTW-R110-10



D1 5 8 7 10 6
2 4 3 9 1

Optimal solution = 2,160

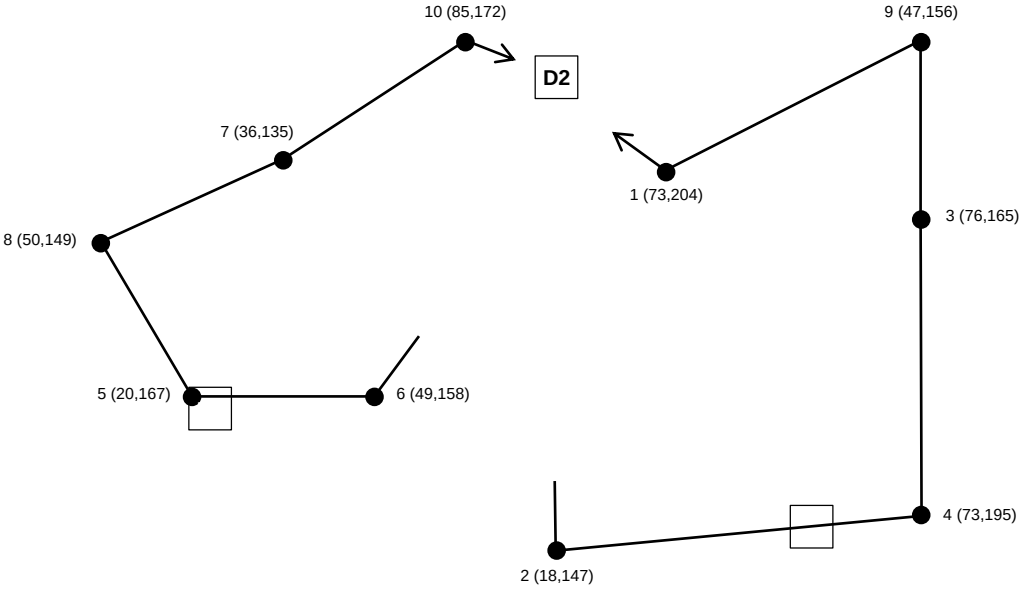
LRPTW-R111-10



D1 5 6 8 10 7
1 3 9 4 2

Optimal solution = 2,184

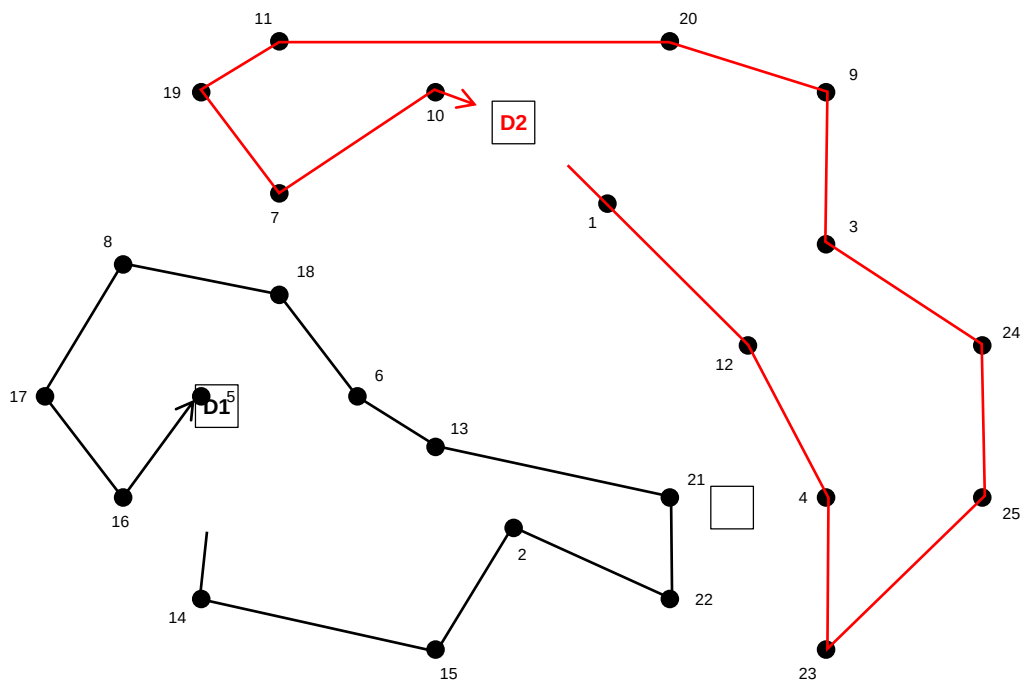
LRPTW-R112-10



D2 6 5 8 7 10
2 4 3 9 1

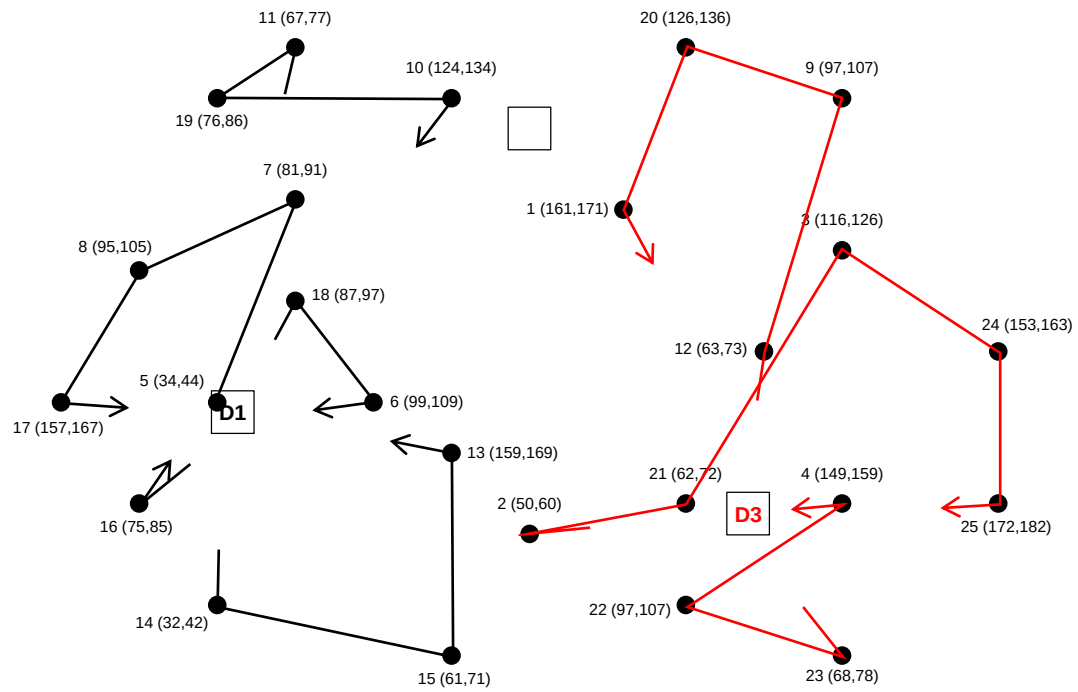
Optimal solution = 2,159

LRP-R100-25



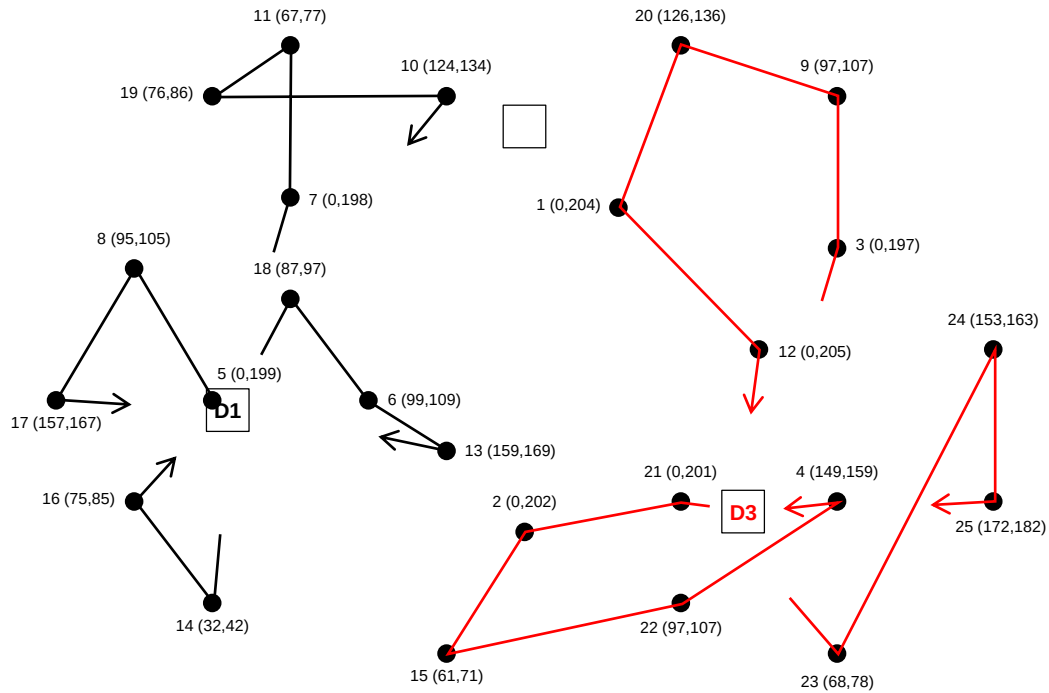
D1	1	17	18	5	25	24	16	9	21	11	20	19	8	1	
D2	2	4	15	7	26	28	27	6	12	23	14	22	10	13	2

Optimal solution = 3,776



D1 16
18 6
5 7 8 17
14 15 13
11 19 10
D2 23 22 4
12 9 20 1
2 21 3 24 25

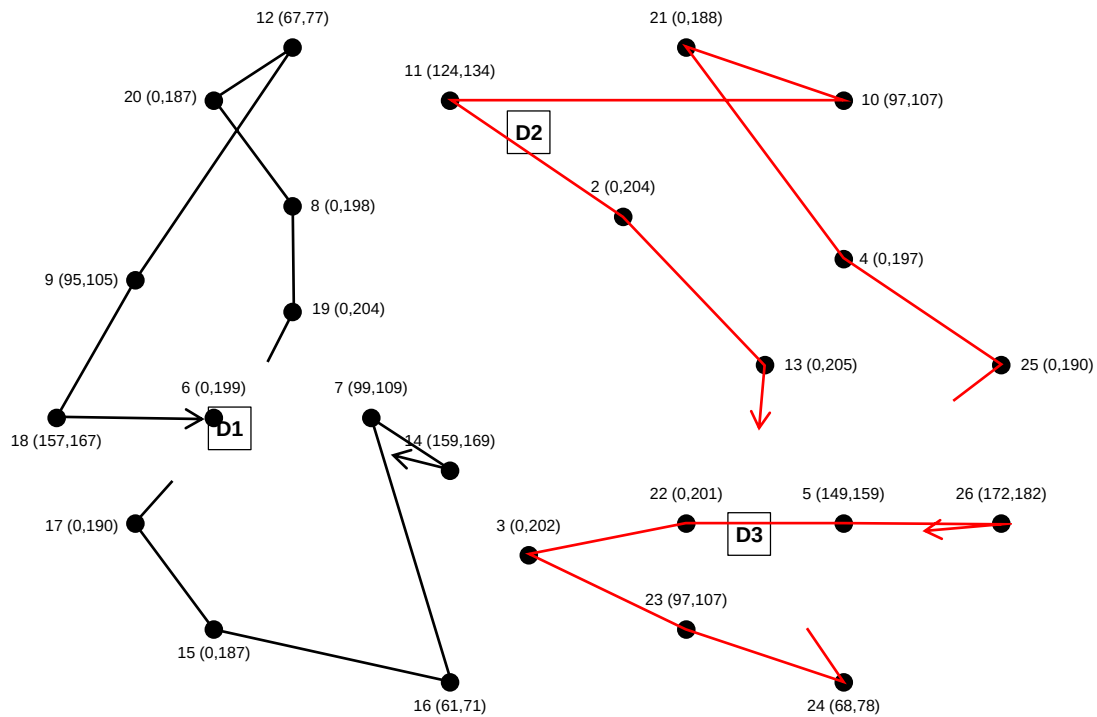
Optimal solution = 5,308



D1	14	16			
	7	11	19	10	
	18	6	13		
	5	8	17		
D3	21	2	15	22	4
	23	24	25		
	3	9	20	1	12

Optimal solution = 5,027

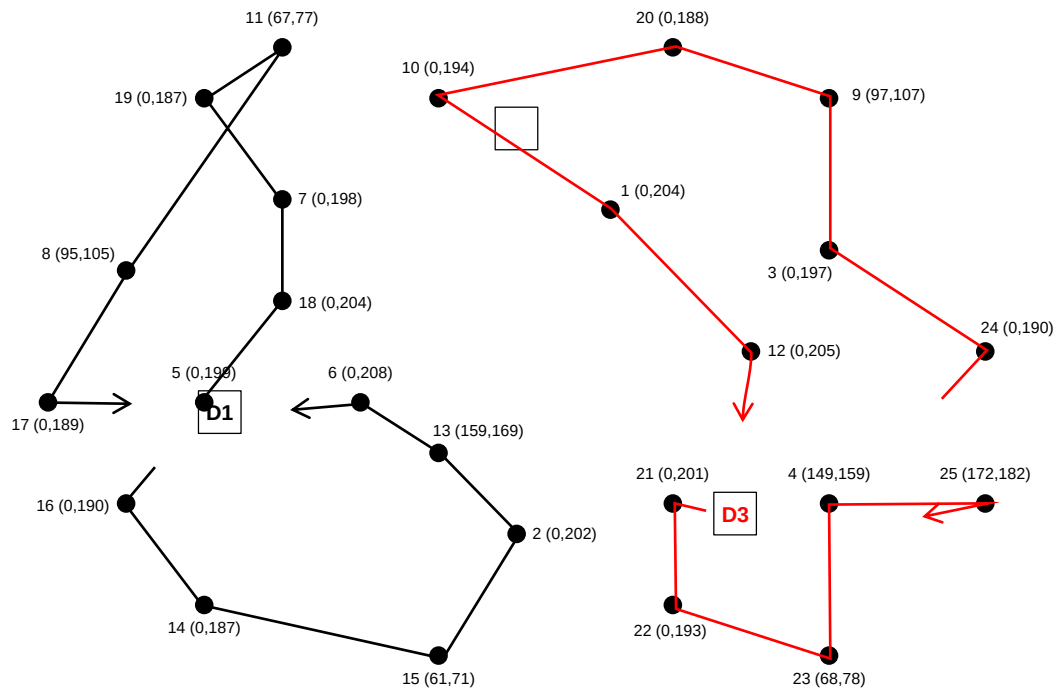
LRPTW-R103-25



D1	16	14	15	6	13		
	18	7	19	11	8	17	5
D3	23	22	2	21	4	25	
	24	3	20	9	10	1	12

Optimal solution = 4,294

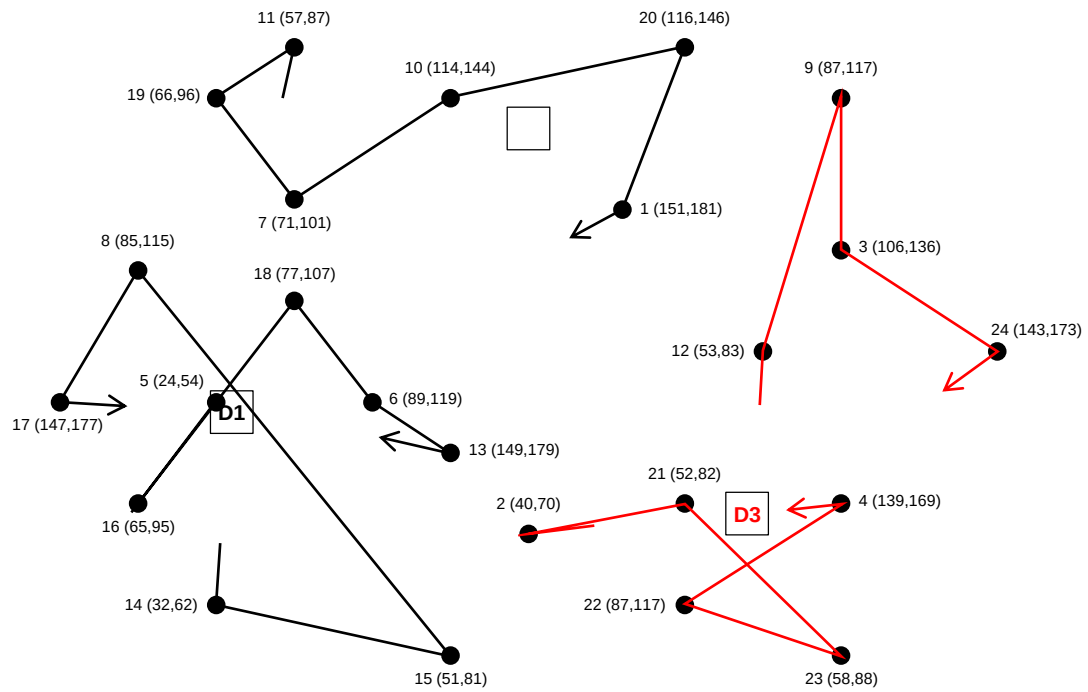
LRPTW-R104-25



D1	18	7	19	11	8	17	5
	16	14	15	2	13	6	
D3	21	22	23	4	25		
	24	3	9	20	10	1	12

Optimal solution = 4,251

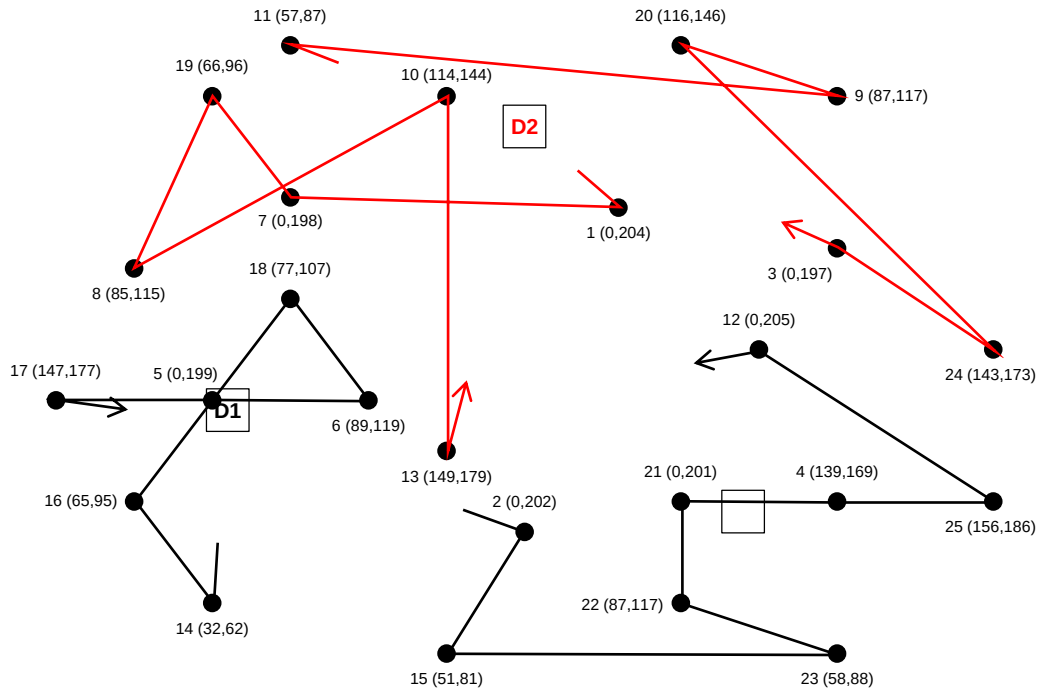
LRPTW-R105-25



D1	11	19	7	10	20	1
	5	16	18	6	13	
	14	15	8	17		
D3	2	21	23	22	4	
	12	9	3	24		

Optimal solution = 4,587

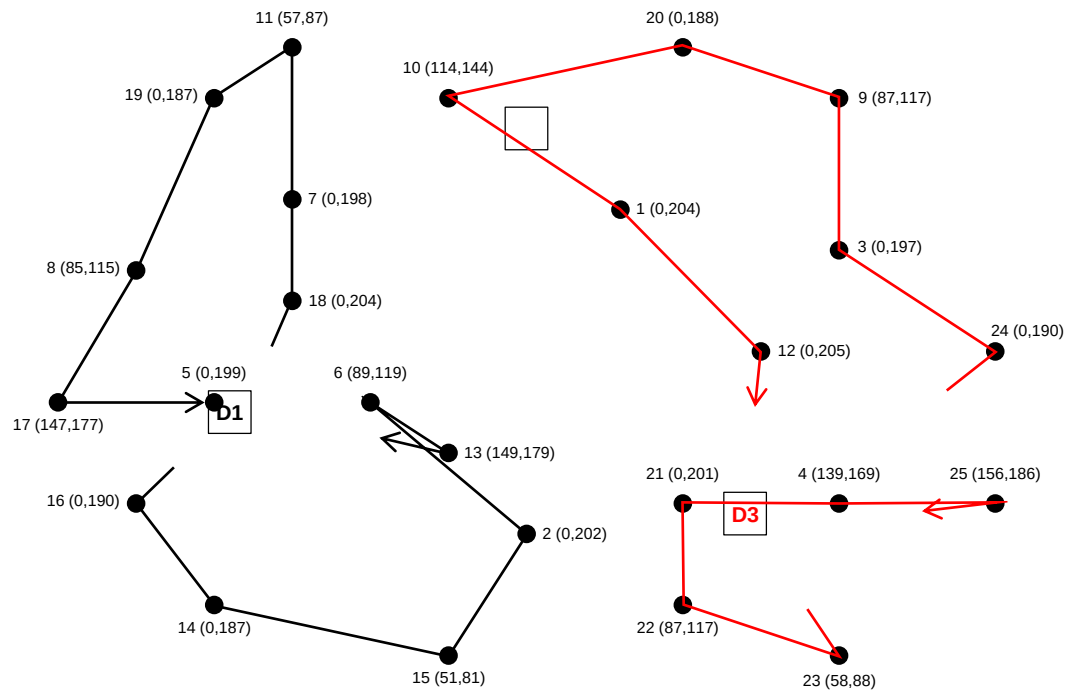
LRPTW-R106-25



D1	14	16	18	6	5	17		
	2	15	23	22	21	4	25	12
D2	1	7	19	8	10	13		
	11	9	20	24	3			

Optimal solution = 4,438

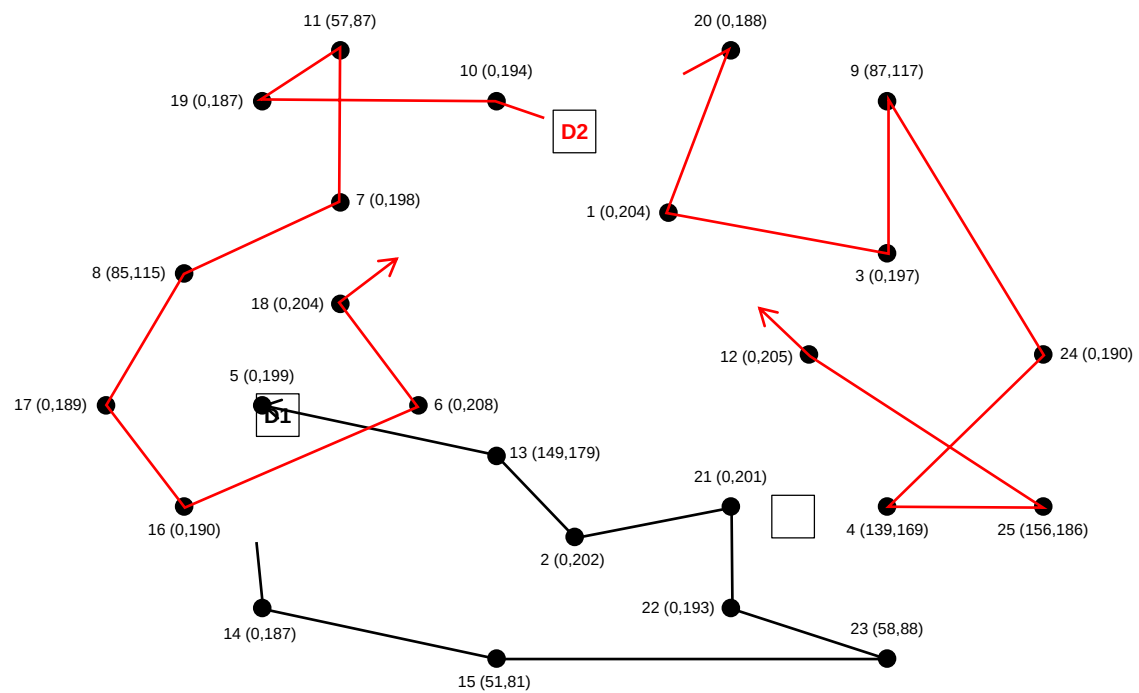
LRPTW-R107-25



D1	16	14	15	2	6	13	
	18	7	11	19	8	17	5
D3	23	22	21	4	25		
	24	3	9	20	10	1	12

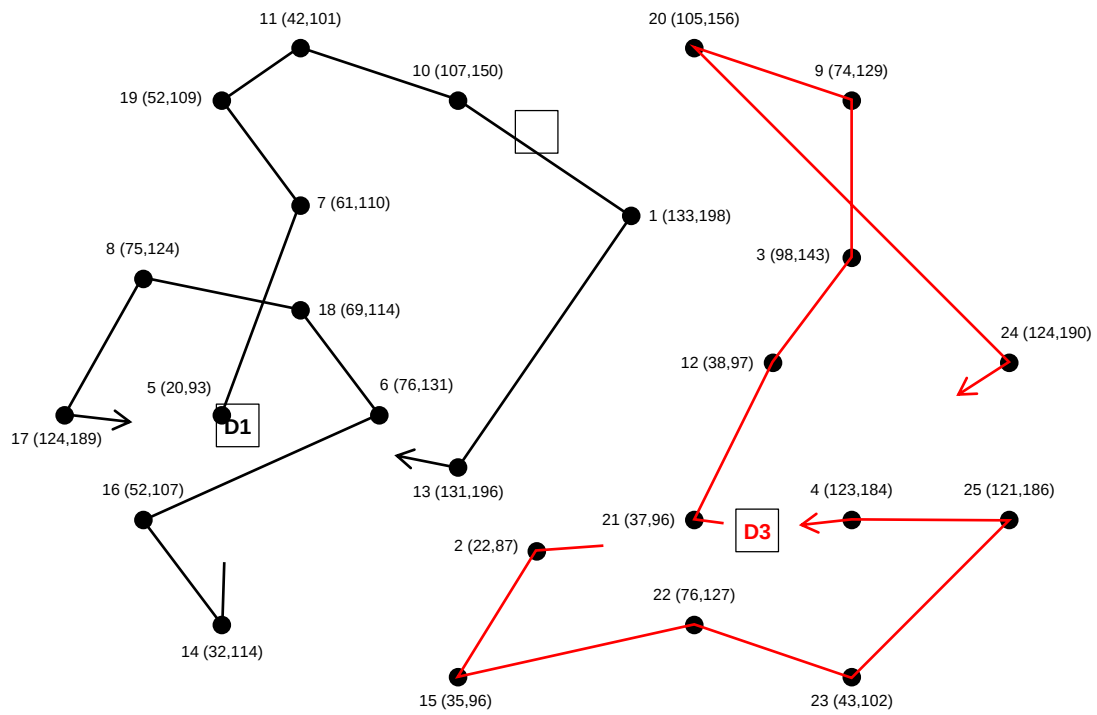
Optimal solution = 4,266

LRPTW-R108-25



D1	14	15	23	22	21	2	13	5	
D2	20	1	3	9	24	4	25	12	
	10	19	11	7	8	17	16	6	18

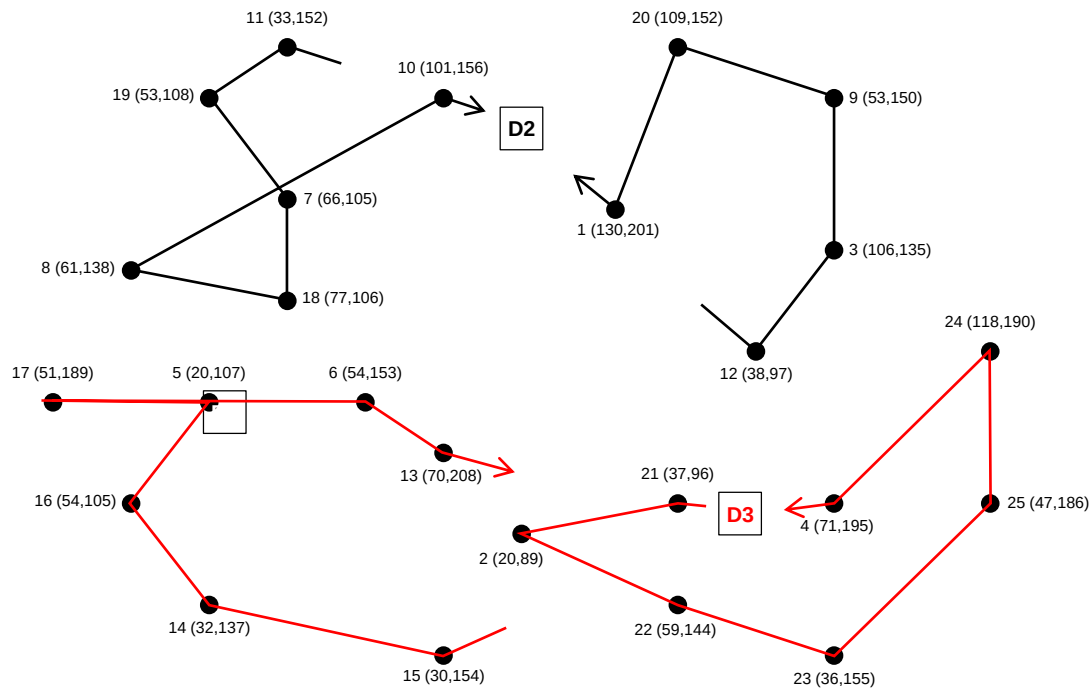
Optimal solution = 4,077



D1	5	7	19	11	10	1	13
	14	16	6	18	8	17	
D3	2	15	22	23	25	4	
	21	12	3	9	20	24	

Optimal solution = 4,299

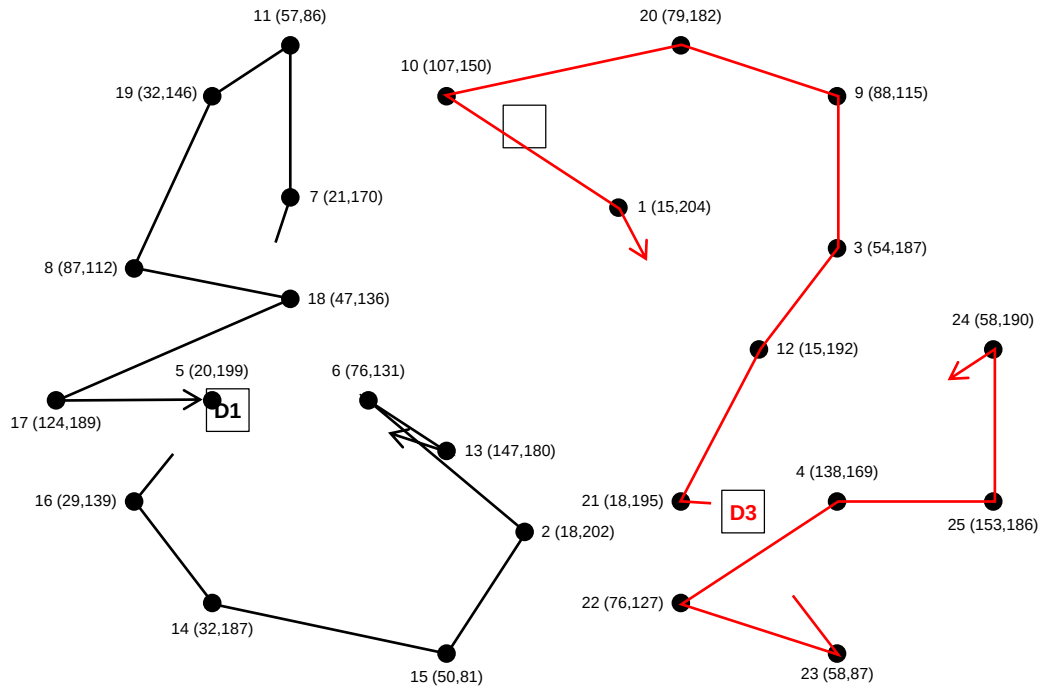
LRPTW-R110-25



D2	11	19	7	18	8	10
	12	3	9	20	1	
D3	21	2	22	23	25	24
	15	14	16	5	17	6

Optimal solution = 4,285

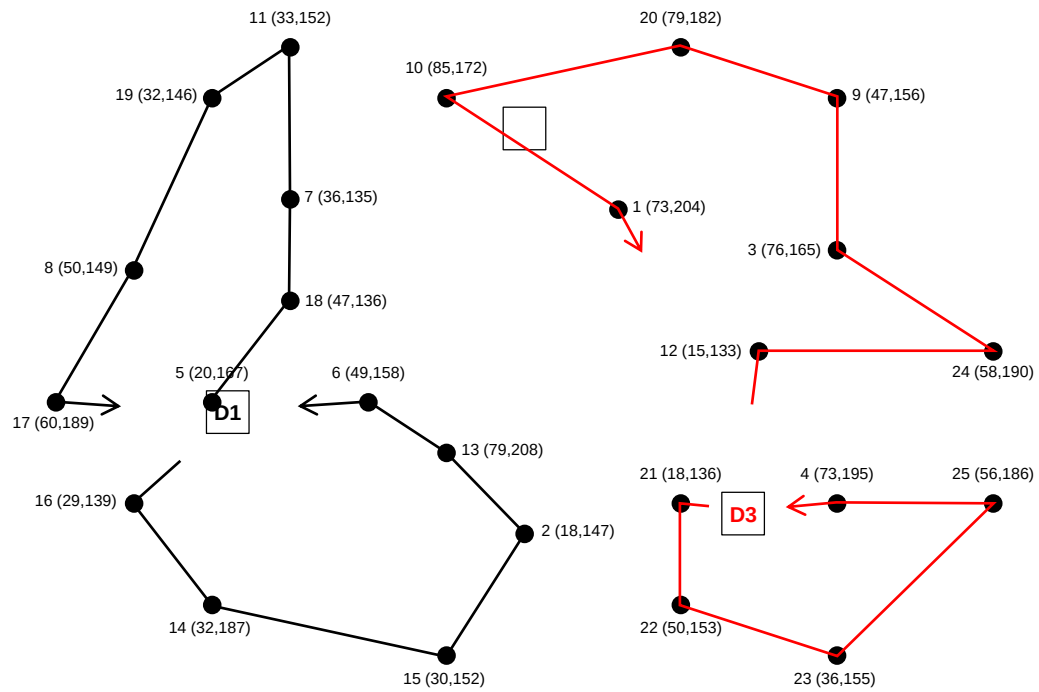
LRPTW-R111-25



D1 16 14 15 2 6 13
7 11 19 8 18 17 5
D3 23 22 4 25 24
21 12 3 9 20 10 1

Optimal solution = 4,289

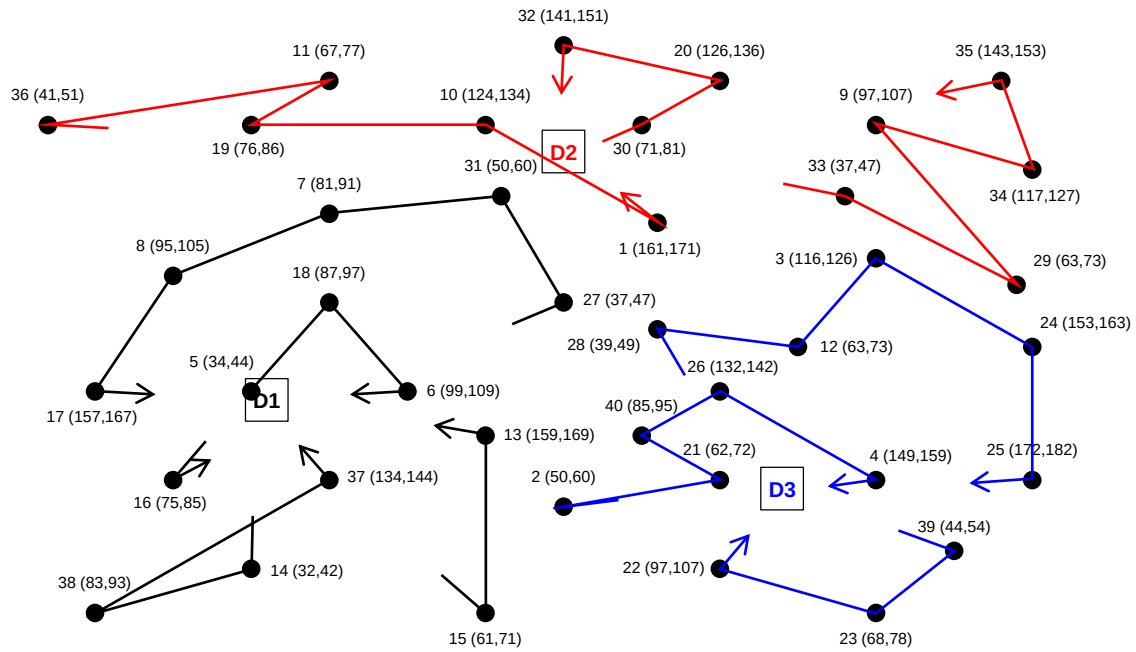
LRPTW-R112-25



D1	16	14	15	2	13	6	
	5	18	7	11	19	8	17
D3	21	22	23	25	4		
	12	24	3	9	20	10	1

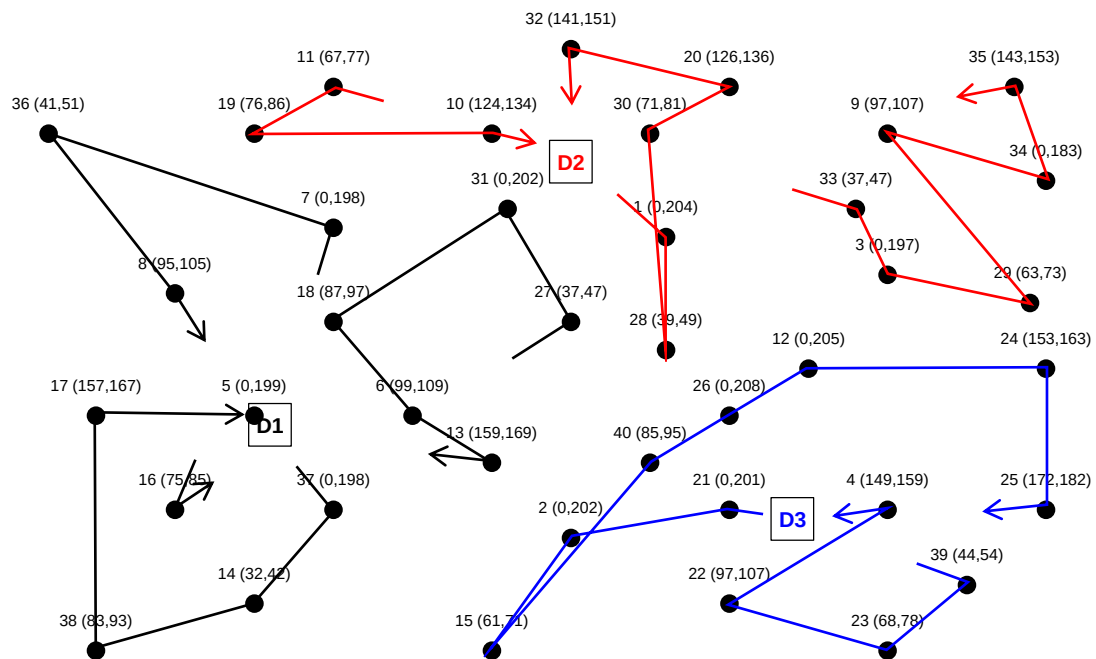
Optimal solution = 4,250

LRPTW-R101-40



D1	16				
	5	18	6		
	14	38	37		
	27	31	7	8	17
	15	13			
D2	30	20	32		
	33	29	9	34	35
	36	11	19	10	1
D3	39	23	22		
	2	21	40	26	4
	28	12	3	24	25

Optimal solution = 7,645



D1 16
37 14 38 17 5
7 36 8
27 31 18 6 13
D2 1 28 30 20 32
33 3 29 9 34 35
11 19 10
D3 39 23 22 4
21 2 15 40 26 12 24 25

Optimal solution = 7,150

Appendix C

Location of Depots and Shelters in Ishinomaki

Depot Information

Depot No.	Location	x	y	Capacity	Cost
D1	Sport Park	38.45778	141.30933	50,000	50,000
D2	Market	38.42923	141.25772	20,000	50,000
D3	Aeon Supercenter	38.42454	141.37451	30,000	50,000
D4	Miyagi Prefectural Fisheries High School	38.42056	141.36965	15,000	50,000
D5	Yamashita Junior High School	38.43799	141.28487	15,000	50,000
D6	Ishinomaki Elementary School	38.42894	141.30500	15,000	50,000
D7	York-Benimaru Okaido	38.42874	141.28680	5,000	50,000
D8	Aeon Supercenter	38.44765	141.26542	30,000	50,000
D9	Sakura Amusement	38.45419	141.28249	5,000	50,000
D10	Ishinomaki Fire Department	38.44454	141.31077	10,000	50,000

Vehicle Information

Capacity	Cost
6,500	25,000

Shelter Information

Shelter No.	x	y	Demand	a	b	Service Time
1	38.44320	141.31416	270	49	179	10
2	38.44302	141.31191	540	433	551	10
3	38.44262	141.30615	690	130	255	10
4	38.44426	141.29738	375	195	323	10
5	38.42846	141.29777	2,100	258	355	10
6	38.42858	141.29633	1,950	109	186	10
7	38.42600	141.29978	780	71	264	10
8	38.42325	141.30406	300	332	508	10
9	38.42227	141.29749	1,110	337	492	10
10	38.43798	141.30146	63	314	436	10
11	38.43417	141.30249	2,400	49	214	10
12	38.43393	141.30757	90	306	460	10
13	38.43602	141.30751	1,050	258	380	10
14	38.43754	141.31243	1,740	112	243	10
15	38.43347	141.31093	54	369	443	10
16	38.42961	141.30811	12	158	320	10
17	38.42754	141.30524	495	468	644	10
18	38.42712	141.30732	150	394	446	10
19	38.43035	141.30268	210	207	329	10
20	38.42753	141.29949	54	481	628	10
21	38.42396	141.29398	30	3	60	10
22	38.42187	141.33622	1,110	145	298	10
23	38.42416	141.33786	159	14	119	10
24	38.43929	141.34446	42	382	523	10
25	38.43972	141.33916	120	280	380	10
26	38.42355	141.34644	1,800	327	413	10
27	38.42073	141.34569	1,140	346	453	10
28	38.42240	141.34159	5,400	265	345	10
29	38.41925	141.33849	60	323	432	10
30	38.41402	141.33076	33	33	183	10

Shelter No.	x	y	Demand	a	b	Service Time
31	38.41906	141.32202	165	485	618	10
32	38.42048	141.32439	90	250	395	10
33	38.41976	141.33080	12	177	295	10
34	38.42060	141.33261	42	461	576	10
35	38.42493	141.32385	90	174	298	10
36	38.43175	141.32616	180	457	643	10
37	38.42422	141.32161	72	265	363	10
38	38.42682	141.31604	3,624	282	480	10
39	38.43110	141.31579	1,020	325	383	10
40	38.43326	141.31486	30	18	183	10
41	38.43944	141.32600	243	294	492	10
42	38.43748	141.31994	225	385	521	10
43	38.45251	141.27817	330	46	197	10
44	38.45164	141.27929	210	124	286	10
45	38.44462	141.27888	660	299	407	10
46	38.44687	141.27500	240	474	562	10
47	38.44406	141.27354	180	190	384	10
48	38.43851	141.26174	45	457	557	10
49	38.45173	141.25800	120	475	624	10
50	38.45200	141.25595	660	434	571	10
51	38.45280	141.25596	180	73	227	10
52	38.44599	141.26401	960	194	349	10
53	38.42214	141.35905	153	446	594	10
54	38.42852	141.35313	210	156	267	10
55	38.42565	141.37219	909	291	388	10
56	38.42526	141.37519	210	232	364	10
57	38.42467	141.37649	240	164	277	10
58	38.41033	141.37069	450	378	502	10
59	38.41350	141.37458	390	419	614	10
60	38.41871	141.36451	2,100	369	486	10
61	38.41698	141.36684	3,000	290	386	10
62	38.41673	141.36302	120	36	156	10
63	38.41693	141.36504	135	356	430	10
64	38.41681	141.35213	162	337	474	10
65	38.41805	141.34938	240	12	83	10
66	38.41953	141.34942	900	485	663	10
67	38.45480	141.29486	660	223	317	10
68	38.45250	141.30706	240	237	397	10
69	38.44642	141.33598	240	69	130	10
70	38.44798	141.35792	150	269	335	10
71	38.43155	141.27672	1,260	75	178	10
72	38.42446	141.27660	72	498	636	10
73	38.42549	141.25454	270	142	320	10
74	38.43268	141.29299	600	266	342	10
75	38.43266	141.29565	513	288	356	10
76	38.42838	141.28903	435	268	352	10
77	38.42859	141.28214	1,800	460	658	10
78	38.43435	141.28250	990	346	430	10
79	38.43225	141.27366	600	122	295	10
80	38.43268	141.26199	2,673	170	367	10
81	38.43509	141.29923	120	368	500	10
82	38.43705	141.30913	660	112	244	10

Shelter No.	x	y	Demand	a	b	Service Time
83	38.43206	141.30906	78	282	417	10
84	38.43193	141.30926	195	96	269	10
85	38.42727	141.28995	90	427	488	10
86	38.42513	141.28824	300	178	307	10
87	38.42597	141.28696	300	367	459	10
88	38.42488	141.32324	1,140	180	257	10
89	38.42879	141.31389	60	62	253	10
90	38.43493	141.35280	486	115	300	10
91	38.42367	141.36261	1,800	84	198	10
92	38.42922	141.34969	450	200	260	10
93	38.42407	141.36951	270	379	465	10
94	38.42503	141.36874	1,065	14	94	10
95	38.42376	141.36237	750	258	448	10
96	38.44300	141.37952	900	387	466	10
97	38.43772	141.39809	300	80	265	10
98	38.41944	141.35442	210	155	343	10
99	38.42041	141.35435	450	112	273	10
100	38.45301	141.27641	90	72	180	10
101	38.42726	141.25856	450	469	605	10
102	38.43201	141.27311	300	229	395	10
103	38.42963	141.28278	990	129	311	10
104	38.42406	141.28123	420	91	217	10
105	38.42686	141.27345	900	41	101	10
106	38.47286	141.35651	300	240	400	10
107	38.44407	141.33182	330	9	98	10
108	38.46174	141.34493	120	487	662	10
109	38.48383	141.37990	450	27	205	10
110	38.44267	141.28548	90	30	97	10
111	38.42426	141.37290	180	140	295	10
112	38.42980	141.29192	1,800	1	152	10
113	38.45204	141.25678	360	33	204	10
114	38.46237	141.30648	90	135	234	10
115	38.42792	141.29350	600	26	225	10
116	38.44580	141.33738	42	47	170	10
117	38.43833	141.31209	300	282	423	10
118	38.49884	141.29150	90	129	299	10
119	38.44273	141.30811	60	365	552	10
120	38.42214	141.35100	900	17	172	10
121	38.45389	141.27378	45	459	613	10
122	38.43111	141.30855	330	479	657	10
123	38.42786	141.37125	36	184	328	10
124	38.43236	141.30517	810	93	212	10
125	38.41971	141.37091	750	456	643	10
126	38.42239	141.32234	495	163	266	10
127	38.42964	141.30510	450	147	321	10
128	38.42654	141.37071	300	454	543	10
129	38.46153	141.30572	30	8	131	10
130	38.42009	141.33697	60	27	205	10
131	38.43205	141.29269	120	123	215	10
132	38.43899	141.31014	1,200	342	498	10
133	38.42065	141.34027	1,290	29	213	10
134	38.41858	141.36957	540	186	368	10

Shelter No.	x	y	Demand	a	b	Service Time
135	38.41849	141.33573	174	80	258	10
136	38.42674	141.37265	3,600	148	247	10
137	38.42089	141.34423	1,200	426	527	10
138	38.41816	141.34836	225	54	183	10
139	38.49782	141.31948	300	256	381	10
140	38.43370	141.30181	105	329	470	10
141	38.45629	141.34471	750	189	375	10
142	38.41946	141.35901	360	361	553	10
143	38.43367	141.26331	717	261	370	10
144	38.45182	141.31923	270	484	658	10
145	38.43870	141.30636	4,800	196	251	10
146	38.42184	141.37164	600	202	398	10
147	38.43461	141.32587	1,650	120	254	10
148	38.43404	141.30557	780	361	560	10
149	38.42993	141.30729	150	127	197	10
150	38.42940	141.27843	750	366	511	10
151	38.41802	141.33105	300	140	212	10
152	38.43166	141.29397	90	422	483	10