A THREE-ECHELON MULTI-COMMODITY LOCATION-ROUTING PROBLEM

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พัฒนพงษ์ แสงหัตถวัฒนา : การออกแบบเครือข่ายการกระจายสินค้าแบบหลายลำดับชั้นจากปัญหาการเลือกสถานที่ตั้งและเส้นทางการขนส่งสำหรับสินค้าหลายประเภท (A THREE-ECHELON MULTI-COMMODITY LOCATION-ROUTING PROBLEM) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: รศ. ดร. พงศา พรชัยวิเศษกุล, อ.ที่ปรึกษาวิทยานิพนธ์ร่วม: ผศ. ดร. มาโนช โลหเตปานนท์, หน้า.

งานวิจัยนี้มีมุ่งเน้นศึกษาปัญหาของการออกแบบเครือข่ายการกระจายสินค้า โดยมีวัตถุประสงค์เพื่อ 1) พัฒนาแบบจำลองเพื่อออกแบบเครือข่ายการกระจายสินค้าที่มีสถานที่ตั้งบางส่วนเปิดดำเนินการอยู่แล้วโดยมุ่งเน้นให้มีต้นทุนในการกระจายสินค้าที่ต่ำลง และ 2) พัฒนาวิธีการในการหาคำตอบสำหรับปัญหาที่มีความซับซ้อนสูง แบบจำลองทางคณิตศาสตร์สำหรับปัญหาการเลือกที่ตั้งของสถานที่ให้บริการและการจัดเส้นทางการขนส่ง (Location Routing Problem: LRP) แบบสามระดับชั้นโดยมีสินค้าสองกลุ่มได้ถูกพัฒนาขึ้น สมการวัตถุประสงค์คำนึงถึงค่าใช้จ่ายในการเปิดและปิดดำเนินการของสถานที่ให้บริการ และต้นทุนการขนส่งตามระยะทาง เนื่องด้วยปัญหา LRP ที่ใช้ในงานวิจัยนี้เป็นปัญหาที่มีขนาดใหญ่ และยากต่อการหาคำตอบโดยใช้วิธีการที่ดีที่สุด งานวิจัยนี้จึงได้พัฒนาวิธีในการหาคำตอบขึ้นมาใหม่ มีขั้นตอนหลักดังนี้ 1) แบ่งปัญหาออกเป็นสองส่วนตามโครงสร้างของปัญหา LRP 2) การจัดกลุ่มของเส้นทางการขนส่ง และหาเส้นทางที่สั้นที่สุดจากปัญหาการเดินทางของพนักงานขาย (Traveling Salesman Problem: TSP) และ 3) กำหนดคลังสินค้าและศูนย์บริการที่เหมาะสม แบบจำลองถูกทดสอบโดยใช้ข้อมูลจากสถานการณ์จริงที่มีการกระจายสินค้าทั้งหมด 5 พื้นที่ ในการศึกษาได้วิเคราะห์ทั้งรูปแบบการกระจายสินค้าแยกแต่ละพื้นที่ และรูปแบบการกระจายสินค้าโดยรวมทุกพื้นที่เข้าด้วยกัน นอกจากนี้ยังมีการทดสอบความไวของคำตอบ โดยมีการทดสอบทั้งหมด 66 สถานการณ์ ผลลัพธ์ที่ได้พบว่า การออกแบบเครือข่ายการกระจายสินค้าโดยรวมทุกพื้นที่เข้าด้วยกันมีต้นทุนการกระจายสินค้าที่ต่ำที่สุด อีกทั้ง วิธีการหาคำตอบที่พัฒนาขึ้นมาให้คำตอบที่ดีกว่าวิธีการหาคำาตอบที่ดีที่สุด โดยมีต้นทุนที่ต่ำกว่า และใช้เวลาในการหาคำตอบที่น้อยกว่า นอกจากนี้จากการจำลองสถานการณ์ภายใต้สภาวะที่ไม่แน่นอน พบว่าเครือข่ายการกระจายสินค้าที่ได้จากแบบจำลองให้ผลที่ดีกว่าเครือข่ายที่ดำเนินการอยู่ในปัจจุบัน

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PATANAPONG SANGHATAWATANA: A THREE-ECHELON MULTI-COMMODITY LOCATION-ROUTING PROBLEM. ADVISOR: ASSOC. PROF. PONGSA PORNCHAIWISESKUL, Ph.D., CO-ADVISOR: ASST. PROF. MANOJ LOHATEPANONT, Sc.D., pp.

This research studies the problem of distribution network design. The purposes of this study are 1) to develop the mathematical model for redesign of current distribution network by focusing on reducing total distribution cost and 2) to develop new solution approach for large-scale complicated problem. This research formulates mixed integer linear programming for the three-echelon two-commodity Location Routing Problem (LRP). The objective function is to minimize facility operating and closure cost and distance cost. Due to large-scale of LRP, which is NP-hardness, this research proposes new sequential solution approach as following steps; 1) decomposing the LRP into two subproblems based on its structure, 2) establishing route by clustering algorithm and identifying shortest route from Traveling Salesman Problem (TSP), and 3) allocating proper warehouse and service center. The proposed model is tested by using data of distribution network from actual case, which consists of five distributed zones. In analyzed phase, both of the distribution network redesign for each particular zone and allowing the distribution across all zones are considered. Additionally, this research conducts sensitivity analysis on each problem. Totally, there are 66 scenarios to perform. The result indicates that solving all zones simultaneously contributes lower cost than solving each zone separately. The proposed solution provides better answer than solving the problem by exact approach, which gives lower cost with shorter computation time. Moreover, the solutions of the proposed model are tested in stochastic environmental by simulation technique. The results show that the redesign of distribution network by proposed model can provide better quality of answer than the current network.

Field of Study:	Logistics Management	Student's Signature	....
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		Co-Advisor's Signature	....

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CHAPTER 1
INTRODUCTION

1.1 Introduction

Distribution network in supply chain aspect refers to systems that used for transferring products from an original source across facilities to a final destination on specified transportation routes. Typically, when a business designs its own distribution network can relevant to locate facilities and construct the delivery routes of vehicle for replenishing the products in retailer. Nowadays a company implements various distribution strategies that align with facility setting. For example, distribution center (DC) is placed between a plant and a retailer which helps company can be efficiently design proper routes for full truck load and less than truck load delivery for inbound and outbound transportation. For this reason, supply chain facilities (DC and warehouse) have become to a significant strategic component for distribution network.

Moreover, ASEAN Economic Community (AEC) will establish regional economic integration by 2015 and the economic size will be expanded. Distribution goods from manufacturing sites to customers will be complicated and the number of distributed products will also increase. According to congested delivery schedules, many companies who operate their own distribution networks are facing higher logistics cost as well as more delay and over-capacity problems which lead to uncontrollable situations. In order to overcome competitors, companies have to redesign distribution networks. Hence, logistics network design becomes more interesting topic for this region to remain competitiveness in term of cost advantage (Martins, Amorim, Figueira, & Almada-Lobo, 2017).

Number, location and size of distribution center, warehouse and shop are the significant dominate factors which affect to distribution efficiency as well as vehicle routing (Perl & Daskin, 1985). Decision without systematic approach has a risk that leads a company to inefficient supply chain performance both of unnecessary facility locations and frequently opening new ones/closing existing facilities.

Hence, to identify optimal number of facilities and locate them in proper candidate sites, formulating mathematical model is one of efficient approach. The systematic approach used to design is called *Facility Location Problem* (FLP). However, most of previous mathematical models in FLP ignored transportation routing in design process. Consequently, configuration of distribution network will be suit for some cases such as most of vehicle are full truck load. Alternatively, harmonizing facility location decision and designing route can contribute more efficiency in term of the ways to satisfy the customer demands and reducing overall cost. Mathematical model considering both of dominated aspects is called Location Routing Problem (LRP) which has been proved by many researchers and practitioners that how facilities location and routing affects distribution cost and time (Gábor Nagy & Said Salhi, 2007).

LRP is a combination of two different managerial levels of decision, which are a facility location problem (long term decision) and a vehicle routing problem (tactical term decision), and inherently recognized as an NP-hardness problem. Many researchers and practitioners have proved that solution obtained from LRP can reduced distribution cost and time (Gábor Nagy & Said Salhi, 2007). Application of LRP can be applied on many cases, for example, a designing an emergency service, an ATM location and replenishment network, and also planet exploration and a general commodity distribution network (Prodhon & Prins, 2014).

In addition, most of distribution networks have been designed for flows of finished goods, therefore, when applying those networks to flows of service parts, it consumes higher cost and longer time (Gzara, Nematollahi, & Dasci, 2014). In case of separating network, it wastes much expenses and resources. Since sharing distribution resource concept has arisen, network flow of products and service parts used for maintenance purposes are also simultaneously planned (Melo, Nickel, & Saldanha-da-Gama, 2009). Hence facility location and vehicle routing decision at once in multi-commodity condition will be holistically studied in this research to minimize distribution cost.

1.2 Case Study

The case study of this research is an electronics company in Thailand that produces and distributes two product families, which are electrical products and service parts as shown in figure 1.1. For finished goods, there are two product families in this category. First one is a home product for regular customers, which satisfy demand at particular retailer. Another one is a shop product for business customers, (e.g., gas stations, retail shops and *etc.*), which company has to provide on-site service to set up these shop products at customer locations.

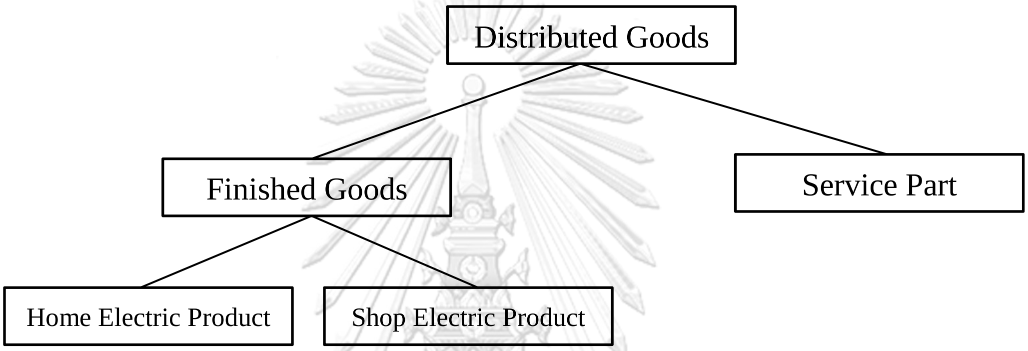


Figure 1.1 Product family of case study

Otherwise, service part distributors have their own systems. There are two cases for after-sale service system as describe below;

- **Home product**; a customer walks into service center which located in some retail shops to drop the item. In this case, service center is operated as a collection center in supply chain aspect. Then a service center mechanic will pull service parts, if required, from depot or warehouse (no directed route from depot to service center) to maintenance customer 's item. Finally, customer has to come back to service center again to bring repaired item back by him/herself. Nonetheless, large-size home products, required onsite service, will use the same system as shop product as mention below.
- **Shop product**; if an end-customer requires after-sale services, a service center mechanic will pull service parts from warehouse or depot (no directed route from depot to service center) to repair customer product by onsite service.

Clearly, this problem consists of four layers in supply chain management aspect including Layer 0: a depot, Layer 1: set of warehouses, Layer 2: set of retailer/service centers and Layer 3: end-customers. Moreover, there are three-echelon of transport route that links between two adjacent layers as shown Figure 1.2. For 1st echelon, each truck pickups and deliveries cargos directly from depot and then drops the cargos in a single warehouse and returns to depot again (replenishment transportation). For the 2nd echelon, each truck circulates cargos by milk run on particular retailers and comes back to original warehouse (tour transportation). In the 3rd echelon, each route begins from service center, visits particular end-customer site and end at same service center (tour transportation).

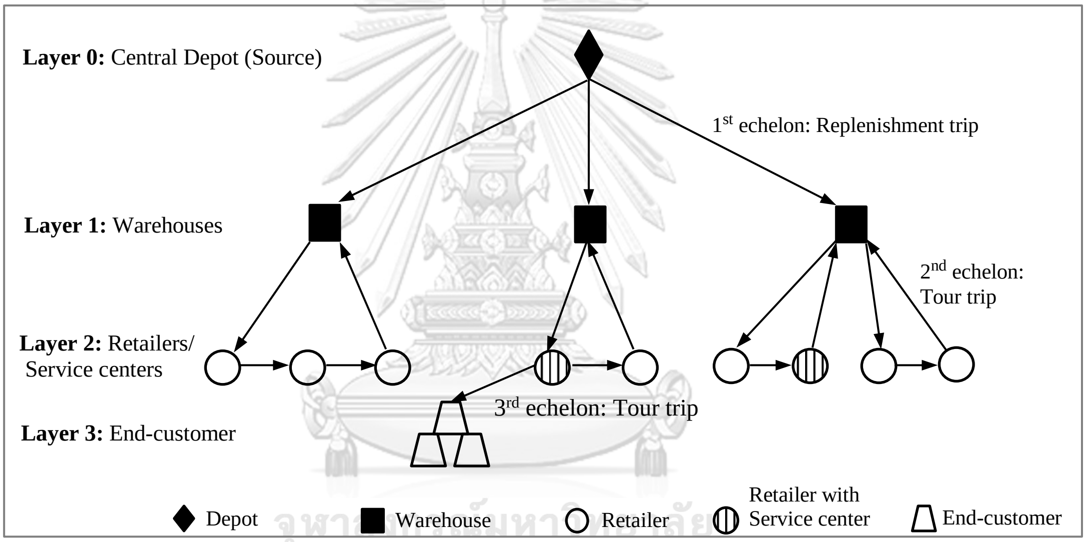


Figure 1.2 Three-echelon distribution network
(modified from Drexl and Schneider (2015))

Due to previous research, LRP has been applied to design distribution network for only two echelon case studies. However, it is known that the future research is required more complicated and realistic problem (Drexl and Schneider, 2015; Prodhon and Prin, 2014; Melo et al., 2009; Nagy and Salhi, 2007; and etc.). In other words, three or more echelons with multi-commodity case study is interesting and suitable problem to investigate and reveal the results for this field of research. Also, in order to redesign distribution network, existing location of facilities should be considered. The characteristics of the case study in this research are matched to the details that mentioned above. Moreover, one of the most importance industries in Thailand is electronics industry. After AEC has been established in 2015, the companies in this sector have considerably expanding. With new opportunities and market, the distribution areas of companies have been widening. Hence, the current distribution network is required to revise.

1.3 Research Aims

The aims of this research are to develop mixed integer linear programming for designing distribution network problems and solving them to identify simultaneously the solutions of three main questions;

- Which warehouses/service centers should be opened?
    - Numbers and location of facilities in a distribution network
- Which warehouse fills up demand for particular retailers/service centers and which service center supports end-customers?
    - Allocate retailer shops/service centers to a warehouse
    - Allocate end-customers to a service center
- How to distribute each product through distribution network?
    - Designing route for transferring products from point to point

1.4 Main Contributions

A main contribution of this research is to propose a new decision mathematical model which can provide a quality configuration of distribution network for a real-world case study. And the most important, the solution will be able to help companies reduce overall distribution and facility costs, in order to compete with the others and gain more advantages from competitors. Moreover, another one is to develop a new iterative solving algorithm due to complexity of the three-echelon location routing problem with multi-commodity.

1.5 The research methodology

To conduct this research, after setting the research objectives, the areas of literature review are defined. This study scopes the previous literatures into two areas, including of formulation model of FLP and LRP, solving technique of decomposition method and clustering-based method. Next, the mathematical model is developed based on literature review and actual case study's characteristics. The data preparation is performed for identifying and gathering the information that are applied to the objective function and constraints in the proposed model. Then this study performs solving the problem both exact method and the proposed solution method. The solution method is developed based on clustering technique. This study applied all codes of the models and solving methods in IBM ILOG CPLEX 64-bit version 12.4 with C# Concert technology and Microsoft Visual Studio 2015. Next, the all problems are tested and the models are performed sensitivity analysis to verify the solution in dynamic environment. Then, this research tests validation of all solutions from based problems by applying simulation technique in stochastic environment. Finally, the research result, finding and implication are concluded and indicated the future research respectively as shown the methodology in Figure 1.3.

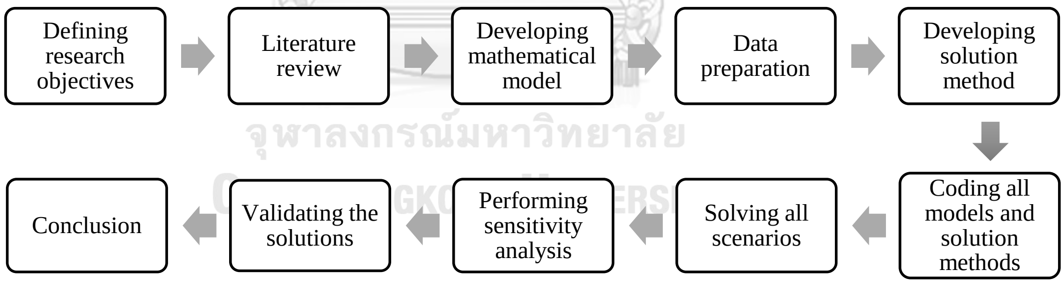


Figure 1.3 the research methodology

CHAPTER 2
LITERATURE REVIEW

The purposes of this chapter are to demonstrate previous research literatures in the field of location planning, location-routing planning, location-routing-inventory planning and reveal the gaps for future work.

2.1 Classification of Problems

2.1.1 Facility Location Problem (FLP)
2.1.2 Facility Location-Routing Problem (LRP)
2.1.3 Facility Location-Routing-Inventory Problem (ILRP)

2.2 Solving Techniques

2.2.1 Decomposition Approach
2.2.2 Clustering Based Approach

2.3 Defining Research Gaps

2.1 Classification of Problems

2.1.1 Facility Location Problem (FLP)

Facility location selection is one of importance decision in supply chain management because a proper facility location in supply chain management will help not only reducing related cost, but also enhancing supply chain competitiveness (Klibi, Martel, & Guitouni, 2010). However, the strategic facility location problem has arisen since last century (Sarkar & Majumder, 2013). In the past, FLP had various formulations due to different design objectives, situations, criteria and planning horizon. The first problem, *p*-median problem, is one of the simplest ways to formulate problems by applying integer programming structure. In this problem, a sub-set of candidate facility sites should be selected based on a total weighted demand and distance from demand sites to service sites, which assumes to be linear function. The second problem is a set covering problem. The objective of a set covering problem is minimizing the number of open facilities or minimizing the opening costs of facilities (Owen & Daskin, 1998). The difference between a *p*-median problem and a set covering problem is that, in a set covering formulation, the service requirement of facility must be firstly identified. For instance, maximum time or distance is allowed in terms of customer service. In the contribution of this formulation, the location of a pizza shop that must be able to deliver pizza to customers within 30 minutes, the location of a fire station that should not be located too far from all serving communities, the locations of hospitals or emergency centers due to limited distance or transportation time, *etc*. (Farahani, Asgari, Heidari, Hosseininia, & Goh, 2012; Farahani, SteadieSeifi, & Asgari, 2010). The third formulation of a FLP is a *p*-center problem. This problem aims to minimize the maximum distance from facility site to demand node which could possibly be occurred. The ignorance of facility capacity of all three problems is inconsistent to real situation. Therefore, researchers have included capacity constraint into the model which is called capacitated facility location problem as shown below.

Let x_{ij} = 1 if allocate customer i to facility j, 0 otherwise; y_j= 1 if facility j is opened, 0 otherwise; f_i, c_{ij} are fixed cost of opening facility j and cost of facility j served customer i respectively; d_i is a demand of customer i and s_j is capacity of facility j.

$$Min\ Z = \sum_{i\in I}\sum_{j\in J} c_{ij}x_{ij} + \sum_{j\in J} f_j y_j \tag{2.1}$$

s.t.

$$\sum_{j\in J} x_{ij} = 1 \qquad \forall i \in I \tag{2.2}$$

$$x_{ij} \le y_j \qquad \forall j \in J \tag{2.3}$$

$$\sum_{i\in I} d_i x_{ij} \le s_j \qquad \forall j \in J \tag{2.4}$$

$$x_{ij} \in \{0,1\} \qquad \forall i \in I\ \ \forall j \in J \tag{2.5}$$

The objective function (1) minimizes the total cost that consists of cost of serving customer and cost of opening facility. Constraints (2.2) refer to each customer can be assigned explicitly to a single facility. Constraints (2.3) refer to only an open facility can be assigned to customer. Constraints (2.4) refer capacity of constraint and constraints (2.5) express that decision variables are binary variables. Capacity of facility depends on production capability in a plant, storage capacity in a warehouse or an amount of flow which operators/equipment can handle in particular facility (Alizadeh, Mahdavi, Mahdavi-Amiri, & Shiripour, 2015).

Clearly, to open facility in distribution network, such as Distribution Center (DC), requires high investment which will have long term effect on supply chain efficiency (Melo *et al*., 2009; Owen & Daskin, 1998). At the beginning, facility costs and transportation cost are main influential criteria which researchers or decision makers have taken into account (Farahani *et al*., 2010). For facility cost, there are two types are proposed in the most models which consist of fixed opening cost and variable operation cost per unit (flow quantity through particular facility). In transportation dimension, full truck load is applied in formulation process which means that products will transfer directly from original facility to its supported destination facility exclude tour transportation. Hence, transportation cost will be calculated based on distance or delivery time between two facilities and transform it to cost per unit (volume, piece or weight). However, the consequence of focusing merely on cost can lead to the problem of facility congestion, because it tends to select only one facility even though it is located in rural area and far from customers' locations. This affects distribution efficiency and service level. Hence, some researchers combined costs and time factors in the design of distribution network by presenting time in monetary value, i.e. lead-time cost (Sarkar & Majumder, 2013) For instance, Eskigun *et al*. (2005) presented a single objective integer programming model for outbound logistics, including traditional cost plus a monetary value of lead-time into objective function. This model helps a practitioner to determine a transportation mode, a number of warehouses and locations under traditional cost and lead-time cost. Similar to objective function, transportation time can be applied as limitation in constraint to reflect some realistic situations, such as to prevent a long delivery trip or a violation of driving time regulation.

In formulating the mathematical model, obviously a number of indexes for decision variables depend on the characteristic of problem. From reviewing literature, for instance, the formats of indexes are as follows (Sadjady & Davoudpour, 2012; Sarkar & Majumder, 2013; Tragantalerngsak, Holt, & Rönnqvist, 2000);

- Two index decision variables; comprises of a candidate location index and a demand node index (Barahona & Chudak, 2005; Klose & Drexl, 2005).
- Three-index decision variable; the first two indexes represent a candidate location and a demand node, while the additional index represents a product type or a planning horizon (Zhuge, Yu, Zhen, & Wang, 2016).
- Four-index decision variable; each index represents a candidate location, a demand node, a product type and a planning horizon (Ashfari, Sharifi, ElMekkawy, & Peng, 2014).

Moreover, the number of index affects to the quality of the answer. In the other word, the higher number of indexes, the harder difficulties to solve the problem. Such as Sarkar and Majumder (2013) constructed two-echelon facility locations and faced problems with three different models. The different among them were the number of indexes and the problem types (use same input data). First, the problem with two indexes was formulated before expanded to three and four indexes which were the product type and transportation mode, respectively. The result shows that the original problem and last problem with multi-product types and transportation mode selection can provide lower cost than the second problem. It indicates that if the decision makers isolate the aggregate demand of each customer to the proportion of product type, the distribution network will scarify more cost to handle them.

In the earliest period of the study of facility location problem, the problem consists of only one echelon (two-layer, such as facility-customer) which aims to find the location of plants or warehouses. But most models have limitation and also provide insufficient efficiency for overall supply chain (Farahani *et al*., 2012). If the problem has more than two layers, mathematical model will extend to be hierarchical location problem structure (Boloori Arabani & Farahani, 2012). However, in supply chain context reviewed by Melo *et al*. (2009), most of the authors formulate problems which are only single-echelon system. Even though, they formulate in multi-echelon system, serving from nearby layer only is allowed. It is opposite to supply chain aspect. But in the latter studies, the proposed models have been developed to be more efficiency by adding multi-layer into the models. Most of them have three layers including a production site, an intermediate distribution site and a retailer site. For example, Ross and Jayaraman (2008) propose the model that can cover the facility location network problem with multi-layer, including a cross-docking site, a warehouse and a customer zone by applying binary integer programming. The problem is solved by hybrid heuristic (Simulated annealing and Tabu search) which gives a better result.

In dynamic FLP, there are two different ways to expand FLP from a static model to dynamic one. Multiple planning periods system, the model will be added more time period index. Despite, for a single-period with continuous time system, the model will transform to non-linear programming, which is harder to solve. Generally, the decision makers can get benefit more from multi-period system, such as designing proper time to open/close facility over planning horizon which is difficult to do in continuous system (Boloori Arabani & Farahani, 2012).

Moreover, sometimes the facility capability is insufficient to satisfy customers' entire requirements. Accordingly, the company executives must think about how to response the customers to obtain as much as overall satisfactions. Despite minimizing cost and time, Correia, Melo, and Saldanha-da-Gama (2013) try to maximize a profit. Four-index integer linear programming is introduced to study two different objective functions; first one is to minimize total cost, another one is to maximize total profit with multi-period, multi-product, and two-echelon supply chain network design problem. In this study, the authors explain how to use a conversion factor to tackle a multi-product situation in facility storage capacity constraint. Moreover, the budget constraint is added into model to limit the number of opening facility in each planning period. The authors mention in their works that, solving the problem with the objective of cost minimization will give a solution with low quality, due to the increasing number of time period. In contrast, the objective of profit maximization is more efficient.

Besides, in problem of designing distribution network, some researches also brought existing facilities into consideration (Melachrinoudis & Min, 2000, 2007; Tayal, 2003). In this case, cost of facility relocation is also considered due to the assumption that opening or closing existing facility could affect total cost.

Melachrinoudis and Min (2007) studied the real-world case study of single-echelon warehouse network redesign problem. The problem was formulated by using mixed-integer linear programming model to identify which warehouse should be operated and capacity of a closing warehouse should be relocated to which operated warehouse. This study considered the cost of moving relocation, the cost saving of closing existing warehouse, and the fixed cost of maintenance over one year planning horizontal. The proposed model was solved by LINGO 7.0. The interesting points mentioned by the authors are the redesign problem should be expanded into more echelon and the multi-commodity should be also brought into the problem.

Melo, Nickel, and Saldanha-da-Gama (2011) conducted a multi-period logistics network redesign work. The authors formulated the problem which allowed facility relocation in several periods. Therefore, they identified fixed cost of closing facility in each period and proposed two phases of solving approach. In order to reduce computation time, the first phase of linear rounding strategy aimed to round fractional location decision variable. In second phase, the heuristics was used in case of infeasible solution or unsatisfactory solution from the first phase.

2.1.2 Facility Location-Routing Problem (LRP)

Standard LRP was defined by Drexl and Schneider (2015) as "*a deterministic, static, discrete, single-echelon, single-objective problem where each customer (vertex) must be visited exactly once for the delivery of goods from a facility, and where no inventory decisions are relevant*". In other words, LRP is a combination of two different managerial levels of decisions which are a facility location problem (long term decision) and a vehicle routing problem (tactical term decision). As many authors prove in their works that, making decision will lead to sub-optimal configuration for distribution networks when a facility location and a vehicle routing are separately designed (Gábor Nagy & Said Salhi, 2007; Prodhon & Prins, 2014). Application of LRP is similar to FLP, such as to design an emergency service, an ATM location & replenishment network, planet exploration (Ahn, de Weck, Geng, & Klabjan, 2012) and a general commodity distribution network. As mentioned earlier, LRP can be clustered into many problem category, depends on problem characteristics and implementing to the real cases. Most of the researchers in the past tried to develop the models in the general form of routing version, where customer 's demand was on vertex or node (Cuda, Guastaroba, & Speranza, 2015). This model is beneficial for general problem in a supply chain aspect. For instance, the study of Aksen and Altinkemer (2008) and the study of Ambrosino and Grazia Scutellà (2005). In opposition to general form, a demand of location arc routing problem is on the arc. This formulation is applicable for the distribution that the distributed items are spreading along the arc or the route of transportation, such as, city garbage collecting or mail delivery (Hashemi Doulabi & Seifi, 2013; Lopes, Plastria, Ferreira, & Santos, 2014).

Most of previous studies in LRP focus only on cost objective. The costs consider in the model of composing cost of facility, the same as traditional FLP, and also cost of routing which obtains from total distance multiplying by transportation cost per distance. Furthermore, some researchers take fixed cost of using each vehicle into consideration. Besides, converting time objective into monetary value as indicates in section 2.1.1, there are some researchers develop multi-objective models in other dimensions. For example, in multi-objective problem, the workload imbalance, transportation route in particular, is one of issue that researchers are interested in (Lin & Kwok, 2006; Martínez-Salazar, Molina, Ángel-Bello, Gómez, & Caballero, 2014). The aim is to reduce the difference between the route with longest distribution distance or biggest quantity and the route with shortest distribution distance or smallest quantity respectively.

To formulate problem, one of the issues, that researchers should concern, is a problem characteristic and a problem size as they affect to the difficulty of solving, especially for LRP which is recognized as NP-hard problem (Gábor Nagy & Said Salhi, 2007). Owing to most decision variables, such as, the decision of opening or closing of each location, route assigning for each truck, are binary variables. A number of echelon and characteristics of problems have an effect on a number of binary variables. Thus, most of researchers deal with two echelons (2E-LRP). The majority of researchers use mathematical model with three-index decision variable. First and second indexes represent facility location in two closest layers in supply chain networks, respectively. The third index refers to a transportation route or a vehicle between facility locations, (Ahn *et al*., 2012; Nguyen, Prins, & Prodhon, 2012). The original formulation of LRP as following mathematical model.

Where z_i= 1 if facility i is opened, 0 otherwise;

y_{ij} = 1 if facility i is assigned to serve customer j, 0 otherwise;

x_{ijk} = 1 if vehicle (transportation route) k travel through arc i-j, 0 otherwise;

c_j is fixed cost of opening facility i;

v_i is variable cost of facility i;

q_j is a demand of customer j;

d_{ij} is a distance cost of arc i-j;

h_k is capacity of vehicle k;

s_i is capacity of facility i;

V is a subset of arc that linked between customer vertex.

$$Min\ Z = \sum_{i\in I} c_i z_i + \sum_{i\in I} v_i \sum_{j\in J} q_j y_{ij} + \sum_{i\in I\cup J}\sum_{j\in I\cup J}\sum_{k\in K} d_{ij}x_{ijk} \tag{2.6}$$

Subject to

$$\sum_{i\in I\cup J}\sum_{k\in K} x_{ijk} = 1 \qquad \forall j \in J \tag{2.7}$$

$$\sum_{j\in I\cup J} x_{ijk} - \sum_{j\in I\cup J} x_{jik} = 0 \qquad \forall i \in I\cup J, \forall k \in K \tag{2.8}$$

$$\sum_{i\in V, j\in \bar{V}}\sum_{k\in K} x_{ijk} \geq 1 \qquad \forall (V, \bar{V}) \tag{2.9}$$

$$\sum_{j\in J}\sum_{i\in I\cup J} q_j x_{ijk} \leq h_k \qquad \forall k \in K \tag{2.10}$$

$$\sum_{i\in I}\sum_{j\in J} x_{ijk} \leq 1 \qquad \forall k \in K \tag{2.11}$$

$$-y_{ij} + \sum_{u\in I\cup J} (x_{iuk} + x_{ujk}) \leq 1 \qquad \forall i \in I, \forall j \in J, \forall k \in K \tag{2.12}$$

$$\sum_{j\in J} q_j y_{ij} \leq s_i z_i \qquad \forall i \in I \tag{2.13}$$

$$x_{ijk}, y_{ij}, z_i \in \{0,1\} \qquad \forall i \in I, \forall j \in J, \forall k \in K \tag{2.14}$$

The objective function (2.6) minimizes the total cost consisting of fixed opening costs of facility, variable costs of facility and delivery cost, respectively.

Constraints (2.7) ensure that each customer is replenished from a single route. Constraints (2.8) conservation of particular node that route travel in and out. Constraints (2.9) guarantee that each vehicle route must visit a facility. Constraints (2.10) ensure that the containing product quantity that serves each customer cannot be exceeded capacity of vehicle (or transportation route). Constraints (2.11) limit a vehicle can be operated only one route. Constraints (2.12) are used to assign each customer to a selected facility, which has a vehicle route from the facility to that customer. Constraints (2.13) are capacity constraint of facility. Finally, Constraints (2.14) are set of decision variables.

But in the study of Contardo, Hemmelmayr, and Crainic (2012), the authors tackle single-source two-echelon capacitated location-routing problem by using two-index vehicle flow with constraints of valid inequalities. This helps decision maker to solve the problems by exact method more efficiently, for only small and medium size of problems.

Moreover, Ambrosino and Grazia Scutellà (2005) extend mathematical model from Perl and Daskin (1985) which has merely single echelons and excluding inventory from consideration into 4/R/T/T problem with three echelons (four-layer), including plants, central depots, transit points and clients. Both of neighboring-layers transportation and cross-layers transportation are allowed for this case. Furthermore, this work is also expanded problem from static to dynamic decision and inventory decision is brought into the model. Then CPLEX is used for solving the problems. This research confirms that commercial solver can be only suitable for small size LRP by providing the optimal solution in a reasonable solving time. But for large & medium scale problems, solver cannot find any feasible solution in limited time.

About the constraints in LRP, normally the structure of capacitated LRP (CLRP) is combination of FLP and Vehicle Routing Problem (VRP) in both of objective function and constraints. Hence LRP model usually should respect some criteria as following;

- Each customer must be served from single vehicle route.
- Every node arrived by a vehicle must be departed by the same vehicle.
- Every vehicle route must start and end at the same facility.

- Every vehicle route cannot connect multiple facilities.
- Satisfied demand in particular route cannot exceed vehicle capacity.
- Flow through particular facility cannot exceed facility capacity.
- Flow in at every facility must be equal to the flow out (conservation of flow).

Some researchers extend the CLRP by adding the constraint of minimum of flow or minimum of production quantity, required from facility for opening the operation into the model. This can also be found in FLP, for example, Melo *et al*. (2011). However, in LRP, there are additional constraints, such as, consideration of minimum allowed vehicle capacity to avoid less than truck load with max allowed distance for each route, for instance, the study of Kchaou Boujelben, Gicquel, and Minoux (2014). Unfortunately, after adding those constraints, the problem becomes tighter, then, the feasible region cannot be attained. Therefore, they transform constraints into penalty cost, in case that the truck loading is lower than minimum capacity. There are two ways to identify penalty cost, first is identify by huge value. Another one is opportunity to save cost per unit from full truck load. It is found that the latter penalty cost can give optimal solution in shorter calculation time.

In static LRP, LRP is the problem which combining two distinct planning management levels; strategic and tactical level as mention before. Note that strategic location planning period is always longer than distribution network planning period (Gábor Nagy & Said Salhi, 2007). After facilities are performed, companies usually have used them for a long time even through nowadays facilities are more frequently relocated or re-opened the new ones by constructing or renting from third party (Segura, Carmona-Benitez, & Lozano, 2014). However, distribution route can always be changed over a shorter planning time bucket as the result of customer demands uncertainty. Hence the researchers develop a dynamic LRP to rectify disadvantages of static LRP which there are two categories; (1) multi-period LRP and (2) periodic LRP. For multi-period LRP, Location decision, decision makers can choose either proper facility locations at the beginning of planning time horizon or allowing facility locations can always be changed over planning horizon which aligns with realistic case studies.

In route decision, vehicle route to particular customer must be designed every planning time buckets. Conversely, periodic LRP, distribution route to each customer is generated by visiting pattern which is gathered information from solving model or predefining by problem characteristics (Hemmelmayr, 2015). Consequently, there are route to visit each customer in some periods.

For example, Prodhon (2011) proposed mixed integer programming in periodic LRP. To response customer demands in particular time period, assignment of customer to service day variables and constraints are merged to general LRP model to define optimal visiting pattern and proper route. For facility problem, single-source assumption and opening facility at beginning of planning period are applied to model. Due to complex and size of problem, only small test problem can be solved by commercial solver. In the sense of large scale problem, hybrid evolutionary local search based on the randomized Extended Clarke and Wright algorithm is applied to solve this problem which provides better performances comparing to previous approaches.

For special formulation of multi-period LRP, Albareda-Sambola, Fernández, and Nickel (2012) work on a multi-period uncapacitated LRP with decoupled time scales of facility location and vehicle routing planning periods. The set of location decision time periods is prespecified for designing opening pattern as well as distribution network is allowed to redesign only specified periods. Formulating problem, facility capacity constraints have been not considered but they are replaced by maximum number of open facility constraints. To solve this complex problem to optimality, assigning constraints is relaxed and then problem is reformulated to rooted forests problem. Note that approximation method is proposed to find the routes in each period. To find proper facility location, solutions of rooted forest problem are used in original problem which is solved period by period. The result indicates that approximation method can provide quality solutions.

2.1.3 Facility Location-Routing-Inventory Problem (ILRP)

One of most importance extended LRP is to combine inventory aspects. In order to apply inventory policy, (Q, r) policy is frequently used in LRP/FLP with inventory policy problem. *Q* stands for replenishment quantity which is typically identified by economic of quantity (EOQ) equation. *r* refers to reorder point, depended on the number of products used in lead time period and safety stock level. However, these problems are insufficient because they are very hard to solve optimally, due to non-linear formulation form when economic of replenishment quantity functions are added into model (Ahmadi Javid & Azad, 2010). Sometimes, an inventory aspect in LRP/FLP is concerned only storage and ordering cost without policy. In this kind of problem, it is easier to solve (Sadjady & Davoudpour, 2012). Nevertheless, FLP/LRP with inventory policy can contribute more information, for example; the optimal safety stock and the frequency to replenish with optimal quantity to align with companies setting (Ahmadi Javid & Azad, 2010).

For instance, Shahabi, Unnikrishnan, Jafari-Shirazi, and Boyles (2014) formulate the multi-echelon facility location-inventory problem by a binary nonlinear integer program. Then, they reconstruct the model to a *Mixed Integer Conic Quadratic Program* (MICQP) and apply the outer approximation for efficient solving. Certainly, MICQP provides better quality solution with zero gap to optimal solution and faster than directly solving original problem.

Furthermore, Nekooghadirli, Tavakkoli-Moghaddam, Ghezavati, and Javanmard (2014) present the model of location-routing-inventory problem which contains two objective functions. First objective is to minimize the cost of distribution and the cost of storage. Another one is to minimize maximum distribution time, i.e. minimax distribution time. This model can be better applied on a real case, for instance, to deliver perishable goods to a final destination in a shorter time, to return a truck back to distribution center within a period of time specified or to prevent violation of regulation of continue driving. Also, distribution time can be represented as distribution length.

2.2 Solving Techniques

FLP, LRP and ILRP have been recognized to be a NP-hard problem as mention before. To solve this class of the problem, many various solving approach are proposed to find optimal solution in reasonable computation time. Due to structure of all three mathematical models, FLP FRP and IFRP, have some relationship. Hence some algorithms can be applied efficiently to solve them. As well, particular problem can be decomposed into many sub-problems which can be solved separately easier.

2.2.1 Decomposition Approach

In iterative and sequential manner, the problem will be decomposed to many sub-problems based on problem characteristics and then efficient technique are applied to solve them sequentially. The solution from first sub-problem is used for finding the answer of second sub-problem and so on (Gábor Nagy & Saïd Salhi, 2007). In attempt to find the solution in particular iteration, a number of authors present different approach or techniques to tackle them, based on type and size of decomposed problems. The main concept of iterative heuristics is that solutions should be feasible to original problem in all replications. Otherwise, fixing procedure is required (Kchaou Boujelben *et al*., 2014; Sadjady & Davoudpour, 2012).

For instance, Perl and Daskin (1985) proposed iterative heuristic by breaking down original warehouse location-routing problem (single-echelon LRP) to three sub-problems, including the 1st multi-depot vehicle dispatch problem, the 2nd warehouse location-allocation problem and the 3rd multi-depot routing allocation problem. The first problem is solved by saving heuristic method to locate warehouse and assembly a route from warehouse to set of customers simultaneously. For the 2nd problem, the warehouse in solution from the first problem is removed and then the new route with linkage among customers is taken into the 2nd problem. Implicit enumeration algorithm is employed for this phase to solve problem to optimum. Finally, the 3rd problem is applied the alike method as the 1st problem to find improved solution. To test this algorithm, realistic data is used for evaluation. The results show that proposed iterative algorithm can provide a better solution than current method and having the best existing configuration.

Furthermore, due to a large number of binary decision variables, a linear relaxation method is one of the efficient techniques to reduce complexity of problems by relaxing binary variable to be linear variable. Sometimes, a linear programming can be solved by commercial solver like CPLEX and Lingo and the result can give a lower bound for master problem (Thanh, Péton, & Bostel, 2010). In order to enhance the performance of linear relaxation method, valid inequalities constraint is added into a model to help the solution value of relaxation decision, variable close to 0 or 1. For example, Thanh *et al*. (2010) perform linear relaxation with rounding procedure to solve mixed integer linear programming of logistics network, designed in multiple products and multiple planning periods. Additional, two valid inequalities constraints are employed. Thanh *et al.* (2010) propose three steps to round fractional variable to 0-1 value. Step 1; a linear relaxation problem (LP) is solved and rounds all variables which value is greater/lower than specified rounding factor and solves iteratively until none fractional variable. Step 2; if the number of rounding variable is not good enough, some fractional variable will be rounded by using new set of rounding factor. Finally in step 3, a modified original problem is solved with some fixed integer variables and less free binary integer variable. Moreover, if the problem is infeasible during solving LP and original problem, correction procedure will relax some integer variable to be linear again. This heuristic is evaluated by comparing objective value and calculation time to MILP solver. The result indicates that LP-rounding solution can provide near optimal solution with maximum 3.8% gap for all instances and faster than MILP solver. In addition, Gendron and Semet (2009) indicate that *"LP relaxation of the path-based model provides a better bound than the LP relaxation of the arc-based model"* for multi-echelon FLP.

Next, Lagrangian Relaxation (LR) is efficient technique which was extensively utilized in various problem including FLP and LRP (Mohammad Nezhad, Manzour, & Salhi, 2013). The main idea of this approach is to relax some constraints and add them to objective function as penalty cost in case of a minimization problem. To solve the problem, Lagrangian multiplier should be iteratively updated by specified method, such as subgradient optimization. Generally, Solution from LR problem can solve easier and provide a lower bound for master problem while an upper bound of master problem can retrieve some information from a LR problem and to solve original problem by some efficient approach.

In capacitated FLP, constraints containing location variables and allocation variables are named a bundle of constraints. Due to complexity of this kind of constraint, it is very hard to tackle. Hence, a bundle of constraints should be removed (example see Mohammad Nezhad *et al.* (2013)). In multi-echelon FLP, many authors determine conservation of flow as a bundle of constraint (example see (Tragantalerngsak, Holt, & Ro¨nnqvist, 1997)). Furthermore, Lagrangian Relaxation of FLP, LRP and ILRP can be separated and reformulate to many kinds of problems, such as knapsack problems which can be solved by commercial solver or competent heuristic, like Eskigun *et al.* (2005) solved knapsack problem which decomposed from Lagrangian relaxed problem by greedy algorithm.

Sadjady and Davoudpour (2012) applied Lagrangian Relaxation to two-echelon, multi-commodity supply chain network design. The allocation constraint (retailer to warehouse) and conservations of flow constraints (linkage particular echelon) are relaxed and decomposes the problem to the 1st and the 2nd echelon location-allocation sub-problem (LR1 and LR2 respectively). Similar to the most decomposition techniques, the objective value of Lagrangian relaxation problem (Z_p) is equal to $Z_{LR1} + Z_{LR2}$ - *summation of Lagrangian multiplier*. Both of LR1 and LR2 problems can be derived into new hierarchical sub-problem again, based on number of candidate location sites, and solve them separately. In this research, Lagrangian multiplier is updated by using set of equation based on a gap of two previous iterations. Terminating criteria is a number of iteration and %gap between upper and lower bound. These algorithms provide a good quality of solution which compare to optimal solution from LINGO with less calculation time.

Mohammad Nezhad *et al.* (2013) apply Lagrangian Relaxation to solve uncapacitated single-source facility location problem. Two different kinds of LR heuristics are developed in this research. Both of them use the similar algorithms, the main different of these heuristics is that canonical cut is applied to improve first heuristic. Starting from bundle constraints which contain two kinds of integer decision variables are relaxed and then the problem is separated into two sub-problems based on set of decision variables. Lower bound is identified by solving both LR sub problem and upper bound can be generated by solving original problem by applying feasible solution from LR phase as shown in figure 2.1.

Lagrangian multipliers are also updated by Subgradient optimization. Moreover, to enhance the upper bound of original problem, they improve three local search techniques including of (1) swap an open facility with closed one (2) exchange product type between two open facilities and (3) add new closed facility. From numerical test results indicate that both LR heuristics provide good enough solution and can be guideline for finding optimal solution, but canonical cut cannot always provide efficient for all test instances.

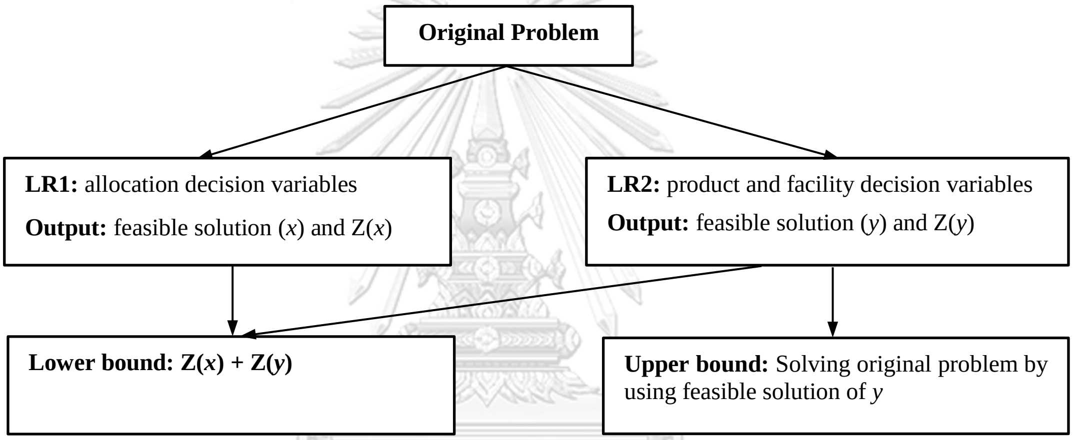


Figure 2.1 LR heuristics proposed by Mohammad Nezhad *et al.* (2013)

In general, LRP and ILRP, a structure of model typically combines a set of objective functions and constraints from *Facility Location Assignment Problem* (FLAP)*, Multi-depot Vehicle Routing Problem* (MDVRP) and connecting constraints. And constraints which contain location and arc variables are named a bundle of constraints. As well, LR can be applied to decompose the huge problem to smaller many sub-problems as shown in figure 2.2.

From figure 2.2, Aksen and Altinkemer (2008) study a location routing problem by applying Lagrangian based solution approach to solve “click and mortar” case study. The model is two- echelon with comprising of warehouse store and customer. The structure of this problem is classified objective function and constraints into three parts including of (1) pure FLAP (2) pure MDVRP and (3) FLAP and MDVRP bundle constraints. The LR based heuristic decomposed problem into two sub-problems by relaxing FLAP and MDVRP bundle constraint. Furthermore, subtour elimination, capacity and time deadline constraints in sub-problem MDVRP are relaxed again. Both of LR multiplier problems are solved by using subgradient optimization. However, the results of test random instances indicate that the solving approach take a long computation time in case of large scale problems.

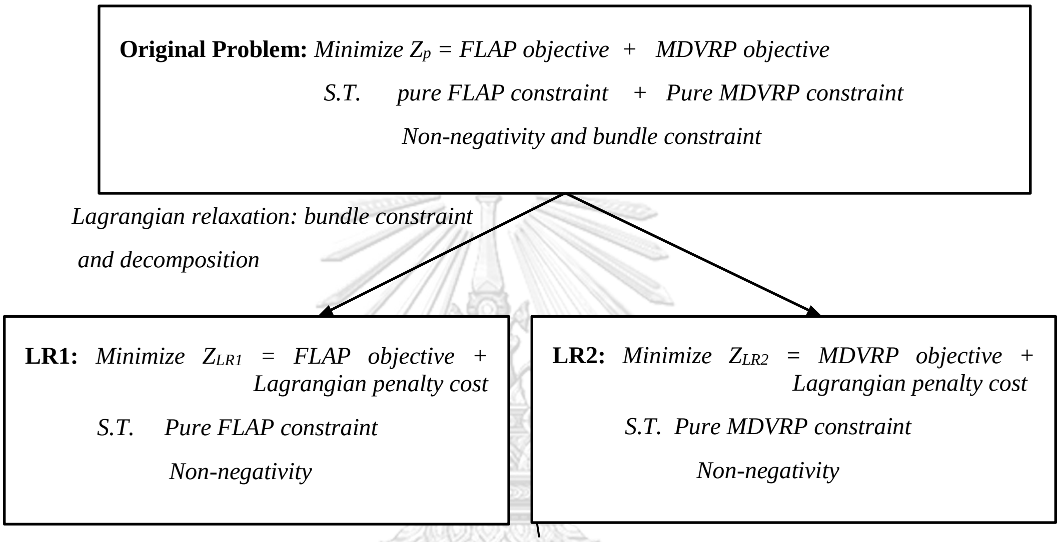


Figure 2.2 Lagrangian Relaxation concept
modified from Aksen and Altinkemer (2008)

Prins, Prodhon, Ruiz, Soriano, and Calvo (2007) studied in solving capacitated LRP by combining two efficient heuristics; LR and granular Tabu search heuristic. In FLAP solving phase, single assignment constraints (assign customers to a depot) are relaxed to grant more efficient computation according to Beasley (1993) suggestion. Note that relaxation FLAP is decomposed to be set of knapsack problems while classical dynamic programming algorithm is employed to solve them. Furthermore, the routing phase, granular Tabu search is applied to solve multi-depot vehicle routing problem (MDVP) sequentially. Due to proposed iterative manner, solution from routing phase is used for reducing original LRP size and transforming the problem to be FLAP by combining customers in each route to create a super-customer node. However, the new route after insert new depot assembly by connecting two nearest two customers and depot for lowest insertion cost in FLAP phase. The result indicates that proposed method in this paper can tackle large scale instance with better performance than basic Tabu search heuristic.

2.2.2 Clustering Based Approach

Typically, LRP combines a huge set of binary integer and constraints from vehicle routing problem that let the model harder to solve (for instance see Ambrosino and Grazia Scutellà (2005); Nguyen *et al.* (2012); Wang *et al*. (2017)). Clustering algorithm is sequence-based method which helps to reduce the number of decision variables, related to customer vertex as well as the number of vehicle routing constraints in original problem by assembly distribution routes. Solving algorithms start from dividing customers' demand vertex into related groups and then designing delivery route for each cluster (Gábor Nagy & Saïd Salhi, 2007). In clustering step, a member of each cluster is defined by closeness among customers and vehicle capacity. Basically, closeness distance in research literatures is formed on Euclidean distance with several proximity measures. Barreto, Ferreira, Paixão, and Santos (2007) refer to six proximity measures as following;

(1) *Single linkage*; the distance between two customer's groups is identified by shortest distance between two customers from both groups.

(2) *Complete Linkage*; distance between two customer's groups is identified by longest distance between two customers from both groups.

(3) *Group average*; distance of two groups is calculated by average distance among customers.

(4) *Centroid*; distance of among customer groups equal to distance between centers of gravity. Center of gravity is an average coordinates x and y of member in each group.

(5) *Ward*; ward distance equal to sum square of distance between centers of gravity and weighted by number of members in both clusters.

(6) *Saving*; saving is a minimized distance after combining member of two clusters calculated by assembly the route between four closest customers from both groups.

Also, four clustering techniques are proposed in this work. Matching between proximity measures and various clustering techniques show no outstanding pair in term of performance to create optimal route. Hence, Barreto *et al.* (2007) suggest that proposed new heuristics should evaluate with some proximity measures before using them.

To decide a cluster, there are actually two different clustering algorithms; the first one is to develop mathematical model (for instance; set-partition problem) and the second one is to design exclusive heuristic algorithm. Despite, the result from set-partition problem can also use to evaluate quality of heuristic algorithms as shown in Kchaou Boujelben *et al.* (2014)

In subsequence step, to decide a route and an allocate serving facility, Gábor Nagy and Saïd Salhi (2007) classified two distinctive methodologies as shown below;

(1) Location first and routing second; in each group of customers, location of serving facility will be given first and then assembly route by solving vehicle routing problem, traveling salesman problem or spanning tree problem (see example Bruns and Klose (1997); (Miranda-Bront *et al.*, 2017).

(2) Routing first and location second; assembly route for each group of customers by solving vehicle routing problem, traveling salesman problem or spanning tree problem and then allocate serving facility to them (see example Kchaou Boujelben *et al.* (2014); (Kwankaew & Paveena, 2014); Lin and Kwok (2006)).

For instance of recent research in this fields, Kchaou Boujelben *et al.* (2014) applied mixed integer programming (MIP) for LRP comprising of minimum volume constraints as mention before. In solving step, customers are clustered to particular group depended on distance among customers and capacity of vehicle. Next step, optimal route is specified by traveling salesman problem. Finally, particular group of customers is allocated to open DCs by solving the modified original problem. Due to large-scale MIP, partial linear relaxation technique and removing some constraint strategy are applied and solved the problem by a sequence-based heuristic (location-first allocation-second). In addition, three algorithms to reintroduction of removing constrains are proposed including of (1) reintroduction all constraints (2) reintroduction

2nd and 1st level transportation constraints respectively and (3) fixing strategy. The result indicates that the clustering method with proposed heuristic can provide a good quality solution for a realistic case study which has large-scale problem in reasonable computation time.

Lin and Kwok (2006) proposed clustering-based metaheuristic to solve multi-objective LRP. The proposed approach combines a three-phased method. The first phase is a location phase, the minimum number of required facility was identified by the ratio of total demand to facility capacity, then sorted by the lowest distance to customer nodes. Greedy method was applied in order to select the set of facilities. In the second phase, they constructed the routes by various version of saving algorithm and the nearest neighbor rule. Then improved them by insert and swap the move algorithms. In final phase, the routes were assigned to the vehicle of each facility by taking this problem as a bin packing problem.

Zare Mehrjerdi and Nadizadeh (2013) proposed the hybrid heuristic (greedy method and *Ant Colony Optimization* (ACO)) to solve the fuzzy demands of capacitated location-routing problem. They applied greedy algorithm to cluster customers and constructed routes by solving *Traveling Salesman Problem* (TSP) with ACO.

In case of getting stuck in local optimum, the additional improvement stage will be a good choice to enhance initial solution as Ambrosino, Sciomachen, and Scutellà (2009) do. In this research, an initial solution is solved by a capacitated concentrator location problem to identify location and fleet assignment, after that solving traveling salesman problem to assembly route. In improvement stage, the multi-exchange, classical move and based local searching heuristic is proposed. In Nadizadeh and Hosseini Nasab (2014) initiate solution by applying greedy based algorithm to cluster customers which depends on customers' demand and vehicles' capacities. In allocation step, depots are ranked by their capacities and fixed opening cost equation. Then, the customer clusters are ranked and based on Euclidean distance of gravity center to a top ranked depot and an allocate group of customers until depot capacity is insufficient. Furthermore, Ant colony method is used for solving TSP to specify a routing in each cluster. In order to improve initial solution, a local search method is proposed to replace a proper new depot to pre-defined route.

2.3 Defining research gaps

For this research, general capacitated LRP structure is used for formulating a model to design distribution network and locates the facilities where the traditional costs of operating facility and transportation costs might be employed in the objective function. For constraints, the model involves general constraint of LRP as mention before. However, from literature review, LRP and FLP proposed by most researchers seems usually involve two or three-layer in a supply chain manner as shown in table 2.1, except Ambrosino and Grazia Scutellà (2005) who proposed four-layer distribution network problem. This research concerns designing distribution network from plant via central depot and regional depot to end customer with only single commodity. Due to size of the problem, the easy methods or commercial solver cannot use to solve these large-scale problems efficiently while Ambrosino and Grazia Scutellà (2005) did not develop a new solving approach for solving them. Hence proposed model in our research not only involve four layers comprise of central depot, warehouse, retailer/service center and end customer but also tackle with multi-commodity distribution network. Consequently, model should be suit for realistic case study and provide a quality solution which can be easier to implement.

Besides, there was insufficient information on the study of multi-commodity and product family on distribution network design. Most of multi-commodity problems can be found in FLP such as Sadjady and Davoudpour (2012), Mohammad Nezhad *et al*. (2013), Correia *et al*. (2013) and *etc*. Nonetheless, LRP can be found in Kchaou Boujelben *et al*. (2014) and Nekooghadirli *et al*. (2014) studies. Kchaou Boujelben *et al*. (2014) study multi-commodity problem which their case study is car types. While Nekooghadirli *et al*. (2014) did not specify product type in their study (general commodities). Comparing to this research, proposed delivery items cover finished goods and maintenance parts which generally use divergent distribution network. To fill this gap, distribution network is simultaneously designed for enhancing facility utilization and combining two distinct delivery routes for both commodities and parts. These are main advantage of proposed model.

To solve the three-echelon multi-commodity LRP, proposed solution approach will be develop based on clustering-based approach. Due to past researches, many researchers have tried to solve problem by applying hybrid approach for example Lagrangian Relaxation and Tabu search. The meta-heuristics have been proven that they can tackle with a very large-scale problem by providing quality solution in reasonable computation time. However, it is doubtful that if a simple hybrid heuristic, which is easier to code the program, can be solved the problem like a meta-heuristic. Moreover, in limitation of the reviewing papers, there is no research paper, which is combined clustering technique and decomposition method to solve this class of the problem.

Typically, the size of LRPs depends on their vehicle routing problem constraints, especially, the subtour elimination constraints. If the model is decomposed based on its structure and echelon, the size of problem will be smaller significantly and let model can be solved separately and easily. For the other decomposition methods such as Lagrangian Relaxation technique, there are more step that can make the problem harder to solve. If the proposed hybrid heuristic combined decomposition and clustering technique is performed, the problem will be small enough to solve by applying exact method to optimality without requiring more unnecessary step as Lagrangian Relaxation method. Unless the problem is small enough, the Lagrangian Relaxation method could be the best choice to apply instead of simple decomposition method.

To solve MDVRP subproblem, the clustering-based technique is one of the efficient methods. The benefit of clustering-first route-second clustering technique is to reduce the search solution space in identifying member of each transportation route process. Moreover, the Traveling Salesman Problems route can be used instead of Vehicle Routing Problem route. Although the algorithm of the clustering-first route-second clustering is more complicated than the others, this solution method is able to provide an efficient initial result in reasonable computation time.

To fill these gaps as mentioned before, this study develops the new solution method to solve three-echelon multi-commodity LRP.

Table 2.1 Literature review on FLP, LRP and ILRP to illustrate research gap

Author	Problem	Objective	Layer	Location	Routing	Inventory	Planning Horizon	Commodity	Solving Technique
Perl and Daskin (1985)	LRP	Cost	WH – Retailer	WHs (capacity)	Routing (capacity)	None	Single	Single	Decomposition based and saving heuristics
Melkote and Daskin (2001)	Uncapaci-tated FLP	Cost	Original - Destination	Originals (un-capacity)	None	None	Single	Multiple	Solver, dual simplex, LP Relaxation
Melachrinoudis and Min (2000)	FLP Redesign	Cost, Time and Incentive score	Supplier - Plant - WH - Retailer	Plant and WH (capacity)	None	None	Multiple	Multiple	Solver (Lingo)
Ambrosino and Grazia Scutellà (2005)	LRP + ILRP (4/R/T/T)	Cost	Plant - CD - RD - Customer	CD and RD (capacity)	Routing (capacity)	Safety stock level	Single and Multiple	Single	CPLEX
(Lin & Kwok, 2006)	1E-LRP	Cost and workload imbalance	WH - Customer	Customer	Routing	None	Single	Single	Clustering technique, Tabu search and Simulated Annealing
Barreto *et al.* (2007)	LRP	Cost	WH - Customer	WH (capacity)	Routing (capacity)	None	Single	Single	4 clustering techniques and 6 proximity measures
Melachrinoudis and Min (2007)	FLP Redesign	Relocation costs and cost savings	Plant - WH - Retailer	WH (capacity)	None	None	Single	Single	Solver (Lingo)
Aksen and Altinkemer (2008)	LRP (3/R/T)	Cost	WH - Store - Customer	Store location and type (Un-capacity)	Routing (capacity)	None	Single	Single	Lagrangian relaxation (LR) method with a subgradient optimization
Ahmadi Javid and Azad (2010)	ILRP	Cost	WH - Customer	WH	Routing	(Q,r) policy	Single	Single	SA +Tabu search
Thanh *et al.* (2010)	Logistics network design	Cost	Supplier - Plant - WH - Customer	Supplier and plant (capacity)	None	None	Multiple	Multiple	SA+Tabu Search (Determine location and then identify routing
Prodhon (2011)	Periodic LRP	Cost	Depot - Customer	Depot (capacity)	Routing (capacity)	None	Multiple (Deterministic)	Single	Evolutionary algorithms

Table 2.1 Literature review on FLP, LRP and ILRP to illustrate research gap (Continue)

Author	Problem	Objective	Layer	Location	Routing	Inventory	Planning Horizon	Commodity	Solving Technique
Melo *et al.* (2011)	Logistics network redesign	Relocation costs	Facilities - Customer	Facilities	None	Inventory level	Multiple	Multiple	Rounding technique and Local search
Nguyen *et al.* (2012)	2-E LRP (3/T/T)	Cost	Depot - Satellite - Customer	Satellite (Capacity)	Routing (capacity)	None	Single	Single	A multi-start iterated local search + Tabu list
Sadjady and Davoudpour (2012)	Logistics network design	Cost	Plant - WH - Retailer	Plant and WH (Capacity)	selecting transportation modes	only cost	Single	Multiple	Lagrangian relaxation heuristic
Correia *et al.* (2013)	FLP	Max. profit and min. cost	Upper - intermediate - customer	Location and area size for each product family	None	None	Multiple (Deterministic)	Multiple	Apply valid inequalities to improve mathematical model and solving by CPLEX
Guerrero, Prodhon, Velasco, and Amaya (2013)	ILRP	Cost	Plant - Depot - Retailer	Depot (capacity)	Routing (capacity)	Inventory level	Multiple (Deterministic)	Single	Metaheuristics (valid inequalities theory Randomized routing heuristic)
Mohammad Nezhad *et al.* (2013)	Incapacitated FLP	Cost	Facility - customer	Facility (Incapacity)	None	None	Single	Multiple	Lagrangian relaxation, canonical cut and Local search
Sarkar and Majumder (2013)	FLP	Cost	Plant - WH - Retailer	Plants and WHs (capacity)	None	None	Single	Multiple	Lingo
Kchaou Boujelben *et al.* (2014)	LRP (3/R/T)	Cost	Assembly plant - DC - Car Dealer	Plants, DCs, (capacity and Min Vol.)	Routing (capacity and Min Vol.)	None	Single	Multiple	Clustering algorithms and 2 phase solving heuristic; using 3 constraint relaxation
Nekooghadirli *et al.* (2014)	ILRP (2/T)	Cost / Balance load time	DC - Customer	DCs (capacity level determination)	With capacity, maximum time and Stochastic	(Q,r) policy	Multiple (stochastic demand)	Multiple	Separate into two models solved by meta-heuristic algorithms
Zare Mehrjerdi and Nadizadeh (2013)	1-E LRP (2/T)	Cost / additional distances	Depot - Customer	Depot (capacity)	Routing (capacity)	None	Single	Single	Greedy clustering algorithm and Ant Colony method
This research	**LRP (4/R/T/T)**	**Cost and Closing Cost**	**Depot - WH - Retailer/Service Center - Customer**	**WH, Service Center (capacity)**	**Routing (No. of drop point)**	None	**Single**	**Multiple**	**Clustering algorithm and decomposition method**

CHAPTER 3
METHODOLOGY

The first section of this chapter is research methodology that applied in this research. Following the research methodology, the problem and assumptions of the model, which apply for formulating the mathematical model, are stated. The third section indicates development of mathematical model for three-echelon multi-commodity LRP based on three-index mixed integer linear program. Moreover, this section explains objective function and constraints in this section. The final section in this chapter is data preparation that use in particular problem.

3.1 Research Methodology

The methodology in this research starts from literature review in relevant topics including FLP, LRP, ILRP, solving approach, *etc*. Then the statement of problem is described in order to formulate model. After data is collected, then the model is solved by 2 methods. First method is optimizing by using commercial solver, i.e., CPLEX. Another method is using heuristics approach. After heuristics approach is developed, then the data is solved by the proposed heuristics algorithm. After obtaining the solutions from both methods, the result will be compared for both of quality of answer and computation time. Finally, the sensitivity analysis will be done. In sensitivity analysis, some parameters are varied to simulate what if some situation is changed. Finally, bringing other parameters other than in model, which could have effect on the solutions are studied in simulation part. The research methodology is presented in Figure 3.1.

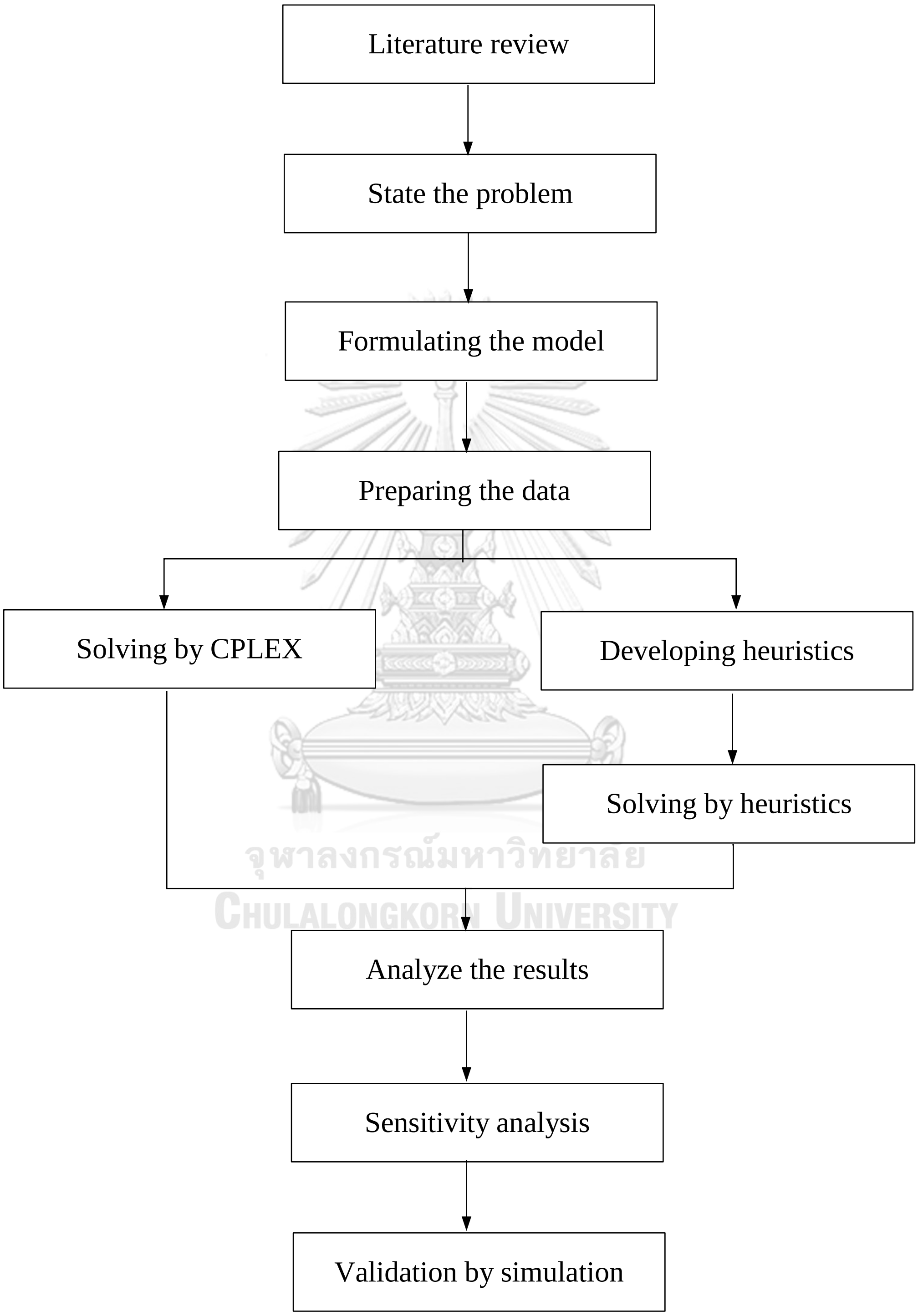


Figure 3.1 Research methodology framework

3.2 Problem Statement

As mentioned in Chapter 1, case study in this research is an electronics company in Thailand that produces and distributes two product families, which are electrical products and service parts. The company classifies products into 2 families; home electrical products and shop products (products used in retailers, such as, food shop-window refrigerators, vending machines, etc.). There are approximately 85 SKUs of products. The service parts are spare parts for maintenance purposes, which there are approximately 300 SKUs as shown in Figure 3.2.

The company currently distributes each home product through its network to satisfy demands at retailers as illustrated in Figure 3.3. For both of shop products and service parts, the maintenance technicians must bring these items to particular customer for on-site service purposes in layer 3. To redesign of distribution network for this case study, this research classifies the products and parts into two commodities based on their destination consisting of product items and service items as shown in Figure 3.2. That can reduce complexity of mathematical formulation.

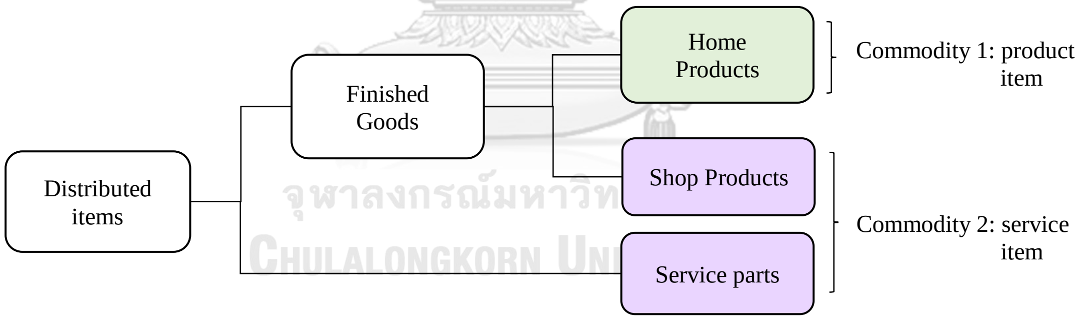


Figure 3.2 Distributed item classification

Furthermore, Figure 3.3 illustrates that there are three layers of facilities and one layer of customer in the distribution network, including of a single depot, the set of warehouses, the set of retailers (plus retailers with a service center) and customers, respectively. There are three-echelon of transport route that links between two adjacent layers. For the 1st echelon, company performs a return route that truck transfers cargos directly from the depot to individual warehouse. For the 2nd echelon, the truck circulates cargos by milk run distribution to each retailer. For the 3rd echelon, the service of each round is a tour transportation, starting from service center to visit customer sites. Based on coding principle of Laporte (1988) mentioned by Ambrosino and Grazia Scutellà (2005), this study denote the problem as 4/R/T/T. Number 4 refers to a number of layers. R stands for replenishment trip and T stands for a tour trip.

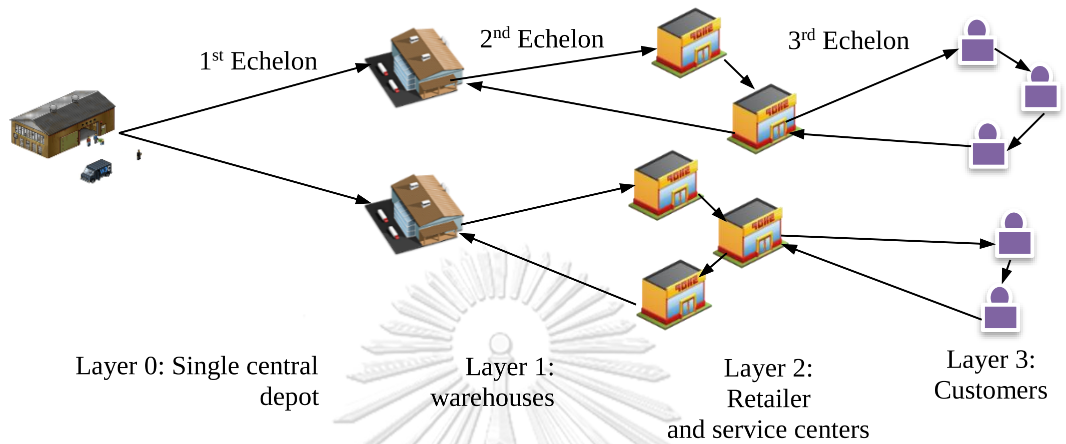


Figure 3.3 Three-echelon distribution network

This research formulates the location routing problem by developing mixed integer linear to identify simultaneously solutions of three main problems;

- Which warehouses and service centers should be operated/closed?
- Which warehouse fill up demand for particular retailers/service centers and which service center supports end customers?
- How to distribute each product/part through distribution network?

Other characteristics of this research problem and assumptions can be described below;

- Depot plays role as source of supply node which can provide all of products and parts.
- Only location of warehouse and service center are allowed to decide to be operated or closed.
- Candidate locations of a warehouse are discrete and finite number including existing locations and new candidate locations identified by company.

- Candidate locations of a service center are discrete and finite number, which can be identified from locations of retailer site.
- Demand of a retailer and each on-site service customer are deterministic and locate on each vertex.
- This research concerns a single planning horizon along with deterministic environment.
- Single-sourcing strategy is considered, which allows a retailer and an end customer to be served from single closest layer facility.
- Each route must start and end at the same facility location.
- Standard volume is given to convert demand quantity and facility capacity.
- Limit number of drop point per transportation route is used instead of vehicle capacity and distance.
- Model is formulated for a period of one year. Therefore, demand, capacity, costs are annual unit.

3.3 Mathematical Model

The notation, parameter and variable used in mathematical model are shown below;

The index, parameter and variable used in mathematical model are shown below;

Index

I: set of warehouse locations (candidate and existing location), indexed by i.

I_1: set of existing warehouse locations, indexed by i.

J: set of retailers to open service centers (candidate and existing location), indexed by j.

J_1: set of existing retailers with service centers, indexed by j.

E: set of service customers, indexed by e.

$K, K1, K2$: set of routes, $K1, K2$ for 2nd and 3rd echelon distribution respectively, indexed by k.

<u>Parameters</u>

α_i: operating cost of warehouse on potential location *i*.

β_j: operating cost of service center on retailer *j*.

γ_i: cost/saving of closing existing warehouse on location *i*.

δ_j: cost/saving of closing existing service center on retailer *j*.

η_i, λ_i: variable cost of warehouse *i* for product/service part respectively.

μ_j: variable cost of service center *j*.

φ_i: fixed and distance cost from depot to warehouse *i*.

σ_k: fixed cost of route *k*.

τ_{ij}, τ_{je}: distance cost in arc *i-j* and *j-e* respectively.

d_j, q_e: demand of product/service part on retailer *j*, customer *e* respectively.

N_1, N_2: limit of number of drop point in level 2nd and 3rd echelons respectively.

θ_i: capacity of warehouse which is operated on location *i*.

ω_j: capacity of service center which is operated on retailer *j*.

M: big value.

<u>Binary decision variables</u>

x_{ijk}, y_{jek} = 1 if arc operated by route *k*, 0 otherwise for 2nd, 3rd echelon respectively.

h_k = 1 if route k is used, 0 otherwise.

w_i = 1 if warehouse *i* is operated, 0 otherwise.

s_j = 1 if service center is operated on retailer *j*, 0 otherwise.

z_{ij} = 1 if customer j is allocated to warehouse *i*, 0 otherwise.

z_{je} = 1 if customer e is allocated to service center on retailer *j*, 0 otherwise.

z_{ic}, z_{jc} = 1 if cluster c is allocated to warehouse *i* /service center on retailer *j*, 0 otherwise.

<u>Continuous decision variables</u>

f_i, g_i: flow of products/service item transfers from central depot to warehouse *i*.

r_{ij}: flow of service item transfers from warehouse *i* to service center on retailer *j*.

This study developed mixed integer linear programming of LRP by applying node-arc formulation that defined as a directed graph *G= (V, A)*. Set of nodes (V) involve node of warehouse (*I*), node of retailers and service centers (*J*) and node of service customers (*E*). A is the set of arcs. Hence, proposed model is modified and extended from Perl and Daskin (1985) and Nguyen *et al.* (2012) as shown below;

$$\begin{aligned} Min\ Z = & \sum_{i\in I}\alpha_i w_i + \sum_{j\in J}\beta_j s_j + \sum_{i\in I_1}\gamma_i(1-w_i) + \sum_{j\in J_1}\delta_j(1-s_j) + \sum_{i\in I}\eta_i f_i \\ & + \sum_{i\in I}\lambda_i g_i + \sum_{i\in I}\sum_{j\in J}\mu_j r_{ij} + \sum_{i\in I}\varphi_i w_i + \sum_{k\in K}\sigma_k h_k \\ & + \sum_{i\in I\cup J}\sum_{j\in I\cup J}\sum_{k\in K_1}\tau_{ij}x_{ijk} + \sum_{j\in J\cup E}\sum_{e\in J\cup E}\sum_{k\in K_2}\tau_{je}y_{ijk} \end{aligned} \tag{3.1}$$

Subject to

$$\sum_{i\in I\cup J}\sum_{k\in K_1} x_{ijk} = 1 \qquad \forall j\in J \tag{3.2}$$

$$\sum_{j\in I\cup J} x_{ijk} - \sum_{j\in I\cup J} x_{jik} = 0 \qquad \forall i\in I\cup J, \forall k\in K_1 \tag{3.3}$$

$$\sum_{i\in S, j\in S} x_{ijk} \le |S|-1 \qquad S\subseteq J, |S|\ge 2, \forall k\in K_1 \tag{3.4}$$

$$\sum_{j\in J}\sum_{i\in I\cup J} x_{jik} \le N_1 \qquad \forall k\in K_1 \tag{3.5}$$

$$\sum_{i\in I}\sum_{j\in J} x_{ijk} \le h_k \qquad \forall k\in K_1 \tag{3.6}$$

$$-z_{ij} + \sum_{u\in I\cup J}(x_{iuk} + x_{ujk}) \le 1 \qquad \forall i\in I, \forall j\in J, \forall k\in K_1 \tag{3.7}$$

$$f_i - \sum_{j\in J} d_j z_{ij} = 0 \qquad \forall i\in I \tag{3.8}$$

$$g_i - \sum_{j\in J} r_{ij} = 0 \qquad \forall i\in I \tag{3.9}$$

$$r_{ij} \leq Mz_{ij} \qquad \forall i \in I, \forall j \in J \qquad (3.10)$$

$$\sum_{j \in J} r_{ij} + \sum_{j \in J} d_j z_{ij} \leq \theta_i w_i \qquad \forall i \in I \qquad (3.11)$$

$$\sum_{j \in J \cup E} \sum_{k \in K_2} y_{jek} = 1 \qquad \forall e \in E \qquad (3.12)$$

$$\sum_{e \in J \cup E} y_{jek} - \sum_{e \in J \cup E} y_{ejk} = 0 \qquad \forall j \in J \cup E, \forall k \in K_2 \qquad (3.13)$$

$$\sum_{j \in S, e \in S} y_{jek} \leq |S| - 1 \qquad S \subseteq E, |S| \geq 2, \forall k \in K_2 \qquad (3.14)$$

$$\sum_{e \in E} \sum_{j \in J \cup E} y_{ejk} \leq N_2 \qquad \forall k \in K_2 \qquad (3.15)$$

$$\sum_{j \in J} \sum_{e \in E} y_{jek} \leq h_k \qquad \forall k \in K_2 \qquad (3.16)$$

$$-z_{je} + \sum_{u \in J \cup E} (y_{juk} + y_{uek}) \leq 1 \qquad \forall j \in J, \forall e \in E, \forall k \in K_2 \qquad (3.17)$$

$$\sum_{i \in I} r_{ij} - \sum_{e \in E} q_e z_{je} = 0 \qquad \forall j \in J \qquad (3.18)$$

$$\sum_{e \in E} q_e z_{je} \leq \omega_j s_j \qquad \forall j \in J \qquad (3.19)$$

$$x_{ijk} \in \{0,1\} \qquad \forall i \in I \cup J, \forall j \in I \cup J, \forall k \in K_1 \qquad (3.20)$$

$$y_{jek} \in \{0,1\} \qquad \forall j \in J \cup E, \forall e \in J \cup E, \forall k \in K_2 \qquad (3.21)$$

$$h_k \in \{0,1\} \qquad \forall k \in K \qquad (3.22)$$

$$z_{ij}, z_{je} \in \{0,1\} \qquad \forall i \in I, \forall j \in J, \forall e \in E \qquad (3.23)$$

$$w_i \in \{0,1\} \qquad \forall i \in I \qquad (3.24)$$

$$s_j \in \{0,1\} \qquad \forall j \in J \qquad (3.25)$$

$$f_i, g_i \geq 0 \qquad \forall i \in I \qquad (3.26)$$

$$r_{ij} \geq 0 \qquad \forall i \in I, \forall j \in J \qquad (3.27)$$

The objective function (3.1) minimizes the overall cost consisting of fixed opening costs of warehouses and service centers ($\sum_{i \in I} \alpha_i w_i + \sum_{j \in J} \beta_j s_j$), fixed closing costs of existing warehouses and existing service centers ($\sum_{i \in I_1} \gamma_i (1 - w_i) + \sum_{j \in J_1} \delta_j (1 - s_j)$), variable costs of warehouses ($\sum_{i \in I} \eta_i f_i + \sum_{i \in I} \lambda_i g_i$), variable costs of service centers ($\sum_{i \in I} \sum_{j \in J} \mu_j r_{ij}$), delivery cost from central depot to particular warehouse in 1st echelon ($\sum_{i \in I} \varphi_i w_i$), fixed cost of operating transportation route

($\sum_{k \in K} \sigma_k h_k$) and delivery cost for the 2nd and the 3rd echelon ($\sum_{i \in I \cup J} \sum_{j \in I \cup J} \sum_{k \in K_1} \tau_{ij} x_{ijk} + \sum_{j \in J \cup E} \sum_{e \in J \cup E} \sum_{k \in K_2} \tau_{je} y_{jek}$), respectively.

Constraints (3.2) – (3.4) are the set of constraints for constructing route on the 2nd echelon distribution. Constraints (3.2) ensure that each retailer is replenished from a single route. Constraints (3.3) require that the route entered to particular retailer must leave from that retailer, in other words, balance in-out for the route in particular node. Constraints (3.4) guarantee that each route for the 2nd echelon transportation must visit a warehouse (subtour-elimination constraints for the 2nd echelon route). Constraints (3.5) ensure that the number of visiting points, in each route, cannot be exceeded the allowable number of retailers. Constraints (3.6) specify that a single vehicle can be operated exactly one route. Constraints (3.7) are added to assign a retailer to a warehouse which has a route from warehouse to that retailer. Constraints (3.8) and (3.9) refer to conservation of flows at particular local. Constraints (3.8) ensure that the quantity of products shipped from each warehouse to be equal to the demand at specific retailers, which assigned to that warehouse, Constraint (3.9) refer to the quantity of service parts. Constraints (3.10) ensure that only flow of service item can be transferred from assigned warehouse. Flow through particular warehouse must be less than or equal to maximum capacity expressed by Constraints (3.11).

Constraints (3.12) - (3.14) are the route construction constraints for the 3rd echelon distribution, same as Constraints (3.2) - (3.4). Constraints (3.12) ensure that the number of visiting points in each route cannot exceed the allowable number of customer on the 3rd echelon. Constraints (3.13) specify that a single vehicle can be operated exactly one route on the 3rd echelon. Constraints (3.14) are used for assigning customers who require maintenance services to an open service center. Constraints (3.15) ensure that the number of visiting points in each route cannot be exceed the allowable number of customers. Constraints (3.16) specify that a single vehicle can be operated for exactly one route. Constraints (3.17) are added to assign a customer to a service center which has route connection. Constraints (3.18) ensure that the flows of the service parts through each service center must satisfy all demands of its served customers (conservation of flow at service center). Flow through particular service center operated at the retailer location must be less than or equal to the capacity of service center expressed by Constraints (3.19). Finally, Constraints (3.20) - (3.27) are the decision variables.

3.4 Data Preparation

To complete the model (3.1)-(3.27), this research collects the data from an actual case study as following part.

3.4.1 Location of Facility and Customer

There are two types of facilities that will be identified proper location in the proposed mathematical model. First one is existing location and second one is candidate location. For candidate locations of warehouse, the data preparation can obtaine the set of candidate warehouse from surveying data performed by zone managers along with supporting teams. For set of candidate service center, the company agreed to define all retailers as candidate locations of service center. In other words, all retailers are able to be service center candidate site in proposed mathematical model. Finally, the locations of customers were transformed from planar area to be a representative point. Each point represents set of customers located in the same district area due to company history sales plan. This research obtained representative location by applied center of gravity theory as shown example of calculation in Table 3.1.

Table 3.1 Example of customer site calculation

Node	Coordinate		Demand (Unit)
	x	y	
sub region 88_1	-133.8	370.3	44
sub region 88_2	-110.7	370.7	76
sub region 88_3	-132.9	379.9	28
Customer Id = 88	-121.8	375.3	148

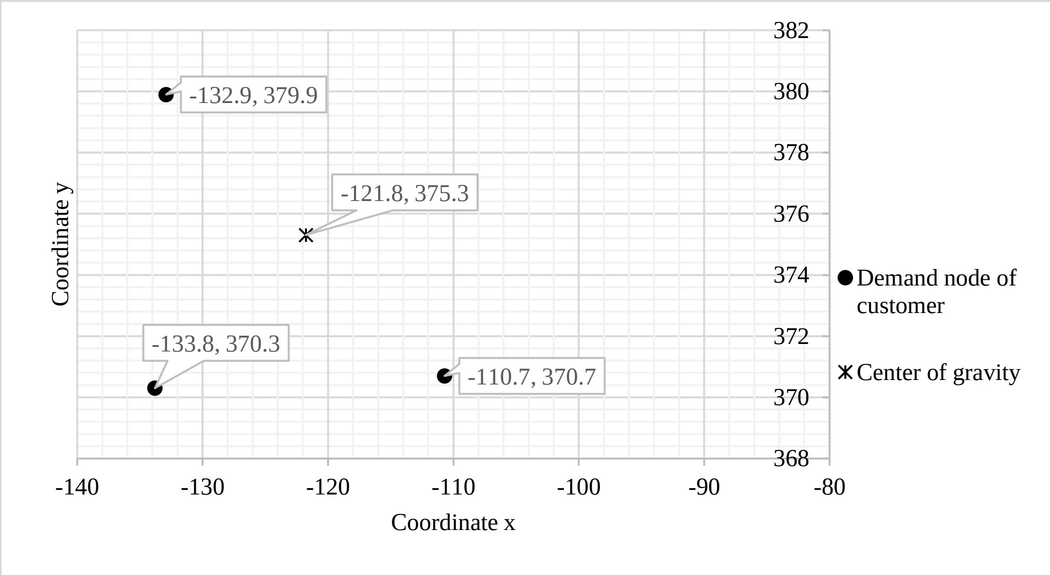


Figure 3.4 Representative node of customer Id =88

To distribute all items to the entire area of Thailand, the company establishes five isolated distribution zones and distributing across zone are not allowed. The number of facilities and customer nodes of particular zone are summarized in Table 3.2.

Table 3.2 shows number of nodes in particular zone. Note that each zone has existing facilities which have been operating, for both of warehouses and service centers opened at a retailer. For example, the central and west zone has 2 existing warehouses, 8 retailers, and 3 existing service centers.

Table 3.2 The number of nodes of particular zone

Zone: Name (Code)	Warehouse		Retailer		Customer
	Existing	Candidate	Retailer	Existing Retailer+ Service center	
1. Central and West Zone (Z1)	2	4	8	3	28
2. East Zone (Z2)	2	3	4	2	15
3. South Zone (Z3)	2	4	10	2	27
4. Northeastern Zone (Z4)	3	3	13	4	36
5. North Zone (Z5)	2	4	10	2	27
All Zone (ZA)	11	18	45	13	133

In summary, the particular node of facilities and customers are illustrated in Figure 3.5-3.8. Note that the location of single depot is located on coordinate x and y at (0,0).

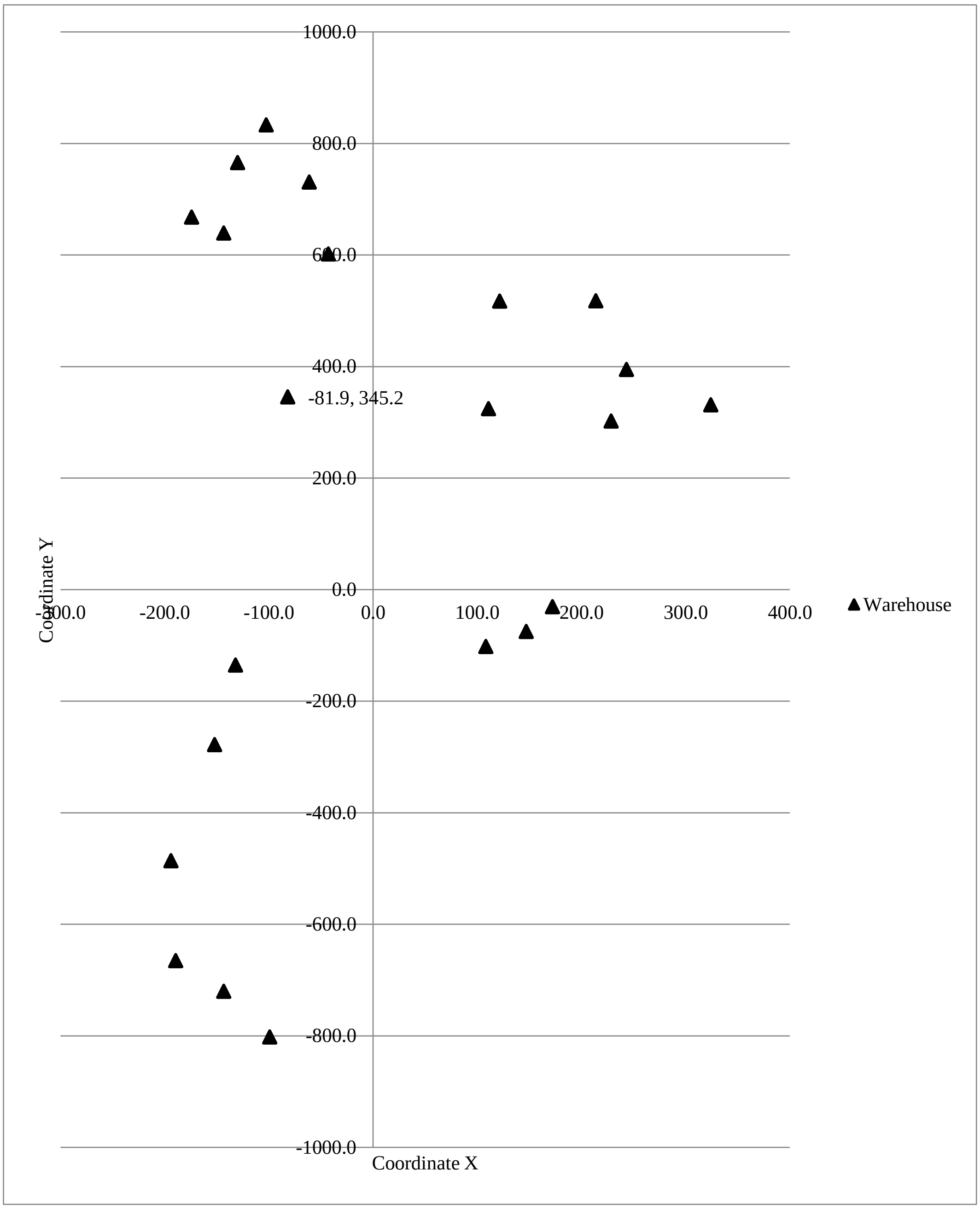


Figure 3.5 Locations of warehouse in layer 1

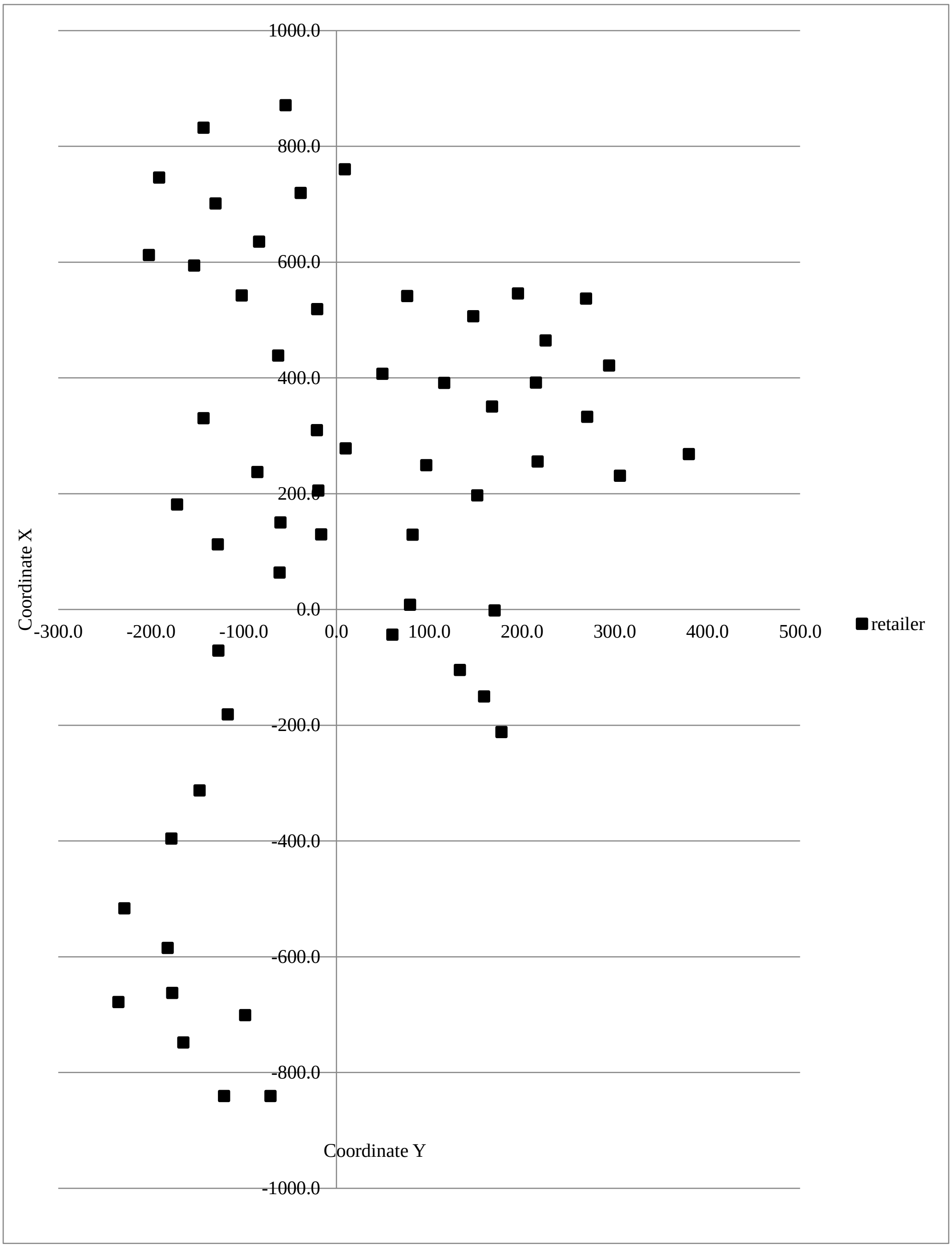


Figure 3.6 Locations of retailer/service center in layer 2

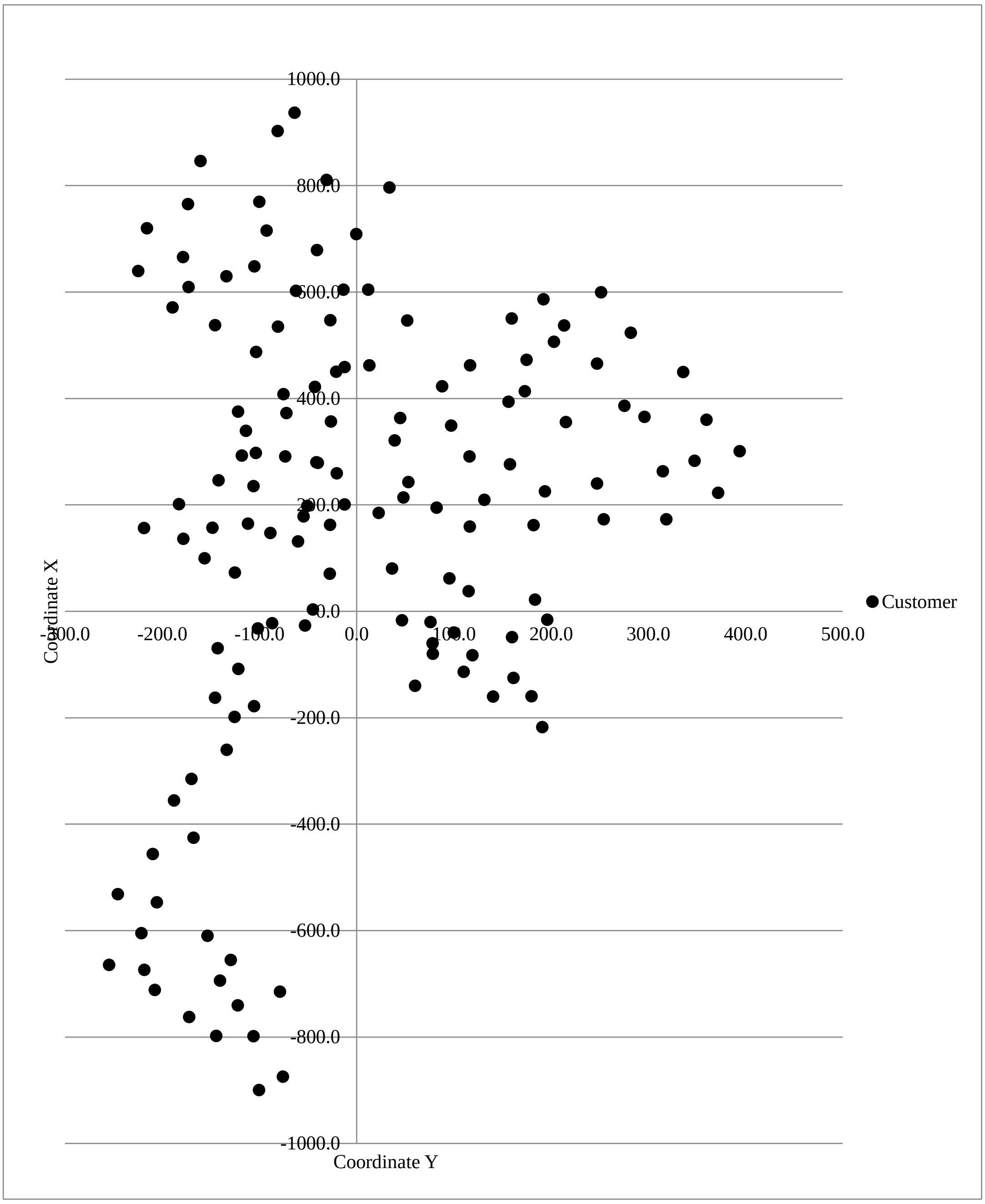


Figure 3.7 Locations of customer in layer 3

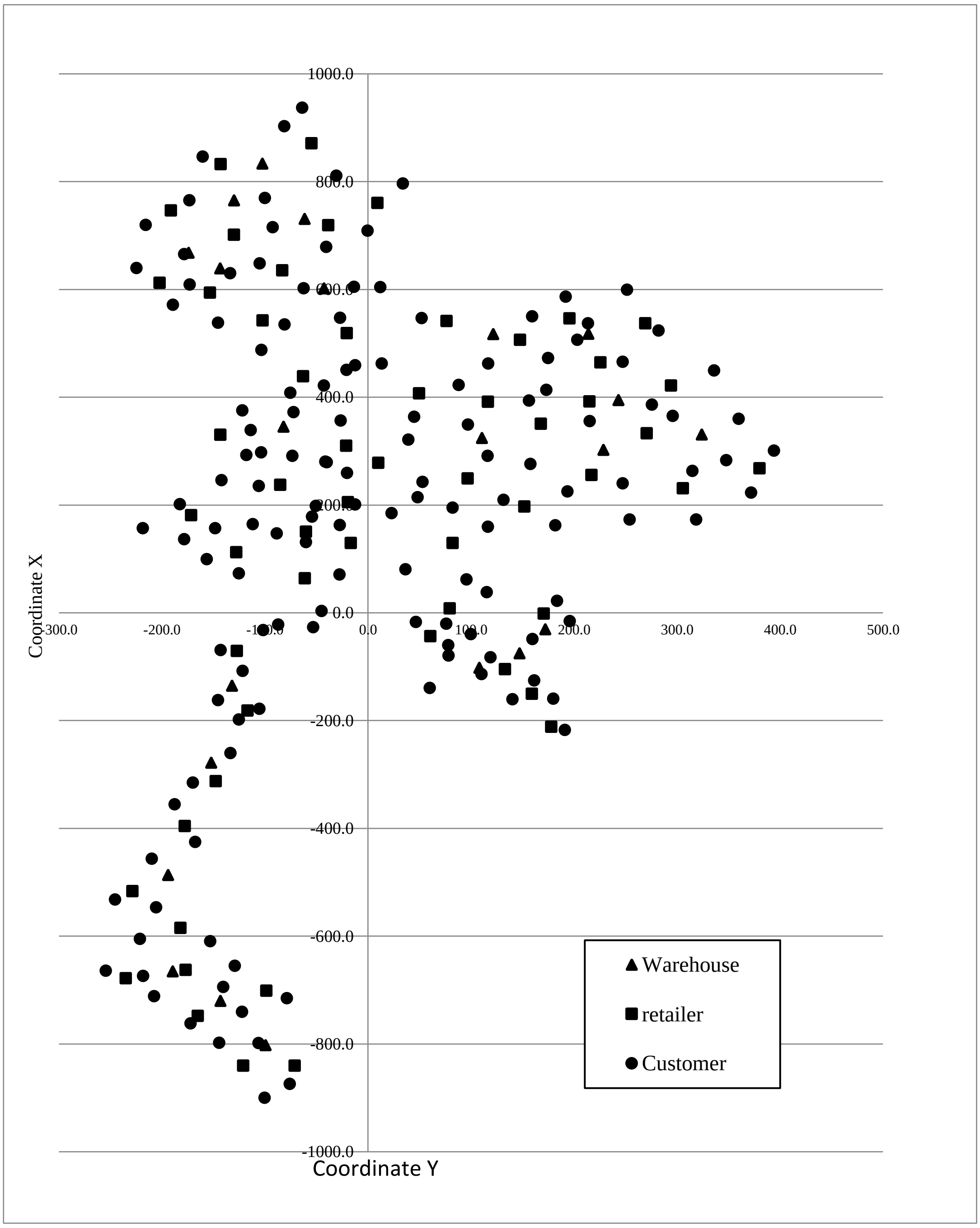


Figure 3.8 Locations of all nodes

3.4.2 Demand Quantity

Firstly, classifying the delivery items into two commodities including of home products and service items (shop products and service parts) is performed as mentioned before. Since there are differences on types and sizes of distributed items in each commodity, in order to compute total demand quantity of particular retailer and customer, this study converts all products and service parts into same equivalent unit. These equivalent unit is also used as facility capacity parameter for both of warehouse and service center. Hence, this study calculates annual demand quantity of each node in terms of ratio comparing to standard volume. The an examples of calculation are shown in Table 3.3.

Table 3.3 Example of unit quantity converting

Product	Unit dimension (m x m x m)	Volume (m^3)	Annual quantity (units)	Converting quantity (equivalent units)
A	0.3x1.2x1.5	0.54	100	2,000
B	0.5x1x1	0.50	150	2,778

From Table 3.3, there are two product items, i.e. Product A and B with different size and quantity of each. Column 2 is size of each product item, column 3 is a volume of each product and column 4 is annual quantity of each product. This study derived annual demand quantity from an average demand of each node over past two years. In order to compute annual demand quantity for each commodity, annual quantity of each product cannot directly add together, since their sizes are different. Because the demand quantity affects the limitation of flow through each facility in the decision model. For example, Product A is bigger than Product B. That means one unit of Product A requires larger space than one unit of Product B. In other words, total demand quantity is not equal to 100+150 = 150 but it must be converted into same equivalent unit or equivalent size as shown following.

The unit volume of Product A equals to 0.54 m^3, Product B is equals to 0.50 m^3. In order to convert to equivalent unit, one product must be set as standard unit. In this research, standard volume is 0.027 m^3 (this volume has largest quantity).

- For Product A, one product of A is 20 times of standard unit. Therefore, equivalent demand quantity of A is equal to 100x20 = 2,000 units.

- For Product B, one product of B is 18.5 times volume of standard unit. Therefore, equivalent demand quantity of B is equal to 150x18.5 = 2,778 units.

After converting, annual demand quantity of particular node is shown in Table A2 and A3 (Appendix A) and can be summarized in Table 3.4.

Table 3.4 demand quantity of each retailer and customer.

Zone	Retailer (equivalent units)	Customer (equivalent units)	Total (equivalent units)
Zone1	65,714	2,694	68,408
Zone2	41,366	1,174	42,540
Zone3	57,766	1,707	59,473
Zone4	109,306	2,704	112,010
Zone5	69,526	1,946	71,472
Total	343,678	10,225	353,903

3.4.3 Facility Capacity

This research defines the capacity of facility in term of the maximum throughput, which each facility can support its assigned demand quantity. The capacity in this case study depends on size of facility and company replenishment policy. For the company replenishment policy, the maximum storage of warehouse must be able to support total demand quantity of 30 days. To calculate annual throughput (capacity per year) of each warehouse, it is derived from maximum capacity and average replenishment period. The example of calculation is presented in Table 3.5.

Table 3.5 Example of warehouse annual throughput calculation

Warehouse Id	Storage volume (m^3)	Unit standard volume (m^3)	Capacity (equivalent unit)	Annual Throughput (equivalent unit)
3	127.5	0.027	4,722	50,370
5	115.0	0.027	4,259	45,432

From Table 3.5, warehouse *Id=3* has storage volume, which is calculated by storage area and maximum storage height, equals to 127.5 m^3. Actually, warehouse *Id=3* stores multiple items, but standard unit volume of item stored in each warehouse is 0.027 m^3. Then capacity of this warehouse, i.e. total number of equivalent products which can be stored simultaneously, is equal to 127.5/0.027 = 4,722 equivalent units. At most of replenishment period policy of company is 30 days and working days per year is 320 days. Therefore, number of annual replenishment time is 320/10 = 10.67 times. Then annual throughput of warehouse Id=3 is equal to 4,722x10.67 = 50,370 equivalent units.

Another example is warehouse *Id=5*, which has storage volume of 115.0 m^3. With standard unit volume of 0.027 m^3, the capacity of warehouse *Id=5* is equal to 128/0.027 = 4,259 equivalent units. With same replenishment period policy and number of working days per year as warehouse *Id=3*, the annual throughput of warehouse *Id=5* is equal to 4,259x10.67 = 45,505 equivalent units.

3.4.4 Cost Component

The cost component in the objective function (3.1) consists of two types of cost, which are facility cost and transportation cost. To identify the facility cost is performed based on the company account and the previous study of Melachrinoudis and Min (2007). The following part describes each type of cost.

(1) Facility Cost

In this problem, there are two types of facility; existing location and new candidate location. For both of existing and new candidate sites, fixed opening cost and variable cost can occur when the model decide to operate them. In contrast, if the model decides to close any existing site, the closing cost will occur for that existing site. There are some different components of cost between ownership location and rental location of facility as shown in Table 3.6.

The main idea of facility cost in objective function is to apply all costs into accumulation cost per year. The detail of each component is described in following details.

Table 3.6 Components of facility cost

Type		Ownership Location	Rental Location
Fixed Cost	Opening Cost	- Depreciation Cost - Maintenance cost - Operator labor cost - Information system license cost	- Rental cost - Maintenance cost - Operator labor cost - Information system license cost
	Closing Cost	- Cost saving from sold property - Laid-off employees cost - Moving cost	- Rental Contract Terminating Cost - Laid-off employees cost - Moving cost
Variable Cost		- Wage of temporary operators - Fuel cost of equipment - Electricity charge - Water charge -Other/ document	

▪ **Fixed opening cost** is fixed annual operating cost for those facilities which are decided to open and operate. This type of cost is derived from 4 components as shown in following equation.

$$\textit{Opening cost} = \textit{Depreciation/Rental cost} + \textit{Maintenance cost} + \textit{Operator labor cost} + \textit{Information system license cost} \tag{3.28}$$

Here is the detail of each component:

- *Depreciation/Rental cost*: For ownership location, depreciation cost is computed by annual depreciation cost of fixed asset, such as, building and equipment, using equation (3.29). For rental location, this study uses annual rental cost as an opening cost for both of existing rental site and new candidate rental site (PANNEERSELVAM, 2013).

$$A = \left(P - \frac{F}{(1+i)^N}\right)\left(\frac{i(1+i)^N}{(1+i)^N - 1}\right) \tag{3.29}$$

Where A = Annual cost

P = Net present value

F = Savage cost

i = Interest rate

N = number of years

The number of years for existing ownership location and equipment depends on the depreciation year that defined by the company account. The company define the number of years equal to 20 years for new candidate site and 10 years for equipment. This research identifies the interest rate from company's long-term loan interest rate.

- *Maintenance cost*: This type of cost is the annual expense that company has to pay in order to maintain and keep facility and equipment in good condition. For existing facility, region manager is responsible to anticipate this cost based on historical data. But for new facility, maintenance cost is calculated from average maintenance cost of existing facility combined with judgment from region managers and assumed to be around 40,000 baht per year.

- *Operator labor cost*: This is annual salary wage of permanent staffs work in each facility. For existing facility, both of rental facility and ownership facility has fewer permanent labors than new facility. Because existing facility has skill full labor, therefore it requires fewer labor (Melachrinoudis & Min, 2007). To open new facility, all resources are terminated can unable to move to new facility, so larger number of labors are required.

- *Information system license cost*: IT license cost is the investment cost on software and IT system used in each facility. For existing facility, this cost is assessed by region manager of that facility for both of rental and ownership facility. For new facility, the investment and installation on IT system around 80,000 baht.

- **Fixed closing cost** is cost occurred if facility is decided to close or to terminate. This type of cost is derived from three components as shown in following equation.

$$\textit{Closing cost} = \textit{Laid-off employees cost} + \textit{Moving cost} - \textit{Cost saving from sold property} + \textit{Rental contract terminating cost} \quad (3.30)$$

If the result is positive, then it is called closing cost, otherwise it is called saving cost. Here is the detail of each component:

- *Laid-off employees cost*: Closing facility means company needs to lay-off all employees. In other words, current labor cannot be transferred to new facility. Therefore, all current employee of closed facility must be compensated.

- *Moving cost*: Once existing facility is closed, equipment which still has good condition will be moved to new location. The expense that company needs to pay in order to transfer equipment to new location is called moving cost.

- *Cost saving from sold property/Rental contract terminating cost*: This type of cost is estimated if existing facility is closed. If closure facility is ownership location, annual saving cost from sold property is taken into account. In other words, company get benefit from salvage value obtained from selling fixed assets. If the closure facility is rental location, then penalty fee for early terminating contract occurs. The value of both costs is estimated by region manager.

If the closing cost, obtained from selling property, is greater than the total cost from laid-off employees and moving to a new location, the closing cost of closure ownership site will be minus (saving cost). In other words, the company will gain benefit from this situation. However, the closing cost of existing rental site is always greater than zero, from the combination of the rental contract terminating cost, the laid-off employees cost and the moving cost.

▪ **Facility variable cost** is annual variable unit cost which depends on degree of operating or shipping quantity. This type of cost is derived from 5 components.

- *Wage of temporary operators*: Temporary operators mean additional daily workers who are hired during peak period. There is no long-term contract between company and temporary operators. This cost is estimated by additional required manpower which is estimated by each facility manager based on historical data.

- *Fuel cost of equipment*: This cost refers to fuel charge of equipment used in warehouse, for example, forklift.

- *Electricity charge*: This cost refers to annual electricity bill of each facility. For existing facility, this is the total electricity bill per year based on actual data but for each new facility, since the actual bill has not occurred yet, so the cost is estimated by using data from nearby existing location.

- *Water charge*: This cost is similar to electricity cost but refers to annual water bill of each facility.

-Other/ document: In order to operate each facility, there are other type of variable cost, such as, documenting cost. Therefore, this type of cost consists of the rest cost other than previous types.

The data of each component of facility cost for all locations are shown in Table A1 and A2 (Appendix A). The cost calculation of some locations is shown in Table 3.7 as the example.

Table 3.7 Examples of facility cost component

Id number	Zone	Type	Fixed operating cost (Baht/year)	Closing cost (Baht/year)	Variable cost (Baht/eq. unit/year)	Capacity (equivalent units)
1	1	New own site	1,252,308	0	34	50,000
3	1	Existing rental site	1,013,743	99,210	36	50,270
5	1	Existing own. site	994,892	-412,321	34	45,423
6	1	New rental site	1,075,423	0	35	50,100

(2) Transportation Cost

Another type of cost is transportation cost. It consists of 2 types of transportation cost. First type is transportation fixed cost and another type is variable cost. The detail of each type of transportation cost is presented in Table 3.8.

Table 3.8 Components of transportation cost

Type	Detail
Transportation Fixed Cost	- Depreciation cost of vehicle - Salary of driver and operator - Equipment cost
Transportation Variable Cost (Distance Cost)	- Fuel cost - Maintenance cost

- **Transportation fixed cost** is annual operating cost of transportation process which has no relationship with mileage. It is derived from three components as shown in following equation.

Transportation fixed cost = Depreciation cost of vehicle + Salary of driver and operator + Equipment cost (3.31)

Here is the detail of each component:

- *Depreciation cost of vehicle:* This annual depreciation cost of vehicle is also calculated using Equation (3.29).

- *Salary of driver and operator:* This cost is calculated by annual total salary of staffs in transportation process.

- *Equipment cost:* This cost is depreciation cost of additional equipment in transporting process rather than vehicles.

Total transportation fixed cost is annual cost per one vehicle. It is not be able to apply in the model because one vehicle can be operated more than one route. Therefore, it is necessary to estimate the number of routes which be able to assign to one vehicle. From company actual data, in the 1st echelon, company operates 12 routes using 2 vehicles, therefore each vehicle can handle 6 routes. In the 2nd echelon and 3rd echelon, the average routes per vehicle is 3 routes. Hence, the estimation of annual fixed transportation cost per route of each echelon is shown in Table 3.9.

Table 3.9 Annual fixed transportation cost per route

cost	echelon		
	1^{st} echelon	2^{nd} echelon	3^{rd} echelon
Fixed transportation cost (bath/route/year)	41,280	155,122	128,694

▪ **Transportation variable cost** is operating cost of transportation process which has relationship with mileage (baht/kilometer/year). It consists of fuel consumption and maintenance cost as shown in equation (3.33).

$$\textit{Transportation variable cost} = \textit{Fuel consumption cost} + \textit{Maintenance cost} \tag{3.33}$$

Here is the detail of each component:

- *Fuel consumption cost:* The data of fuel consumption cost is collected from company's actual fuel charge but the data does not cover all routes that model possibly creates. Therefore, the average fuel consumption will be applied too all the routes, including the routes which are not currently operated, in order to calculate total variable transportation cost. Table 3.10 presents average fuel consumption of each region classified by echelon.

Table 3.10 Average fuel consumption

Region	Average fuel consumption (baht/kilometer)		
	1^{st} echelon	2^{nd} echelon	3^{rd} echelon
Zone 1	9.32	7.59	4.31
Zone 2	9.12	7.52	4.24
Zone 3	9.41	7.73	4.49
Zone 4	9.38	7.60	4.34
Zone 5	9.52	7.84	4.58

It must be ensured that cost estimation from the calculation is not different from real situation if that route is operated. Validating cost estimation from the calculation uses paired-T test. The comparison between estimated cost from calculation and actual fuel charge is tested by using paired-t test. The hypothesis is:

H_0: Actual fuel cost and cost estimated from the calculation are equal

H_1: Actual fuel cost and cost estimated from the calculation are different

With the significance level equal to 0.05, the test results are shown in Table 3.11.

Table 3.11 Results of paired t test between actual cost and cost estimated from calculation

Region	1st echelon		2nd echelon		3rd echelon	
	n	*p*-value	n	*p*-value	n	*p*-value
Zone 1	30	0.621	30	0.417	30	0.581
Zone 2	30	0.589	30	0.389	30	0.512
Zone 3	30	0.613	30	0.412	30	0.362
Zone 4	30	0.674	30	0.654	30	0.542
Zone 5	30	0.591	30	0.483	30	0.394

From Table 3.11, the results indicate that all *p*-values are greater than 0.05. Therefore, all null hypothesizes are accepted. Actual fuel cost and cost estimated from the calculation are equal for all zone and echelon. In other words, average fuel consumptions are able to applied on cost estimation in the model.

- *Maintenance:* This type of cost is the expense that company has to pay in order to maintain and keep vehicles in good condition (baht per kilometer).

This research applies systematic assumption, which means forward and backward direction should be equal, because the most of delivery arc perform long-haul or delivery in rural area. The distances between nodes are collected from Google Map. Table 3.12 shows some parts of distance matrix between each node.

Table 3.12 Example of distance matrix (kilometers)

Id	1	2	3	4	5	6	7	8	9	10	11	12
1	-	40	90	96	88	29	27	96	154	102	217	84
2	40	-	71	98	52	68	24	109	121	71	181	123
3	90	71	-	51	47	107	92	77	76	33	140	146
4	96	98	51	-	96	101	112	29	120	84	181	120
5	88	52	47	96	-	114	75	118	70	25	130	164
6	29	68	107	101	114	-	55	92	177	125	241	56
7	28	24	92	112	75	55	-	118	145	95	205	111
8	96	109	77	29	118	92	118	-	149	110	210	98
9	154	121	76	120	70	177	145	149	-	52	64	221
10	102	71	33	84	25	125	95	110	52	-	116	170
11	217	181	140	181	130	241	205	210	64	116	-	285
12	84	123	146	120	164	56	111	98	221	170	285	-

Table 3.13 Example of total distance cost per year (Baht/year)

Id	1	2	3	4	5	6	7	8	9	10	11	12
1	-	13,769	30,932	33,319	30,300	9,908	9,645	33,223	53,225	35,130	74,831	43,618
2	13,769	-	24,351	33,997	17,794	23,599	8,371	37,755	41,835	24,411	62,644	63,706
3	30,932	24,351	-	17,587	16,341	37,040	31,806	26,594	26,268	11,303	48,351	75,631
4	33,319	33,997	17,587	-	33,070	34,704	38,770	10,023	41,486	28,873	62,511	62,081
5	30,300	17,794	16,341	33,070	-	39,329	26,062	40,788	24,231	8,644	44,869	84,993
6	9,908	23,599	37,040	34,704	39,329	-	18,993	31,656	61,230	43,143	83,183	28,921
7	9,645	8,371	31,806	38,770	26,062	18,993	-	40,634	50,184	32,763	70,820	57,380
8	33,223	37,755	26,594	10,023	40,788	31,656	40,634	-	51,405	37,828	72,532	50,811
9	53,225	41,835	26,268	41,486	24,231	61,230	50,184	51,405	-	18,126	22,192	11,4508
10	35,130	24,411	11,303	28,873	8,644	43,143	32,763	37,828	18,126	-	40,062	88,262
11	74,831	62,644	48,351	62,511	44,869	83,183	70,820	72,532	22,192	40,062	-	14,7787
12	29,087	42,483	50,434	41,398	56,677	19,286	38,264	33,883	76,360	58,858	98,552	-

The numbers in Table 3.12 refers to the distance between each node. In other words, it is the distance traveled for one time. Nevertheless, the unit of distance cost of each arc (τ_{ij}, τ_{je}) in Equation (3.1) is baht/year. Therefore, transportation variable cost must be multiplied by total distance traveled in a year, in order to convert to annual distance cost. In order to calculate annual distance, this work multiplies distance by average frequency or number of travel times per year of each pair of nodes. Finally, the results of distance cost per year are shown in Table 3.13. Please be noted that, only some nodes are shown in this table.

Hence, all parameter and data input, which used in model can be summarized as shown in Table A1-A4 (Appendix A).

CHAPTER 4
SOLUTION APPROACH AND RESULT

In this chapter the formulated mixed integer linear programming of three echelon multi-commodity LRP is solved by proposed approach. First, proposed decompose problem is performed and then clustering-based algorithms is applied to solve these NP-hardness problems. Moreover, sensitivity analysis is reported for demand expansion facility cost and transportation cost. Finally, the solutions are analyzed and discussed as following part.

4.1 Solution Approach

    4.1.1 Exact method

    4.1.2 Heuristic Approach

4.2 Computational Study and Result

    4.2.1 Case Study and Scenario

    4.2.2 Experimental results

    4.2.3 Solutions and Sensitivity Report

4.3 Special Scenario and Discussion

4.1 Solution Approach

4.1.1 Exact method

The main consequence of the node-arc formulation is the size of problem that grows exponentially as illustrated in Table 4.1. The largest zone is the Problem Z4, which consists of 6 candidate warehouse sites, 17 retailer sites and 36 customer sites. The formulated mathematical model (3.1) - (3.27) consists of 66,324 decision variables and 196,863 constraints. The smallest problem is the Z2, which consists only 5,914 decision variables and 5,925 constraints. The Problem *"ZA"* is the special problem that allows the distribution across different zones and redesign them in one problem. The Problem ZA contains 29 warehouse sites, 58 retailer sites and 133 customer nodes. This problem generates 1,804,313 decision variables and approximately 18,859,609 constraints.

Due to past studies (Ambrosino *et al.*, 2009; Contardo *et al.*, 2012) an exact method can solve only small and medium size problems of LRP. With applying exact method on the Problems Z1-Z5, only the feasible solutions are obtained but it cannot solve to optimality. Especially for the largest Problem ZA, the exact method cannot provide any feasible solution in approximately four hours runtime limit. Later, the results of exact method will be shown in Section 4.2.2. Therefore, this research develops new solution approach that the dominant part is a clustering technique to deal with larger problem. The proposed algorithm is described in Section 4.1.2.

Table 4.1 Number of decision variables and constraints

Problems	Number of binary decision variables	Number of continuous decision variables	Total number of decision variables	Number of Constraints
Zone 1 (Z1)	31,965	114	32,079	75,285
Zone 2 (Z2)	5,134	65	5,199	5,914
Zone 3 (Z3)	27,919	120	28,039	58,216
Zone 4 (Z4)	66,174	150	66,324	196,863
Zone 5 (Z5)	27,919	120	28,039	61,639
All Zone (ZA)	1,802,573	1,740	1,804,313	18,859,609

4.1.2 Heuristic Approach

This study develops the heuristic approach that emphasizes on clustering-based algorithm. The proposed method consists four main phases as shown in Figure 4.1. Phase 1 is to decompose the original problem into two subproblems. As mentioned before, that the structure of *Location Routing Problem* (LRP) consists of *Facility Location Allocation Problem* (FLAP) and *Multi-Depot Vehicle Routing Problem* (MDVRP).

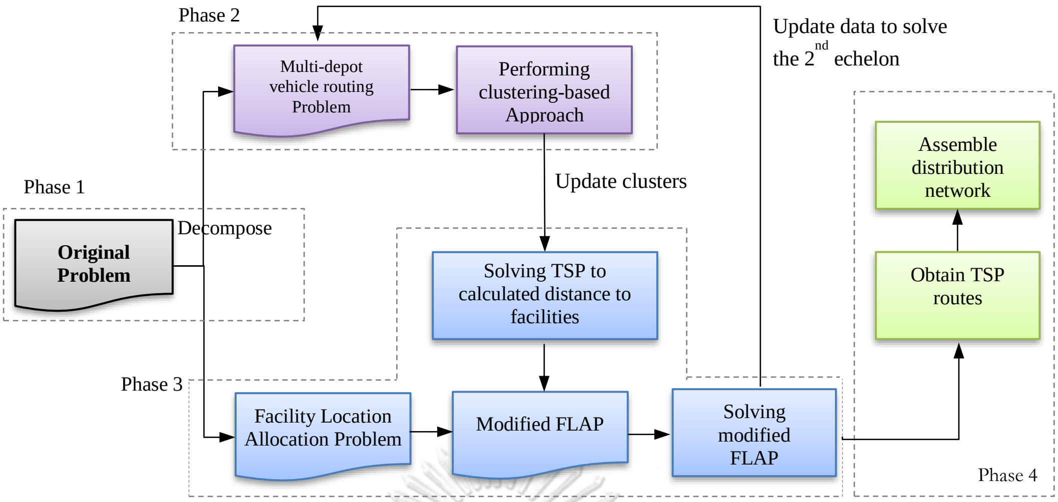


Figure 4.1 Main proposed solution method for three-echelon multi-commodity LRP

Phase 2 is to perform cluster first – route second concept (Miranda-Bront *et al.*, 2017) to establish transportation routes for the 3rd echelon. Then, in Phase 3, the customer clusters and the demand of each clusters are brought into the modified FLAP as representative nodes to allocate a service center. In this phase, the distance to each facility is calculated by *Traveling Salesman Problem* (TSP) route.

Next, the processes are repeated to solve the 2nd echelon in order to construct retailer-cluster and assign a warehouse to particular cluster. It is important to note that the demands of clustered customers in layer 3 are added to a retailer with a service center before constructing the 2nd echelon transportation route. After the entire steps are performed, the proposed method obtains the routes from TSP within the 2nd and 3rd echelon and combines all parts together to create a completed distribution network in Phase 4. The detail of proposed algorithms of Phase 2 and 3 in Section 4.2.1 and 4.2.2 respectively.

4.1.2.1 Phase 2: Clustering-based Approach

This study proposes sequential clustering-based approach to solve MDVRP. This phase is developed based on the past research of Lin and Kwok (2006) and Kchaou

Boujelben *et al.* (2014). There are two main algorithms, which are initial-grouping algorithm and clustering algorithm as described in following parts.

▪ . *Phase 2.1: Initial-grouping algorithm*

The main idea of initial group algorithm is to reduce the size of the search space by using a facility location as a reference point to construct an initial group as shown in Figure 4.2. First is opening the initial set of operating facilities to be dispersed over the entire distributed zone and being near a demand node as close as possible. The key parameter of this algorithm is the coverage distance, which defines the catchment area within which customers are allocated to individual warehouse. Hence, this research determines suitable value by varying the distance from 100 to 300 km (with a step size of 50 km) for the Problem Z1-Z5 and 100-600 for the Problem ZA. The coverage distance that returns the best solution will be selected. The initial group phase algorithm is described as in following parts.

Parameter: facility and demand nodes, facility capacity, demand quantity, coverage distance and distance between nodes

Step 1: Compute number of initial operating facilities, which is derived from the ratio of total demand to average facility capacity.

Step 2: Identify the member demand nodes of each facility, which distance from demand node to each facility is less than or equal to the coverage distance. Next, sort facilities in descending order of the average distance from each facility to its member demand nodes.

Step 3: Select a facility that provides minimum average distance and bring all member demand nodes to the next step.

Step 4: Update the average distance between the member demand nodes and facilities but excluding the demand nodes, which already grouped. Then repeat Steps 2 and 3 if a number of selected facility are equal to a number of initial operating facility.

Step 5: Swap each demand node to a nearest selected facility. This step is to confirm that every demand node is assigned to the nearest facility.

Step 6: If there are unassigned demand nodes which are located out of the coverage distance, assign them to the nearest selected facility.

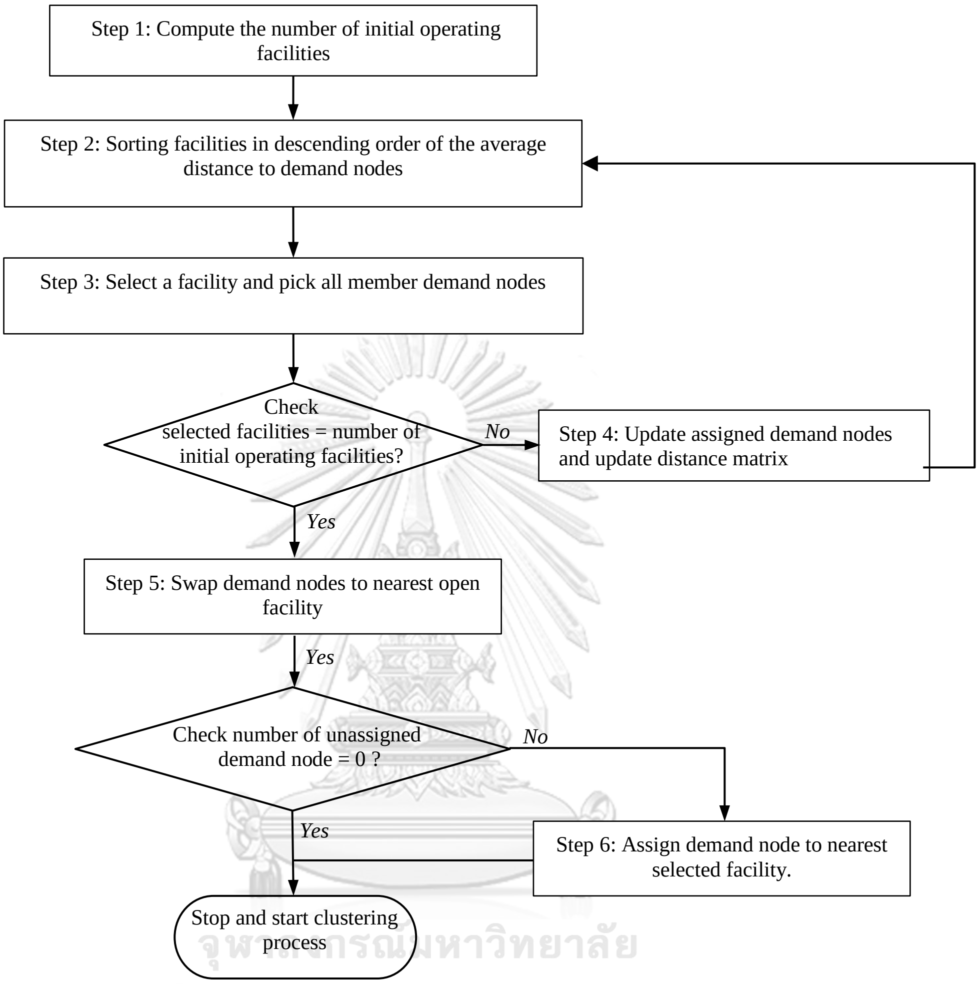


Figure 4.2 Phase 2.1: Initial-grouping algorithm

- *Phase 2.2: Clustering algorithm*

The purpose of clustering algorithm is to establish the cluster of transportation route for both of retailers and customers from particular group that obtained from initial grouping phase. The step performs *Nearest Neighbor Algorithms* (NNA) (Rosenkrantz, Stearns, & Lewis, 2009) to identify the particular member of cluster. Moreover, the solution method also adopts exchange algorithm to enhance the transportation route in terms of shorter distance before feeding the results to next phase as shown in Figure 4.3.

This research introduces the allowable demand quantity per cluster to prevent combining nodes with large size of demands that leads to inability to allocate the facilities in the phase of solving modified FLAP. The suitable value of allowable demand quantity is derived from the best solution of 30%, 40% and 50% of average facility capacity. The following section explains the steps of clustering demand nodes.

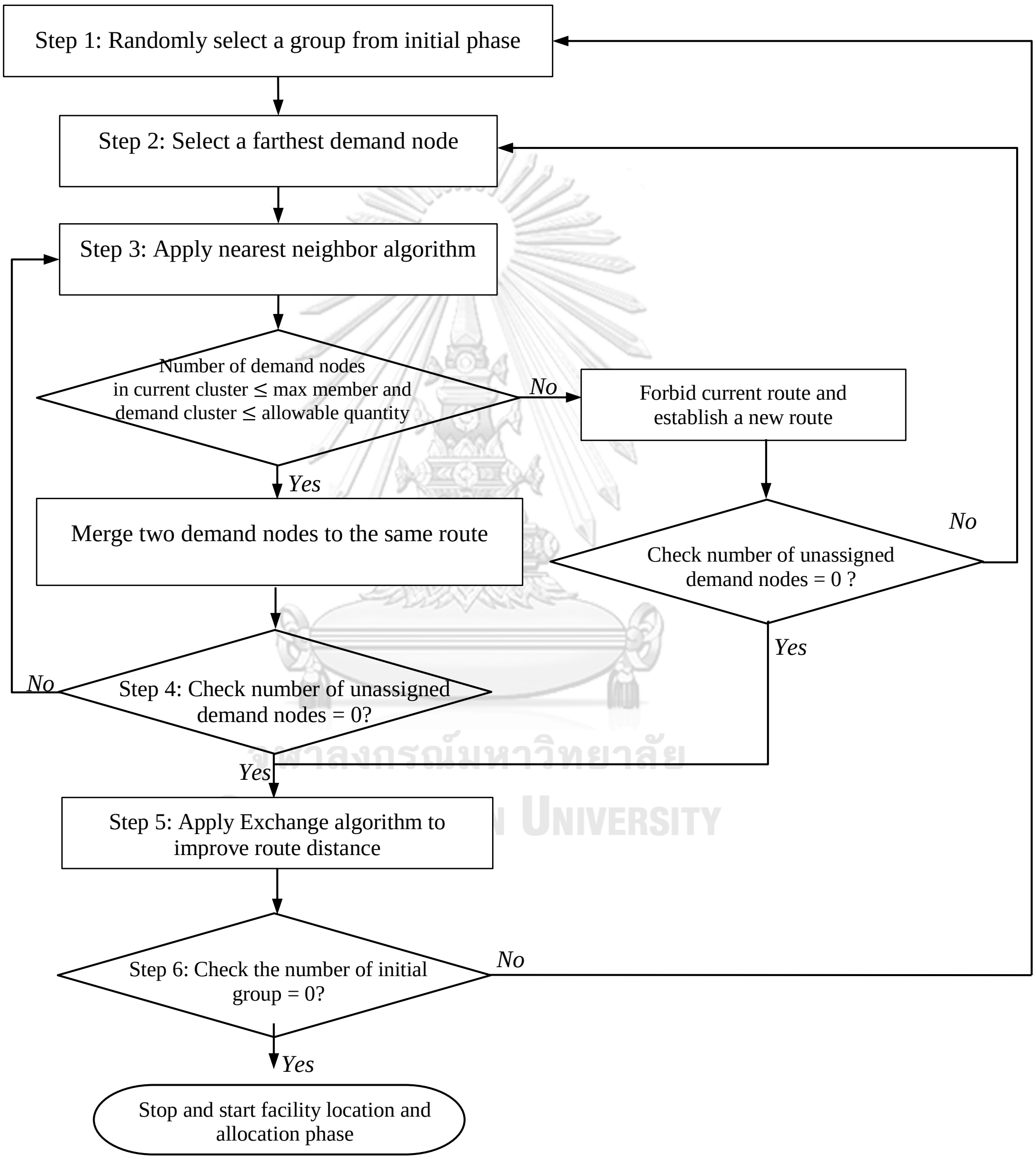


Figure 4.3 Phase 2.2: Clustering algorithm

Parameter: initial groups from the 1st phase, distance, the allowable number of drop point and the allowable demand per cluster

Step 1: Randomly choose a group to create a cluster.

Step 2: Pick up the farthest demand node from the selected facility location of chosen group. Assemble cluster from nodes at boundary first can prevent bias from grouping far nodes together (Barreto *et al.*, 2007).

Step 3: Perform NNA by selecting the nearest demand node next to the latest member node, then add this demand node into same cluster if:

- member of the cluster is less than allowable number of the drop point and
- total demand is not greater than the allowable demand quantity.

Then, the latest location of member is used as a reference in order to find the next nearest demand node.

Step 4: Repeat Steps 2 and 3 until there is no demand node left.

Step 5: Improve the quality of the transportation route by exchanging demand nodes between the different clusters that are adjacent. The closeness of each route is defined by using group average proximity measure derived from the study of Barreto *et al.* (2007). Let *a* and *b* are the member node of cluster *X* and *Y* respectively. Hence, the equation calculated group average distance is shown in equation 4.1.

$$d(X,Y) = \frac{\sum_{a \in X, b \in Y} d(a,b)}{|X||Y|} \tag{4.1}$$

Then, the process performs *(1,1)* exchange move; swaps a demand node from one cluster to another cluster and *(1,0)* exchange move; removes a demand node from one cluster and insert to another cluster (Funke, Grünert, & Irnich, 2005). But this is applied only in the case of:

- member of the cluster is less than allowable number of the drop point,
- total demand is not greater than the allowable demand quantity,
- the total distance, solved by TSP starts from selected facility, is improved.

Step 6: Repeat Steps 1, 2 and 3 until all initial groups are solved.

4.1.2.2 Phase 3: Modified Facility Location Allocation Problem

Cluster representative nodes from previous phase will be reassigned to new facility by solving the modified FLAP. After decomposing problem into FLAP, this research modifies demand nodes to the cluster representative nodes and adds a new constraint to impose any cluster node to be served by only one facility. Moreover, the cost of transportation, from facility to each cluster representative node, is calculated by constructing the TSP route. Therefore, the models to allocate the facility of each echelon are presented in the following parts:

Index

C set of clustered customer or retailer, indexed by c.

Parameters

d_c: demand of product of clustered c in the 2nd echelon.

l_c: demand of service part of clustered c in the 2nd echelon.

q_c: demand of service part of clustered c in the 3rd echelon.

Binary decision variables

z_{ic}, = 1 if cluster c is allocated to warehouse i, 0 otherwise.

z_{jc} = 1 if cluster c is allocated to service center on retailer j, 0 otherwise.

- Facility Location Allocation Problem for the 2nd echelon

$$Min\ Z = \sum_{i \in I} \alpha_i w_i + \sum_{i \in I_1} \gamma_i (1 - w_i) + \sum_{i \in I} \varphi_i w_i \tag{4.2}$$

$$+ \sum_{i \in I} \sum_{c \in C} \big((d_c \eta_i) + (l_c \lambda_i) + \tau_{ic} \big) z_{ic}$$

Subject to

$$\sum_{i \in I} z_{ic} = 1 \qquad \forall c \in C \tag{4.3}$$

$$\sum_{c \in C} (d_c + l_c) z_{ic} \le \theta_i w_i \qquad \forall i \in I \qquad (4.4)$$

$$z_{ic} \in \{0,1\} \qquad \forall i \in I, \forall c \in C \qquad (4.5)$$

$$w_i \in \{0,1\} \qquad \forall i \in I \qquad (4.6)$$

The objective function (4.2) minimizes the overall cost consisting of the fixed operating costs of warehouses ($\sum_{i \in I} \alpha_i w_i$), fixed closing costs of existing warehouses ($\sum_{i \in I_1} \gamma_i (1 - w_i)$), delivery cost from central depot to particular warehouse ($\sum_{i \in I} \varphi_i w_i$) in the 1st echelon, variable costs of operating the open warehouses and transportation cost from warehouse to cluster ($\sum_{i \in I} \sum_{c \in C} ((d_c \eta_i) + (l_c \lambda_i) + \tau_{ic}) z_{ic}$), respectively.

Constraints (4.3) impose that each retailer cluster is replenished from a single warehouse. Constraints (4.4) ensure that flow through the particular warehouse must be less than or equal to maximum capacity. Constraints (4.5) - (4.6) are the decision variables.

- Facility Location Allocation Problem for the 3rd echelon

$$Min\ Z = \sum_{j \in J} \beta_j s_j + \sum_{j \in J_1} \delta_j (1 - s_j) + \sum_{j \in J} \sum_{c \in C} \left((q_c \mu_j) + \tau_{jc} \right) z_{jc} \qquad (4.7)$$

Subject to

$$\sum_{j \in J} z_{jc} = 1 \qquad \forall c \in C \qquad (4.8)$$

$$\sum_{c \in C} q_c z_{jc} \le \omega_j s_j \qquad \forall j \in J \qquad (4.9)$$

$$z_{jc} \in \{0,1\} \qquad \forall j \in J, \forall c \in C \qquad (4.10)$$

$$s_j \in \{0,1\} \qquad \forall j \in J \qquad (4.11)$$

The objective function (4.7) minimizes the overall cost consisting of fixed operating costs of service centers ($\sum_{j \in J} \beta_j s_j$), fixed closing costs of existing service centers ($\sum_{j\in J_1}\delta_j(1-s_j)$), variable costs of operating service centers and transportation cost to cluster ($\sum_{j\in J}\sum_{c\in C}((q_c\,\mu_j+\tau_{jc})z_{jc})$, respectively.

Constraints (4.8) ensure that each customer cluster is replenished from a single service center. Constraints (4.9) ensure that flow through the particular service center must be less than or equal to the capacity of service center. Constraints (4.10) - (4.11) are decision variables.

4.2 Computational Study and Result

4.2.1 Case Study and Scenario

This work studies the redesign of distribution network of real-life five-zone case study, as mentioned in Section 3 and 4, involving zone 1 (Z1), zone 2 (Z2), zone 3 (Z3), zone 4 (Z4) and zone 5 (Z5) and one special problem that involves all zones together (ZA). The detail and code of scenario are presented in Table 4.2. First, this research tests all problems (Problems Z1-ZA) with normal demand pattern that collected from the case study. These set of problems are coded as P1, for example, the Z1P1 refers to problem of zone 1 and deal with realistically based demand pattern.

Then, this study performs sensitivity analysis for all problems by varying demand quantity, facility cost and transportation cost. These will prove whether or not the solutions of proposed LRP are robust. The sensitivities of demand quantities are 20%, 44%, 50% and 107% of based pattern for both of products and parts. These set of problems are coded as P2-P5, respectively.

Next, this research observes 25%, 50% and 75% sensitivities of facility costs as well as coefficient of: α_i, β_j, γ_i, δ_j, η_i, λ_i and μ_j in each scenario, the same as sensitivity of transportation costs, which vary coefficient of: φ_i, σ_k, τ_{ij} *and* τ_{je}. The codes are defined as a25, a50 and a75, respectively, for sensitivities of facility cost, and t25, t50 and t75 for sensitivities of transportation cost. Totally, 66 scenarios are tested as shown in Table 4.3.

Table 4.2 Scenario coding and Sensitivity analysis detail on demand, facility cost and transportation cost

Sensitivity	Scenario (scenario code = %sensitivity)				
Demand	P1 = 0%	P2 = 20%	P3 = 44%	P4 = 72%	P5 = 107%
Facility cost	a25 = 25%	a50 = 50%	a75 = 75%		
Transportation Cost	t25 = 25%	t50 = 50%	t75 = 75%		

Table 4.3 List of all test scenarios

Zones	Zone1		Zone 2		Zone 3		Zone 4		Zone 5		All Zone	
List of Scenarios	*Z1P1*	*Z1a25*	*Z2P1*	*Z2a25*	*Z3P1*	*Z3a25*	*Z4P1*	*Z4a25*	*Z5P1*	*Z5a25*	*ZAP1*	*ZAa25*
	Z1P2	*Z1a50*	*Z2P2*	*Z2a50*	*Z3P2*	*Z3a50*	*Z4P2*	*Z4a50*	*Z5P2*	*Z5a50*	*ZAP2*	*ZAa50*
	Z1P3	*Z1a75*	*Z2P3*	*Z2a75*	*Z3P3*	*Z3a75*	*Z4P3*	*Z4a75*	*Z5P3*	*Z5a75*	*ZAP3*	*ZAa75*
	Z1P4	*Z1t25*	*Z2P4*	*Z2t25*	*Z3P4*	*Z3t25*	*Z4P4*	*Z4t25*	*Z5P4*	*Z5t25*	*ZAP4*	*ZAt25*
	Z1P5	*Z1t50*	*Z2P5*	*Z2t50*	*Z3P5*	*Z3t50*	*Z4P5*	*Z4t50*	*Z5P5*	*Z5t50*	*ZAP5*	*ZAt50*
		Z1t75		*Z2t75*		*Z3t75*		*Z4t75*		*Z5t75*		*ZAt75*

4.2.2 Experimental results

To solve all scenarios, all solution approaches are run on PC with Intel Core i7 3.9 GHz processor, with 16 GB of RAM and 400 GB of hard disk. IBM ILOG CPLEX 64-bit version 12.4 with C# Concert technology is the commercial solver applies exact solution method as referent solutions for evaluating the qualities of heuristic approach (computation time and %gap of objective value). This research codes all algorithms on Microsoft Visual Studio 2015.

To solve these scenarios by CPLEX, this research determines CPLEX runtime limitation at 15,000 seconds (250 minutes) and relative %gap tolerance at 0.01%. This research runs all node selected strategies and choose the best for particular scenario.

For proposed heuristic approach, the coverage distance is set to equal to 200 km as key parameter with allowable demand at 30% for all Z1, Z2 and Z5 problems. While the best setup for the Z3 and the Z4 problem is the coverage distance equal to 250 km with allowable demand at 40%. For the ZA problem, the coverage distance of 300 km with allowable demand at 40% is the most suitable value. To solve the modified FLAP and TSP, CPLEX runtime is set a limitation at 500 seconds and relative %gap tolerance at 0.01%.

After a proper tuning, the results of CPLEX runtime that found best known solution and computation time of heuristic approach are compared and shown in Figure 4.4 (the completed result is shown in Table B1-B4 of Appendix B).

According to Figure 4.4, X-axis refers to each scenario arranging in ascending order of their sizes of problem. Due to the high difference of computation time between CPLEX and proposed solution method, Y-axis is the computation time in logarithm base 10. And CPLEX records the runtime when the best-known solution is found.

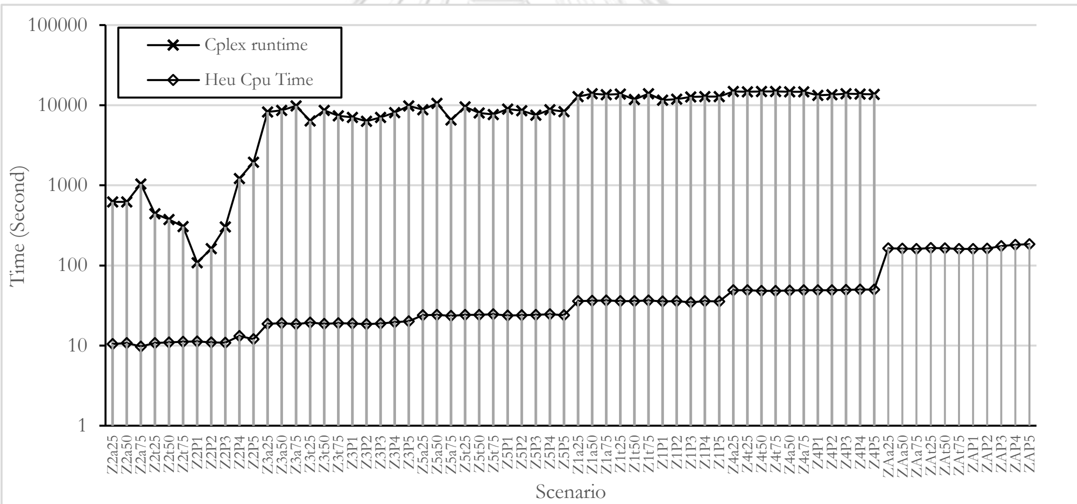


Figure 4.4 The comparison between computation time of CPLEX and proposed heuristic approach

Solving the mathematical model (3.1)-(3.27) using commercial solver, e.g., CPLEX, is suitable for small and medium size problem, e.g., Problem Z2. Especially the Problems Z2, CPLEX found the best-known solutions at runtime 108 to 1,947 seconds as shown in Figure 4.4 (the shortest runtime is 108.4 seconds for the Scenario Z2P1). A closer inspection of the results reveals that CPLEX spends a significant amount of time trying to close the gap. This is due in part to the weak LP relaxation bound of formulation model (3.1)-(3.27). Hence, the gaps for Problems Z2 are around 18.1%-36.9% as shown in Figure 4.5.

For larger instances, CPLEX can only obtain feasible solutions when the solution time reaches time limit (250 minutes). The runtime of larger problems, until the best-known solutions are found, is extremely greater (especially, the Problems Z4). For special largest Problem ZA, it cannot solve this problem by commercial solver. The operating system reported that there was out of storage memory (400 GB of hard disk) with no return of any feasible solution.

In contrast, proposed heuristic approach provides the feasible solutions for all scenarios. Computation times of heuristic approach vary from 10 to 185 seconds, which are extremely lower than CPLEX runtimes. Exclusively, the effectiveness of proposed approach indicates that it can solve the largest Problem ZA in computation time varies from 160 to 185 seconds.

The quality of answer from CPLEX can be defined by %gap of best known integer solution comparing to the best lower bound solution of LP relaxation, which is obtained from program. While the quality of heuristic approach is evaluated using equation 4.12.

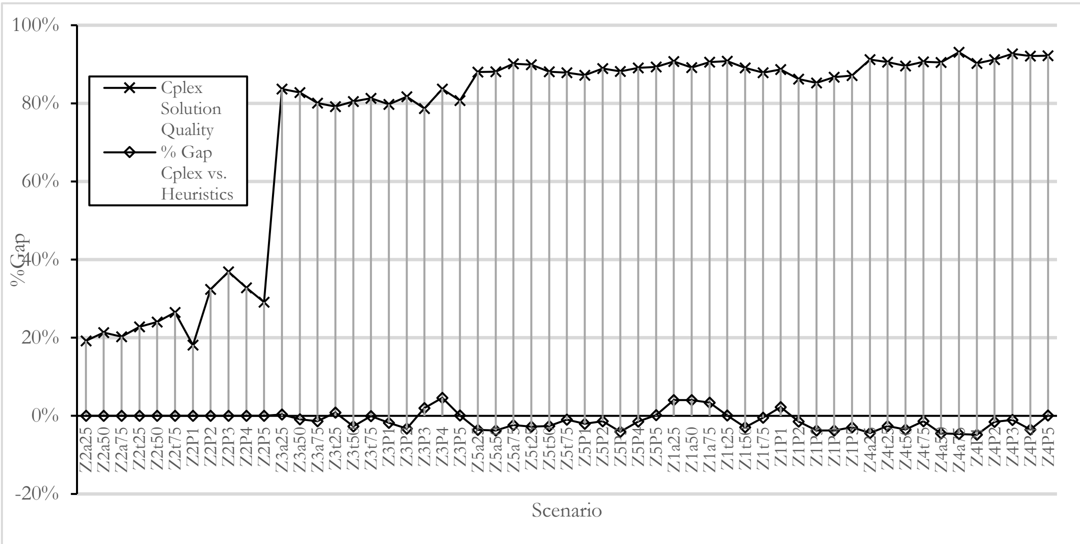
$$\%gap = \frac{(Z_{Heuristic} - Z_{CPLEX})}{Z_{CPLEX}}. \tag{4.12}$$

Where $Z_{Heuristic}$ = objective value from proposed heuristic approach

Z_{CPLEX} = objective value from CPLEX solving

The quality of CPLEX and heuristic approach are shown in Figure 4.5. The result indicates that the Z2 solutions provide the best gap around 18%-39%. Furthermore, when the size of problem is increasing, CPLEX provides the worst gap due to large number of binary variables and constraints, especially subtour elimination constraints.

Nevertheless, most of the results from heuristic approach provide better quality than CPLEX that vary from -4.84% (Z4P1) to 4.86% (Z3P4). For a small size problem (all Scenarios Z2), heuristic solutions provide the similar results and the total cost as CPLEX solutions. For a medium size problem like the Scenarios Z1, Z3, Z4 and Z5, heuristic also provides better solutions.



*The quality of Scenarios ZA is omitted because it cannot obtain any solution from CPLEX solving.

Figure 4.5 CPLEX solution quality and %gap CPLEX solution compares to heuristic solution.

According to the quality of proposed approach, clustering phase can reduce the number of binary decision variables in formulation modified FLAP (4.2)-(4.11). For example, there are 17 and 26 of demand nodes in the 2nd and the 3rd echelon in Scenario Z4, respectively. After establishing the transportation routes, the number of clusters of the 2nd and the 3rd echelon is reduced to 6-7 routes and 13-15 routes, respectively. Moreover, performing the cluster first -route second concept helps to determine each route by TSP. Therefore, both of modified FLAP and TSP can be solved to the optimality in every scenario with acceptable computation time. In summary, when the problems are larger in terms of binary decision variable and the number of constraint, heuristic can provide better solutions than CPLEX as shown in Figure 4.5.

In contrast, CPLEX provides better solution than heuristic method for the Scenarios Z3P3 and Z3P4. This is because the heuristic approach generates one more transportation route than CPLEX, which is the consequence of the parameter of allowable demand quantity. Although this research tries to test the higher value of allowable demand quantity to reduce the number of route, but the results revealed that the increasing of allowable demand quantity leads to the higher number of open facilities and total cost.

For the Scenarios Z1P1, Z1a25, Z1a50 and Z1a75, the proposed heuristic approach returns lower quality of solution due in part to the number of operating service centers from heuristic is greater than the solutions from CPLEX. To observe these scenarios in CPLEX solutions, the solution revealed that the capacities of service centers are very tight, which compares to assigned demand quantity. Hence, the clustering transportation route first – location allocation second subsequence process of the proposed heuristic approach let the model open an excess service center (the combination of clustered routes cannot be served by the similar number of service centers that equal to CPLEX solution).

4.2.3 Solutions and Sensitivity Report

4.2.3.1 Solutions

The results from solving Scenarios Z1P1-Z5P1 by the proposed heuristic approach are shown in Figure 4.6. It presents the solutions of all Scenario P1 (base problem) in terms of the number of opening, retaining and closing facilities (both of warehouse and service center). Note that the number of operating facilities in each zone must be the summation of number of open new facilities and retaining existing facilities. For example, the Scenario Z3P1, the solution suggests to open a new location site and to retain an existing warehouse. Totally, the number of operating warehouses is equal to two sites. Moreover, there are only a closure existing warehouse and two service centers for this problem.

To solution shows that only the Scenarios Z2P1 and Z3P1 suggest to close existing warehouses. For the Scenario Z2P1, one of closing warehouse is company ownership site and this redesign of distribution network can consequently gain benefit from saving cost. However, a closure warehouse in the Scenario Z3P1 is a rental site, therefore, there is no cost saved from closure in this zone. Nevertheless, to open new sites of warehouse can provide lower facility cost and lower average distance to all retailers (comparing to current distribution network). The total number of operating warehouses, including new warehouses and retaining existing warehouses, suggested from model is equal to number of existing warehouses in as-is model. Hence, there is no excess warehouse opened from heuristic solving for the Problems Z1-Z5.

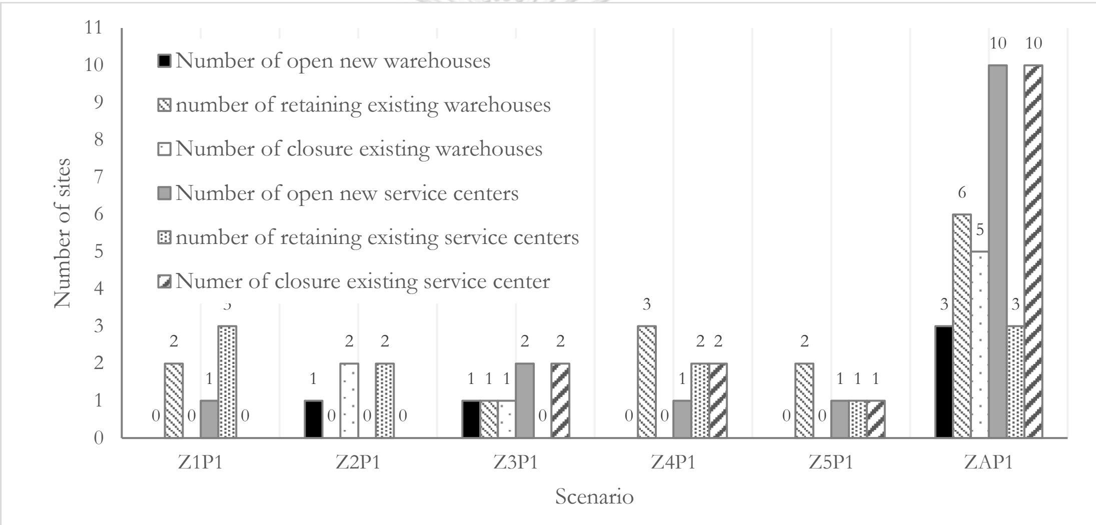


Figure 4.6 Number of open and closure if facilities in particular scenario of P1

Due to Figure 4.6, there are closing service centers in the Scenarios Z2P1 and Z3P1. Although all of them are rental locations that lead to additional cost of contract terminating and moving to new candidate site, the open new sites of service center can contribute significantly lower transportation cost. Moreover, there is a closure ownership service center exclusive in the Scenario Z4P1 that can earn benefit from closure facility in term of saving cost.

For the Scenarios Z3P1, Z4P1 and Z5P1, the new location sites of service center are selected from lower distance cost even though all of them provide not much different in cost of facility comparing to existing sites. For Scenario Z4P1, it is important to refer that the distribution network only requires three sites to support the customers' demand. The solution suggests to operate three service centers, whereas there are four existing service centers in current distribution network (as-is model). This means that the redesign of distribution network can offer lower fixed opening cost of service center.

Note that there is no closure facility in the Scenario Z1P1. However, the solution advises to open one more excess service center to support customers' demand. This lead to additional cost of operating facility for this zone as mentioned in previous section. Due to the solutions of all Scenarios Z1-Z5 in Figure 4.6, the number of operating sites is equal to the number of existing service centers in total.

Hence, it can be concluded that the number of closure service centers is greater than the number of closure warehouses, based on the lower closing cost and larger number of alternative service centers, which located nearer to customer sites.

According to result of ZAP1, solving all zones simultaneously provides lower number of operating warehouses than solving separately. It suggests to operate nine warehouses in the ZAP1, while the total number of operating warehouses in solving each zone separately is ten sites. Because it allows distribution across zones, therefore excess capacity of warehouses can share properly and opening cost of warehouse is high. The solution of selected service centers is not different in number but it is different in location. Most of selected ones are new locations, which provide lower facility cost or transportation cost.

To discuss further about the efficiency of the solution from heuristic approach, the results of number of operating facility are compared with the results from CPLEX and the calculation of minimum number of facilities required. The minimum number of facilities required is the summation of demand divided by average capacity. The results are shown in Table 4.4-4.9.

Zone 2 is the only one zone which has same result among three problems for all scenarios. Zone 1 has largest different number of operating facilities from minimum requirement. Nevertheless, the rest zones have similar result between heuristics and CPLEX, and between heuristic and minimum requirement.

Table 4.4 Comparing number of operating facility from solution vs. CPLEX and number of required facility of zone 1

Scenario	CPLEX		Proposed Solution Method		Calculation	
	warehouse	service center	warehouse	service center	warehouse	service center
Z1P1	2	3	2	4	2	3
Z1P2	2	4	2	4	2	4
Z1P3	**3**	**5**	**3**	**5**	2	4
Z1P4	**3**	**6**	**3**	**6**	3	5
Z1P5	**3**	**6**	**3**	**6**	3	6
Z1a25	2	3	2	4	2	3
Z1a50	2	3	2	4	2	3
Z1a75	2	3	2	4	2	3
Z1t25	2	3	2	4	2	3
Z1t50	2	**4**	2	4	2	**3**
Z1t75	2	**4**	2	4	2	**3**

Table 4.5 Comparing number of operating facility from solution vs. CPLEX and number of required facility of zone 2

Scenario	CPLEX		Proposed Solution Method		Calculation	
	warehouse	service center	warehouse	service center	warehouse	service center
Z2P1	1	2	1	2	1	2
Z2P2	2	2	2	2	2	2
Z2P3	2	2	2	2	2	2
Z2P4	2	3	2	3	2	3
Z2P5	2	3	2	3	2	3
Z2a25	1	2	1	2	1	2
Z2a50	1	2	1	2	1	2
Z2a75	1	2	1	2	1	2
Z2t25	1	2	1	2	1	2
Z2t50	1	2	1	2	1	2
Z2t75	1	2	1	2	1	2

Table 4.6 Comparing number of operating facility from solution vs. CPLEX and number of required facility of zone 3

Scenario	CPLEX		Proposed Solution Method		Calculation	
	warehouse	service center	warehouse	service center	warehouse	service center
Z3P1	2	4	2	2	2	2
Z3P2	2	4	2	3	2	3
Z3P3	2	4	2	3	2	3
Z3P4	3	4	3	**4**	3	**3**
Z3P5	3	**5**	3	**4**	3	4
Z3a25	2	3	2	2	2	2
Z3a50	2	3	2	2	2	2
Z3a75	2	3	2	2	2	2
Z3t25	2	3	2	2	2	2
Z3t50	2	3	2	2	2	2
Z3t75	2	3	2	3	2	2

Table 4.7 Comparing number of operating facility from solution vs. CPLEX and number of required facility of zone 4

Scenario	CPLEX		Proposed Solution Method		Calculation	
	warehouse	service center	warehouse	service center	warehouse	service center
Z4P1	3	4	3	3	3	3
Z4P2	3	4	3	4	3	4
Z4P3	4	5	4	4	4	4
Z4P4	5	6	**5**	5	**4**	5
Z4P5	5	6	5	6	5	6
Z4a25	3	4	3	3	3	3
Z4a50	3	4	3	3	3	3
Z4a75	3	4	3	3	3	3
Z4t25	3	4	3	3	3	3
Z4t50	3	3	3	3	3	3
Z4t75	3	3	3	3	3	3

Table 4.8 Comparing number of operating facility from solution vs. CPLEX and number of required facility of zone 5

Scenario	CPLEX		Proposed Solution Method		Calculation	
	warehouse	service center	warehouse	service center	warehouse	service center
Z5P1	2	3	2	2	2	2
Z5P2	2	3	2	3	2	3
Z5P3	3	4	3	3	3	3
Z5P4	3	4	3	4	3	4
Z5P5	4	5	**4**	5	**3**	5
Z5a25	2	3	2	2	2	2
Z5a50	2	3	2	2	2	2
Z5a75	2	3	2	2	2	2
Z5t25	2	3	2	3	2	2
Z5t50	2	3	2	3	2	2
Z5t75	2	3	2	3	2	2

Table 4.9 Comparing number of operating facility from solution vs. CPLEX and number of required facility for all zone

Scenario	Summation of particular zone (CPLEX)		All Zone (Heuristic)		Summation of particular zone (Heuristic)		Number of required facility	
	warehouse	service center	warehouse	service center	warehouse	service center	warehouse	Service center
ZAP1	10	16	9	13	10	13	8	11
ZAP2	11	17	9	15	11	16	9	13
ZAP3	14	20	13	18	14	17	11	15
ZAP4	16	23	16	21	16	22	13	18
ZAP5	17	25	17	25	17	24	15	22
ZAa25	10	15	9	13	10	13	8	11
ZAa50	10	15	9	13	10	13	8	11
ZAa75	**10**	**15**	**8**	**12**	**10**	**13**	**8**	**11**
ZAt25	10	15	9	13	10	14	8	11
ZAt50	10	15	9	13	10	14	8	11
ZAt75	10	15	9	13	10	15	8	11

The next issue to be discussed is the number of transportation route in the 2nd and 3rd echelon. The solutions from heuristic are compared with the results from CPLEX and the calculation of minimum number of transportation route required. The minimum number of transportation route required is the number of demand nodes divided by allowable number of visiting point per route. The results are shown in Table 4.10-4.15.

Zone 1 and zone 2 have the same result among three problems for all scenarios. Zone 1 has largest different number of operating facilities from minimum requirement. However, the rest zones have similar result between heuristics and CPLEX, and between heuristic and minimum requirement. In zone 3 and zone 4, the number of transportation route in echelon 2 from heuristic and CPLEX are same as the minimum number for most of the rest zones, only solutions from echelon 3 are different. In the problem of solving all zone altogether, there is no result from CLPEX, because it cannot solve as explained earlier. However, the results from heuristic have one more transportation route than minimum number for all scenarios, both of echelon 2 and 3.

Table 4.10 Comparing number of transportation route from solution vs. CPLEX and minimum number of route of zone 1

Problem Id	CPLEX		Proposed Solution Method		Calculation	
	Echelon 2	Echelon 3	Echelon 2	Echelon 3	Echelon 2	Echelon 3
Z1P1	4	10	4	10	4	10
Z1P2	4	10	4	10	4	10
Z1P3	4	10	4	10	4	10
Z1P4	4	10	4	10	4	10
Z1P5	4	10	4	10	4	10
Z1a25	4	10	4	10	4	10
Z1a50	4	10	4	10	4	10
Z1a75	4	10	4	10	4	10
Z1t25	4	10	4	10	4	10
Z1t50	4	10	4	10	4	10
Z1t75	4	10	4	10	4	10

Table 4.11 Comparing number of transportation route from solution vs. CPLEX and minimum number of route of zone 2

Problem Id	CPLEX		Proposed Solution Method		Calculation	
	Echelon 2	Echelon 3	Echelon 2	Echelon 3	Echelon 2	Echelon 3
Z2P1	2	5	2	5	2	5
Z2P2	2	5	2	5	2	5
Z2P3	2	5	2	5	2	5
Z2P4	2	5	2	5	2	5
Z2P5	2	5	2	5	2	5
Z2a25	2	5	2	5	2	5
Z2a50	2	5	2	5	2	5
Z2a75	2	5	2	5	2	5
Z2t25	2	5	2	5	2	5
Z2t50	2	5	2	5	2	5
Z2t75	2	5	2	5	2	5

Table 4.12 Comparing number of transportation route from solution vs. CPLEX and minimum number of route of zone 3

Problem Id	CPLEX		Proposed Solution Method		Calculation	
	Echelon 2	Echelon 3	Echelon 2	Echelon 3	Echelon 2	Echelon 3
Z3P1	4	**9**	4	**10**	4	**9**
Z3P2	4	**9**	4	**10**	4	**9**
Z3P3	4	**9**	4	**10**	4	**9**
Z3P4	4	**9**	4	**10**	4	**9**
Z3P5	4	**10**	4	**10**	4	**9**
Z3a25	4	**9**	4	**10**	4	**9**
Z3a50	4	**9**	4	**10**	4	**9**
Z3a75	4	**9**	4	**10**	4	**9**
Z3t25	4	**9**	4	**10**	4	**9**
Z3t50	4	**9**	4	**10**	4	**9**
Z3t75	4	**9**	4	**10**	4	**9**

Table 4.13 Comparing number of transportation route from solution vs. CPLEX and minimum number of route of zone 4

Problem Id	CPLEX		Proposed Solution Method		Calculation	
	Echelon 2	Echelon 3	Echelon 2	Echelon 3	Echelon 2	Echelon 3
Z4P1	6	**12**	6	**13**	6	**12**
Z4P2	6	**12**	6	**13**	6	**12**
Z4P3	6	**12**	**7**	**13**	6	**12**
Z4P4	6	**12**	**7**	**15**	6	**12**
Z4P5	**7**	**15**	**7**	**15**	6	**12**
Z4a25	6	**12**	6	**13**	6	**12**
Z4a50	6	**12**	6	**13**	6	**12**
Z4a75	6	**12**	6	**13**	6	**12**
Z4t25	6	**12**	6	**13**	6	**12**
Z4t50	6	**12**	6	**13**	6	**12**
Z4t75	6	**12**	6	**13**	6	**12**

Table 4.14 Comparing number of transportation route from solution vs. CPLEX and minimum number of route of zone 5

Problem Id	CPLEX		Proposed Solution Method		Calculation	
	Echelon 2	Echelon 3	Echelon 2	Echelon 3	Echelon 2	Echelon 3
Z5P1	4	9	4	9	4	9
Z5P2	4	9	4	9	4	9
Z5P3	4	9	4	9	4	9
Z5P4	4	10	4	10	4	9
Z5P5	**5**	**11**	**5**	**10**	**4**	**9**
Z5a25	4	9	4	9	4	9
Z5a50	4	9	4	9	4	9
Z5a75	4	9	4	9	4	9
Z5t25	4	9	4	9	4	9
Z5t50	4	9	4	9	4	9
Z5t75	4	9	4	9	4	9

Table 4.15 Comparing number of transportation route from solution vs. CPLEX and minimum number of route for all zone

Problem Id	CPLEX		Proposed Solution Method		Calculation	
	Echelon 2	Echelon 3	Echelon 2	Echelon 3	Echelon 2	Echelon 3
ZAP1	-	-	**21**	**46**	**20**	**45**
ZAP2	-	-	**21**	**46**	**20**	**45**
ZAP3	-	-	**21**	**46**	**20**	**45**
ZAP4	-	-	**21**	**46**	**20**	**45**
ZAP5	-	-	**21**	**49**	**20**	**45**
ZAa25	-	-	**21**	**46**	**20**	**45**
ZAa50	-	-	**21**	**46**	**20**	**45**
ZAa75	-	-	**21**	**46**	**20**	**45**
ZAt25	-	-	**21**	**46**	**20**	**45**
ZAt50	-	-	**21**	**46**	**20**	**45**
ZAt75	-	-	**21**	**46**	**20**	**45**

4.2.3.2 Sensitivity Report

Zone 1 (Z1)

The solutions have been changed when sensitivity analysis is performed on demand in the Scenarios Z1P3-Z1P5 (44%, 72% and 107%) as shown in Figure 4.7. The models suggest to open three warehouses (two of them are the same locations to base problem). The four service centers, similar to the Scenario Z1P1, are selected and a new service center is opened more on the rental site of retailer in the Scenario Z1P3. In the Scenarios Z1P4 and Z1P5, two rental service centers are selected more compare to the Z1P1 solution. In summary, the reason to open new facilities is to support the demand expansion and the selected warehouses/service centers in base scenario are still selected on the Scenarios Z1P2-Z1P5.

About sensitivity of facility cost, it suggests not to open the company's ownership warehouse and select another site instead when saving cost rises higher to 75% of base scenario. This saving cost covers higher transportation cost, when compares to the base solution. Total cost of the Scenario Z1a75 saves 0.13% if the model applies the solution from the base problem to the Z1a75 run as shown in Figure 4.7.

After the sensitivity analysis on transportation cost shown in Figure 4.7, the results show that nothing has changed in all runs (25%, 50% and 75% sensitivities).

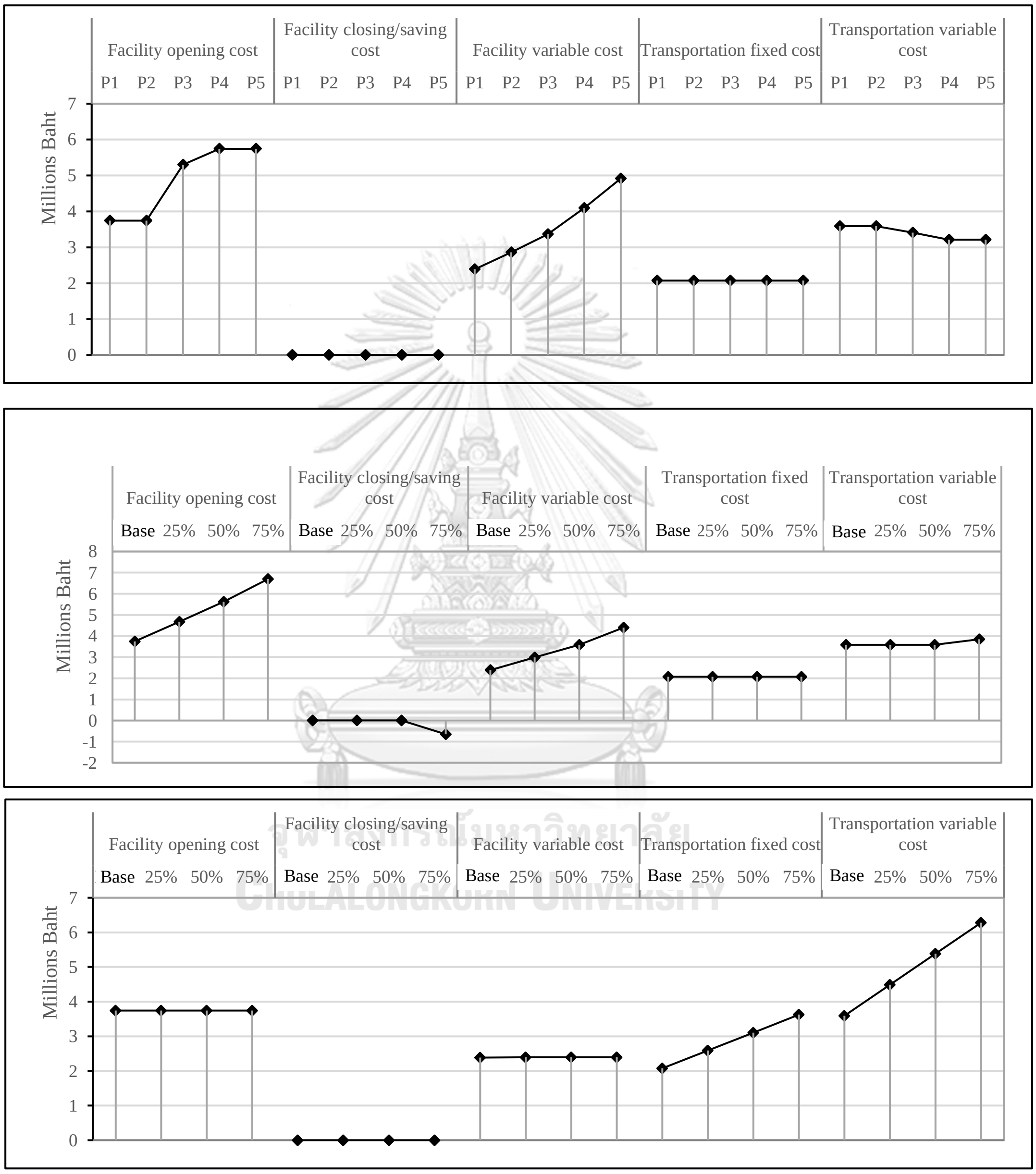


Figure 4.7 Cost component of sensitivity of zone 1

<u>Zone 2 (Z2)</u>

This zone requires two warehouses for supporting flow of products and service parts when demand sensitivity is performed in Scenarios Z2P2-Z2P5. The sensitivity results are shown in Figure 4.8.

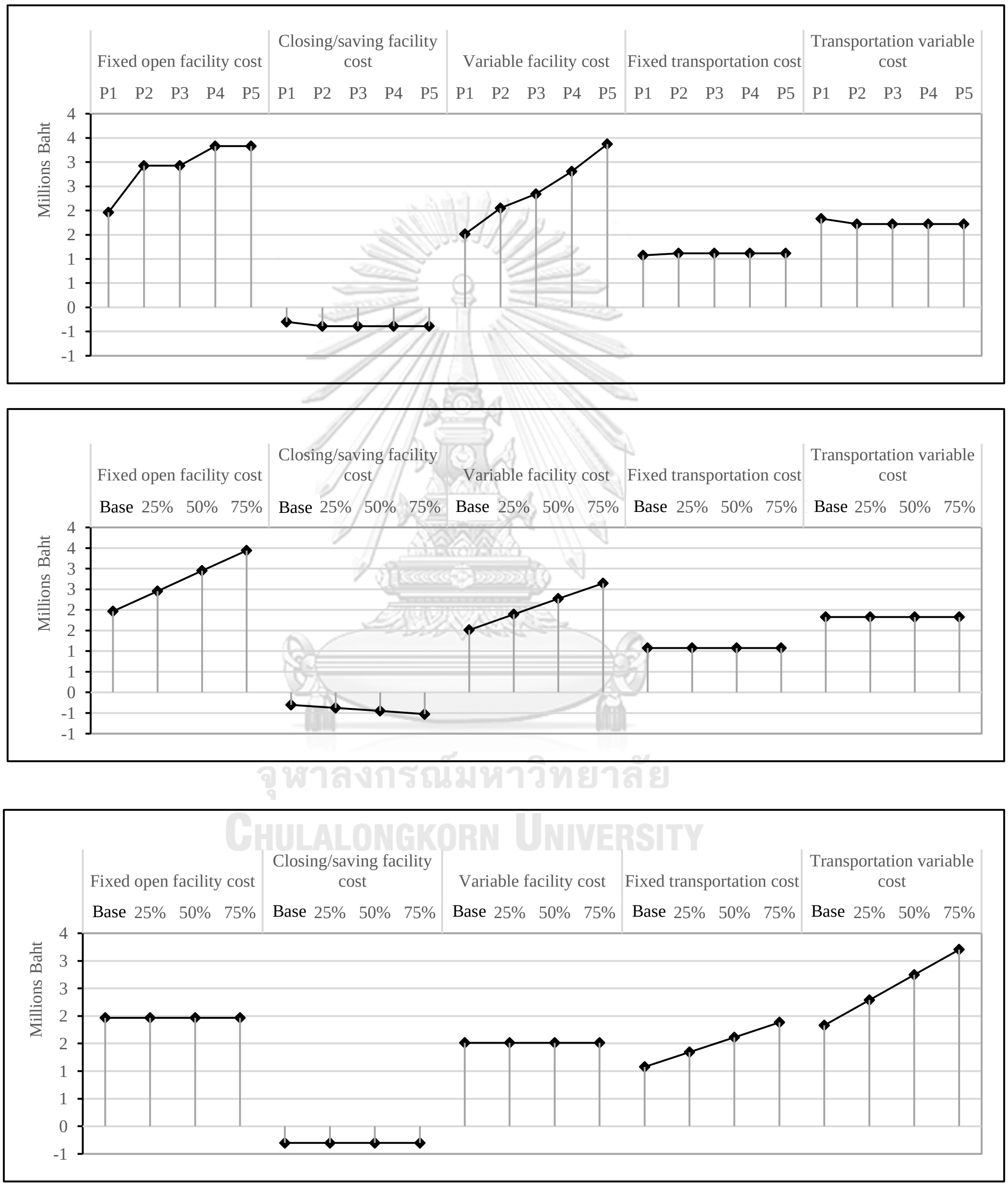


Figure 4.8 Cost component of sensitivity of zone 2

From Figure 4.8, each scenario suggests to retain a warehouse on similar location of the Scenario Z2P1 solution and open one more rental existing site (while still close one company ownership existing warehouse for a saving cost). It is reasonable results because both of them can provide the lowest facility cost and the lowest average distance to all retailers. The solutions of selected service centers have been changed when the demand quantity has risen over 72% of base demand in Scenarios Z2P4 and Z2P5. Due to demand expansion, both of the Scenarios Z2P4 and Z2P5 are opened three service centers. Two of them are located in the similar location to the Problem Z2P1, another one is rental location.

No solution is changed in 25%, 50% and 75% on facility cost/transportation cost sensitivity as shown in Figure 4.8.

<u>Zone 3 (Z3)</u>

There are greater number of open rental service centers when demand is expanded to 20% in the Scenario Z3P2 as shown in Figure 4.9. In the Scenario Z3P4, the solution suggests to open one more warehouse and one more service center for the same reason. One of company ownership service center is still closed for the benefit of saving cost similar to the base problem.

The solutions of 25% and 50% of facility cost sensitivity have provided the similar distribution networks as base problem (Z3P1), as shown in Figure 4.9. Except, the model relocates the service center to an existing rental one when the facility cost is higher than 75%, despite of slightly higher transportation cost but total cost is still reduced 0.24% if use the same solution from the Z3P1.

In 75% sensitivity on transportation cost, the solution provides lower transportation cost and closing cost at 494,345 baht. This lower cost covers the higher facility cost of service center (increase cost by 406,871 baht) as shown in Figure 4.9.

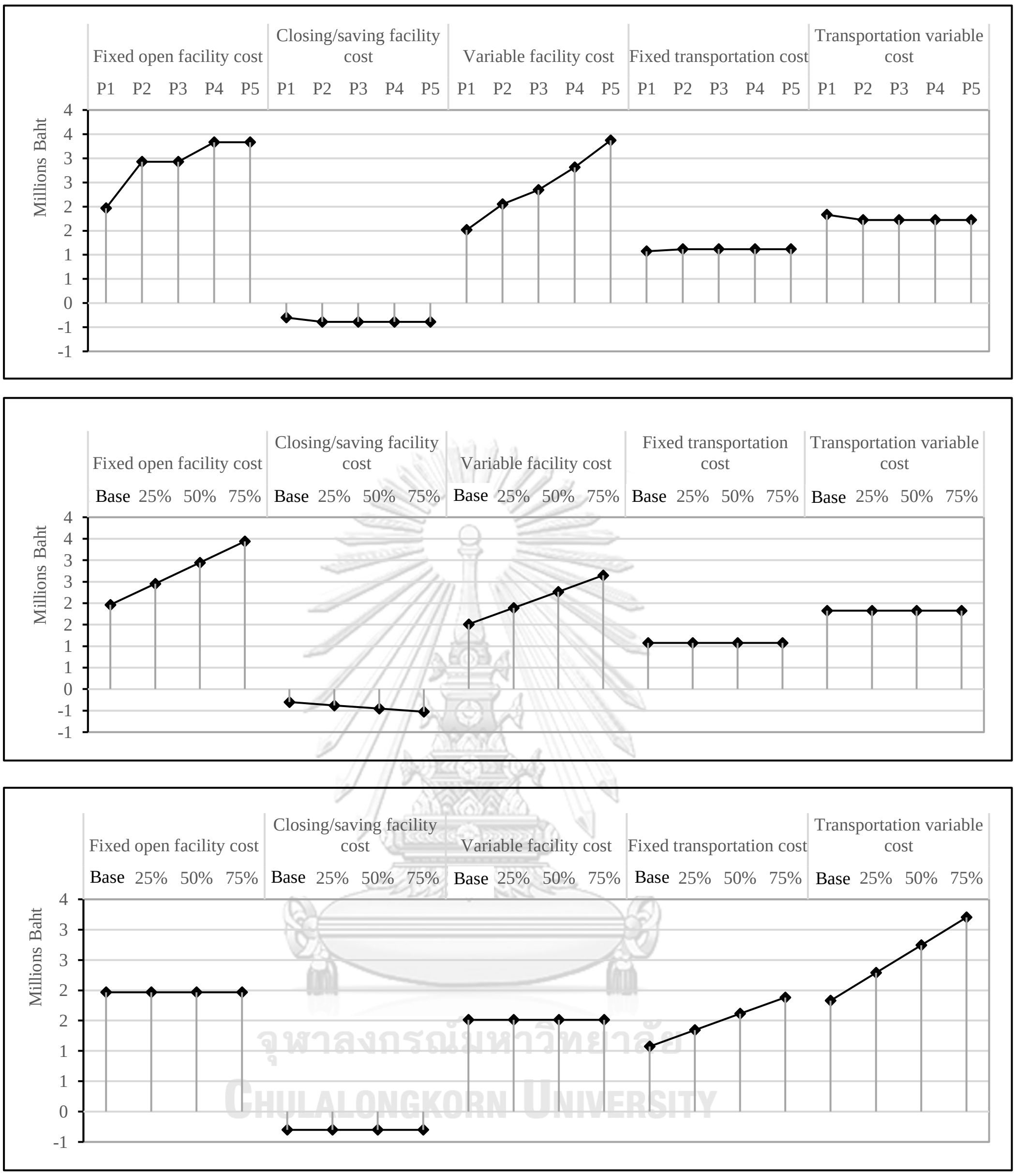


Figure 4.9 Cost component of sensitivity of zone 3

<u>Zone 4 (Z4)</u>

According to Figure 4.10, increasing the number of warehouses and service centers in the Scenarios Z4P2-Z4P5 is to support the demand expansion. Moreover, the results can be concluded that the relocation of service center is easier than relocation of warehouse, due to the solutions from the Scenarios Z4P2-Z4P5 are divergent.

The solution has been changed when facility cost is increased more than 25% (Z4a25) from base problem. All of three existing service centers are now rented, despite of the higher total transportation cost and the total fixed opening cost. It is reasonable solution due to receiving more saving cost of closing the existing service center and the lower facility variable cost (overall, save cost 0.13% if use the same result from base problem) as shown in Figure 4.10.

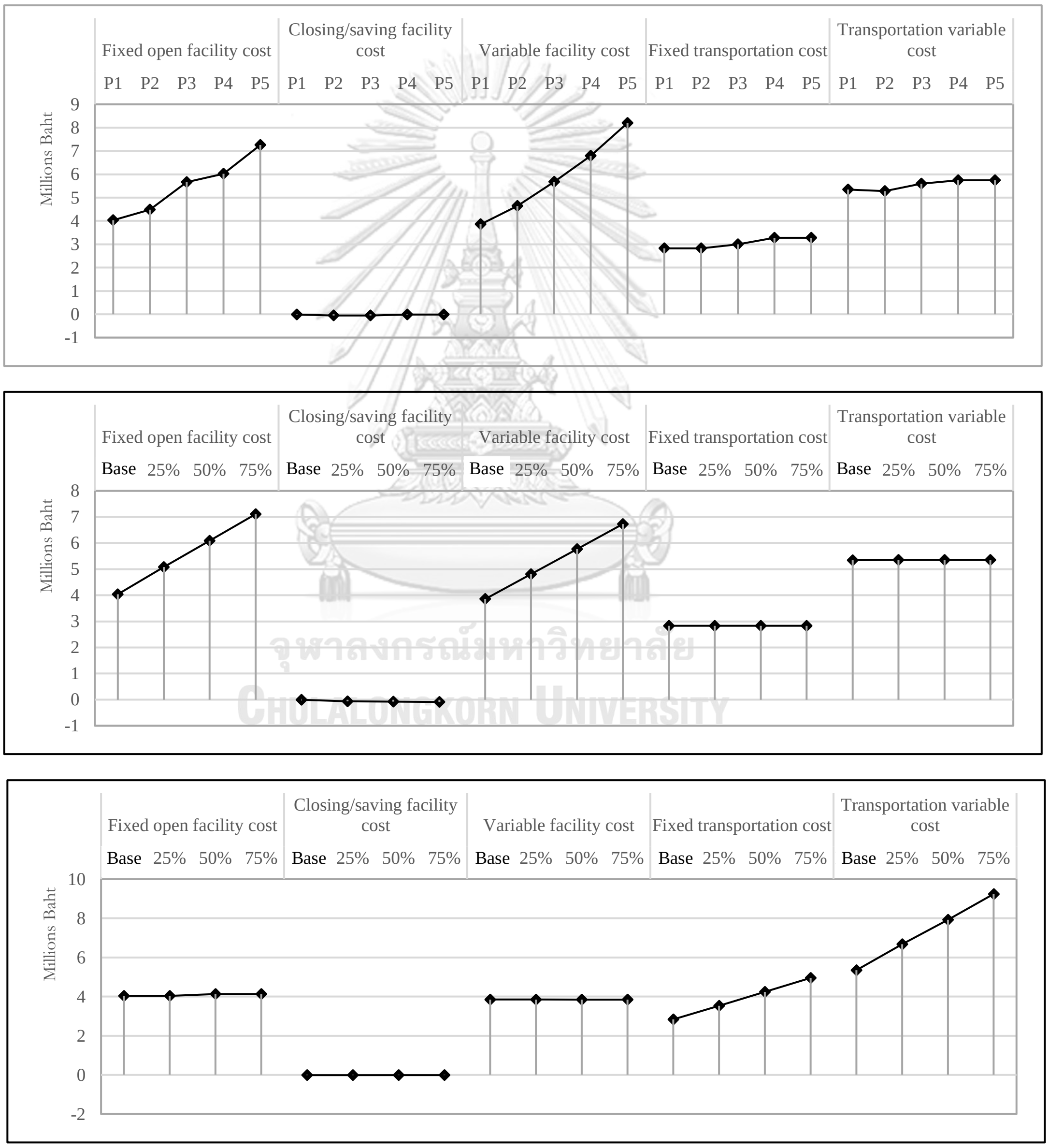


Figure 4.10 Cost component of sensitivity of zone 4

When the transportation cost increases over 50% (Z4t50) from base problem, the solution is changed. The provided solutions have reduced 0.89% and 0.12% (in 50% and 75% sensitivity analysis respectively) comparing to the base solution. But there is no change in warehouse solutions as shown in Figure 4.10.

Zone 5 (Z5)

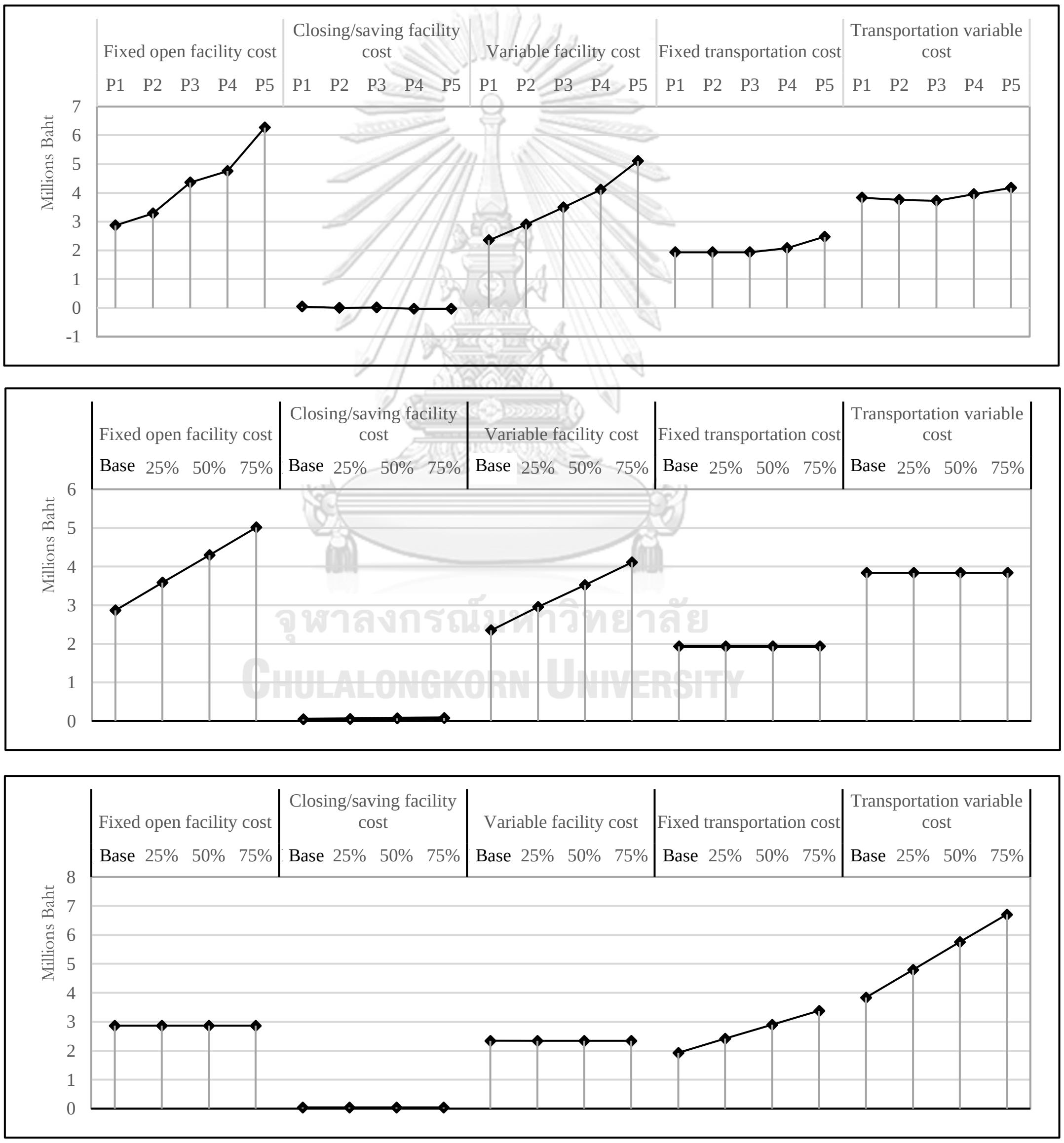


Figure 4.11 Cost component of sensitivity of zone 5

The results of sensitivity of zone 5 is shown in Figure 4.11. The number of opened warehouses has been changed when demand sensitivity increases to 44% and 107% of base quantity (Z5P3, Z5P5). All existing warehouses are selected in all demand sensitivity. Hence, there is no closing cost of warehouse, as shown in Figure 4.11. Nevertheless, the set of operating service centers is sensible across the demand sensitivity in terms of number and location to support increasing of demand.

The problems are performed sensitivities at 25%, 50% and 75% on facility cost/transportation cost but nothing has changed in facility locations. However, a number of transportation routes have been changed in Scenarios Z5P4 and Z5P5 due to allowed demand quantity parameter in clustering phase. This prevents to open more excess facility.

All Zone (ZA)

The solutions of ZAP1-ZAP5 show that increasing the number of operating facilities is to support demand expansion as shown in Figure 4.12. Both of chosen warehouse and service centers are different locations across scenarios. Moreover, it still benefits from closure existing warehouses, whereas slightly suffers from closure existing service centers across demand sensitivity. Because most closure service centers are the rental sites.

The existing warehouse is closed when the saving cost of closure the existing site is raised to 50% and 75% from the base problem, despite of the higher transportation cost. Overall, the provided solution reduces total cost 0.10% and 0.17% if uses the similar result from base problem.

Solution suggests to reopen existing warehouses and service centers when the transportation cost is increased more than 50% from original setting, despite of higher facility cost. There is still more saving cost of closing existing warehouse and facility variable cost. In summary, the model can reduce cost 0.35% and 0.24% in 50% and 75%.

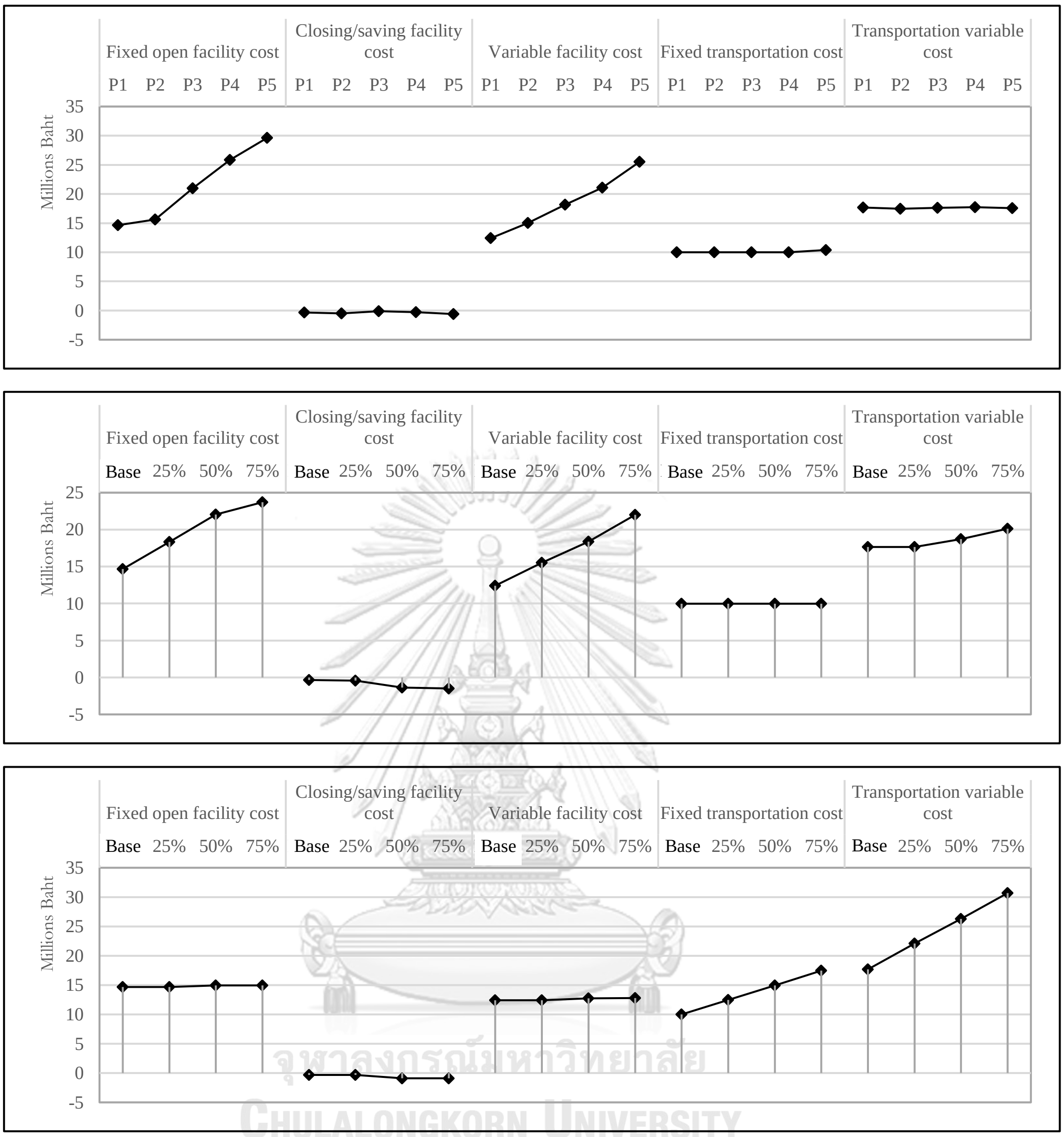


Figure 4.12 Cost component of sensitivity of all zones

4.3 Special Scenario and Discussion

This section analyzes the results from solving each zone individually and all zones simultaneously. The results are shown in Table 4.16. Columns 2-3 present total costs from solving each zone individually for both of CPLEX and proposed heuristic approach, respectively. Column 4 shows total costs of solving all zones simultaneously by proposed heuristic approach. Finally, Columns 5-7 present %different total cost comparing with particular result that mentioned before.

The results of allowing the distribution across different zones (ZA) provide the best solutions (except Scenario ZAP5). Its total cost is lower than solutions from solving each region independently for both of CPLEX and heuristic approach, averaged 3.20% and 1.94% respectively. Moreover, the summation of total cost from solving individual zone by heuristic also provides lower costs than CPLEX with an average lower cost of 1.27%.

Table 4.16 Comparison on the solutions from solving each region independently and allowing the distribution across different zones

Scenario	Sum of total cost for all zone			% different total cost		
	Solving each zone individually by CPLEX (1)	Solving each zone individually by heuristic (2)	Across different zones problem (ZA) by heuristic (3)	$\frac{(2)-(1)}{(1)}\%$	$\frac{(3)-(1)}{(1)}\%$	$\frac{(3)-(2)}{(2)}\%$
P1	56,612,155	55,640,866	54,391,788	-1.72%	-3.92%	-2.24%
P2	61,244,280	60,242,243	57,647,024	-1.64%	-5.87%	-4.31%
P3	68,358,552	67,261,172	66,592,059	-1.61%	-2.58%	-0.99%
P4	75,399,872	74,417,148	74,363,330	-1.30%	-1.43%	-0.07%
P5	82,881,784	82,481,008	82,506,539	-0.48%	-0.50%	0.03%
a25	63,267,542	62,534,828	61,079,684	-1.16%	-3.46%	-2.33%
a50	70,406,804	69,392,015	67,700,273	-1.44%	-3.84%	-2.44%
a75	77,308,234	76,204,695	74,325,207	-1.43%	-3.86%	-2.47%
t25	63,389,865	62,674,654	61,301,839	-1.13%	-3.29%	-2.19%
t50	71,595,667	69,689,974	67,974,168	-2.66%	-5.06%	-2.46%
t75	77,100,369	76,552,064	74,939,002	-0.71%	-2.80%	-2.11%
Average				**-1.27%**	**-3.20%**	**-1.94%**

The solutions from the Problem ZA have fewer number of operating facilities. As the sharing of facilities across zones is allowed, the utilization of each facility is increased. Also, locations of operating facilities are moved to more proper locations. The lower cost of solving across different zones problem has two cases;

- With smaller number of operating facilities: The cost saved from fixed facility cost can compensate for the increasing of transportation distance cost. Therefore, the total cost is lower than the sum of individual zone.

- With the equal number of operating facilities: Although the number of operating facilities is the same as solving each zone individually in some scenarios, but the operating facilities are more properly assigned, especially for the boundary node. Therefore, the Problems ZA provide significantly lower cost of transportation than solving each zone individually.

Nevertheless, allowing distribution across zone is against the company original policy. In order to get benefit from these results, the company needs to re-zone the distribution to comply with solutions, especially the demand nodes in the boundary.

From Table 4.16, based problem of solving all zones altogether (ZAP1) gives lower cost at 54,391,788 baht. The ratio of transportation cost to facility cost is 41.5% to 59.7% as shown in Figure 4.13. Also, Figure 4.14 presents the detail of each type of cost. Transportation variable cost is the highest cost, follows by variable cost of warehouse. While service center closing/saving cost is the lowest cost, follows by warehouse saving/closing cost.

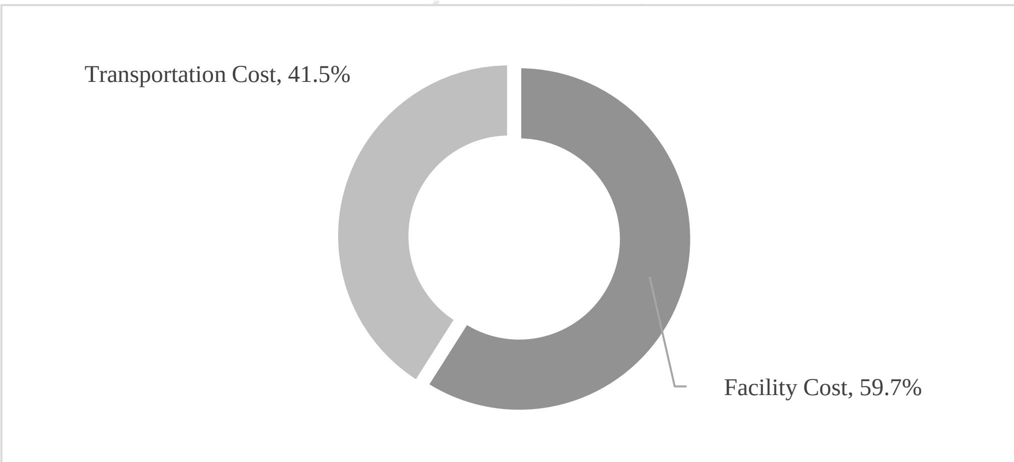


Figure 4.13 Proportion of transportation cost to facility cost of ZAP1

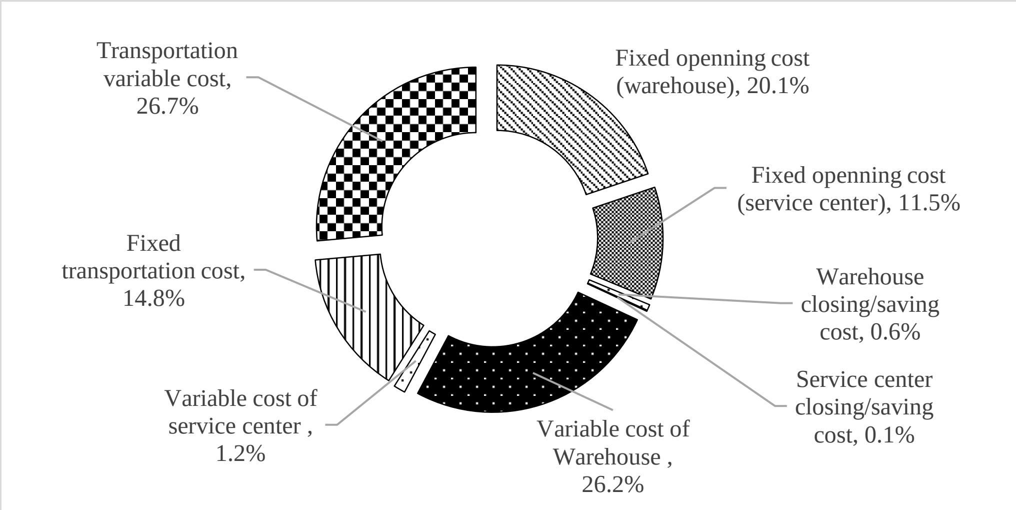


Figure 4.14 Detail of each type of cost of ZAP1

Next, this study compares the result of current distribution network (as-is) to base problems that solving by proposed solution method as shown in Table 4.17.

Table 4.17 Comparison on the solutions to current distribution network

Zone	Cost (Baht)			Number of facilities			Number of routes		
	(1)	(2)	(3) ***	(1)	(2)	(3)	(1)**	(2)	(3)
1	11,627,478	11,528,717*	12,202,777	5	6	4	-	16	18
2	7,584,569	6,083,007	6,273,042	4	3	3	-	8	9
3	11,255,476	10,688,392	10,915,463	4	4	5	-	16	16
4	16,401,261	16,057,958	14,419,073	6	6	5	-	22	19
5	11,159,067	11,021,509	10,657,432	5	4	5	-	15	14
Summation	58,027,851	55,379,583	54,467,788	24	23	22	-	77	76

Note that (1) current distribution network, (2) result from individual zone and (3) result of across different zones solving.

* Solution from CLEX that provide better result than heuristic.

** Cannot identify number of routes for current distribution network.

*** The zone of ZAP1 solution is based on warehouse locations and their networks.

The total distribution cost of actual case study is equal to 58,027,851 baht. But redesigning distribution network of each zone separately (Z1P1, Z2P1, Z3P1, Z4P1 and Z5P1 scenario) has cost at 55,379,583 baht, while solving all zones together without any limitation of distribution management policy (ZAP1 scenario) contributes 54,467,788 baht of overall cost (see Table B5 in Appendix B).

Once again, allowing distribution across different zones provides the lowest total cost. This confirms by overall cost is lower than the current distribution network at 6.13%. Zone 1, which is located in the middle area and has boundary linked to other zones, has largely changed on distribution network for Problem ZA. A warehouse in zone 1 is assigned to distribute products to serve a retailer in zone 3. Another warehouse and service center in zone 1 also distributes goods to retailers and customers in the boundary of zone 4. Hence, the number of operating warehouses is lower than the current one because the current utilizations of warehouses in this zone are not density. Hence, the total demand of zone 1 is increased, whereas the total demand of zone 4 is reduced as shown in final column of Table 4.17. The advantage of this situation is the responsibility of regional manager of these zones is more balanced.

The result also indicates that the remaining capacity of facilities in zone 4 is assign to serve some retailers and customers in zone 5. Most distributions in zone 2 and 3 are similar to the problem of solving each zone individually, because of their regions are located in isolated zones. Nonetheless, the purpose of increasing number of open facilities (service center) in zone 3 and 5 is to reduce distance cost. However, the solving simultaneously across different zones is still open fewer facility sites than the current one and solving each zone individually. In conclusion, most of the changing occur in the boundary area. Therefore, it is reasonable and easy to modify distribution networks in order to get lower cost.

Because there is no zoning in ZAP1, cost of each zone must be identified by allocating total cost to each zone in order to in-depth analyze the changing of each zone. The total cost is shared to each zone by considering the location of opened warehouse. If the location is located on which zone, the operating cost is allocated to that zone, in order to analyze the cost saving compared to as-is distribution network and the problem of solving each zone separately. The comparisons are shown in Figure 4.15.

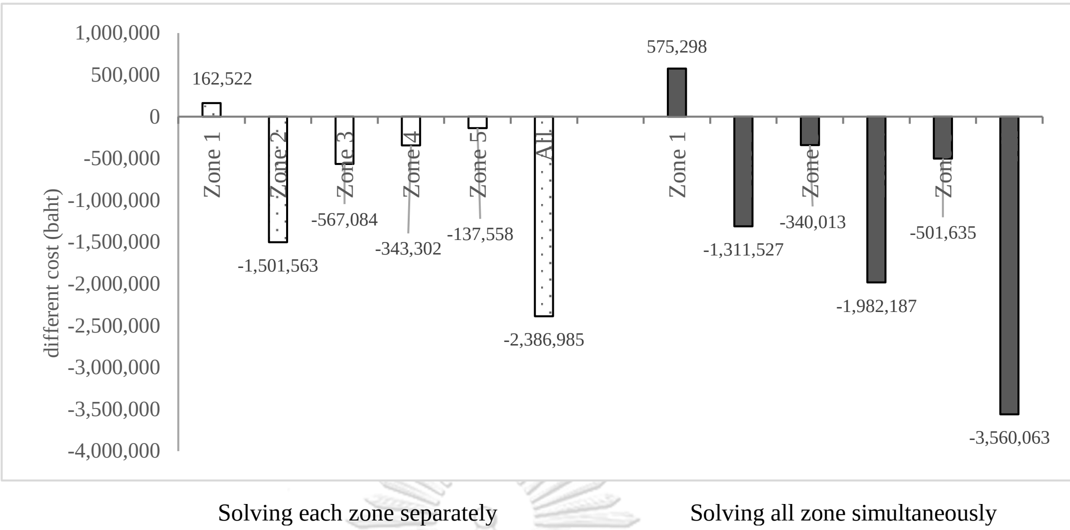


Figure 4.15 The comparison of cost saving between solving each zone separately and solving all zone simultaneously

From Figure 4.15, cost saved from solving each zone separately mostly comes from zone 2 as the solution suggest to operate only one warehouse, also transportation cost is reduced. Even cost of zone 1 is increased, but the total cost is reduced up to 2,386,985 baht.

The solution from solving all zones together can reduce cost up to 3,560,063 baht which mostly comes from zone 2 and zone 4. Reduced cost of zone 2 comes from lower number of opened warehouse same as the problem of solving each zone separately. Reduced cost from zone 4 comes from reassigning demand to zone 1. Moreover, with lower number of operated facilities and rezoning responsible area lead to lowest cost compared with other zones. However, demand of zone 4 is particularly reassigned to zone 1, therefore cost of zone 1 is increased by higher variable cost of Warehouse (see Table B5 in Appendix B). Figure 4.16 illustrates all sources of reduced cost.

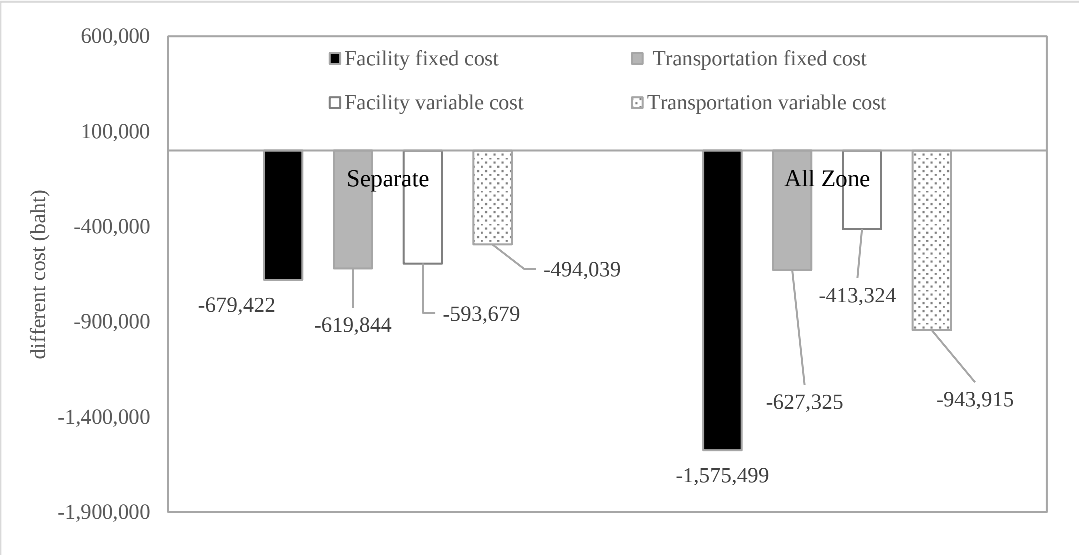
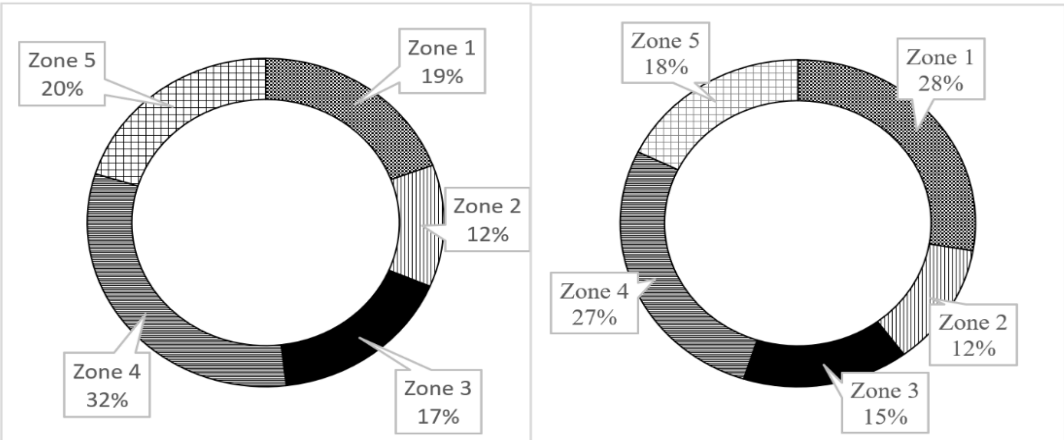


Figure 4.16 Sources of reduced cost



(a) Solving each zone individually (b) solving all zone simultaneously

Figure 4.17 Demand distribution in each zone

Figure 4.17 presents demand distribution in particular zone for each type of problem. And solving all zone simultaneously can provide better balance of demand distribution. Zone 4 and zone 1 have most changes in demand proportion as shown in Figure 4.15. From Figure 4.15 (b), 27% of overall demand per year is assigned to zone 4, which is reduced from 32% when solving each zone individually. Most of decreasing demand in zone 4 is transferred to zone 1. Therefore, in zone 1, demand has increased from 19% to 28%. In summary, solving all zone together leads to more balance in demand distribution.

The studied problem is LRP, which focusing on selecting location with consideration of cost of round trip transportation, in order to design the network. To obtain the best solution, the results of each problem is compared together. In other words, the results of solving each zone independently and solving all zone together are compared together (see Table B6 Appendix B). The comparison of number of opened warehouses, throughputs, and warehouse utilization are shown in Table 4.18.

Table 4.18 Assigned demand for particular warehouse for all problems

Zone	current distribution network			Solved by separated zone			Solved by all zone		
	Warehouse Id	Throughput	Utilization	Warehouse Id	Throughput	Utilization	Warehouse Id	Throughput	Utilization
1	3	41,182	81.9%	3	27,305	42.4%	2	51,570	99.2%
	5	27,226	59.9%	5	41,103	90.5%	3	46,458	92.4%
2	8	11,996	29.9%	9	42,540	85.0%	9	42,869	85.6%
	11	30,544	60.5%						
3	13	32,532	64.8%	15	44,097	87.7%	13	39,073	77.9%
	16	26,941	53.6%	16	15,376	30.6%	17	14,478	28.9%
4	18	45,140	81.6%	18	42,486	76.8%	18	53,051	95.9%
	20	28,563	63.4%	20	19,648	43.6%	21	43,378	86.5%
	21	38,307	76.4%	21	49,876	99.4%			
5	25	33,377	66.3%	25	30,284	60.2%	25	19,760	39.3%
	28	38,095	76.0%	28	41,188	82.2%	28	43,266	86.4%
	average		64.9%	average		69.8%	average		76.9%

From Table 4.18, it shows that solving all zone together has lowest number of opened warehouses which leads to highest utilization. However, %utilization of some warehouse is fairly low compared to its capacity, for example, warehouse ID 17, which is new rental warehouse. Therefore, management team must consider to reduce capacity of this warehouse as this is new rental location. Another warehouse which has low utilization is warehouse ID 25 which is existing rental location. Therefore, this warehouse must be resized after the contract expires.

In contrast to warehouse ID 7 and 25, warehouse ID 2 has very tight capacity as its utilization is almost reach to 100%. Thus, this warehouse should be considered to expand its size in order to meet demand quantity in the future.

Same as warehouses, results of service center are shown in Table 4.19. Note that all solutions from as-is and both of heuristic solving indicate that average of utilization of capacity are not different.

Table 4.19 Assigned demand for particular service center for all problems

Zone	As-is distribution network			Solved by separated zone			Solved by all zone		
	Service center id	Demand	Utilization	Service center id	Demand	Utilization	Service center id	Demand	Utilization
1	32	916	87.2%	32	686	65.3%	33	903	89.7%
	34	997	90.6%	34	584	53.1%	35	866	86.0%
	40	781	82.2%	35	896	89.0%			
				40	528	55.6%			
2	42	503	50.3%	42	404	40.4%	42	756	75.6%
	45	670	66.5%	45	770	76.4%	45	747	74.1%
3	47	922	91.8%	48	718	71.5%	48	808	80.5%
	51	785	78.2%	52	989	98.1%	52	630	62.5%
							54	359	35.8%
4	59	622	62.1%	62	918	91.3%	62	787	78.3%
	64	838	83.5%	67	944	93.5%	67	993	98.4%
	67	784	77.7%	71	842	83.8%	68	943	94.2%
	71	460	45.7%						
5	77	996	99.6%	77	976	97.5%	76	628	62.5%
	80	950	100.0%	82	970	96.5%	84	853	85.2%
							87	952	94.6%
	average		78.1%	average		77.8%	average		78.3%

In this chapter, the base problems of three-echelon multi-commodity LRP along with sensitivity analysis scenarios are solved by both exact method and proposed heuristic. The results indicate that the proposed hybrid heuristic provides more efficient solution than exact method. It is obvious that it can be significantly achieve the lower computation time and overall distribution cost than exact method. Moreover, most solutions from the models can provide solid solutions across demand and cost sensitivity. A deeper inspection of the solutions reveals that the locations of selected warehouse are not changed across sensitivity analysis. In contrast, the locations of operated service center are changed easily in particular problem because most service centers have lower closing cost (moving cost) and there are many more candidate sites than warehouses. Finally, the redesign of existing distribution network by allowing distribution across different zones provides lowest cost comparing to the current one and the problem of solving each zone separately.

Nevertheless, the design of distribution network in this research is based on deterministic environment. Implementing the solution may have risk to inappropriate decision in strategic level which needs high investment and can leads to inadequate consequences. Hence, the solution will be tested under uncertain circumstance of distribution environment by simulation using Arena which will be explained in the next chapter.

CHAPTER 5
VALIDATION BY SIMULATION

The purpose of this chapter is to evaluate the solutions from three-echelon location routing model solved in chapter 4. This chapter is first described the conceptual simulation model as well as the main input variables and uncontrollable variables applied to model in order to test stochastic environmental. Next, the output variables are also determined as key effectiveness to compare the particular solutions. To run simulation model, the key parameters are identified and calculated suitable value for the models. Finally, the results of simulation models are presented and analyzed.

5.1 Conceptual Design of Simulation

    5.1.1 Simulation Steps

    5.1.2 The Conceptual Simulation Model

    5.1.3 Goodness of Fit

5.2 Simulation Model

    5.2.1 Model Development

    5.2.2 Parameter Setting

5.3 Simulation result and Discussion

5.1 Conceptual Design of Simulation

5.1.1 Simulation Steps

Since the proposed mathematical model shown in chapter 3 and 4 is formulated in deterministic environmental, to implement the solution may have different result in real-life situation. Because the proposed model concerns only facility capacity and deterministic demand quantity with single-sourcing and the route can be always operated as tour transportation in the 2^{nd} and the 3^{rd} echelon of distribution network. Therefore, this study applies simulation technique to evaluate the solutions from model in different stochastic environments.

This research performs steady-state simulation with replication/deletion method in this research due to this case study is distribution network problem, which is continuous process and can continually perform until finishing the task (Law & Kelton, 2000). Figure 5.1 represents all simulation steps. It can be described as the following steps:

1. Find the distribution patterns of data, which is collected from research. The distribution patterns will be used in simulation model.
2. Develop as-is simulation models, which is the model of current distribution network. This research uses Arena software version 15.00.
3. Perform 30 replications of pilot run. Then identify warm up period and calculate suitable number of replications.
4. Validate the model by comparing to historical data, using two-sample t test.
5. Plan and run models with solution from mathematical model.

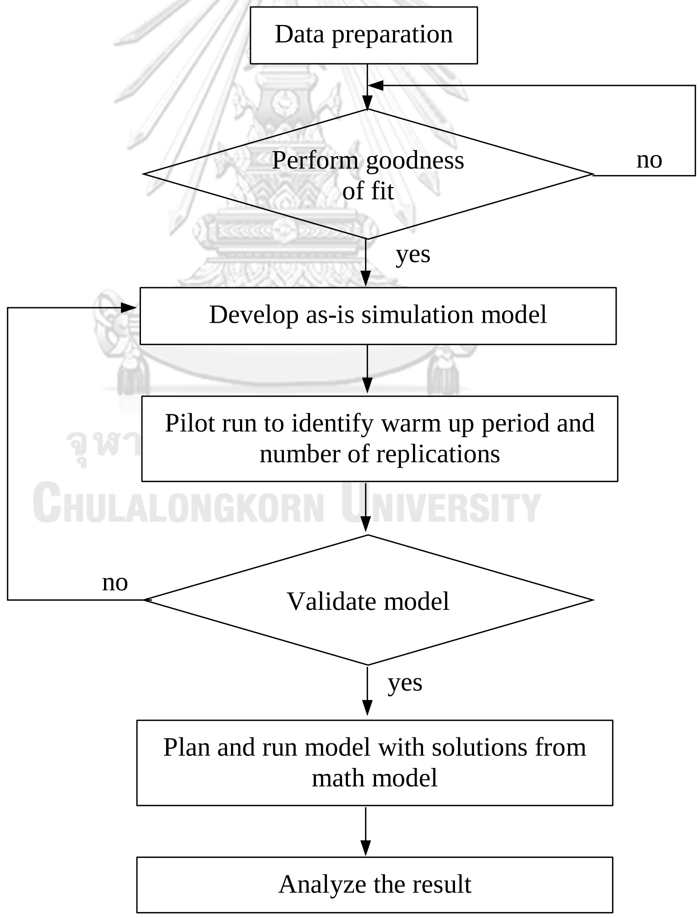


Figure 5.1 Simulation steps

6. Collect the output from Arena then analyze the results from as-is model and models with solution from mathematical model.

5.1.2 The Conceptual Simulation Model and Input Data

There are three types of data; input data, random data, and output data, which are applied in simulation model as shown in conceptual simulation model in Figure 5.2. Input data comes from two sources. The first one is operating facility locations, allocation patterns and routes, which obtained from mathematical models solved by proposed heuristic (both of separated zone solving and all zones simultaneously solving). Another source is stochastic environmental data, which has four inputs, i.e. number of trucks, distance, maximum waiting time, and replenishment policy. Random variable means uncontrollable data, which are demand frequency and demand quantity. Output data is the index for efficiency measurement, which comprises of total cost and throughput. The conceptual model is presented in Figure 5.2.

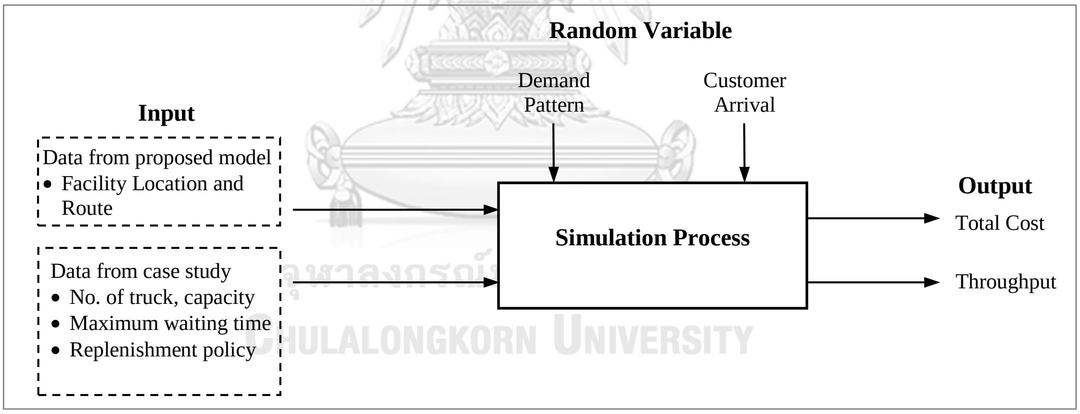


Figure 5.2 Conceptual simulation model

In the simulation, the transportation in the 1st echelon is assumed to be full truckload because the company always performs return route to deliver goods from a depot to each warehouse. The transportation in the 2rd echelon is a round trip, therefore, multiple retailers are able to combine into same vehicle based on their quantity and vehicle capacity. The company manager sets the maximum number of visiting points per route equal to three points to avoid transporting after hours and late return of vehicle. The company applies the maximum number of visit points instead of maximum traveling time because it is easier for the planners to construct routes and traveling time do not affect actual time, which each vehicle is used for transferring goods in each round.

In the 3rd echelon, the transportation is the return trip and round trip based on delivery item. If the delivery items are shop products, the company perform return route to satisfy demand of customer directly (because of its big size). When the delivery items are service parts, it is possible to combine route in the simulation model due to the maximum number of visiting point and allowable waiting time. As this type of customer needs urgent maintenance service, waiting until there is request from nearby customer is not possible. Hence, route to serve only one customer could occur. The assumptions of transportation are showed in the following parts:

- Shipping volume from single depot to each warehouse is equal to vehicle capacity with normal replenishment period of 30 days. The transportation always takes two days for all destinations (one day for a head haul and one day for a backhaul). Number of trucks and its capacity (equivalent unit) are shown in Table 5.1.

Table 5.1 Number and capacity of vehicles of each echelon

Echelon	Number of vehicle	Capacity (Unit)
1st echelon	3 trucks	1,500
2nd echelon	2 trucks per warehouse	450
3rd echelon	2 small truck per service center	-

Table 5.2 Probability of shop product (return route) vs. service part (round trip)

Data	Frequency	% Frequency	% Accumulated frequency
Return route	47	13.6%	13.6%
Round trip	298	86.4%	100.0%

- The transportation from a warehouse to each retailer/service center has policy to replenish in every five days (weekday). Each transportation takes one day. The number of vehicle and its capacity are shown in Table 5.1.

- The transportation from a service center to each customer can be both of return route (the number of shop product trip that obtained from historical data) and round trip (the number of service part trip) as probability shown in Table 5.2. Each transportation takes one day. Based on company policy, maximum waiting time for combining route equals to two days. If there are three routes combined together, the transportation starts.

Assumptions to run simulation in this thesis are:

- Each replenishment of directed transportation to deliver finished goods and part from depot to warehouse in the 1st echelon is always full truck load. For the 2nd echelon, transportation load depends on replenished demand distribution.

- It is assumed that there are always sufficient products and service parts available in the studied simulation model.

- One vehicle can manage and operate only one tour trip per day.

5.1.3 Goodness of Fit

Before inputting data into simulation model, the probability distribution of data must be identified. The collected data is tested the goodness of fit by Chi-square test (Kelton, Sadowski, & Sturrock, 2003) as the following hypothesis:

H_0: Fitted distribution adequately represents the data

H_1: Fitted distribution adequately not represents the data

Notice that *p*-value is used as indicator that identify fit level. If *p*-value is greater than significant level (0.05), the null hypothesis is accepted and the collected data can be fit to theoretical distribution. In other words, the expression can apply to use in Arena model precisely. The input analyzer in Arena version 15.00 has been used to identify demand pattern (Kelton *et al.*, 2003).

According to different demand quantity occurred in each zone and different solution from each type of solving (separated zone and all zone simultaneously), this study identifies the demand occurred at retailer as shown in Table 5.3 and 5.4. Table 5.5 and 5.6 are customer demand distribution, which are applied to the model for the 2nd echelon only (the 3rd echelon transportation does not consider the vehicle capacities as mentioned before).

Table 5.3 Retailer demand distribution for separated zone problem (units per week)

Zone	Distribution	Expression (Units)	Square Error	Corresponding *p*-value
Zone 1	Normal	NORM(1217, 112)	0.010145	0.364
Zone 2	Beta	673 + 184 * BETA(1.2, 1.38)	0.006312	0.587
Zone 3	Uniform	UNIFORM(921, 1102)	0.0212	0.176
Zone 4	Triangular	TRIA(1541, 1862, 1942)	0.01721	0.218
Zone 5	Normal	NORM(1291, 173)	0.013172	0.328

Table 5.4 Retailer demand distribution for all zone problem (units per week)

Zone	Distribution	Expression (Units)	Square Error	Corresponding *p*-value
Zone 1	Triangular	TRIA(1045, 1297, 1352)	0.012145	0.332
Zone 2	Normal	NORM(894, 50.6)	0.007674	0.429
Zone 3	Beta	715 + 291 * BETA(3.68, 1.5)	0.012411	0.687
Zone 4	Beta	1.34e+003 + 414 * BETA(1.25, 0.882)	0.007877	0.396
Zone 5	Triangular	TRIA(1041, 1.360, 1.482)	0.009207	0.377

Table 5.5 Customer demand distribution for separated zone problem (units per week)

Zone	Distribution	Expression (Units)	Square Error	Corresponding *p*-value
Zone 1	Uniform	UNIF(25, 70)	0.013521	0.531
Zone 2	Weibull	14.5 + WEIB(4.57, 1.75)	0.008169	0.419
Zone 3	Lognormal	20.5 + LOGN(9.33, 12.5)	0.016967	0.093
Zone 4	Normal	NORM(50.7, 3.27)	0.019136	0.341
Zone 5	Weibull	16.5 + WEIB(22.1, 1.39)	0.016606	0.153

Table 5.6 Customer demand distribution for all zone problem (units per week)

Zone	Distribution	Expression (Units)	Square Error	Corresponding *p*-value
Zone 1	Beta	30.5 + 48 * BETA(1.3, 1.43)	0.020614	0.0994
Zone 2	Normal	NORM(24.1, 2.98)	0.018506	0.102
Zone 3	Lognormal	19.5 + LOGN(8.08, 9.81)	0.020654	0.223
Zone 4	Normal	NORM(49.1, 3.7)	0.018127	0.244
Zone 5	Weibull	15.5 + WEIB(24.7, 1.52)	0.014631	0.116

It is easy to model the problem when model set the entity as a customer who request for a service. Hence, the data for 3rd echelon transportation will be identified as an inter-arrival time of customer as shown in Table 5.7 and 5.8 and define customer ID by using discrete probability depend on data in Table A3 (Appendix A).

Table 5.7 Arrival rate of request for service (for as-is and separate model)

Zone	Arrival rate (customer per day)
Zone 1	11
Zone 2	7
Zone 3	9
Zone 4	13
Zone 5	9

Table 5.8 Arrival rate time of request for service (for simultaneous model)

Zone	Arrival rate (customer per day)
Zone 1	13
Zone 2	8
Zone 3	8
Zone 4	11
Zone 5	8

5.2 Simulation Model

5.2.1 Model Development

This research has developed the simulation model in Arena version 15.00. There are three simulation models to test in this research, which are, 1) as-is model, 2) solving each zone individually model, and 3) solving all zones together model. The example of simulation model is presented in Figure 5.3-5.6.

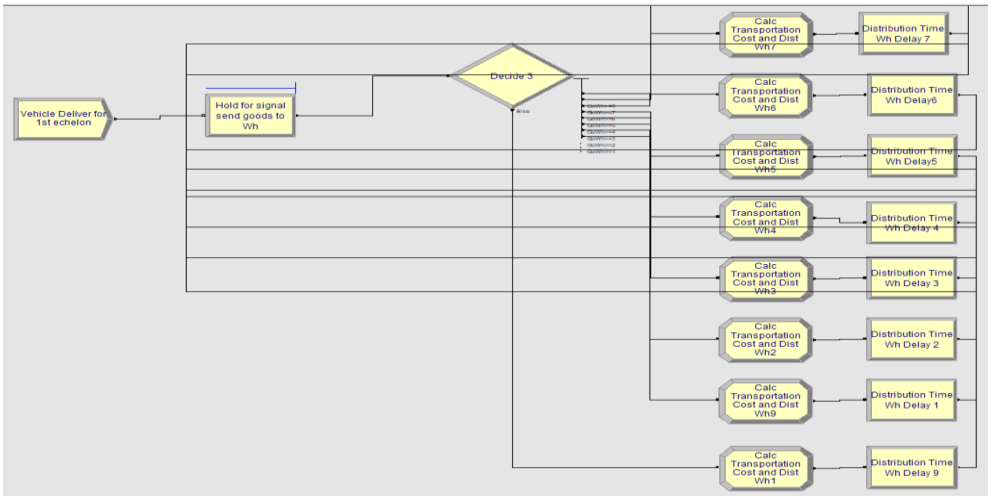


Figure 5.3 The model for the 1st echelon distribution network (physical flow)

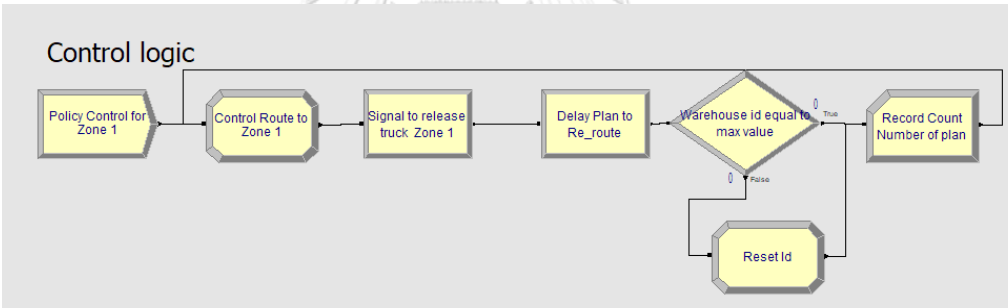


Figure 5.4 The model for the 1st echelon distribution network (control logic)

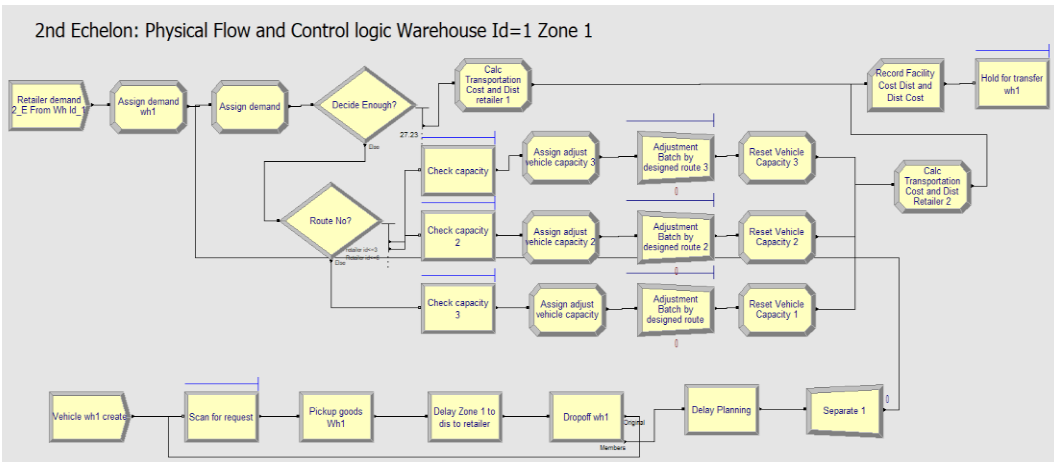


Figure 5.5 The simulation model for the 2nd echelon distribution network

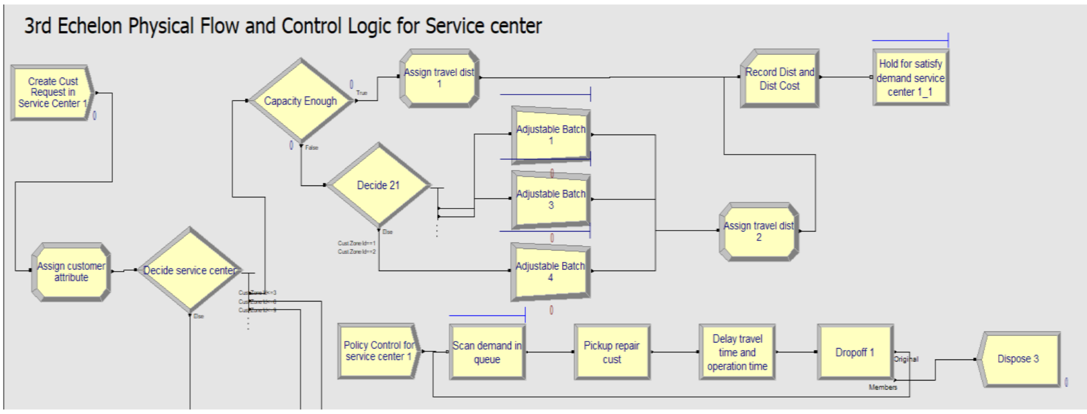


Figure 5.6 The simulation model for the 3rd echelon distribution network

5.2.2 Parameter Setting

To run steady-state simulation, pilot run is first conducted in order to identify warm up period and number of proper replications. Replication length of pilot run equals to 52 weeks. Figure 5.7 presents results of weekly total cost from pilot run. The Figure 5.7 indicates that total weekly cost is rising from the beginning (warm up period), after that, it becomes more stable.

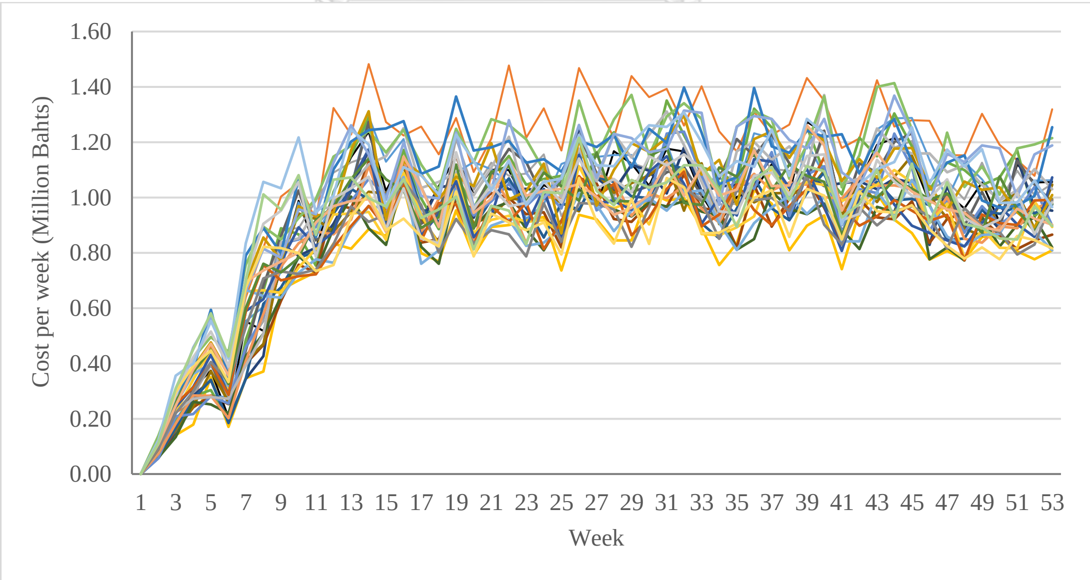


Figure 5.7 Result from pilot run

To specify the critical point between transient and steady state, this research applies Welch's method. This method smooths the simulation output data to identify transient state. It is calculated by equation 5.1 (Kelton *et al.*, 2003; Law & Kelton, 2000).

$$\bar{Y}_i(w) = \begin{cases} \dfrac{\sum_{s=-w}^{w} \bar{Y}_{i+s}}{2w+1} & \text{if } i = w+1,\ldots,m-w \\ \dfrac{\sum_{s=-(i-1)}^{i-1} \bar{Y}_{i+s}}{2i-1} & \text{if } i = 1,\ldots,w \end{cases} \tag{5.1}$$

Where w = Welch's smoothness index such that $w \leq [m/4]$

To conduct Welch's method, this research set *w*=4. From the result shown in Figure 5.8, the line of total weekly cost is fairly smooth. Therefore, setting *w*=4 is acceptable. From Figure 5.8, transient state or warm up period is from week 1 to week 16. Therefore, actual replication length is two years plus 16 weeks (120 weeks).

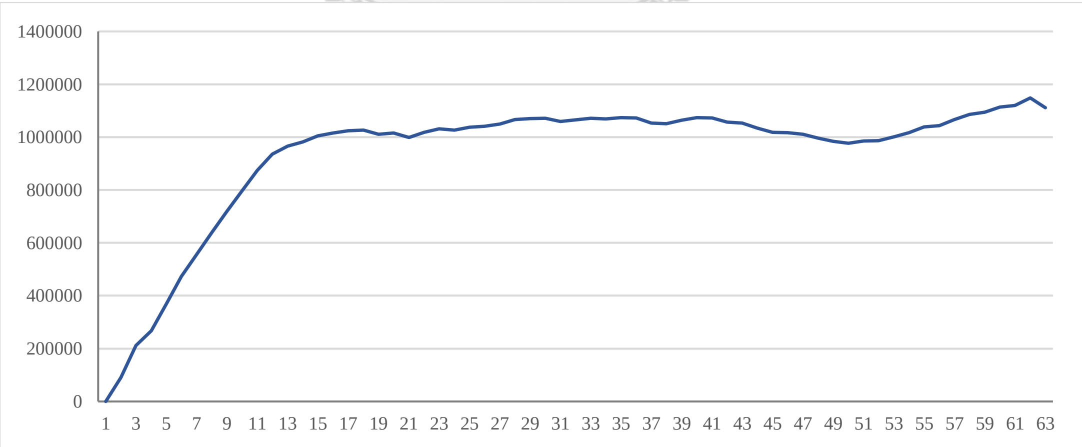


Figure 5.8 Result from Welch's method

To prevent any bias in analyzing result phase, to identify the number of proper replication is the important step. After determining warm up period, pilot run to find initial half-width is run with replication length of 120 weeks. The results are shown in

Table 5.9. Initial half-width (h_0) is calculated by using equation 5.2 (Kelton *et al*., 2003; Law & Kelton, 2000).

$$h_0 = t_{n-1,\alpha/2} \frac{s}{\sqrt{n}} \tag{5.2}$$

Where n = number of replications of pilot run

$t_{n-1,\alpha/2}$ = critical value from t table

s = standard deviation

Table 5.9 Results from pilot run of as-is simulation model

Model	Total cost (Baht/year) (Y)	Standard deviation (Baht/year) (s)	Half-width (Baht/year) (h_0)	α	n
as-is model	58,505,489	1,978,911	738,937	0.05	30

Once analyzed result obtains the initial half-width (h_0), then the simulation model can identify the desired half-width (h). The value of h should be lower than h_0. Since the total cost is in ten million digits and h_0 is = 738,937 baht, the new h is set at 400,000 baht (approximately 50%) to enhance precisely comparing the result. Then the value of h is used to estimate the suitable number of replications using equation 5.3 (Kelton *et al*., 2003; Law & Kelton, 2000).

$$n_R = t^2_{n-1,\alpha/2} \frac{s^2}{h^2} \tag{5.3}$$

Where n_R = number of replications

$t_{n-1,\alpha/2}$ = critical value from t table

s = standard deviation

h = prefer half-width

The number of replications computed by equation 5.3 is 50 replications. But all simulation models are performed with 70 replications. It allows 20 more replications in case there is outliers.

In conclusion, the simulation models are run by applying these setting parameters:

- Warm up period is set at 16 weeks (96 days).
- Model is simulated for 120 weeks per replication (two years combined with warm up period). There are 312 days per year. Hence replication length is approximately equal to 720 days.
- Time base unit is hour.

5.2.3 Model Validation

To validate the simulation model, the study compares the results from the as-is model to actual distribution network. The model is evaluated validation on two key output variables; total cost and flow of quantity that transferred through the facilities. The total cost of current distribution network equals to 58,163,348 baht, whereas the confidence interval of total cost of as-is model is (57,806,050 to 58,520,645) as shown in Table 5.10.

Table 5.10 Total cost from the as-is model and current distribution network

Scenario	Simulation: Total Cost (Baht)		Actual System: Total Cost (Baht)
	Mean	Half width	Mean
Zone 1	11,686,837	148,800	11,627,478
Zone 2	7,695,450	96,470	7,584,569
Zone 3	11,227,517	149,000	11,255,476
Zone 4	16,420,293	196,855	16,401,261
Zone 5	11,133,251	221,012	11,159,067
All Zone	58,163,348	357,298	58,027,851

All simulation models are checked the validation by comparing total cost of as-is model to total cost derived from historical data, using two-sample t test with following hypothesis;

H0: the total cost from simulation model is equal to 58,027,851 baht

H1: the total cost from simulation model is not equal to 58,027,851 baht

From the one sample t-test as shown in Figure C1 (Appendix C), the result can be concluded that the total cost is not different from 58,027,851 baht (actual cost) at 0.05 significant level. Hence, the simulation model can provide the similar result to the actual system of distribution network.

Moreover, this study also validates the model by collecting the number of goods that flow through warehouse as shown in Table 5.11

Table 5.11 Flow through facility from the as-is model and actual current distribution network

	Simulation				Actual System	
Scenario	Flow through warehouse (Units/year)		Flow through service center (Units/year)		Flow through warehouse (Units/year)	Flow through service center (Units/year)
	Mean	Half width	Mean	Half width		
Zone 1	67,957	3,204	2,673	274	65,714	2,694
Zone 2	42,307	1,995	1,264	129	41,366	1,174
Zone 3	59,131	2,788	1,653	169	57,766	1,707
Zone 4	111,661	5,264	2,591	265	109,306	2,704
Zone 5	71,174	3,356	1,927	197	69,526	1,946
All Zone	352,230	13,724	10,107	797	343,678	10,225

To validate the model, this study performs one sample t-test of the quantity of flow through warehouse by following hypothesis;

H0: the quantity of flow through warehouse from simulation model is equal to 343,678 units

H1: the quantity of flow through warehouse from simulation model is not equal to 343,678 units

From one sample t-test as shown in Figure C2 (Appendix C), the result can conclude that the flow through warehouse for all zones is not different from 343,678 units at 0.05 significant level. Hence, the simulation model can provide the similar result to the actual system of distribution network.

Next, this research performs full running for all simulation models including of as-is model, solution from separated zone solving model and solution from all zones simultaneously solving model. The result will be shown in the next section.

5.3 Simulation Result and Discussion

This research develops the simulation models to evaluate the solutions from proposed three-echelon two-commodity LRP in stochastic environmental and the results are shown in Table 5.12.

Table 5.12 The results of simulation models

Scenario	Flow through warehouse (Units)		Flow through service center (Units)		Total Cost (Baht)	
	Mean	Half width	Mean	Half width	Mean	Half width
Zone 1 as-is	67,957	3,204	2,673	356	11,686,837	148,800
Zone 2 as-is	42,307	1,995	1,264	168	7,695,450	96,470
Zone 3 as-is	59,131	2,788	1,653	220	11,227,517	149,000
Zone 4 as-is	111,661	5,264	2,591	345	16,420,293	196,855
Zone 5 as-is	71,174	3,356	1,927	257	11,133,251	221,012
All Zone as-is	352,230	13,724	10,107	797	58,163,348	357,298
Zone 1 Separate	68,108	3,090	2,659	269	11,935,105	162,073
Zone 2 Separate	42,283	1,918	1,136	115	6,255,581	103,260
Zone 3 Separate	59,193	2,685	1,649	167	11,076,034	166,406
Zone 4 Separate	111,797	5,071	2,591	262	16,179,613	205,421
Zone 5 Separate	71,369	3,237	1,931	195	11,090,556	186,128
All Zone Separate	352,749	13,225	9,965	596	56,536,889	380,199
Zone 1 Simultaneous	97,842	2,941	3,086	298	12,567,881	154,087
Zone 2 Simultaneous	42,638	1,831	1,216	128	6,368,228	104,532
Zone 3 Simultaneous	53,514	2,563	1,457	185	10,942,640	161,375
Zone 4 Simultaneous	96,217	4,835	2,396	290	14,469,544	176,563
Zone 5 Simultaneous	62,471	3,080	1,786	215	10,886,072	156,873
All Zone Simultaneous	352,681	12,604	9,940	660	55,234,366	320,914

The column 2-5 in Table 5.12 show the goods quantity that flow through facilities. The quantity that flow through facilities is a key to reflect that whether the solutions from proposed mathematical model can be operated efficiently in stochastic demand or not. The results indicate that the solution from separated zone solving and simultaneously all zones solving have provided similar quantity of flow through facilities in all runs. In other words, all demands, which occurred in a year are completely delivered to the destinations.

From Table 5.12, redesign of distribution network provides the solutions that are similar to the previous results in Chapter 4 in terms of total cost. However, the total costs derived from the simulation models are little higher than one derived from the mathematical model. The increasing cost comes from facility variable cost and transportation variable cost. The components of cost for all model are shown in Table C1 (Appendix C)

Additionally, the simulation models of solving all zones simultaneously provide the lowest cost, although the zone 1 and zone 2 models provide higher total cost than other simulation models in the same zone as shown in Table 5.11 and Figure 5.5. This is a consequence of the higher assigned demand quantity to both of them. Next, the results of solving separated zone simulation model also provide lower cost than current distribution network model (as-is). Note that this study performs the two samples t-test to compare total cost derived from simulation by using Minitab version 16.2.1. As expectation, the results as mentioned above that solving all zones simultaneously provides the best solution in terms of total cost (Figure 5.9) at significant level of 0.05. The test results are illustrated in Figure C3-C5 (Appendix C).

Furthermore, the transportation variable cost of solving simultaneously model provides lowest cost compared to ones that obtained from simulation model (Figure 5.10) at significant level of 0.05. The test results are illustrated in Figure C6-C8 (Appendix C).

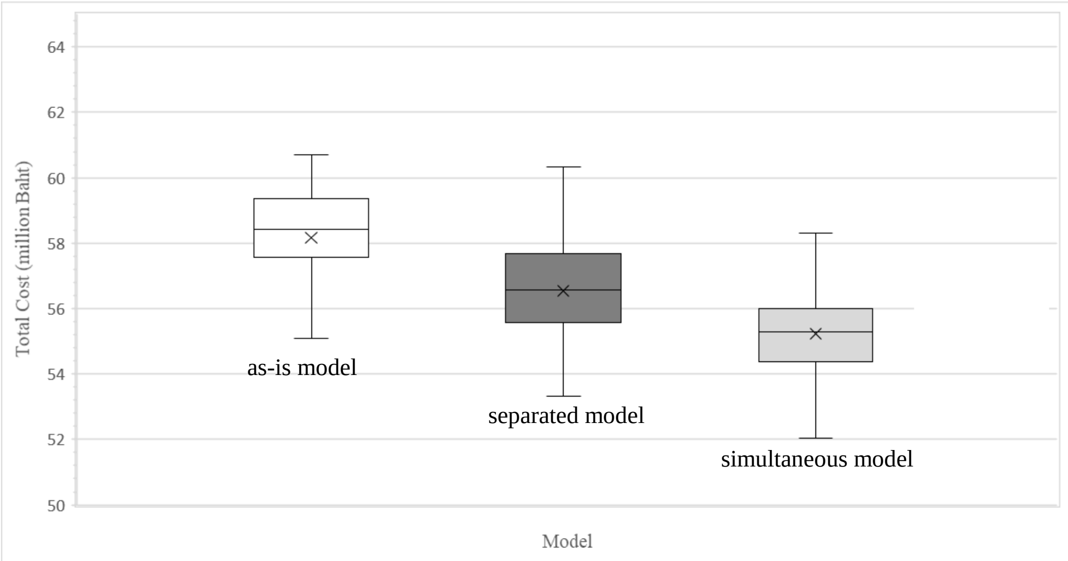


Figure 5.9 Comparison of total cost on particular simulation model

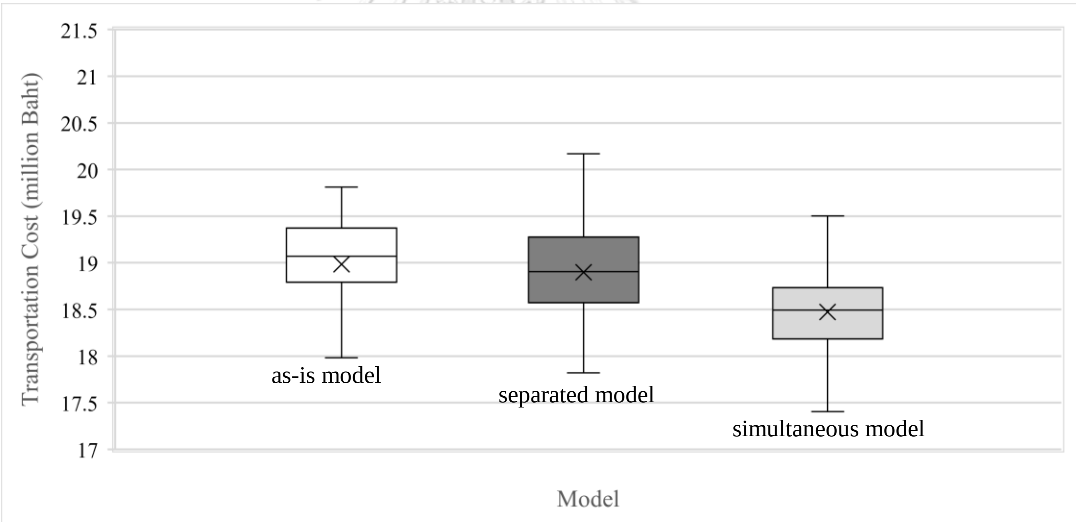


Figure 5.10 Comparison of transportation cost on particular simulation model

The main aim of simulation phase is focusing on transportation planning in operational level that including number of vehicles and criteria for establishing route in real-life situation. Most of simulation models provide higher transportation variable cost than the results from proposed solution method. Due to establishing route in simulation model, round trip will be performed when capacity of vehicle is sufficient for its cargo and waiting time is still in the range of allowable waiting time to assembly the route. The consequence of these factors affects the higher delivery distance as well as transportation variable cost. As a comparison with the formulated mathematical model, most of transportation routes perform round-trip route with average three visiting points. The number of routes obtained from simulation model are shown in Table 5.13 and 5.14 for the 2nd and 3rd echelon, respectively.

Table 5.13 presents number of drop points in the 2nd echelon. For example, in the scenario of as-is model in zone 1, there are 36.8 routes or 12.9% have only one drop point. While 175.1 routes or 61.7% have two drop points per route and the rest routes have three drop points. The results of the simulation models indicate that most of transportations in the 2nd echelon have two drop point per round.

Table 5.13 Number of member in particular vehicle routes in the 2nd echelon

Scenario		Number of member per vehicle route			%Number of member per vehicle route		
		1	2	3	1	2	3
as-is model	Zone 1	36.8	175.1	72.1	12.9%	61.7%	25.4%
	Zone 2	20.3	78.9	57.1	13.0%	50.5%	36.5%
	Zone 3	29.1	95.6	91.0	13.5%	44.3%	42.2%
	Zone 4	44.3	140.5	129.4	14.1%	44.7%	41.2%
	Zone 5	27.4	102.2	80.7	13.0%	48.6%	38.4%
Summation		**157.8**	**592.5**	**430.4**	**13.4%**	**50.2%**	**36.5%**
Separated model	Zone 1	37.2	164.8	85.0	13.0%	57.4%	29.6%
	Zone 2	20.5	80.5	57.9	12.9%	50.7%	36.4%
	Zone 3	29.3	90.0	94.6	13.7%	42.1%	44.2%
	Zone 4	43.2	136.6	132.7	13.8%	43.7%	42.5%
	Zone 5	27.7	95.9	82.0	13.5%	46.6%	39.9%
Summation		**157.8**	**567.8**	**452.3**	**13.4%**	**48.2%**	**38.4%**
Simultaneous model	Zone 1	41.0	164.8	123.5	12.5%	50.0%	37.5%
	Zone 2	20.4	81.0	59.3	12.7%	50.4%	36.9%
	Zone 3	25.3	76.7	80.0	13.9%	42.2%	44.0%
	Zone 4	43.3	131.5	122.7	14.6%	44.2%	41.2%
	Zone 5	26.8	94.4	80.1	13.3%	46.9%	39.8%
Summation		**156.8**	**548.4**	**465.6**	**13.4%**	**46.8%**	**39.8%**

The results of 3rd echelon is shown in Table 5.14. For customer service in the 3rd echelon, the results are similar to the 2nd echelon. Most of transportations perform two drop points per round. Only zone 1, in the model of simultaneously solving all zones, have number of transportation with three drop points per round more than one and two drop points. The number of transportation with only one drop point is return trip, which delivers shop products and service parts. In simulation model, the allowable waiting time is set to be 2 days. Therefore, combing route to increase drop points per transportation is not allowed. This leads to lower number of transportations with three drop points compared to deterministic model, which all transportations are assumed to have three drop points and affects to higher cost.

Table 5.14 Number of member in particular vehicle routes in the 3rd echelon

Model		Number of member per vehicle route			%Number of member per vehicle route		
		1	2	3	1	2	3
as-is model	Zone 1	117.4	422.4	269.0	14.5%	52.2%	33.3%
	Zone 2	62.3	194.4	178.9	14.3%	44.6%	41.1%
	Zone 3	122.6	460.9	284.2	14.1%	53.1%	32.8%
	Zone 4	184.7	715.3	384.7	14.4%	55.7%	29.9%
	Zone 5	133.2	473.1	289.0	14.9%	52.8%	32.3%
Summation		**620.3**	**2,266.1**	**1,405.9**	**14.4%**	**52.8%**	**32.8%**
Separated model	Zone 1	125.1	417.1	277.9	15.3%	50.9%	33.9%
	Zone 2	64.2	191.5	183.7	14.6%	43.6%	41.8%
	Zone 3	128.6	455.2	293.8	14.7%	51.9%	33.5%
	Zone 4	188.1	706.9	398.8	14.5%	54.6%	30.8%
	Zone 5	133.0	469.4	299.7	14.7%	52.0%	33.2%
Summation		**639.0**	**2,240.1**	**1,453.9**	**14.8%**	**51.7%**	**33.5%**
Simultaneous model	Zone 1	155.9	441.6	480.5	14.5%	41.0%	44.6%
	Zone 2	62.6	195.2	189.8	14.0%	43.6%	42.4%
	Zone 3	126.3	473.2	271.3	14.5%	54.3%	31.2%
	Zone 4	152.2	541.1	328.9	14.9%	52.9%	32.2%
	Zone 5	127.6	473.0	284.0	14.4%	53.5%	32.1%
Summation		**624.7**	**2,124.1**	**1,554.5**	**14.5%**	**49.4%**	**36.1%**

In summary, the results solving by mathematical model, which are deterministic environment, are proved that they can be applied on stochastic environment. To test the solutions of base case study derived from mathematical model, the input variables and random variables, including of vehicle capacity, replenishment policy, allowable waiting time and demand pattern, are added to simulation models. Then this research performs steady state simulation to analyze the efficiency of the redesign distribution network comparing to the company's current one. The results indicate that allowing distribution across different zones is the best distribution network which is similar to the result of mathematical model in Chapter 4. Moreover, the redesigned distribution networks can efficiently transfer the quantity of distributed items from depot to their destinations. However, the interesting finding from the simulation results is that the transportation costs are slightly higher than the cost from model in Chapter 4.

CHAPTER 6
CONCLUSION

6.1 Conclusion

This research has two objectives. One is to develop mathematical model for redesigning actual distribution network of electronic company in Thailand. Another one is to develop solution method to solve three main problems; suitable locations of facilities, allocation demand nodes to proper facility, and designing route for transferring products from point to point. To conduct this research, the case study, which is an electronic company, is selected based on their complexity of problem that performs currently three-echelon distribution network. Furthermore, the points of demand nodes are located in different layers (Layer 2 of retailer/service center and Layer 3 of customer). However, the current distribution network, that designed by the company by using experience and unsystematic approach can led to higher distribution cost.

Hence, this research formulates three-echelon multi-commodities *Location Routing Problem* (LRP) as a *Mixed Integer Linear Program* (MILP) in pattern of node-arc formulation. Due to MILP, there are two types of decision variables. One is binary variables that used for deciding to open or close candidate facilities and identify operating transportation routes. Another one is continuous variables that applied for identifying the suitable flow from particular layer-to-layer of supply chain. From literature review and cost occurred in real-life operation of case study, the objective function in the previous studies mostly consider facility opening cost and transportation cost, both of fixed cost and variable cost. To better reflect real-world case study distribution network, this research also considers closing cost of closure existing facility in the objective function.

The problem in this research consists of four-layer distribution, i.e., depot, warehouse, retailer/service center, and customer. The aim of proposed model is to identified suitable location of warehouses and service centers and allocate them to their customers in order to lower facility cost and transportation cost. The model also establishes distribution return transportation route for the 1st echelon and round transportation route for the 2nd and 3rd echelon, respectively. The problem is concerned two types of commodities; products and service required items, which demands occur at each retailer of layer two and customer of layer three of distribution network, respectively.

In this study, distribution network regions can be separated based on Thailand geography. There are five isolated zones; central-west zone, eastern zone, southern zone, northeastern zone and northern zone, represented by Z1-Z5, respectively. Moreover, this research proposes the special problem of redesign distribution network of solving all zones simultaneously. In summary, case study in this research comprises six main problems. Alternative locations in this research have two types, i.e. existing facilities which is currently operated and candidate facilities. Candidate facilities of warehouse are identified by company region manager along with supporting team, while candidates of service center can be located on particular existing retailer.

According to past literatures, it is known that LRP cannot be solved by exact method, especially for large-scale problems. From literature review, there is no literature that applied hybrid heuristics method to solve the redesign of three-echelon multi-commodity LRP. Hence, this study proposes the new solution approach to cope with NP-hardness and large-scale problem, which comprises four main phases based on clustering technique. Most previous research applied clustering-based method to single or two-echelon (Cuda *et al.*, 2015; Drexl & Schneider, 2015; Lin & Kwok, 2006; Wang *et al.*, 2017) but this research applied to solve three-echelon. Hence, this research proposes sequential clustering method to solve the 3rd and the 2nd echelon respectively.

In first phase, the proposed solution method decomposes the problem based on its structure and echelon into four subproblems including of MDVRP and FLAP for the 2nd and 3rd echelon. For second phase, initial-group algorithm establishes initial set of selected facilities from all possible lists based on average distance between customer site and facility site in descending order. Next, the algorithm brings the set of customers in particular selected facility, which locate nearer than maximum coverage distance, into the next step. Then, clustering algorithm is iteratively combined customer routes based on *Nearest Neighbor Algorithm* (NNA) with limitation of maximum number of visiting point and allowable demand quantity in each cluster. In third phase, the clustered routes are applied to modified FLAP, which distance cost is identified by *Traveling Salesman Problem* (TSP) route, to determine proper served facility. The solving process starts from 3^{rd} echelon transportation, then the updated information is brought into 2^{nd} echelon sequentially. In final phase, the proposed approach gathers the solutions obtained from each phase in order to complete the distribution network and identify total cost. The proposed solution method can help to tackle the problem that exact method cannot solve in acceptable computation time or cannot provide any quality solution.

To evaluate the proposed solution method, 66 scenarios are tested and the results indicate that the proposed clustering-based approach provides good quality solution and reduces computation time for all scenarios. Because the clustering phase approach can reduce complexity and size of problems, therefore, the modified FLAP and TSP can be solved to optimality for all runs. Especially, it can solve largest Problem ZA (combining and solving all zones simultaneously), which commercial solver (CPLEX) cannot find any feasible solution.

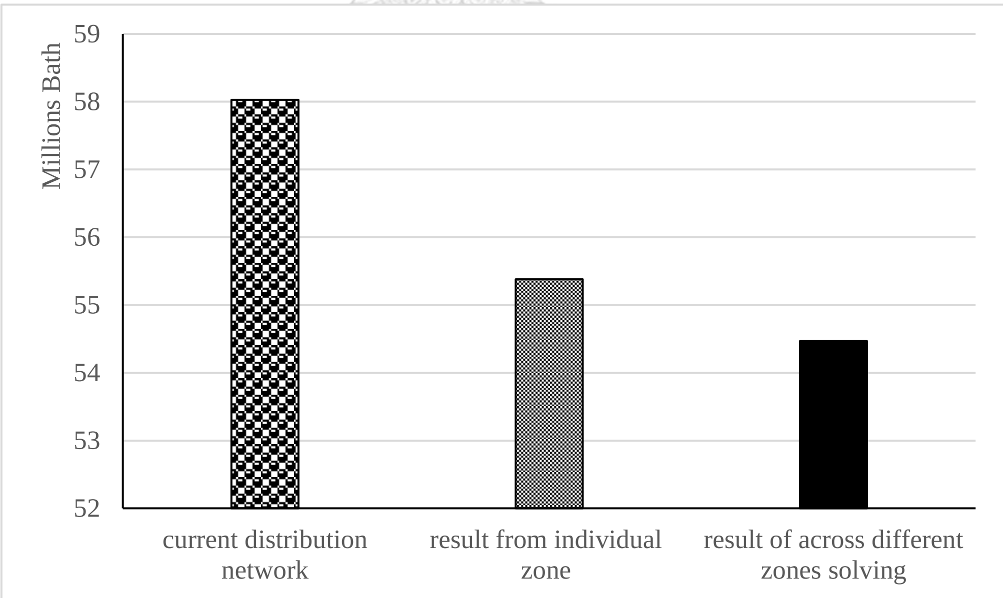


Figure 6.1 Comparing the total cost of distribution network among current one, solving individual zone and solving across different zones.

The solutions of Problem ZA are different from solving Problem Z1-Z5 independently. The retailers/service centers and customers, located on the boundary, are served by new allocated zone. This leads to lower cost compared to solving each zone separately. The consequences are decreasing of the number of demand nodes in some zone and improving the balance of allocating customer to each zone. Finally, redesigned solution can provide lower overall cost of distribution than the current distribution network as shown in Figure 6.1.

Also, it is found that most of existing warehouses are still operated because the saving cost from closing cannot compensate the increasing of other costs. Most of rental existing service centers are easily to close as they have inexpensive cost of moving and cost of terminating contract. Also, the candidate sites can be located on retailers, therefore, there are many substitute locations to replace.

For Problem ZA, the allocation of retailers and customers, which located on the boundary are changed and served by new allocated zone. This leads to lower cost. The consequence is the demand node in some zone is decreased and the balance of allocating customer to each zone is improved.

Table 6.1 Conclusion of sensitivity report.

Problem	Sensitivity		
	Demand	Facility Cost	Transportation Cost
Zone 1	44% or more	25% or more	No change
Zone 2	20% or more	No change	No change
Zone 3	20% or more	25% or more	75%
Zone 4	20% or more	25% or more	50% or more
Zone 5	44% or more	No change	No change
All zone	20% or more	50% or more	50% or more

To verify the solutions in dynamic environment, some parameters, which are applied in the objective function and constraints, are performed sensitivity analysis on demand, facility cost and transportation cost. This study performs 20%, 44%, 72% and 107% on demand sensitivity, 25%, 50% and 75% on facility cost and transportation cost sensitivity. The results indicate that the proposed models still provide solid solutions across sensitivity analysis. There are some slightly changes in solutions of particular scenario as shown in Table 6.1. However, most selected location sites of warehouse in base problem are still selected across demand sensitivity analysis. The divergent solution occurs significantly only for service center locations due to lower moving cost and lots of candidate location sites.

Finally, all results are proved in stochastic environment, which is different from the model. Additional factors, which are added into simulation model, are replenishment interval time, demand distribution pattern and vehicle capacity. The result indicates that the redesigned distribution network from three-echelon multi-commodity LRP can provide better effectiveness than current one in terms of overall cost as shown in Table 6.2. More deeply inspection of result from simulation phase, the cause, which distribution cost from stochastic environment is slightly higher than the cost from mathematical model (deterministic environment) come from transportation cost. In case that transportation routing plan in daily operation concerns vehicle capacity and allowable waiting time for combining customer into the same route, the most number of members of each route is two visiting point per route.

Table 6.2 Results from simulation.

Scenario	Flow through warehouse (Units)		Flow through service center (Units)		Total Cost (Baht)	
	Mean	Half width	Mean	Half width	Mean	Half width
Current distribution network	352,230	13,724	10,107	797	58,163,348	357,298
Separate zone distribution network	352,749	13,225	9,965	596	56,536,889	380,199
Across different zone distribution network	352,681	12,604	9,940	660	55,234,366	320,914

6.2 Contribution and Implication

6.2.1 Academic Contribution and Implication

The main academic contribution in this research is a redesigning of actual distribution network by applying mathematical model. Due to previous studies, the researchers have applied a general LRP to design distribution only for single or two echelons in order to avoid Large scale problem. Moreover, due to future research mentioned in review literatures (Cuda *et al.*, 2015; Drexl *et al.*, 2015; Prodhon *et al.*, 2014), it is known that new formulation of LRP requires more complexity and reality compare to the previous ones. Hence, this study applies LRP to three-echelon multi-commodity actual case study, with existing facilities in two layers of supply chain. Especially, the results from the model can provide better solutions than the current one.

Another contribution is that the proposed sequential clustering-based method can provide better quality solutions. The research finding reveals that when the models formulated in node-arc formulation, the problem size growth exponentially due to subtour elimination constraints. The exact method can solve only small-sized and medium-sized problems, which conform to previous researches. However, the proposed solution method can tackle these class of LRP by achievement of computation time and total cost compared to solving by exact method. This research is paving the way to the new hybrid solution method in the future research.

6.2.2 Business Contribution and Implication

The main contribution of this research in business aspect is the systematic design of distribution network that provide lower cost for real-life problem. Furthermore, the entire distribution network of all zones is redesigned in two distinctive ways in this study. First, the separately solving particular zone is performed. The benefit of this solving way is that models can provide the small and medium size problems, which are easier to solve. Another way is allowing the model to search proper locations of facilities across different zones and solve it simultaneously in one problem. The benefit of this solving way is that model can provide theoretically better solution than another one in terms of cost. This research can prove and provide the complete and quality solution from the second way solving, which can be implemented to the real-life case study. The conclusion helps business to realize that distribution zoning policy can obstruct the efficiency of distribution, which may lead to higher cost.

Next, the main concept of proposed solution method to solve this problem came from the idea that combine two simple and efficient solution methods; decomposition method and clustering method. This help the companies and practitioners can learn and applied the solution method for solving their problems easier than meta-heuristics or exact method.

Due to general location routing problem, this problem can be applied to general problem of supply chain facility, especially, to design distribution network in long term decision or even selecting facility and route in daily operation. Hence, LRP can be applied to most companies in every sector but it is suitable for the problem that performs tour trip transportation in their distribution network at least one echelon. Due to problem size as indicated in this research, if the company perform only return route transportation in distribution network, the Facility Location Problem will be suitable due to its smaller and easier to solve. Note that the objective function and constraints of proposed model are fitted to this research's case study, i.e., the number of echelon and constraints of visit point per transportation route. Hence, the enterprises or practitioners, who will apply this model to their case study, must understand their characteristics and constraints which may different from this case study. In this case, the modification of the objective function is necessary. The particular case study must identify factor and key characteristics of establishing routing process by their own, for example, vehicle capacity, traveling time, minimum load per route, etc.

6.3 Limitations and Future Research

Due to limitation of this research, the decision model is formulated in deterministic assumption and tests the solutions in stochastic manner. But in the context of implementation in real-life operation, there are many more factors affecting to distribution. The main factor that the practitioner or implementer must concern is the daily operation to plan the tour trip transportation route, i.e., vehicle capacity, traveling time of each route and limitation, load balancing among transportation routes and etc. These factors can lead the higher cost than expectation.

Based on scope of redesign distribution network problem, the proposed three-echelon LRP is modeled on the assumption of selling all property when closing facility. In different points of view, the company can move labor or equipment to new sites, hence, model should be modified sets of decision variables of facility closure condition in order to make problems more realistic. Additional set of variables allowing the model to decide whether it should be transfer all properties or transfer some part of existing capacity in order to earn the highest benefit.

Moreover, the key barrier of solving this case study is that demand node can be served by only one facility. This assumption leads to higher number of opening facilities. In fact, logistics manger can swap to other operating facility site when reaching maximum capacity and establish route to transfer goods to final destination. Hence, to support this circumstance, the decision variable should be modified to allow to decide ratio of satisfied demand quantity of particular node.

Moreover, when the number of open facilities is increased, it affects the imbalance of allocating customers among facilities. This issue should also be brought into consideration.

One of the important issues to be developed is the model formulation. The ultimate obstacle of node-arc formulation in this research is a large number of subtour-elimination constraints. Therefore, future research should develop new formulation for this real-life case study and exact method to provide better solution. Moreover, the heuristic method performs better if facility capacity is not tight. Proposed solution method should be developed in order to deal with problems with large-sized demand node. Finally, clustering method should be into iterative solving, in order to re-route if number of opening facilities are greater than the minimum required to get optimality.

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APPENDIX

APPENDIX

APENDIX A: Input Data

Table A1 Parameter and coefficient for warehouses in layer one of distribution network

Id number	Zone	Type	Coordinate		Fixed operating cost (Baht/year)	Closing/ Saving cost (Baht/year)	Variable cost (Baht/unit/year)	Capacity (unit)
			x	y				
1	1	New own site	-103.5	297.5	1,252,308	0	34	50,000
2	1	New own site	-12.2	201.0	1,214,631	0	34	52,000
3	1	Existing rental site	-39.8	279.2	1,064,215	99,210	36	50,370
4	1	New own site	-54.3	178.1	1,293,190	0	31	44,167
5	1	Existing own site	-111.6	164.4	994,241	-412,321	34	45,432
6	1	New rental site	-41.2	280.2	1,076,006	0	35	50,100
7	2	New own site	76.2	-20.4	1,259,703	0	37	50,235
8	2	Existing rental site	78.2	-60.2	1,053,379	98,210	40	40,160
9	2	New rental site	147.1	-75.1	1,096,970	0	34	50,060
10	2	New own site	172.2	-30.8	1,286,631	0	37	40,100
11	2	Existing own site	108.2	-102.1	933,848	-432,321	37	50,490
12	3	New own site	-193.9	-486.3	1,091,577	0	36	50,060
13	3	Existing rental site	-143.2	-720.2	1,041,314	76,695	38	50,180
14	3	New own site	-99.3	-802.5	1,156,584	0	34	50,475
15	3	New own site	-189.4	-665.6	1,119,034	0	34	50,310
16	3	Existing rental site	-132.0	-135.3	977,014	84,217	36	50,235
17	3	New rental site	-152.2	-278.2	947,754	0	35	50,025
18	4	Existing own site	121.5	517.3	996,968	-242,563	33	55,341
19	4	New rental site	110.7	324.5	1,148,289	0	35	50,130
20	4	Existing rental site	324.1	331.0	955,977	85,561	34	45,054
21	4	Existing own site	228.6	302.3	898,723	-262,724	33	50,170
22	4	New rental site	243.2	394.6	1,145,684	0	36	50,450
23	4	New own site	213.9	517.5	1,181,684	0	34	50,415
24	5	New rental site	-61.4	730.7	1,049,583	0	36	50,030
25	5	Existing Rental	-130.0	765.3	1,041,841	85,439	35	50,330
26	5	New rental site	-102.5	833.4	1,079,950	0	34	50,065
27	5	New own site	-42.7	601.8	1,091,663	0	34	50,500
28	5	Existing own site	-139.4	639.2	995,949	-312,845	30	50,105
29	5	New own site	-174.2	687.8	1,030,840	0	34	50,110

Table A2 Parameter and coefficient for retailers/service centers in layer two of distribution network

Id	Zone	Type	Coordinate		Fixed operating cost (Baht/year)	Closing/ Saving cost (Baht/year)	Variable cost (Baht/unit /year)	Capacity (unit)	Demand (unit)	%Demand
			x	y						
30	1	New rental site	-81.9	345.2	427,802	0	51	1,010	7,212	2.1%
31	1	New own site	-21.0	309.7	453,552	0	51	1,002	7,101	2.1%
32	1	Existing rental site	10.2	278.1	440,923	43,121	49	1,050	6,616	1.9%
33	1	New rental site	-85.0	237.3	429,216	0	52	1,007	4,486	1.3%
34	1	Existing rental site	-171.7	181.0	420,923	43,044	50	1,100	8,921	2.6%
35	1	New rental site	-127.8	112.3	402,211	0	50	1,007	6,424	1.9%
36	1	New own site	-60.2	150.2	471,750	0	52	1,009	3,464	1.0%
37	1	New own site	-19.3	205.3	441,000	0	52	1,003	4,062	1.2%
38	1	New rental site	-16.4	129.4	432,762	0	51	1,004	4,562	1.3%
39	1	New own site	-61.1	63.8	484,035	0	52	1,003	6,402	1.9%
40	1	Existing rental site	-143.2	330.2	421,211	43,595	50	950	6,464	1.9%
41	2	New own site	79.5	8.1	464,457	0	52	1,004	7,130	2.1%
42	2	Existing rental site	60.6	-43.5	436,923	43,112	51	1,000	5,820	1.7%
43	2	New rental site	170.6	-1.8	426,719	43,121	53	1,010	5,636	1.6%
44	2	New own site	159.3	-150.2	427,033	0	54	1,005	8,920	2.6%
45	2	Existing rental site	133.1	-104.7	430,953	43,164	58	1,007	7,610	2.2%
46	2	New rental site	178.0	-211.7	403,467	0	57	1,002	6,250	1.8%
47	3	Existing own site	-127.1	-71.1	416,341	-37,232	51	1,004	6,012	1.7%
48	3	New own site	-116.9	-181.3	406,982	0	51	1,004	4,260	1.2%
49	3	New own site	-177.8	-395.7	413,726	0	53	1,006	5,024	1.5%
50	3	New own site	-228.6	-516.6	445,625	0	54	1,006	2,046	0.6%
51	3	Existing rental site	-182.0	-584.8	419,304	52,983	49	1,004	4,328	1.3%
52	3	New own site	-176.9	-662.5	424,675	0	55	1,009	6,186	1.8%
53	3	New rental site	-235.0	-678.3	408,878	0	51	1,004	4,502	1.3%
54	3	New rental site	-98.4	-701.1	412,242	0	53	1,004	6,044	1.8%
55	3	New own site	-121.1	-840.5	442,651	0	54	1,002	5,600	1.6%
56	3	New own site	-147.6	-312.6	426,321	0	55	1,000	4,386	1.3%
57	3	New own site	-165.1	-748.2	455,402	0	54	1,005	5,408	1.6%
58	3	New own site	-71.1	-840.5	429,179	0	54	1,005	3,970	1.2%
59	4	Existing own site	76.4	541.5	405,855	-51,232	55	1,001	8,504	2.5%

Table A2 Parameter and coefficient for retailers/service centers in layer two of distribution network (continue)

Id	Zone	Type	Coordinate		Fixed operating cost (Baht/year)	Closing/ Saving cost (Baht/year)	Variable cost (Baht/unit /year)	Capacity (unit)	Demand (unit)	%Demand
			x	y						
60	4	New own site	82.3	129.3	421,649	0	50	1,008	5,468	1.6%
61	4	New own site	49.7	407.2	424,336	0	56	1,001	6,524	1.9%
62	4	New own site	195.8	545.9	393,508	0	52	1,006	7,272	2.1%
63	4	New own site	269.2	536.9	433,331	0	56	1,010	7,504	2.2%
64	4	Existing rental site	225.8	464.6	418,798	40,518	55	1,004	8,184	2.4%
65	4	New rental site	294.2	421.5	413,672	0	57	1,003	5,794	1.7%
66	4	New rental site	167.9	350.5	407,492	0	54	1,002	7,562	2.2%
67	4	Existing rental site	270.6	333.0	411,604	41,004	56	1,009	4,404	1.3%
68	4	New own site	97.0	249.1	423,958	0	52	1,002	6,100	1.8%
69	4	New own site	152.0	196.9	455,647	0	55	1,007	5,876	1.7%
70	4	New rental site	217.1	255.5	455,450	0	55	1,002	6,146	1.8%
71	4	Existing rental site	116.4	391.5	416,409	41,725	52	1,005	6,066	1.8%
72	4	New own site	305.8	230.8	463,080	0	57	1,010	6,704	2.0%
73	4	New rental site	215.2	392.0	471,229	0	57	1,004	5,426	1.6%
74	4	New rental site	147.8	506.6	443,079	0	56	1,008	4,242	1.2%
75	4	New rental site	380.2	268.1	420,555	0	54	1,009	7,530	2.2%
76	5	New rental site	-54.8	871.1	428,129	0	55	1,004	6,588	1.9%
77	5	Existing own site	-102.1	542.3	402,337	-32,232	49	1,001	8,464	2.5%
78	5	New own site	9.3	760.3	421,070	0	49	1,007	5,456	1.6%
79	5	New own site	-20.6	518.6	434,642	0	51	1,005	4,418	1.3%
80	5	Existing rental site	-83.1	635.2	415,319	43,007	55	950	7,110	2.1%
81	5	New rental site	-202.1	612.0	420,312	0	50	1,007	6,726	2.0%
82	5	New rental site	-143.0	832.3	434,519	0	50	1,005	3,824	1.1%
83	5	New own site	-38.5	719.2	432,855	0	51	1,005	3,264	0.9%
84	5	Existing rental site	-62.8	438.8	447,572	0	54	1,001	3,662	1.1%
85	5	New own site	-130.1	701.4	443,270	0	55	1,009	4,704	1.4%
86	5	New own site	-191.2	746.3	435,282	0	56	1,001	9,872	2.9%
87	5	New rental site	-153.3	593.9	411,825	0	51	1,006	5,438	1.6%

Table A3 Parameter customer nodes in layer three of distribution network

Id	Zone	Coordinate		Demand (unit)	%Demand	Id	Zone	Coordinate		Demand (unit)	%Demand
		x	y					x	y		
88	1	-121.8	375.3	148	1.4%	**123**	2	119.2	-82.7	113	1.1%
89	1	-26.3	356.6	45	0.4%	**124**	2	46.7	-17.1	26	0.3%
90	1	-20.2	259.2	90	0.9%	**125**	2	60.2	-139.8	72	0.7%
91	1	-73.4	291.0	84	0.8%	**126**	2	110.3	-113.9	36	0.4%
92	1	-118.1	292.6	30	0.3%	**127**	2	161.5	-125.5	36	0.4%
93	1	-142.0	246.1	64	0.6%	**128**	2	140.4	-160.4	84	0.8%
94	1	-106.0	235.1	30	0.3%	**129**	2	180.0	-159.5	130	1.3%
95	1	-50.6	198.2	99	1.0%	**130**	2	191.1	-217.7	106	1.0%
96	1	22.9	184.8	63	0.6%	**131**	3	-86.9	-22.2	110	1.1%
97	1	-88.5	146.9	75	0.7%	**132**	3	-142.8	-69.4	72	0.7%
98	1	-60.0	131.2	90	0.9%	**133**	3	-125.3	-198.4	54	0.5%
99	1	-178.2	136.2	39	0.4%	**134**	3	-133.5	-260.5	46	0.4%
100	1	-156.3	99.5	42	0.4%	**135**	3	-187.7	-355.4	54	0.5%
101	1	-125.2	72.9	66	0.6%	**136**	3	-209.6	-456.2	64	0.6%
102	1	48.2	214.1	135	1.3%	**137**	3	-205.5	-546.9	80	0.8%
103	1	36.5	80.7	105	1.0%	**138**	3	-221.2	-605.1	42	0.4%
104	1	-27.6	70.8	180	1.8%	**139**	3	-153.1	-609.7	74	0.7%
105	1	-44.9	3.2	164	1.6%	**140**	3	-254.4	-664.3	82	0.8%
106	1	-101.6	-32.3	90	0.9%	**141**	3	-218.1	-673.8	86	0.8%
107	1	-53.0	-26.7	60	0.6%	**142**	3	-207.5	-711.6	56	0.5%
108	1	-75.2	408.1	140	1.4%	**143**	3	-129.2	-655.1	64	0.6%
109	1	-182.6	201.3	178	1.7%	**144**	3	-140.3	-694.1	104	1.0%
110	1	-148.2	156.8	100	1.0%	**145**	3	-122.1	-740.5	46	0.4%
111	1	-27.2	162.6	112	1.1%	**146**	3	-78.6	-715.0	84	0.8%
112	1	-218.4	156.6	162	1.6%	**147**	3	-144.3	-798.1	65	0.6%
113	1	-20.8	450.4	60	0.6%	**148**	3	-105.3	-178.4	68	0.7%
114	1	39.4	320.9	63	0.6%	**149**	3	-145.5	-162.3	76	0.7%
115	1	-113.8	339.0	180	1.8%	**150**	3	-167.7	-425.4	84	0.8%
116	2	95.7	61.6	48	0.5%	**151**	3	-245.5	-531.9	42	0.4%
117	2	115.4	38.0	60	0.6%	**152**	3	-172.1	-762.2	44	0.4%
118	2	183.7	22.1	98	1.0%	**153**	3	-106.0	-798.6	46	0.4%
119	2	196.1	-15.7	108	1.1%	**154**	3	-75.7	-874.4	44	0.4%
120	2	159.9	-48.9	86	0.8%	**155**	3	-100.3	-899.8	30	0.3%
121	2	100.0	-39.9	38	0.4%	**156**	3	-121.5	-108.1	34	0.3%
122	2	78.4	-79.7	132	1.3%	**157**	3	-169.9	-315.1	56	0.5%

Table A3 Parameter customer nodes in layer three of distribution network (continue)

Id	Zone	Coordinate		Demand (unit)	%Demand	Id	Zone	Coordinate		Demand (unit)	%Demand
		x	y					x	y		
158	4	52.3	546.5	50	0.5%	**192**	4	318.8	172.8	76	0.7%
159	4	13.4	462.3	100	1.0%	**193**	4	372.0	222.7	64	0.6%
160	4	44.9	363.3	102	1.0%	**194**	5	-63.6	937.0	142	1.4%
161	4	88.2	422.7	40	0.4%	**195**	5	12.1	604.2	44	0.4%
162	4	116.8	462.4	80	0.8%	**196**	5	-26.9	547.0	90	0.9%
163	4	159.6	550.0	112	1.1%	**197**	5	-80.7	534.7	42	0.4%
164	4	192.2	586.6	80	0.8%	**198**	5	-103.2	487.4	64	0.6%
165	4	251.7	599.5	134	1.3%	**199**	5	-145.5	537.9	138	1.3%
166	4	282.2	523.5	84	0.8%	**200**	5	-62.2	602.1	50	0.5%
167	4	213.7	537.3	62	0.6%	**201**	5	-40.5	678.8	78	0.8%
168	4	203.2	506.3	72	0.7%	**202**	5	-13.5	604.6	88	0.9%
169	4	174.9	472.6	113	1.1%	**203**	5	34.0	796.5	90	0.9%
170	4	156.5	393.8	36	0.4%	**204**	5	-30.7	810.8	42	0.4%
171	4	247.3	465.5	80	0.8%	**205**	5	-81.2	902.5	112	1.1%
172	4	336.2	449.5	107	1.0%	**206**	5	-160.4	846.1	114	1.1%
173	4	97.3	349.0	46	0.4%	**207**	5	-173.3	765.2	60	0.6%
174	4	173.3	413.5	90	0.9%	**208**	5	-215.6	719.8	42	0.4%
175	4	275.7	386.2	24	0.2%	**209**	5	-100.0	769.3	52	0.5%
176	4	215.3	355.3	36	0.4%	**210**	5	-92.3	715.3	90	0.9%
177	4	296.1	365.2	126	1.2%	**211**	5	-72.1	372.3	64	0.6%
178	4	360.1	360.1	54	0.5%	**212**	5	-42.8	421.8	66	0.6%
179	4	116.3	290.9	20	0.2%	**213**	5	-12.2	459.0	82	0.8%
180	4	157.8	276.3	148	1.4%	**214**	5	-0.2	709.0	76	0.7%
181	4	82.3	194.9	56	0.5%	**215**	5	-105.1	648.3	72	0.7%
182	4	53.2	243.0	32	0.3%	**216**	5	-172.9	609.2	54	0.5%
183	4	131.7	209.7	80	0.8%	**217**	5	-189.3	571.2	40	0.4%
184	4	116.4	159.3	144	1.4%	**218**	5	-178.3	665.6	72	0.7%
185	4	394.3	300.6	104	1.0%	**219**	5	-133.7	629.7	40	0.4%
186	4	347.9	282.8	56	0.5%	**220**	5	-224.6	639.4	42	0.4%
187	4	315.2	263.1	52	0.5%						
188	4	247.4	240.1	102	1.0%						
189	4	193.8	225.2	54	0.5%						
190	4	182.1	162.0	30	0.3%						
191	4	254.3	172.9	58	0.6%						

Table A4 Parameter and coefficiency of transportation cost separated by zone

Zone	Fixed transportation cost (bath/route/year)			Transportation variable cost (bath/k.m./year)		
	1st echelon	2nd echelon	3rd echelon	1st echelon	2nd echelon	3rd echelon
1	41,280	155,122	128,694	587	666	804
2	41,280	165,122	128,694	460	518	777
3	41,280	165,122	128,694	536	610	707
4	41,280	165,122	128,694	585	665	751
5	41,280	165,122	128,694	641	725	776

APENDIX B: Solutions

Table B1 Solutions from CPLEX solving: total cost

Run	Problem Id	Demand	CPLEX Runtime	Gap from Cplex	Objective Value	Fixed opening cost (warehouse)	Fixed opening cost (service center)	Warehouse closing/saving cost	Service center closing/saving cost	Variable cost of Warehouse	Variable cost of service center	Fixed transportation cost	Transportation variable cost
1	Z1P1	68,408	11,543.7	88.7%	11,528,717	1,878,456	1,389,003	0	0	2,327,501	145,755	2,071,857	3,716,145
2	Z1P2	82,090	11,943.5	86.2%	12,449,769	1,878,456	1,685,268	0	0	2,749,423	167,510	2,071,857	3,897,256
3	Z1P3	98,508	12,721.1	85.2%	14,692,916	3,171,646	2,114,484	0	0	3,173,352	207,582	2,071,857	3,953,993
4	Z1P4	118,209	12,794.3	86.7%	15,706,619	3,171,646	2,555,484	0	0	3,827,535	247,737	2,071,857	3,832,360
5	Z1P5	141,851	12,782.5	87.1%	16,412,086	3,171,646	2,555,484	0	0	4,479,113	301,626	2,071,857	3,832,360
6	Z2P1	42,540	108.4	18.1%	6,083,007	1,096,970	867,877	-300,700	0	1,444,423	68,549	1,075,929	1,829,959
7	Z2P2	51,048	162.3	32.4%	7,426,887	2,060,350	867,877	-389,089	0	1,966,893	82,667	1,115,929	1,722,260
8	Z2P3	61,258	302.2	36.9%	7,721,014	2,060,350	867,877	-389,089	0	2,243,770	99,916	1,115,929	1,722,260
9	Z2P4	73,509	1,214.6	32.8%	8,590,779	2,060,350	1,271,344	-389,089	0	2,691,045	118,940	1,115,929	1,722,260
10	Z2P5	88,211	1,947.6	29.1%	9,152,776	2,060,350	1,271,344	-389,089	0	3,229,254	142,727	1,115,929	1,722,260
11	Z3P1	59,473	7,037.0	79.7%	10,879,704	2,095,061	1,605,266	84,217	52,983	1,779,353	97,878	1,933,163	3,231,782
12	Z3P2	71,368	6,316.9	81.7%	11,798,553	2,095,061	2,043,498	84,217	52,983	2,129,173	115,062	1,933,163	3,345,396
13	Z3P3	85,642	7,045.5	78.7%	11,695,555	2,095,061	1,605,266	84,217	52,983	2,555,008	138,074	1,933,163	3,231,782
14	Z3P4	102,771	8,121.2	83.7%	13,416,583	3,195,110	1,636,516	84,217	52,983	3,136,009	165,689	1,933,163	3,212,896
15	Z3P5	123,326	9,838.4	80.7%	14,922,308	3,195,110	2,082,626	84,217	15,751	3,834,054	196,788	2,133,163	3,380,600

Table B1 Solutions from CPLEX solving: total cost (continue)

Run	Problem Id	Demand	CPLEX Runtime	Gap from Cplex	Objective Value	Fixed opening cost (warehouse)	Fixed opening cost (service center)	Warehouse closing/saving cost	Service center closing/saving cost	Variable cost of Warehouse	Variable cost of service center	Fixed transportation cost	Transportation variable cost
16	Z4P1	112,010	13,307.3	90.2%	16,874,490	2,850,789	1,710,128	0	9,493	3,706,261	159,069	2,691,702	5,747,048
17	Z4P2	134,412	13,517.5	91.2%	17,463,224	2,790,177	1,671,143	0	9,493	4,558,810	172,980	2,691,702	5,568,919
18	Z4P3	161,294	13,944.1	92.7%	20,108,052	3,891,078	2,065,992	0	9,493	5,331,651	208,235	2,691,702	5,909,901
19	Z4P4	193,553	13,752.3	92.1%	22,612,470	4,770,050	2,450,866	0	9,493	6,549,366	254,718	2,691,702	5,886,275
20	Z4P5	232,264	13,673.0	92.2%	24,438,543	4,770,050	2,471,370	0	9,493	7,864,635	299,631	3,101,980	5,921,384
21	Z5P1	71,472	8,953.9	87.2%	11,246,237	2,067,355	1,195,207	85,439	10,775	2,211,189	101,775	1,933,163	3,641,336
22	Z5P2	85,766	8,570.4	88.9%	12,038,148	2,067,355	1,236,474	85,439	43,007	2,658,121	119,703	1,933,163	3,894,887
23	Z5P3	102,920	7,528.9	88.2%	14,073,318	3,116,937	1,587,544	85,439	43,007	3,181,024	144,173	1,933,163	3,982,032
24	Z5P4	123,504	8,823.7	89.1%	15,073,421	3,116,937	1,640,624	85,439	0	3,806,744	173,438	2,083,161	4,167,080
25	Z5P5	148,204	8,312.3	89.3%	17,956,071	4,147,778	2,076,855	85,439	0	4,860,694	209,753	2,314,310	4,261,242
26	ZAP1	353,903	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
27	ZAP2	424,684	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
28	ZAP3	509,621	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
29	ZAP4	611,546	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
30	ZAP5	733,856	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table B1 Solutions from CPLEX solving: total cost (continue)

Run	Problem Id	Demand	CPLEX Runtime	Gap from Cplex	Objective Value	Fixed opening cost (warehouse)	Fixed opening cost (service center)	Warehouse closing/saving cost	Service center closing/saving cost	Variable cost of Warehouse	Variable cost of service center	Fixed transportation cost	Transportation variable cost
31	Z1a25	68,408	12,788.9	90.7%	12,809,778	2,348,070	1,672,162	0	0	2,829,041	181,044	2,071,857	3,707,603
32	Z1a50	68408	13,882.2	89.2%	14,288,812	2,817,684	2,006,595	0	0	3,491,251	218,633	2,071,857	3,682,792
33	Z1a75	68408	13,541.4	90.6%	15,827,477	3,287,298	2,245,351	0	0	4,073,126	255,071	2,071,857	3,894,774
34	Z2a25	42,540	619.8	19.2%	6,877,286	1,371,213	1,084,846	-375,875	0	1,805,528	85,686	1,075,929	1,829,959
35	Z2a50	42,540	622.0	21.3%	7,671,566	1,645,456	1,301,815	-451,050	0	2,166,634	102,823	1,075,929	1,829,959
36	Z2a75	42,540	1,044.3	20.2%	8,465,846	1,919,698	1,518,784	-526,225	0	2,527,739	119,961	1,075,929	1,829,959
37	Z3a25	59,473	8,215.8	83.7%	11,926,991	3,239,499	1,613,809	-515,401	0	2,204,871	118,073	1,933,163	3,332,978
38	Z3a50	59,473	8,654.6	82.8%	13,354,804	3,887,399	1,897,236	-618,482	0	2,716,429	143,996	1,933,163	3,395,063
39	Z3a75	59,473	9,775.0	80.1%	14,679,407	4,535,299	2,259,332	-721,562	0	3,086,820	165,302	1,933,163	3,421,055
40	Z4a25	112,010	14,853.4	91.2%	18,438,080	3,563,487	2,149,526	-328,405	-64,040	4,525,642	153,120	2,691,702	5,747,048
41	Z4a50	112,010	14,763.3	90.5%	20,441,857	4,088,503	2,413,877	-394,086	-76,848	5,634,628	232,173	2,691,702	5,851,909
42	Z4a75	112,010	14,739.4	93.1%	23,009,963	4,772,940	2,963,627	0	0	6,469,849	271,068	2,691,702	5,840,778
43	Z5a25	71,472	8,801.6	88.1%	12,822,961	2,584,193	1,524,442	106,799	0	2,761,324	125,745	1,933,163	3,787,295
44	Z5a50	71,472	10,538.1	88.1%	14,178,830	3,101,032	1,819,561	128,159	0	3,308,165	155,804	1,933,163	3,732,948
45	Z5a75	71,472	6,547.7	90.1%	15,325,540	3,527,871	1,956,846	149,518	0	3,709,055	177,959	1,933,163	3,871,128

Table B1 Solutions from CPLEX solving: total cost (continue)

Run	Problem Id	Demand	CPLEX Runtime	Gap from Cplex	Objective Value	Fixed opening cost (warehouse)	Fixed opening cost (service center)	Warehouse closing/saving cost	Service center closing/saving cost	Variable cost of Warehouse	Variable cost of service center	Fixed transportation cost	Transportation variable cost
46	ZAa25	353,903	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
47	ZAa50	353,903	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
48	ZAa75	353,903	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
49	Z1t25	68,408	13,798.8	90.8%	13,194,269	1,878,456	1,332,770	0	0	2,276,778	148,239	2,589,821	4,968,204
50	Z1t50	68,408	11,836.3	89.1%	15,061,976	1,878,456	1,767,092	0	0	2,369,014	143,613	3,107,786	5,796,015
51	Z1t75	68,408	13,937.3	87.9%	16,118,791	2,191,567	1,724,048	-313,111	43,044	2,170,934	147,126	3,625,750	6,529,433
52	Z2t25	42,540	441.3	22.8%	6,809,479	1,096,970	867,877	-300,700	0	1,444,423	68,549	1,344,911	2,287,449
53	Z2t50	42,540	374.3	24.0%	7,535,951	1,096,970	867,877	-300,700	0	1,444,423	68,549	1,613,893	2,744,939
54	Z2t75	42,540	304.9	26.4%	8,262,423	1,096,970	867,877	-300,700	0	1,444,423	68,549	1,882,875	3,202,429
55	Z3t25	59,473	6,387.8	79.1%	11,985,731	2,095,061	1,238,064	84,217	52,983	1,763,897	94,806	2,416,453	4,240,250
56	Z3t50	59,473	8,591.6	80.5%	13,855,637	2,011,070	1,196,388	84,217	52,983	1,810,953	97,274	2,899,744	5,703,009
57	Z3t75	59,473	7,378.9	81.3%	14,743,574	2,095,061	1,196,388	84,217	52,983	1,763,897	97,274	3,383,034	6,070,720
58	Z4t25	112,010	14,672.2	90.6%	18,580,840	2,725,668	1,593,040	0	41,725	3,697,260	150,867	3,364,628	7,007,652
59	Z4t50	112,010	14,805.8	89.5%	20,862,182	2,990,118	1,268,654	-262,724	41,725	3,746,784	156,690	4,037,553	8,883,382
60	Z4t75	112,010	14,864.7	90.7%	22,477,901	3,167,957	1,343,002	-242,563	-51,232	3,882,367	164,091	4,710,479	9,503,801

Table B1 Solutions from CPLEX solving: total cost (continue)

Run	Problem Id	Demand	CPLEX Runtime	Gap from Cplex	Objective Value	Fixed opening cost (warehouse)	Fixed opening cost (service center)	Warehouse closing/saving cost	Service center closing/saving cost	Variable cost of Warehouse	Variable cost of service center	Fixed transportation cost	Transportation variable cost
61	Z5t25	71,472	9,574.4	89.9%	12,819,547	2,067,355	1,240,954	85,439	10,775	2,227,791	105,021	2,416,453	4,665,759
62	Z5t50	71,472	8,005.5	88.1%	14,279,921	2,067,355	1,213,694	85,439	10,775	2,209,059	102,657	2,899,744	5,691,198
63	Z5t75	71,472	7,666.6	87.8%	15,497,680	2,067,355	1,198,706	85,439	10,775	2,211,959	101,073	3,383,034	6,439,338
64	ZAt25	353,903	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
65	ZAt50	353,903	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
66	ZAt75	353,903	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table B2 Solutions from CPLEX solving: number of facility and route

Run	Problem Id	Number of open warehouse	Number of open service center	Number of closing warehouse	Number of closing service center	Number of Directed Route (Echelon 1)	Number of Tour Route (Echelon 2)	Number of Tour Route (Echelon 3)
1	Z1P1	2	3	0	0	2	4	10
2	Z1P2	2	4	0	0	2	4	10
3	Z1P3	3	5	0	0	3	4	10
4	Z1P4	3	6	0	0	3	4	10
5	Z1P5	3	6	0	0	3	4	10
6	Z2P1	1	2	2	0	1	2	5
7	Z2P2	2	2	1	0	2	2	5
8	Z2P3	2	2	1	0	2	2	5
9	Z2P4	2	3	1	0	2	2	5
10	Z2P5	2	3	1	0	2	2	5
11	Z3P1	2	4	1	1	2	4	9
12	Z3P2	2	4	1	1	2	4	9
13	Z3P3	2	4	1	1	2	4	9
14	Z3P4	3	4	1	1	3	4	9
15	Z3P5	3	5	1	2	3	4	10
16	Z4P1	3	4	0	1	3	6	12
17	Z4P2	3	4	0	1	3	6	12
18	Z4P3	4	5	0	1	4	6	12
19	Z4P4	5	6	0	1	5	6	12
20	Z4P5	5	6	0	1	5	7	15
21	Z5P1	2	3	1	2	2	4	9
22	Z5P2	2	3	1	1	2	4	9
23	Z5P3	3	4	1	1	3	4	9
24	Z5P4	3	4	1	0	3	4	10
25	Z5P5	4	5	1	0	4	5	10
26	ZAP1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
27	ZAP2	N/A	N/A	N/A	N/A	N/A	N/A	N/A
28	ZAP3	N/A	N/A	N/A	N/A	N/A	N/A	N/A
29	ZAP4	N/A	N/A	N/A	N/A	N/A	N/A	N/A
30	ZAP5	N/A	N/A	N/A	N/A	N/A	N/A	N/A
31	Z1a25	2	3	0	0	2	4	10
32	Z1a50	2	3	0	0	2	4	10
33	Z1a75	2	3	0	0	2	4	10
34	Z2a25	1	2	2	0	1	2	5
35	Z2a50	1	2	2	0	1	2	5
36	Z2a75	1	2	2	0	1	2	5

Table B2 Solutions from CPLEX solving: number of facility and route (continue)

Run	Problem Id	Number of open warehouse	Number of open service center	Number of closing warehouse	Number of closing service center	Number of Directed Route (Echelon 1)	Number of Tour Route (Echelon 2)	Number of Tour Route (Echelon 3)
37	Z3a25	2	3	1	0	2	4	9
38	Z3a50	2	3	1	0	2	4	9
39	Z3a75	2	3	1	0	2	4	9
40	Z4a25	3	4	1	1	3	6	12
41	Z4a50	3	4	1	1	3	6	12
42	Z4a75	3	4	0	0	3	6	12
43	Z5a25	2	3	1	0	2	4	9
44	Z5a50	2	3	1	0	2	4	9
45	Z5a75	2	3	1	0	2	4	9
46	ZAa25	N/A	N/A	N/A	N/A	N/A	N/A	N/A
47	ZAa50	N/A	N/A	N/A	N/A	N/A	N/A	N/A
48	ZAa75	N/A	N/A	N/A	N/A	N/A	N/A	N/A
49	Z1t25	2	3	0	0	2	4	10
50	Z1t50	2	4	0	0	2	4	10
51	Z1t75	2	4	2	1	2	4	10
52	Z2t25	1	2	2	0	1	2	5
53	Z2t50	1	2	2	0	1	2	5
54	Z2t75	1	2	2	0	1	2	5
55	Z3t25	2	3	1	1	2	4	9
56	Z3t50	2	3	1	1	2	4	9
57	Z3t75	2	3	1	1	2	4	9
58	Z4t25	3	4	0	1	3	6	12
59	Z4t50	3	3	1	1	3	6	12
60	Z4t75	3	3	1	1	3	6	12
61	Z5t25	2	3	1	2	2	4	9
62	Z5t50	2	3	1	2	2	4	9
63	Z5t75	2	3	1	2	2	4	9
64	ZAt25	N/A	N/A	N/A	N/A	N/A	N/A	N/A
65	ZAt50	N/A	N/A	N/A	N/A	N/A	N/A	N/A
66	ZAt75	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table B3 Solutions from proposed heuristic approach: total cost

Run	Problem Id	Demand	Computation Time(sec)	Objective Value	Fixed operating cost (warehouse)	Fixed operating cost (service center)	Warehouse closing/saving cost	Service center closing/saving cost	Variable cost of Warehouse	Variable cost of service center	Fixed transportation cost	Transportation variable cost
1	Z1P1	68,408	35.5	68,444	2,058,456	1,685,268	0	0	2,252,085	133,579	2,071,855	3,588,756
2	Z1P2	82,090	36.0	82,126	2,058,456	1,685,268	0	0	2,702,502	160,295	2,071,855	3,588,756
3	Z1P3	98,508	34.5	98,542	3,183,087	2,118,030	0	0	3,175,423	193,761	2,071,855	3,404,109
4	Z1P4	118,209	36.0	118,245	3,183,087	2,559,030	0	0	3,855,082	234,816	2,071,855	3,210,061
5	Z1P5	141,851	35.5	141,886	3,183,087	2,559,030	0	0	4,629,868	282,819	2,071,855	3,210,061
6	Z2P1	42,540	11.3	42,551	1,096,970	867,877	-300,700	0	1,444,423	68,549	1,075,929	1,829,959
7	Z2P2	51,048	11.0	51,059	2,060,350	867,877	-389,089	0	1,966,893	82,667	1,115,929	1,722,260
8	Z2P3	61,258	10.8	61,269	2,060,350	867,877	-389,089	0	2,243,770	99,916	1,115,929	1,722,260
9	Z2P4	73,509	13.1	73,522	2,060,350	1,271,344	-389,089	0	2,691,045	118,940	1,115,929	1,722,260
10	Z2P5	88,211	12.0	88,223	2,060,350	1,271,344	-389,089	0	3,229,254	142,727	1,115,929	1,722,260
11	Z3P1	59,473	18.9	59,492	2,046,048	831,657	76,695	15,751	2,041,346	91,294	2,071,855	3,513,746
12	Z3P2	71,368	18.6	71,387	2,046,048	1,238,528	76,695	-37,232	2,449,615	109,553	2,071,855	3,460,454
13	Z3P3	85,642	18.9	85,661	2,046,048	1,238,528	76,695	-37,232	2,939,538	131,464	2,071,855	3,460,454
14	Z3P4	102,771	19.5	102,791	3,202,632	1,652,254	76,695	-37,232	3,537,942	152,577	2,071,855	3,379,595
15	Z3P5	123,326	20.1	123,346	3,202,632	1,652,254	76,695	-37,232	4,399,810	194,679	2,071,855	3,379,595

Table B3 Solutions from proposed heuristic approach: total cost (continue)

Run	Problem Id	Demand	Computation Time(sec)	Objective Value	Fixed operating cost (warehouse)	Fixed operating cost (service center)	Warehouse closing/saving cost	Service center closing/saving cost	Variable cost of Warehouse	Variable cost of service center	Fixed transportation cost	Transportation variable cost
16	Z4P1	112,010	48.9	112,059	2,815,668	1,221,522	0	-10,714	3,710,372	143,466	2,830,394	5,347,250
17	Z4P2	134,412	49.3	134,461	2,815,668	1,670,769	0	-51,232	4,475,093	172,436	2,830,394	5,278,348
18	Z4P3	161,294	49.4	161,344	3,961,352	1,702,458	0	-51,232	5,466,517	208,825	3,001,980	5,603,906
19	Z4P4	193,553	50.1	193,603	3,961,352	2,066,035	0	-10,714	6,543,690	246,025	3,279,010	5,739,859
20	Z4P5	232,264	50.2	232,314	4,731,641	2,528,875	0	-10,228	7,903,699	292,431	3,279,010	5,738,851
21	Z5P1	71,472	23.8	71,496	2,037,790	826,856	0	43,007	2,250,699	95,342	1,933,161	3,834,655
22	Z5P2	85,766	23.9	85,790	2,037,790	1,242,175	0	0	2,784,041	117,897	1,933,161	3,758,469
23	Z5P3	102,920	24.2	102,944	3,068,630	1,287,809	0	10,775	3,345,165	142,085	1,933,161	3,717,414
24	Z5P4	123,504	24.5	123,528	3,068,630	1,679,915	0	-32,232	3,932,087	174,442	2,071,855	3,956,165
25	Z5P5	148,204	23.9	148,228	4,148,580	2,120,305	0	-32,232	4,901,327	203,490	2,474,310	4,171,165
26	ZAP1	353,903	160.8	354,064	9,222,366	5,449,798	-518,989	186,900	11,858,199	553,311	9,975,712	17,664,491
27	ZAP2	424,684	162.0	424,846	9,200,494	6,405,318	-660,710	187,386	14,405,227	650,209	9,975,712	17,483,389
28	ZAP3	509,622	174.8	509,796	13,245,923	7,716,075	-295,294	176,317	17,378,048	781,750	9,975,712	17,613,528
29	ZAP4	611,546	180.8	611,727	16,898,019	8,941,754	-518,198	257,760	20,133,863	941,168	9,975,712	17,733,252
30	ZAP5	733,856	184.4	734,041	18,951,938	10,675,905	-606,587	7,157	24,400,890	1,139,963	10,391,794	17,545,480

Table B3 Solutions from proposed heuristic approach: total cost (continue)

Run	Problem Id	Demand	Computation Time(sec)	Objective Value	Fixed operating cost (warehouse)	Fixed operating cost (service	Warehouse closing/saving cost	Service center closing/savin	Variable cost of Warehouse	Variable cost of service center	Fixed transportation cost	Transportation variable cost
31	Z1a25	68,408	36.1	68,444	2,573,070	2,106,585	0	0	2,815,481	174,831	2,071,855	3,588,756
32	Z1a50	68,408	36.3	68,444	3,087,684	2,527,902	0	0	3,378,577	209,797	2,071,855	3,588,756
33	Z1a75	68,408	36.6	68,445	3,745,388	2,949,219	-649,406	0	4,151,673	244,764	2,071,855	3,851,506
34	Z2a25	42,540	10.5	42,551	1,371,213	1,084,846	-375,875	0	1,805,528	85,686	1,075,929	1,829,959
35	Z2a50	42,540	10.8	42,551	1,645,456	1,301,815	-451,050	0	2,166,634	102,823	1,075,929	1,829,959
36	Z2a75	42,540	9.8	42,550	1,919,698	1,518,784	-526,225	0	2,527,739	119,961	1,075,929	1,829,959
37	Z3a25	59,473	18.6	59,492	2,557,560	1,039,571	95,869	19,689	2,551,682	114,118	2,071,855	3,513,746
38	Z3a50	59,473	19.0	59,492	3,069,073	1,247,485	115,043	23,627	3,062,018	136,941	2,071,855	3,513,746
39	Z3a75	59,473	18.5	59,491	3,580,585	1,446,001	134,217	-65,156	3,572,355	148,888	2,071,855	3,591,965
40	Z4a25	112,010	49.2	112,059	3,519,586	1,558,514	0	-64,040	4,637,966	166,114	2,830,394	5,355,573
41	Z4a50	112,010	48.8	112,059	4,223,503	1,870,217	0	-76,848	5,565,559	199,336	2,830,394	5,355,573
42	Z4a75	112,010	49.3	112,059	4,927,420	2,181,919	0	-89,656	6,493,152	232,559	2,830,394	5,355,573
43	Z5a25	71,472	23.9	71,496	2,547,237	1,033,570	0	53,759	2,813,374	143,013	1,933,161	3,834,655
44	Z5a50	71,472	24.2	71,496	3,056,685	1,240,284	0	64,511	3,376,048	143,013	1,933,161	3,834,655
45	Z5a75	71,472	23.5	71,495	3,566,132	1,446,998	0	75,262	3,938,723	166,849	1,933,161	3,834,655
46	ZAa25	352,903	164.4	353,067	11,527,958	6,812,247	-648,736	233,625	14,822,749	691,639	9,975,712	17,664,491

Table B3 Solutions from proposed heuristic approach: total cost (continue)

Run	Problem Id	Demand	Computation Time(sec)	Objective Value	Fixed operating cost (warehouse)	Fixed operating cost (service center)	Warehouse closing/saving cost	Service center closing/saving cost	Variable cost of Warehouse	Variable cost of service center	Fixed transportation cost	Transportation variable cost
47	ZAa50	352,903	162.4	353,065	13,887,412	8,174,697	-1,669,658	280,350	17,525,604	829,967	9,975,712	18,696,190
48	ZAa75	352,903	160.8	353,064	14,910,835	8,793,965	-1,815,293	327,075	21,040,241	965,563	9,975,712	20,127,109
49	Z1t25	68,408	36.0	68,444	2,058,456	1,685,268	0	0	2,252,384	139,865	2,589,819	4,485,945
50	Z1t50	68,408	35.8	68,444	2,058,456	1,685,268	0	0	2,252,384	139,865	3,107,783	5,383,134
51	Z1t75	68,408	36.5	68,445	2,058,456	1,685,268	0	0	2,252,384	139,865	3,625,746	6,280,324
52	Z2t25	42,540	10.8	42,551	1,096,970	867,877	-300,700	0	1,444,423	68,549	1,344,911	2,287,449
53	Z2t50	42,540	11.0	42,551	1,096,970	867,877	-300,700	0	1,444,423	68,549	1,613,893	2,744,939
54	Z2t75	42,540	11.1	42,551	1,096,970	867,877	-300,700	0	1,444,423	68,549	1,882,875	3,202,429
55	Z3t25	59,473	19.3	59,492	2,046,048	831,657	76,695	15,751	2,041,346	91,294	2,589,819	4,392,182
56	Z3t50	59,473	18.6	59,492	2,046,048	831,657	76,695	15,751	2,041,346	91,294	3,107,783	5,270,618
57	Z3t75	59,473	19.0	59,492	2,046,048	1,238,528	76,695	-37,232	2,040,780	86,681	3,625,746	5,654,710
58	Z4t25	112,010	49.3	112,059	2,815,668	1,221,522	0	-10,714	3,710,372	143,466	3,537,992	6,684,062
59	Z4t50	112,010	48.4	112,058	2,815,668	1,310,657	0	-10,228	3,710,372	144,106	4,245,590	7,921,544
60	Z4t75	112,010	48.1	112,058	2,815,668	1,310,657	0	-10,228	3,710,372	143,996	4,953,189	9,241,801

Table B3 Solutions from proposed heuristic approach: total cost (continue)

Run	Problem Id	Demand	Computation Time(sec)	Objective Value	Fixed operating cost (warehouse)	Fixed operating cost (service center)	Warehouse closing/saving cost	Service center closing/saving cost	Variable cost of Warehouse	Variable cost of service center	Fixed transportation cost	Transportation variable cost
61	Z5t25	71,472	24.2	71,496	2,037,790	826,856	0	43,007	2,255,452	93,402	2,416,451	4,793,319
62	Z5t50	71,472	24.2	71,496	2,037,790	826,856	0	43,007	2,255,452	93,402	2,899,741	5,751,983
63	Z5t75	71,472	24.5	71,497	2,037,790	826,856	0	43,007	2,255,452	93,402	3,383,031	6,710,646
64	ZAt25	353,903	166.0	354,069	9,222,366	5,449,798	-518,989	186,900	11,858,199	553,311	12,469,640	22,080,613
65	ZAt50	353,903	163.2	354,066	9,477,340	5,440,442	-1,037,310	143,893	12,162,993	554,730	14,963,568	26,268,513
66	ZAt75	353,903	160.4	354,063	9,477,340	5,440,442	-1,037,310	143,893	12,203,387	568,475	17,457,496	30,685,279

Table B4 Solutions from proposed heuristic approach: number of facility and route

Run	Problem Id	Number of open warehouse (Wi)	Number of open service center (Sj)	Number of closing warehouse (Wi)	Number of closing service center (Sj)	Number of Directed Route (Echelon 1)	Number of Tour Route (Echelon 2)	Number of Tour Route (Echelon 3)
1	Z1P1	2	4	0	0	2	4	10
2	Z1P2	2	4	0	0	2	4	10
3	Z1P3	3	5	0	0	3	4	10
4	Z1P4	3	6	0	0	3	4	10
5	Z1P5	3	6	0	0	3	4	10
6	Z2P1	1	2	2	0	1	2	5
7	Z2P2	2	2	1	0	2	2	5
8	Z2P3	2	2	1	0	2	2	5
9	Z2P4	2	3	1	0	2	2	5
10	Z2P5	2	3	1	0	2	2	5
11	Z3P1	2	2	1	2	2	4	10
12	Z3P2	2	3	1	1	2	4	10
13	Z3P3	2	3	1	1	2	4	10
14	Z3P4	3	4	1	1	3	4	10
15	Z3P5	3	4	1	1	3	4	10
16	Z4P1	3	3	0	2	3	6	13
17	Z4P2	3	4	0	1	3	6	13
18	Z4P3	4	4	0	1	4	7	13
19	Z4P4	5	5	0	2	5	7	15
20	Z4P5	5	6	0	2	5	7	15
21	Z5P1	2	2	0	1	2	4	9
22	Z5P2	2	3	0	0	2	4	9
23	Z5P3	3	3	0	2	3	4	9
24	Z5P4	3	4	0	1	3	4	10
25	Z5P5	4	5	0	1	4	5	11
26	ZAP1	9	13	5	5	9	21	46
27	ZAP2	9	15	7	10	9	21	46
28	ZAP3	13	18	2	10	13	21	46
29	ZAP4	16	21	5	8	16	21	46
30	ZAP5	17	25	4	6	17	21	49
31	Z1a25	2	4	0	0	2	4	10
32	Z1a50	2	4	0	0	2	4	10
33	Z1a75	2	4	1	0	2	4	10
34	Z2a25	1	2	2	0	1	2	5
35	Z2a50	1	2	2	0	1	2	5
36	Z2a75	1	2	2	0	1	2	5

Table B4 Solutions from proposed heuristic approach: number of facility and route (continue)

Run	Problem Id	Number of open warehouse (Wi)	Number of open service center (Sj)	Number of closing warehouse (Wi)	Number of closing service center (Sj)	Number of Directed Route (Echelon 1)	Number of Tour Route (Echelon 2)	Number of Tour Route (Echelon 3)
37	Z3a25	2	2	1	2	2	4	10
38	Z3a50	2	2	1	2	2	4	10
39	Z3a75	2	2	1	1	2	4	10
40	Z4a25	3	3	0	1	3	6	13
41	Z4a50	3	3	0	1	3	6	13
42	Z4a75	3	3	0	1	3	6	13
43	Z5a25	2	2	0	1	2	4	9
44	Z5a50	2	2	0	1	2	4	9
45	Z5a75	2	2	0	1	2	4	9
46	ZAa25	9	13	5	10	9	21	46
47	ZAa50	9	13	6	10	9	21	46
48	ZAa75	8	12	7	8	8	21	46
49	Z1t25	2	4	0	0	2	4	10
50	Z1t50	2	4	0	0	2	4	10
51	Z1t75	2	4	0	0	2	4	10
52	Z2t25	1	2	2	0	1	2	5
53	Z2t50	1	2	2	0	1	2	5
54	Z2t75	1	2	2	0	1	2	5
55	Z3t25	2	2	1	2	2	4	10
56	Z3t50	2	2	1	2	2	4	10
57	Z3t75	2	3	1	1	2	4	10
58	Z4t25	3	3	0	2	3	6	13
59	Z4t50	3	3	0	2	3	6	13
60	Z4t75	3	3	0	2	3	6	13
61	Z5t25	2	3	0	1	2	4	9
62	Z5t50	2	3	0	1	2	4	9
63	Z5t75	2	3	0	1	2	4	9
64	ZAt25	9	13	5	5	9	21	46
65	ZAt50	9	13	7	9	9	21	46
66	ZAt75	9	13	7	9	9	21	46

Table B5 Comparing solutions solved by proposed heuristic approach with current distribution network: cost component

Scenario	Zone	Objective Value	Fixed operating cost (warehouse)	Fixed operating cost (service center)	Warehouse closing/saving cost	Service center closing/saving cost	Variable cost of Warehouse	Variable cost of service center	Fixed transportation cost	Transportation variable cost
AS-IS	Zone 1	11,627,478	2,058,456	1,283,057	0	0	2,383,575	134,115	2,071,855	3,696,419
AS-IS	Zone 2	7,584,569	1,987,228	867,877	0	0	1,648,510	67,100	1,075,929	1,937,927
AS-IS	Zone 3	11,255,476	2,018,329	835,645	0	0	2,208,530	84,770	2,243,083	3,865,120
AS-IS	Zone 4	16,401,261	2,851,668	1,233,868	0	0	3,747,855	149,818	3,140,316	5,277,736
AS-IS	Zone 5	11,159,067	2,037,790	817,657	0	0	2,299,649	100,913	2,071,855	3,831,204
Summary		58,027,851	10,953,470	5,038,104	0	0	12,288,119	536,715	10,603,037	18,608,406
Solved separate	Zone 1	11,528,717	1,878,456	1,878,456	0	0	2,327,501	2,327,501	2,327,501	2,327,501
Solved separate	Zone 2	6,083,007	1,096,970	867,877	-300,700	0	1,444,423	68,549	1,075,929	1,829,959
Solved separate	Zone 3	10,688,392	2,046,048	831,657	76,695	15,751	2,041,346	91,294	2,071,855	3,513,746
Solved separate	Zone 4	16,057,958	2,815,668	1,221,522	0	-10,714	3,710,372	143,466	2,830,394	5,347,250
Solved separate	Zone 5	11,021,509	2,037,790	826,856	0	43,007	2,250,699	95,342	1,933,161	3,834,655
Summary		55,379,583	9,874,932	5,626,368	-224,005	48,044	11,774,341	2,726,152	10,238,840	16,853,111
All Zone	Zone 1	12,202,777	2,278,846	831,427	-412,321	105,130	3,351,160	94,663	2,414,305	3,539,567
All Zone	Zone 2	6,273,042	1,096,970	867,877	-300,700	0	1,438,905	86,519	1,174,622	1,908,849
All Zone	Zone 3	10,915,463	1,989,068	1,243,899	84,217	43,620	1,960,946	95,534	2,071,855	3,426,325
All Zone	Zone 4	14,419,073	1,895,692	1,229,070	109,815	-11,600	3,136,141	146,709	2,520,472	5,392,773
All Zone	Zone 5	10,657,432	2,037,790	1,277,525	0	49,750	1,971,046	129,887	1,794,458	3,396,976
Summary		54,467,788	9,298,366	5,449,798	-518,989	186,900	11,858,199	553,311	9,975,712	17,664,491

Table B6 Comparing solutions solved by proposed heuristic approach with current distribution network: number of facility and route

Scenario	Zone	Number of open warehouse	Number of open service center	Number of closing warehouse	Numer of closing service center	Number of Directed Route (Echelon 1)	Number of Tour Route (Echelon 2)	Number of Tour Route (Echelon 3)
AS-IS	Zone 1	2	3	0	0	11	4	10
AS-IS	Zone 2	2	2	0	0	11	2	5
AS-IS	Zone 3	2	2	0	0	11	5	10
AS-IS	Zone 4	3	3	0	0	11	7	14
AS-IS	Zone 5	2	3	0	0	11	4	10
Summary		11	13	0	0	55	22	49
Solved separate	Zone 1	2	3	0	0	2	4	10
Solved separate	Zone 2	1	2	2	0	1	2	5
Solved separate	Zone 3	2	2	1	2	2	4	10
Solved separate	Zone 4	3	3	0	2	3	6	13
Solved separate	Zone 5	2	2	0	1	2	4	9
Summary		10	12	3	5	10	20	47
All Zone	Zone 1	2	4	1	0	2	6	10
All Zone	Zone 2	1	2	2	0	1	2	6
All Zone	Zone 3	2	2	1	2	2	4	10
All Zone	Zone 4	2	3	1	2	2	5	12
All Zone	Zone 5	2	2	0	1	2	4	8
Summary		9	13	5	5	9	21	46

APPENDIX C: Simulation Statistical Testing

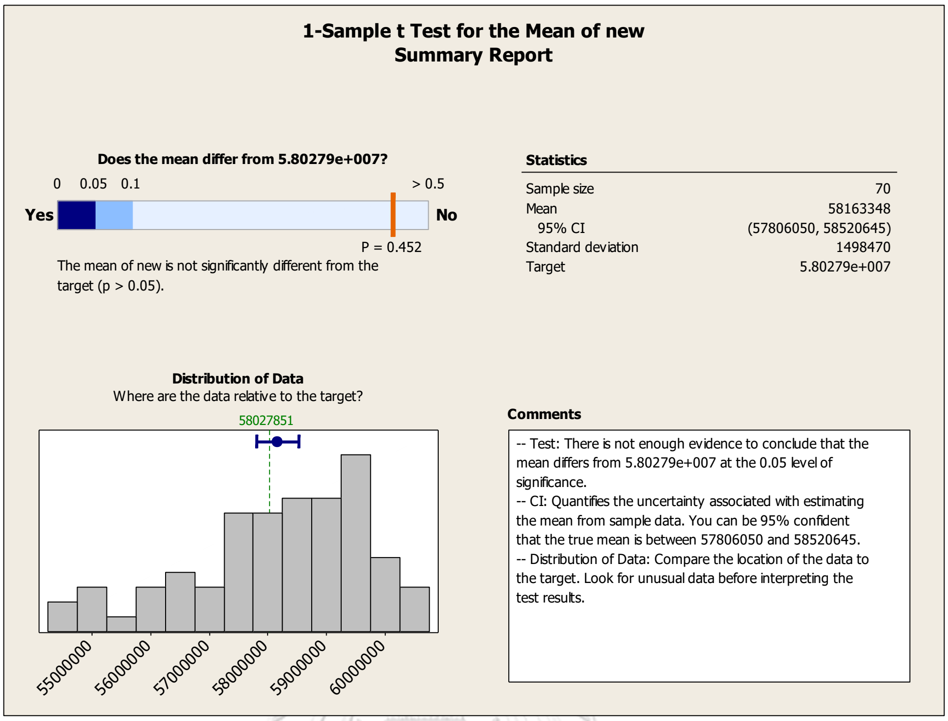

Figure C1 Validation model: test of total cost (as-is model vs. current distribution network) by using Minitab version 16.2.1

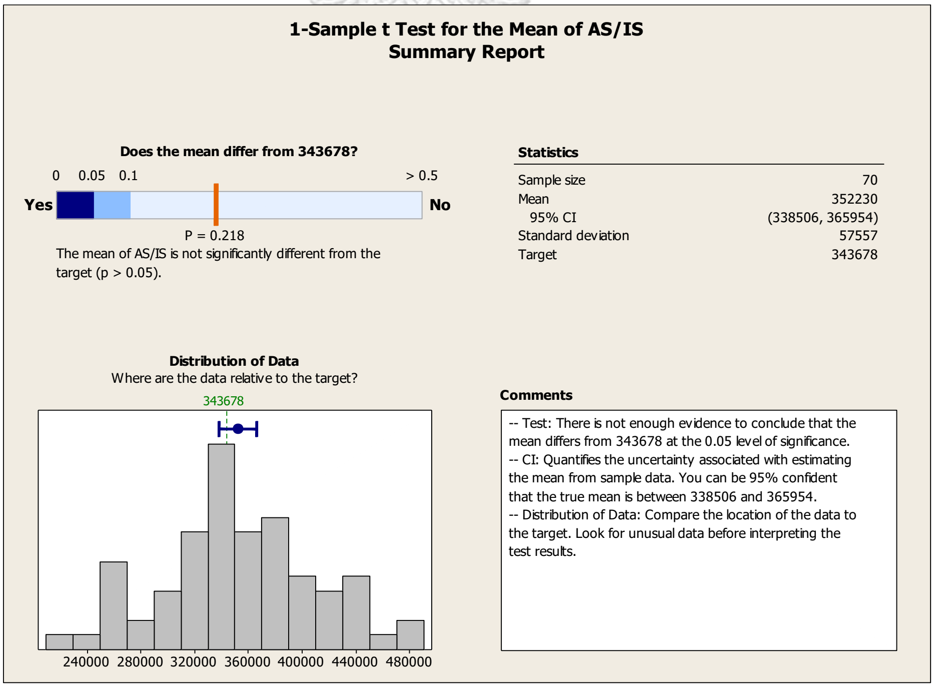

Figure C2 Validation model: test of flow through warehouse (as-is model vs. current distribution network) by using Minitab version 16.2.1

Table C1 Solution of simulation model: as-is model and separated model

Scenario	Average flow through warehouse		Average flow through service center		Facility fixed cost		Facility variable cost of warehouse		Facility variable cost of service center		Transportation fixed cost	Transportation variable cost		Total Cost	
	Mean	Half width	Mean	Half width	Warehouse	Service center	Mean	Half width	Mean	Half width		Mean	Half width	Mean	Half width
Zone 1 as-is	67,957	3,204	2,673	356	2,058,456	1,283,057	2,352,055	30,205	133,481	1,700	2,071,855	3,787,932	49,474	11,686,837	148,800
Zone 2 as-is	42,307	3,204	1,264	356	1,987,228	867,877	1,640,717	20,568	66,782	837	1,075,929	2,056,918	26,760	7,695,450	96,470
Zone 3 as-is	59,131	3,204	1,653	356	2,018,329	835,645	2,108,089	29,171	84,369	1,120	2,243,083	3,938,002	52,572	11,227,517	149,000
Zone 4 as-is	111,661	3,204	2,591	356	2,851,668	1,233,868	3,730,137	44,719	149,110	1,788	3,140,316	5,315,194	65,710	16,420,293	196,855
Zone 5 as-is	71,174	3,204	1,927	356	2,037,790	817,657	2,218,778	45,436	100,436	1,994	2,071,855	3,886,736	78,001	11,133,251	221,012
All zones as-is	352,230	3,204	10,107	356	10,953,470	5,038,104	12,049,776	75,129	534,178	3,281	10,603,037	18,984,782	116,624	58,163,348	357,298
Zone 1 Separate	68,108	3,204	2,659	356	2,058,456	1,685,268	2,244,744	30,483	133,144	1,808	2,071,855	3,711,704	50,403	11,935,105	162,073
Zone 2 Separate	42,283	3,204	1,136	356	796,271	867,877	1,439,715	23,765	68,326	1,128	1,075,929	1,991,406	50,403	6,255,581	103,260
Zone 3 Separate	59,193	3,204	1,649	356	2,122,744	847,408	2,034,692	30,569	90,997	1,367	2,071,855	3,877,073	50,403	11,076,034	166,406
Zone 4 Separate	111,797	3,204	2,591	356	2,815,668	1,210,808	3,698,279	46,954	142,999	1,816	2,830,394	5,437,614	50,403	16,179,613	205,421
Zone 5 Separate	71,369	3,204	1,931	356	2,037,790	869,863	2,243,363	37,649	95,031	1,595	1,933,161	3,880,057	50,403	11,090,556	186,128
All zones Separate	352,749	3,204	9,965	356	9,830,928	5,481,224	11,660,792	78,416	530,496	3,567	9,983,193	18,897,854	50,403	56,536,889	380,199

Table C2 Solution of simulation model: simultaneously model

Scenario	Average flow through warehouse		Average flow through service center		Facility fixed cost		Facility variable cost of warehouse		Facility variable cost of service center		Transportation fixed cost	Transportation variable cost		Total Cost	
	Mean	Half width	Mean	Half width	Warehouse	Service center	Mean	Half width	Mean	Half width		Mean	Half width	Mean	Half width
Zone 1 simultaneous	97,842	2,941	3,086	298	1,866,525	936,557	3,339,612	40,945	94,336	1,157		3,916,546	48,018	12,567,881	154,087
Zone 2 simultaneous	97,842	2,941	3,086	298	796,271	867,877	1,433,947	23,538	86,221	1,415	1,174,622	2,009,292	32,982	6,368,228	104,532
Zone 3 simultaneous	97,842	2,941	3,086	298	2,073,285	1,287,519	1,954,189	28,819	95,204	1,404	2,071,855	3,460,588	51,034	10,942,640	161,375
Zone 4 simultaneous	97,842	2,941	3,086	298	2,005,507	1,217,471	3,125,334	38,137	146,204	1,784	2,520,472	5,454,557	66,559	14,469,544	176,563
Zone 5 simultaneous	97,842	2,941	3,086	298	2,037,790	1,327,275	1,964,254	28,306	129,439	1,865	1,794,458	3,632,855	52,351	10,886,072	156,873
All zones simultaneous	97,842	2,941	3,086	298	8,779,377	5,636,698	11,817,337	68,659	551,405	3,204	9,975,712	18,473,837	107,334	55,234,366	320,914

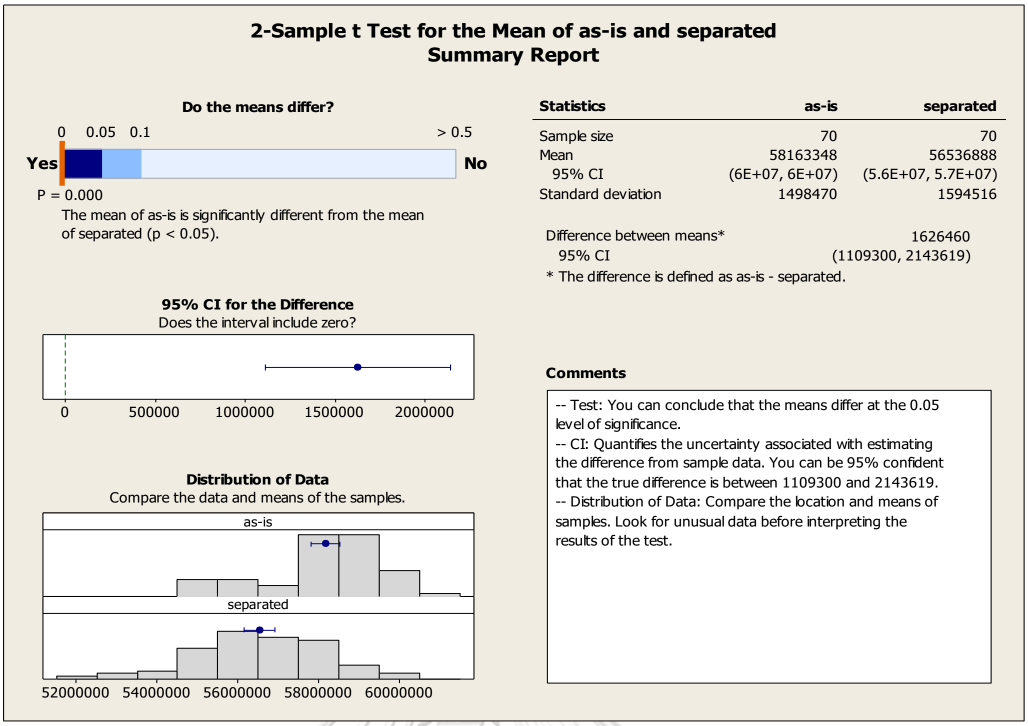

Figure C3 Two samples t-test of total cots between as-is and separated model by Minitab 16.2.1

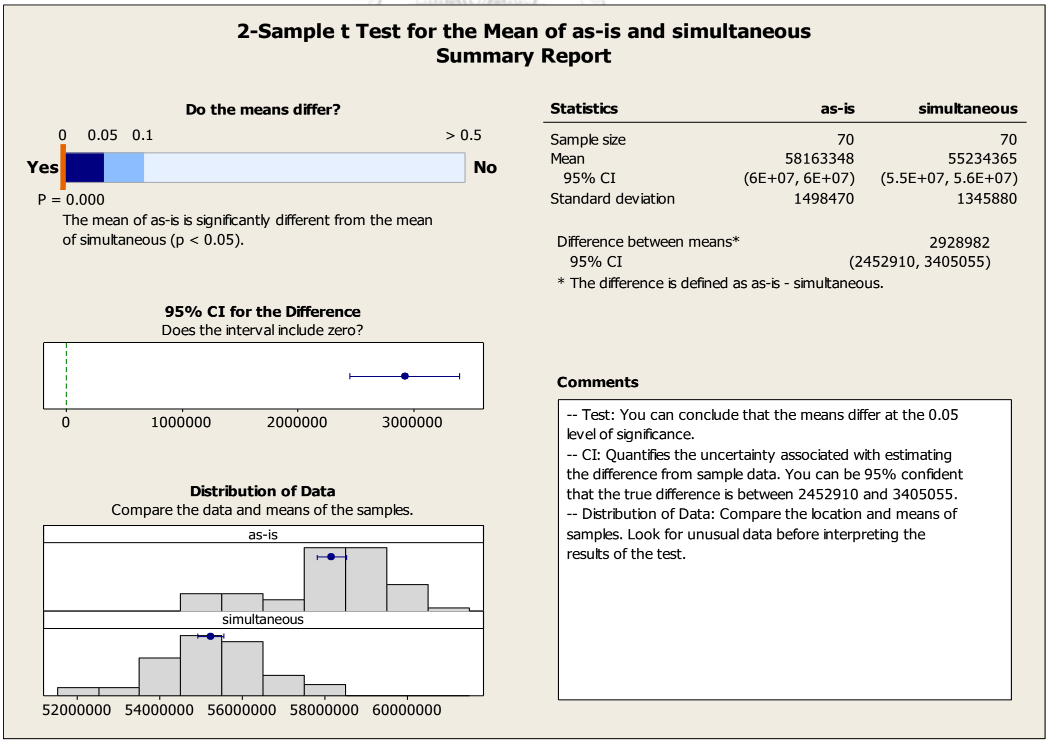

Figure C4 Two samples t-test of total cots between as-is and simultaneous model by Minitab 16.2.1

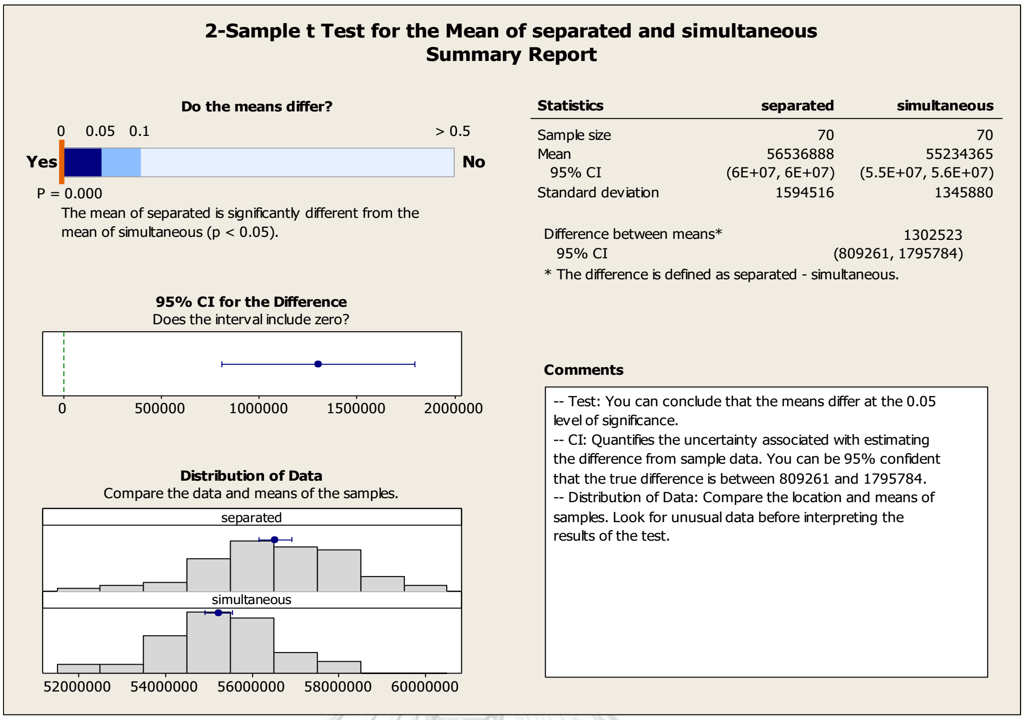

Figure C5 Two samples t-test of total cots between separated and simultaneous model by Minitab 16.2.1

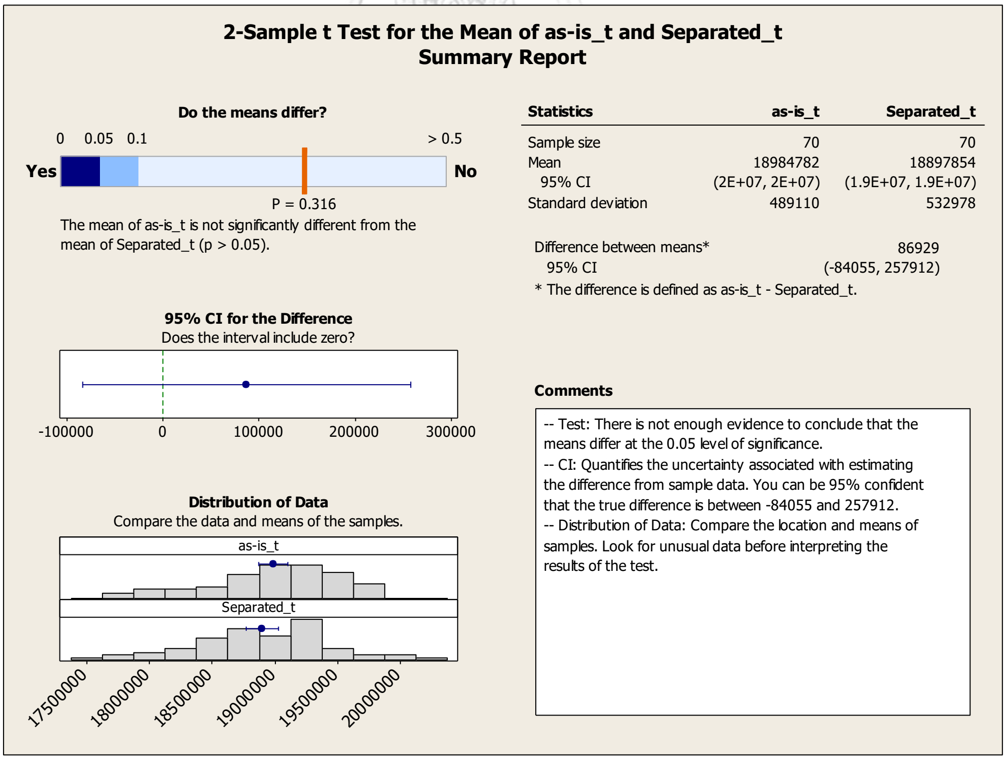

Figure C6 Two samples t-test of transportation cost between as-is and separated model by Minitab 16.2.1

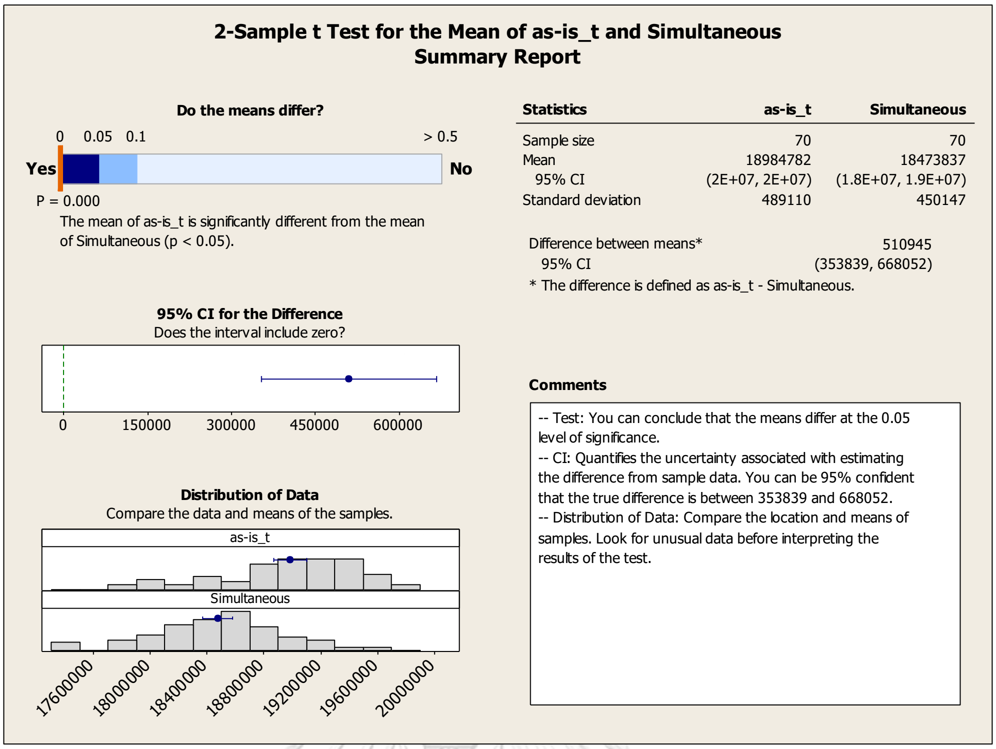

Figure C7 Two samples t-test of transportation cost between as-is and simultaneous model by Minitab 16.2.1

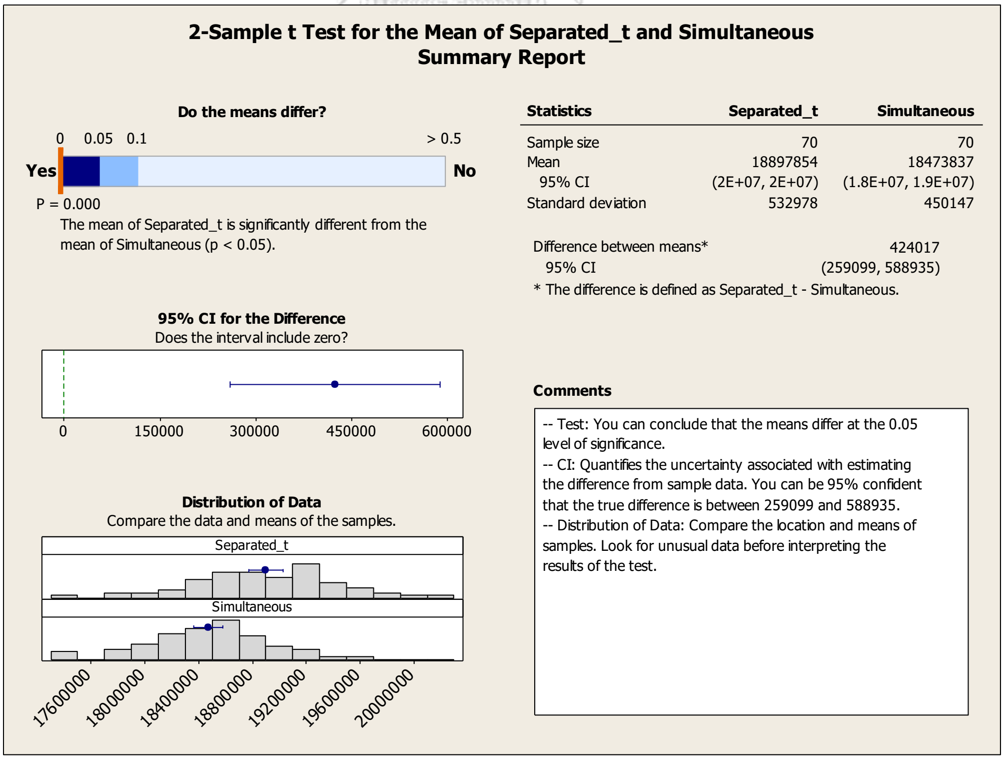

Figure C8 Two samples t-test of transportation cost between separated and simultaneous model by Minitab 16.2.1

VITA

Patanapong Sanghatawatan was born in 1979 in Bangkok. After graduate from Bodindecha (Sing Singhaseni) 2 School, he went to Chaing Mai University, where he obtained a bachelor degree in Industrial Engineering in 2001. He went to Japan for language learning purpose. After graduated in Master degree in Industrial Engineering at Chulalongkorn University in 2006, he has been working as a lecturer in Industrial and Logistics Engineering at Mahanakorn University of Technology. He had worked as head of department of Industrial and Logistics Engineering for six years. And he also had professional experiences in Logistics consultant of Bureau of Logistics, Department of Industrial and Mines for years.