THESIS – TI 235401

ADAPTIVE LARGE NEIGHBORHOOD SEARCH FOR THE TWO-ECHELON LOCATION ROUTING PROBLEM WITH SIMULTANEOUS PICKUP AND DELIVERY AND PARCEL LOCKERS

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THESIS APPROVAL SHEET

The Thesis is Proposed to Fulfill the Requirement to Obtain
Magister Teknik (MT)
in
Institut Teknologi Sepuluh Nopember
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STATEMENT OF ORIGINALITY

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Hereby declare that the thesis entitled

"Adaptive Large Neighborhood Search for the Two-Echelon Location Routing Problem with Simultaneous Pickup and Delivery and Parcel Lockers"

is truly my own work, original, and all references quoted or cited have been fully listed in the bibliography. If this statement is found to be untrue, I am willing to accept sanctions according to the applicable regulations.

Surabaya, July 27, 2024

Declarant

Rafli Muhammad Rangga Kusuma

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ADAPTIVE LARGE NEIGHBORHOOD SEARCH FOR THE TWO-ECHELON LOCATION ROUTING PROBLEM WITH SIMULTANEOUS PICKUP AND DELIVERY AND PARCEL LOCKERS

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ABSTRACT

Last-mile delivery in urban areas has become more challenging due to the more crowded environment in the city. It leads to increasing traffic congestion and delivery lateness because of difficult access to customers' houses. These challenges contribute to the high proportion of cost in the supply chain activity. Alternative delivery strategy such as parcel locker and distribution network optimization can be the solutions for these problems. This research extends the Two-Echelon Location Routing Problem with Simultaneous Pickup and Delivery (2E-LRPSPD) by integrating parcel lockers, creating the 2E-LRPSPD-PL model. The single depot, opened satellites, and opened parcel lockers make up the first echelon of the 2E-LRPSPD-PL. On the other hand, the second tier is characterized by opened satellites that establish routes to satisfy the needs of home service consumers and by opened parcel lockers that meet the needs of parcel locker customers. Two-indexed Mixed Integer Linear Programming (MILP) is made to describe the model. CPLEX solver and ALNS algorithm are proposed to solve the data instances of 2E-LRPSPD-PL. Generally, the result shows that ALNS algorithm can outperform the CPLEX in terms of solution quality and computational time. The use of parcel lockers has also proven to effectively reduce the total cost. Even with adjustments to several parameters, using parcel lockers can be more efficient than traditional last-mile delivery.

Keywords: *ALNS, CPLEX, Parcel Locker, Satellite, Two-Echelon Location Routing Problem with Simultaneous Pickup and Delivery*

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ABSTRAK

Pengiriman *last-mile* di daerah perkotaan menjadi lebih menantang karena lingkungan kota yang semakin padat. Hal ini menyebabkan meningkatnya kemacetan lalu lintas dan keterlambatan pengiriman karena akses yang sulit ke rumah pelanggan. Tantangan-tantangan ini berkontribusi pada proporsi biaya yang tinggi dalam aktivitas rantai pasokan. Strategi pengiriman alternatif seperti loker paket dan optimalisasi jaringan distribusi dapat menjadi solusi untuk masalah-masalah ini. Penelitian ini memperluas *Two-Echelon Location Routing Problem with Simultaneous Pickup and Delivery* (2E-LRPSPD) dengan mengintegrasikan *parcel locker*, menciptakan model 2E-LRPSPD-PL. Depot tunggal, satelit yang dibuka, dan *parcel locker* yang dibuka membentuk tingkat pertama dari 2E-LRPSPD-PL. Di sisi lain, tingkat kedua ditandai dengan satelit yang dibuka yang membentuk rute untuk memenuhi kebutuhan layanan rumah konsumen dan *parcel locker* yang dibuka yang memenuhi kebutuhan pelanggan *parcel locker*. *Two-indexed Mixed Integer Linear Programming* (MILP) dibuat untuk menggambarkan model tersebut. *Solver* CPLEX dan algoritma ALNS diusulkan untuk menyelesaikan data *instances* dari 2E-LRPSPD-PL. Secara umum, hasil menunjukkan bahwa algoritma ALNS dapat mengungguli CPLEX dalam hal kualitas solusi dan waktu komputasi. Penggunaan *parcel locker* juga terbukti efektif mengurangi total biaya. Bahkan dengan penyesuaian beberapa parameter, penggunaan *parcel locker* dapat lebih efisien dibandingkan dengan pengiriman *last-mile* tradisional.

Kata kunci: *ALNS, CPLEX, Parcel Locker,* Satelit, *Two-Echelon Location Routing Problem with Simultaneous Pickup and Delivery*

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ACKNOWLEDGEMENT

First and foremost, I want to express my gratitude to Allah SWT for guiding me and blessing me with patience and perseverance throughout the completion of this thesis.

I am deeply thankful to my parents for their unwavering support and prayers during my master's thesis journey.

Special appreciation goes to my supervisors, Prof. Vincent F. Yu, Prof. Iwan Vanany, and Dr. Niniet Indah Arvitrida, despite not being physically present in Taiwan, for their invaluable guidance and dedication in helping me complete my thesis online.

I am also grateful to Nabila Yuraisyah and Wahyu Kurniawan for their mentorship and insightful discussions that significantly contributed to the success of this thesis.

Additionally, I extend my thanks to my lab mates in MA-003—Tuan Anh, Soumen, Tony, Huy, William, Kevin, Mai, Shan, Ella, Hendy, Firda, and Vio—for their presence and interactions that made this journey memorable.

My Indonesian and Taiwanese friends in MA-421—Octa, Alam, Prana, Aldi, John, Atha, Azmi, Natalie, and Arei—have been like a second family to me, providing a supportive environment to refresh myself amidst thesis challenges.

Ilham, Fauzan, Yudhis, Reno, Tavio, Riza, Syarif, Arya, Albert, Samuel, Fatiha, Andiny, and Listi also supported me a lot during this thesis working process. One more man that should be appreciated is Dr. Panca. His video AMPL tutorial and his papers gave me a lot of insights.

To everyone mentioned above, your support and encouragement have been instrumental in achieving this success. I deeply cherish our connections and wish them all the very best in their future endeavours.

Taipei, July 2024

Rafli Muhammad Rangga Kusuma

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CHAPTER I

INTRODUCTION

This section explains the research background, research problem formulation, research purposes, research limitations, and assumptions, research benefits as well as the systematics of preparing research reports. These sub-chapters are explained in more detail in the form of explanatory points. The following is an explanation of each sub-chapter.

1.1 Background

When people or customers buy products through e-commerce, traditionally, products are delivered to the customer's location by logistics service companies. This concept is well known as last-mile delivery. Nowadays, last-mile delivery in urban areas has become more challenging because of the increasing number of people in the area, occupying more space in a city. The more crowded people in many cities cause more urban traffic congestion and difficult access to customers' houses. Moreover, many stopping points (house-by-house delivery) which are faced by couriers enlarge the challenge of last-mile delivery in urban areas. As a result, some lateness of deliveries can happen and that leads to decreasing customer satisfaction. Based on a survey that was held in Jakarta, Indonesia in 2019, out of 247 respondents who have experienced online shopping, more than 50% have faced lateness in the delivery process (Nahry & Vilardi, 2019). Furthermore, this last-mile delivery in urban areas incurs high costs during the implementation. Last-mile delivery is calculated for 13% - 75% of the total costs during supply chain activity (Gevaers et al., 2009). The high cost also comes from the condition in which the customer is not at the destination which causes the products to be sent back to the warehouse (delivery failure). Consequently, logistics service companies as unseparated partners of e-commerce must find alternative delivery methods to solve some aforementioned challenges.

Parcel locker is one of the alternative solutions to handle the challenges of last mile delivery. Parcel locker is a strategy in which couriers send customers' delivery products at assigned lockers that make customers more flexible to take the products anytime (Yu et al., 2023). Other than taking products from parcel locker, customers also can put products in the parcel locker to be picked up by couriers, for example, when customers want to return defect product. The implementation of parcel locker can lead to the savings of 55% - 66% of transportation costs, compared to the traditional delivery methods (Deutsch & Golany, 2018). Parcel locker also provides faster service in terms of delivery and pickup products since collecting and putting products can be done anonymously and flexibly over time (Weltevreden, 2008). In terms of real-world implementation, parcel locker has been implemented successfully in more than 20 countries, such as US, UK, Europe, and Canada (Deutsch & Golany, 2018). There are Amazon which opened 40 parcel lockers in 25 regions in Toronto and Canada post which also located more than 60 parcel lockers for free at several buildings (Deutsch & Golany, 2018). InPost parcel locker, the most widely distributed parcel locker in the world, has 4000 lockers in 20 countries (Yu, Susanto, Jodiawan, et al., 2022). In Indonesia, parcel locker is still not popular yet. Based on a survey that was held in Jakarta, Indonesia in 2019, out of 247 respondents who have experienced online shopping, only 3% of respondents have used parcel locker as delivery methods (Nahry & Vilardi, 2019). While 81% of respondents never heard about parcel locker (Nahry & Vilardi, 2019).

Even parcel locker is rarely implemented in Indonesia right now, customers have good tendency to try using parcel locker if it is massively executed. Based on the same survey, respondents have declared that punctuality factor (38.8% of respondents) is the most important factor to be considered to choose delivery method (Nahry & Vilardi, 2019). New delivery method, such as parcel locker can be solution in which couriers do not need to do many house-by-house deliveries, but couriers just visit some parcel lockers to deliver products. This creates faster delivery and pickup of product. In terms of customers, there will be flexibility over time to take the products. The second important factor to be considered to choose delivery method is cost (25.1% of respondents) (Nahry & Vilardi, 2019). Based on the survey, customers choose the cheapest delivery method. Customers tend to use parcel locker if it is cheaper than traditional last-mile delivery (Nahry & Vilardi, 2019). The third factor to be considered to choose delivery method is location (18.2% of respondents) (Nahry & Vilardi, 2019). In practice right now, customers prefer to use traditional last-mile delivery because it is assumed that current location of parcel lockers are too far from customer's house (Nahry & Vilardi, 2019). The parcel locker must be located at the reasonable range in which customers are willing to visit. The last factor is information (17.9% of respondents) in which customers wants to have good tracking system (Nahry & Vilardi, 2019).

The challenges of last-mile delivery can also be reduced by optimizing distribution network. A distribution network consists of two main elements, namely facilities' locations and routes that connect locations in distribution network (Demircan-Yildiz et al., 2016). Optimizing distribution network means that an optimization technique is needed to accommodate the two elements to be effectively determined in the logistics activity. Location Routing Problem (LRP) is the technique which can be used to determine the decisions of those elements simultaneously. Generally, a facility is defined as a depot location that can directly serve customers (direct shipment). However, the direct shipment concept is not always practical in cities or urban areas, as the traffic conditions can cause delivery delays in logistics. Other than that, direct shipment prevents logistics from doing extra delivery consolidation that results in an inefficiency of delivery and vehicles used. Therefore, intermediate facilities are needed in city logistics. The network turns out to be two-echelon network. It means that the LRP technique which is used to determine facilities locations and routing decisions is changed into two-echelon LRP (2E-LRP). 2E-LRP consists of primary facility or depot, primary vehicles, intermediate facilities, vehicles in second echelon, and customers (Demircan-Yildiz et al., 2016).

Generally, the 2E-LRP concept only considers delivery demand (Demircan-Yildiz et al., 2016). Meanwhile in some cases of e-commerce transactions, customers may also return the products due to defective product or other causes. The increasing trend of online shopping delivery through e-commerce is accompanied by the increasing trend of product returns. Based on a survey conducted in September 2020 about concerns on returning to e-commerce platforms among customers in Indonesia, 14% to 59% of customers were concerned about the ease of return shipping (Nurhayati-Wolff, 2023). By having some explanation above, it can be said that customers may have pickup and delivery demands, and customers may ask both demands to be fulfilled at the same time (Demircan-Yildiz et al., 2016). There are pickup demand for returning products (reverse logistics) and delivery demand for ordering products from e-commerce. This consumer behavior affects the logistics activity in urban area. Therefore, the basic 2E-LRP was upgraded to the two-echelon LRP with simultaneous pickup and delivery (2E-LRPSPD).

Research about 2E-LRPSPD is very rarely done. The first research of 2E-LRPSPD was initiated by Demircan-Yildiz et al., (2016) which emphasized the mixed integer programming formulations and did a comparative analysis. The next research about 2E-LRPSPD was done by Fan et al.,(2020) which developed a multi-start hybrid heuristic to solve 2E-LRPSPD. The last research about 2E-LRPSPD was developed by Yıldız et al., (2023) which explained multi depots concept in 2E-LRPSPD. So, there are still only three research articles about this topic. The underlying purpose of 2E-LRPSPD is to optimize the distribution network in the city logistics by considering simultaneous pickup and delivery. The optimization will result in cost reduction of last-mile delivery. Other than 2E-LRPSPD, reducing the cost of last-mile delivery also potentially can be done by adopting another delivery method like parcel locker, which was explained before. A combination of 2E-LRPSPD and parcel locker has possibility to result in more efficient logistics activity.

This study is focused on combining 2E-LRPSPD with parcel locker (2E-LRPSPD-PL). In 2E-LRPSPD-PL, the facility location decisions involve determining the locations and the number of intermediate facilities, namely satellites and parcel lockers, which will be opened. Satellite can be defined as a warehouse or distribution center which is usually located between depot and customers. Then, the routing decision is made in the first echelon which consists of a depot, opened satellites, and opened parcel lockers. While the routing of the second echelon consists of opened parcel lockers, opened satellites, and customers who are divided into home service customers and parcel locker customers. Home service customers are serviced by satellites through the usage of vehicles which deliver and pick up some products at the customer's home. While parcel locker customers are customers who go directly to the parcel locker to put and take the product. The description of the 2E-LRPSPD-PL network can be seen in Figure 1.

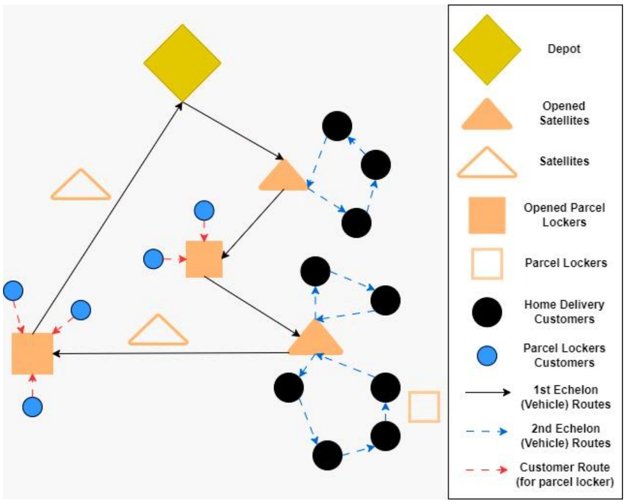

Figure 1 Distribution Network of 2E-LRPSPD-PL

2E-LRPSPD-PL which is proposed in this study is an NP-hard problem since it is a combinatorial complex problem which combines the decision of locations and the decision of routing. Moreover, 2E-LRPSPD-PL consists of a two-echelon network and integrates pickup and delivery demand at the same time which increases the problem's complexity. As a result, finding a solution to this problem within a reasonable time frame becomes challenging as the network size increases. Therefore, a metaheuristic approach is proposed in this study. The ALNS (Adaptive Large Neighborhood Search) method is chosen to solve this problem. ALNS has been widely implemented in many cases of VRP variants, such as PDPTW, 2E-VRP, 2E-VRP-CO, and many more. In PDPTW research by Ropke and Pisinger (2006), ALNS algorithm showed better results than LNS algorithm. In 2E-VRP, ALNS algorithm has better performance than multi-start heuristic, math-heuristic, and cluster-based heuristic (Perboli et al., 2010). In LRP, ALNS often outperforms other algorithms. ALNS always has better result than tabu search, LRGTS (Lagrangean Relaxation-Granular Tabu Search), and VLNS (Variable Large

Neighborhood Search) (Hemmelmayr et al., 2012). ALNS is often better than simulated annealing in several datasets (Hemmelmayr et al., 2012). Additionally, ALNS has not been used in previous research on 2E-LRPSPD, making its application a novel contribution to this area of study. Finally, sensitivity analysis is conducted to gain further insights.

1.2 Problem Formulation

Based on the background explained previously, the following are the problems formulated in this research:

1. How to develop a 2E-LRPSPD-PL model that can determine the number of intermediate facilities opened (satellites and parcel lockers), customer allocation to facilities, and routing decisions?
2. How does the performance of the ALNS method in solving the 2E-LRPSPD-PL model compare with the results obtained from the CPLEX solver, especially in terms of calculation process speed and solution quality?

1.3 Purpose

The following are the purposes or objectives to be achieved in the research:

1. Make a Two-Echelon Location Routing Problem with Simultaneous Pickup and Delivery and Parcel Locker (2E-LRPSPD-PL) model to determine the number of opened intermediate facilities (satellites and parcel lockers), determine the customer’s allocation to facilities, and determine the routing decision.
2. Solve the 2E-LRPSPD-PL model with ALNS to speed up the calculation process and compare it to the CPLEX result.

1.4 Limitations and Assumptions

This section explains the limitations and assumptions of the research as a guideline for achieving the research objectives. The following are the limitations of the research:

1. Research was conducted in the context of product return and last-mile delivery in the scope of city logistics.
2. The facilities and customers' locations are determined before the trip is carried out or executed.
3. The data which is used in this research comes from the data of previous similar research or secondary source (the focus of this research is developing a model).
4. Related to location determination in the data, potential parcel lockers are located randomly in the range of minimum and maximum coordinates of customers.

Apart from limitations, assumptions are also considered in this research, namely:

1. Every customer requests pickup and delivery at the same time.
2. There are two types of customers, namely home delivery customers and parcel locker customers.
3. The characteristic of products to be picked up and delivered is homogenous.
4. Parcel locker customers only go to parcel lockers in which the distance is still within the covering range of the parcel locker. The customer's distance within the covering range can be assumed as the acceptable distance for customers to go to the parcel locker.
5. The capacity of parcel locker is enough to fulfill the demand of parcel locker customers within its covering range.
6. Each vehicle in the first echelon has the same capacity, and each vehicle in the second echelon has the same capacity.
7. Each customer has fixed delivery and pickup demand, and each customer is only served by one-second echelon vehicle.
8. Each intermediate facility is served only by one first-echelon vehicle.
9. Each route starts and ends at the same node.

1.5 Benefits

The benefits that can be obtained from this research are as follows:

1. The logistics service company will have insight about how to adopt parcel lockers in last-mile delivery and reverse logistics efficiently.
2. The logistics service company will be helped to decide facility locations to be opened and design routing decisions with parcel lockers in consideration of simultaneous pickup and delivery.
3. This research will develop the model of 2E-LRPSPD to 2E-LRPSPD-PL.

1.6 Systematic Arrangement of Master Thesis

This thesis is explained in six chapters. Here are the outlines for each chapter.

Chapter I: It explains the research background, the problem formulations, purposes, limitations & assumptions, and benefits of the research.

Chapter II: It explains parcel locker, location routing problem with simultaneous pickup and delivery, two-echelon location routing problem with simultaneous pickup and delivery, ALNS method, and research position.

Chapter III: It explains model development which consists of problem description and mathematical formulation.

Chapter IV: It explains the solution methodology of ALNS. It begins with explaining the solution representation, initial solution generation, and the flow of implementing ALNS. An explanation of detailed destroy operators, repair operators, local search, and adaptive mechanisms is also added here.

Chapter V: It explains the test instances used in this research, the parameter tuning of ALNS, and the test results of 2E-LRPSPD-PL. There is also a sensitivity analysis to gain further insight into this research.

Chapter VI: It consists of a conclusion and future research ideas.

CHAPTER II
LITERATURE REVIEW

This section explains in detail the theoretical basis used in this research. Explanations related to this chapter start with a general explanation of parcel locker, 2E-LRP, 2E-LRPSPD, and ALNS. Other than that, a comparison between the current research and previous similar research is also carried out in this chapter.

2.1 Parcel Locker

Parcel lockers have the potential to be the location point for returning or picking up products. Parcel locker can be defined as a self-service storage media with multiple functions, including a collection of product returns for e-commerce or a spot for picking up products from e-commerce (Vakulenko et al., 2018). Parcel locker provides flexibility, a fast-collecting process for product returns from customers, and a fast-picking process of products (Vakulenko et al., 2018). The points of flexibility and fast collecting or picking are the two points that make a parcel locker can handle the problem of last-mile delivery. Parcel lockers can be located at the retailer, convenience store, and even small road that has closer access to customer's locations. Moreover, a parcel locker does not need a big space to be built. Some studies have explained parcel lockers as the solution to various logistics services. For instance, the research about home and locker delivery coordination in urban last-mile delivery by considering time window (Zang et al., 2023), the research about combining electric vehicles and parcel locker to reduce emission carbon in last-mile delivery(Vukićević et al., 2023), the research about location routing problems with locker boxes for delivering products in multi-period (Grabenschweiger et al., 2022), and many more. Most of them explored parcel lockers as a solution for last-mile delivery service. In terms of parcel lockers research in reverse logistics, some studies have explained parcel lockers in pickup and delivery cases. The examples are research on vehicle routing problem with simultaneous pickup and delivery with parcel lockers (Yu, Susanto, Yeh, et al., 2022), research about pickup and delivery vehicle routing problem with lockers

(PDVRPL) (Dell'Amico et al., 2023), research about mobile lockers in simultaneous pickup and delivery (Ensafian et al., 2023), and many more.

2.2 Location Routing Problem with Simultaneous Pickup and Delivery (LRPSPD)

Location Routing Problem (LRP) is a strategic, tactical, and operational problem which consider several facilities and customers by using several decision variables, namely number of opened facilities, customer allocation to facilities, and routing decision to service customers (Tordecilla et al., 2023). While LRPSPD is a variant of LRP in which every customer has pickup and delivery demand that must be accommodated with the same vehicle to minimize cost (Karaoglan et al., 2011). The distribution network of LRP and LRPSPD is the same since the difference between both variants is only in the demand. Here is the distribution network of LRP and LRPSPD (Tordecilla et al., 2023):

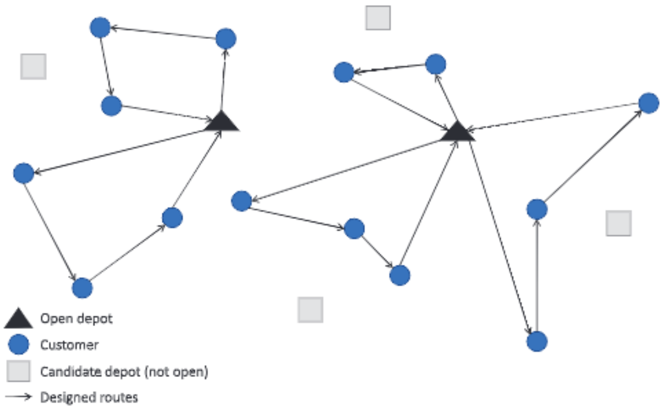

Figure 2 Distribution Network of LRP and LRPSPD

The distribution network in Figure 2 describes several depot options that can be chosen in LRP. The triangle symbol represents the depot that is opened, while the gray box represents the depot that is not opened. The opened depot creates several routes that meet the demand of customers. The problem of LRPSPD is displayed using a two-index flow-based formulation which is presented below (Karaoglan et al., 2011).

Decision Variables and Parameters:

U_{ij}	Remaining delivery demands after leaving node i if a vehicle travels from node i to node j, $\forall i,j \in N, i \neq j$
V_{ij}	Cumulated pickup demands up to node i if a vehicle travels from node i to node j, $\forall i,j \in N, i \neq j$
x_{ij}	1 If a vehicle travels from node i to node j, otherwise $x_{ij} = 0$, $\forall i,j \in N, i \neq j$
y_k	1 If a depot k is opened, otherwise $y_k = 0$, $\forall k \in N_o$
Z_{ik}	If customer i is assigned to depot k, $z_{ik} = 1$; otherwise $z_{ik} = 0$, $\forall i \in N_c, k \in N_o$
c_{ij}	Distance between node i and node j.
CD_k	Capacity of depot k $\forall k \in N_o$
FD_k	Fixed cost of depot k $\forall k \in N_o$
CV	Vehicle capacity
FV	Fixed cost of vehicle
p_i	Pickup demand at node i, $\forall i \in N_c$
d_i	Delivery demand at node i, $\forall i \in N_c$

$$Min\ Z = \sum_{i \in N} \sum_{j \in N} c_{ij} x_{ij} + \sum_{k \in No} FD_k y_k + + \sum_{k \in No} \sum_{i \in Nc} FV x_{ki}$$

Subject to:

$$\sum_{j \in N} x_{ij} = 1, \ \forall i \in Nc \tag{2.1}$$

$$\sum_{j \in N} x_{ji} = \sum_{j \in N} x_{ij}, \ \forall i \in N \tag{2.2}$$

$$\sum_{j \in N} U_{ji} - \sum_{j \in N} U_{ij} = d_i, \ \forall i \in Nc \tag{2.3}$$

$$\sum_{j \in N} V_{ij} - \sum_{j \in N} V_{ji} = p_i, \ \forall i \in Nc \tag{2.4}$$

$$U_{ij}+V_{ij}\leq CVx_{ij},\ \forall i,j\in N,\ i\neq j \tag{2.5}$$

$$\sum_{j\in Nc} U_{kj} = \sum_{j\in Nc} z_{jk}d_j,\ \forall k\in No \tag{2.6}$$

$$\sum_{j\in Nc} U_{jk}=0,\ \forall k\in No \tag{2.7}$$

$$\sum_{j\in Nc} V_{jk} = \sum_{j\in Nc} z_{jk}p_j,\ \forall k\in No \tag{2.8}$$

$$\sum_{j\in Nc} V_{kj}=0,\ \forall k\in No \tag{2.9}$$

$$U_{ij}\leq (CV\text{-}d_i)x_{ij},\ \forall i\in Nc,\ j\in N \tag{2.10}$$

$$V_{ij}\leq (CV\text{-}p_i)x_{ij},\ \forall i\in N,\ j\in Nc \tag{2.11}$$

$$U_{ij}\geq d_jx_{ij},\ \forall i\in N,\ j\in Nc \tag{2.12}$$

$$V_{ij}\geq p_jx_{ij},\ \forall i\in Nc,\ j\in N \tag{2.13}$$

$$\sum_{k\in No} z_{ik}=1,\ \forall i\in Nc \tag{2.14}$$

$$\sum_{i\in Nc} d_iz_{ik}\leq CD_ky_k,\ \forall k\in No \tag{2.15}$$

$$\sum_{i\in Nc} p_iz_{ik}\leq CD_ky_k,\ \forall k\in No \tag{2.16}$$

$$x_{ik}\leq z_{ik},\ \forall i\in Nc,\ k\in No \tag{2.17}$$

$$x_{ki}\leq z_{ik},\ \forall i\in Nc,\ k\in No \tag{2.18}$$

$$x_{ij}+z_{ik}+\sum_{m\in No,\ m\neq k} z_{jm}\leq 2,\ \forall i,j\in Nc,\ i\neq j,\ \forall k\in No \tag{2.19}$$

$$x_{ij}\in\{0,1\},\forall i,j\in N \tag{2.20}$$

$$z_{ik}\in\{0,1\},\forall i\in Nc,\ k\in No \tag{2.21}$$

$$y_k\in\{0,1\},\ \forall k\in No \tag{2.22}$$

$$U_{ij},\ V_{ij}\geq 0,\ \forall i,j\in N \tag{2.23}$$

The objective function of LRPSPD model above is the total traveling cost, fixed cost for opening satellites and parcel lockers, and cost of using vehicles. The explanation in detail of constraints 2.1 – 2.19 are referred to model explained in chapter 3 (constraint 3.5 – 3.23). For constraint (2.20) – (2.22) is binary constraint, while constraint (2.23) is non - negativity constraint.

2.3 Two Echelon Location Routing Problem with Simultaneous Pickup and Delivery (2E-LRPSPD)

Some problems of logistics distribution are more practical if the cases are described in the two echelons. For instance, the logistics distribution in a city where the main depot directly delivers products to end customers is considered to be not practical and it needs intermediate facilities in the middle (Demircan-Yildiz et al., 2016). It is because direct delivery from the main depot to customers usually uses big trucks in which it can disturb the traffic in the city and cause delivery delays. Other than that, direct delivery also reduces the flexibility of having demand consolidation in the delivery process. Therefore, to implement LRPSPD in the city logistics, the concept of two echelons is introduced. Here is the description of the distribution network of 2E-LRPSPD (Yıldız et al., 2023):

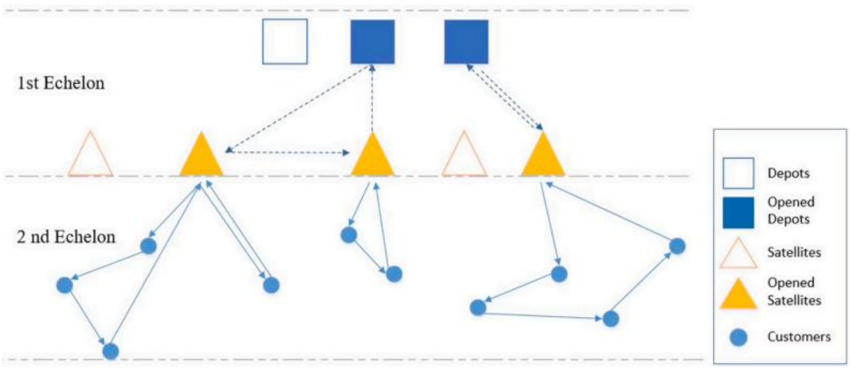

Figure 3 Distribution Network of 2E-LRPSPD

The existence of secondary or intermediate facilities is the main difference between LRPSPD and 2E-LRPSPD. In 2E-LRPSPD, facility decisions can be made for the primary facility (depot) or intermediate facility. In the research of 2E-LRPSPD which was first created by Demircan-Yildiz et al.,(2016), the facility decisions are the number of secondary facilities to be opened. While in the research of 2E-LRPSPD by Yıldız et al., (2023), the facility decisions are number of depots opened and number of secondary facilites opened. In terms of routing, the two echelon concept means that there are the routing decision of first echelon and the routing decision of second echelon.

2.4 Adaptive Large Neighborhood Search (ALNS)

ALNS is a metaheuristic method which was firstly introduced by Ropke and Pisinger (2006) to solve pickup and delivery problem with time windows. This method is a development of Large Neighborhood Search (LNS) which was developed by Shaw in 1989. LNS is a method where solutions are "destroyed" and "repaired" partially or fully (Turkeš et al., 2021). In terms of VRP sector, "destroyed" and "repaired" mean that nodes in the distribution network routes are repeatedly removed and re-inserted to result in the best solution. The destroy-repair mechanism is one of differences between LNS and ALNS. ALNS algorithm proposes several destroy and repair operators which interact in the algorithm to increase robustness (Turkeš et al., 2021).

There are several operators which can be considered for destroy and repair. Destroy operators consist of random removal operator, worst removal operator, shaw removal operator, cluster-based removal operator, and many more. While repair operators include greedy insertion, random insertion, hybrid insertion, and many more. When certain destroy and repair operators are selected to be used in the ALNS, it is difficult to know in advance which operators' combination between destroy and repair are the best for certain data (Turkeš et al., 2021). The performance of an operator can be variative during iterations (Turkeš et al., 2021). Therefore, ALNS chooses the operators in an adaptive way based on the operators past performance (Turkeš et al., 2021). Adaptive way means that destroy and repair operators which have resulted in good solutions previously, are more likely to be chosen again by ALNS in the next iteration. This adaptive mechanism is a strength of ALNS to find better solution than other metaheuristics or heuristics algorithm.

2.5 Research Position

Here is a comparison table of previous studies and the current research being conducted in this thesis. The purpose of this table is to highlight the differences between this study and similar previous research, making the novelty of this research clearly visible.

Table 1 Summary of Literatures Related to 2E-LRPSPD-PL

No	Author	Model	Method	Objective	Decision Variable
1	(Yu, Susanto, Yeh, et al., 2022)	VRPSPDPL (Vehicle Routing Problem with Simultaneous Pickup and Delivery and Parcel Lockers	Simulated Annealing	Minimizing the total traveling cost	Routing decisions, customer allocation to a parcel locker
2	(Enthoven et al., 2020)	2E-VRP-CO (Two-Echelon Vehicle Routing Problem with Covering Options)	Adaptive Large Neighborhood Search (ALNS)	Cost-minimizing solutions by selecting locations and routes to serve all customers	Routing decisions, covering location and satellite location determination, customer allocation to a covering location
3	(Yıldız et al., 2023)	2E-LRPSPD (Two-Echelon Location Routing Problem with Simultaneous Pickup and delivery)	Branch and Cut-based (B&C) exact algorithm	Minimizing the total traveling cost and fixed cost for opening locations	Depot and satellite locations determination opened satellite assignment to the depot, customer assignment to satellites, routing decisions
4	(Hemmelmayr et al., 2012)	2E-VRP (Two-Echelon Vehicle Routing Problem), LRP (Location Routing Problem)	Adaptive Large Neighborhood Search (ALNS)	Minimizing total traveling costs, cost of using vehicles, and opening costs of the subset depots	Depot location determination, routing decision, and number of vehicles used
5	(Schiffer & Walther, 2018)	LRPIF (Location Routing Problem with Intra-route Facilities)	Adaptive Large Neighborhood Search (ALNS)	Minimizing traveling costs, fixed costs for vehicles and facilities	Routing decisions, number of vehicles used, and number of facilities opened
6	(Zhou et al., 2016)	LRPSHC (Location Routing Problem with Simultaneous Home delivery and Customer's pickup)	Combination of Genetic Algorithm (GA) and Local Search (LS)	Minimizing traveling costs, fixed cost for pickup point, fixed vehicle cost, second delivery cost	Routing decisions, customer allocation to selected pickup points, allocation of selected pickup points to a depot, customer service, pickup point location determination
7	(Karaoglan et al., 2012)	LRPSPD (Location Routing Problem with Simultaneous Pickup and delivery) (Two polynomial MILP)	Two-Phase Heuristic approach based on Simulated Annealing	Minimizing system total cost (traveling cost, fixed cost of depot, and fixed cost of vehicles)	Routing decisions, depot location determination, and customer assignment to certain depots
8	(Yu & Lin, 2016)	LRPSPD (Location Routing Problem with Simultaneous Pickup and delivery)	Simulated Annealing	Minimizing total transportation cost, fixed cost for opening depot, and fixed cost of vehicles	Routing decisions, depot location determination, and customer assignment to depots

No	Author	Model	Method	Objective	Decision Variable
9	(Grabenschweiger et al., 2022)	MPLRPLB (Multi-Period Location Routing Problem with Locker Boxes)	ADD construction heuristic	Minimizing traveling costs, fixed cost of locker box customers, and fixed cost of site	Routing decisions, customer allocation to locker box, whether customer service at home or locker box, opening locker box, and start time of service
10	(Tilk et al., 2021)	VRPDO (Vehicle Routing Problem with Delivery Options)	Branch-Price-and-Cut-Algorithm	Minimizing traveling costs	Routing decisions
11	(Yu & Lin, 2014)	LRPSPD (Location Routing Problem with Simultaneous Pickup and delivery)	Multi-Start Simulated Annealing	Minimizing total transportation cost, fixed cost for opening depot, and fixed cost of vehicles	Routing decisions, depot location determination, and customer assignment to depots
12	(Grabenschweiger et al., 2021)	VRPHLB (Vehicle Routing Problem with Heterogenous Locker Boxes)	Adaptive Large Neighborhood Search (ALNS)	Minimizing the travel cost plus total compensation cost for assigning customers to locker	Routing decisions, whether customer is serviced at home or locker box
13	(Ensafian et al., 2023)	2E- Multi Depot VRPSPD (Two Echelon Multi Depot Vehicle Routing Problem with Simultaneous Pickup and Delivery) and a fleet of Autonomous Mobile Lockers (AMLs)	Adaptive Backtracking-Simulated Annealing metaheuristic (ABSM)	Minimizing total traveling costs, fixed cost for operating AML, and fixed cost of courier per day	Routing decisions, delivery and pickup demand assignment to each stopping zone, the decision for visiting the stopping zone, the decision for employing certain AMLs or couriers
14	(Demircan-Yildiz et al., 2016)	2E-LRPSPD (Two-Echelon Location Routing Problem with Simultaneous Pickup and delivery)	Mixed Integer Linear Programming (MILP)	Minimizing total traveling cost, vehicle fixed cost, and opening facility cost	Routing decision, depot location determination to be opened, customer assignment to secondary facilities
15	(Yu et al., 2023)	Electric Vehicle Routing Problem with Time Windows, Partial Recharges, and Parcel Lockers (EVRPTW-PR-PL)	Adaptive Large Neighborhood Search (ALNS)	Minimizing traveling cost	Routing decision, which customer belong to parcel locker and home delivery, total parcels delivered to parcel locker
16	(Yu, Susanto, Jodiawan, et al., 2022)	Vehicle Routing Problem with Parcel Lockers (VRPPL)	Simulated Annealing	Minimizing traveling cost	Routing decision, customer delivery decision (home or parcel locker), customer allocation to parcel locker
17	(Fan et al., 2020)	2E-LRPSPD (Two-Echelon Location Routing Problem with Simultaneous Pickup and delivery)	Multi-Start Hybrid Heuristic	Minimizing traveling cost, cost for opening facilities, and vehicle fixed cost	Routing decision, custoomer allocation to satellite, satellite location determination to be opened

No	Author	Model	Method	Objective	Decision Variable
18	(Karaoglan et al., 2011)	Location-Routing Problem with Simultaneous Pickup and Delivery (LRPSPD)	Branch-and-Cut-Algorithm	Minimizing traveling cost, cost for opening facilities, and vehicle fixed cost	Routing decision, depot location determination to be opened, customer allocation to depot
19	(Nguyen et al., 2010)	Two-Echelon Location Routing Problem (LRP-2E)	a New Hybrid Metaheuristic between a Greedy Randomized Adaptive Search Procedure (GRASP) and an Evolutionary/Iterated Local Search (ELS/ILS)	Minimizing traveling cost and cost for opening facilities	Routing decision, satellite location determination to be opened
20	***Current Research***	**Two-Echelon Location Routing Problem with Simultaneous Pickup and Delivery and Parcel Locker (2E-LRPSPD-PL)**	**Exact method using CPLEX and Adaptive Large Neighborhood Search (ALNS)**	**Minimize the total traveling cost, fixed cost for opening satellites and parcel lockers, cost of using vehicles, and compensation cost of customer's travel to a parcel locker.**	**Routing decision, satellite location determination, parcel locker location determination, customer allocation to satellite & parcel locker, number of vehicles used,**

CHAPTER III

RESEARCH FRAMEWORK & MODEL DEVELOPMENT

In this section, the research framework and problem description of 2E-LRPSPD-PL are explained technically. The new model of 2E-LRPSPDP-PL is also displayed here.

3.1 Research Framework

The research framework can be seen in Figure 4.

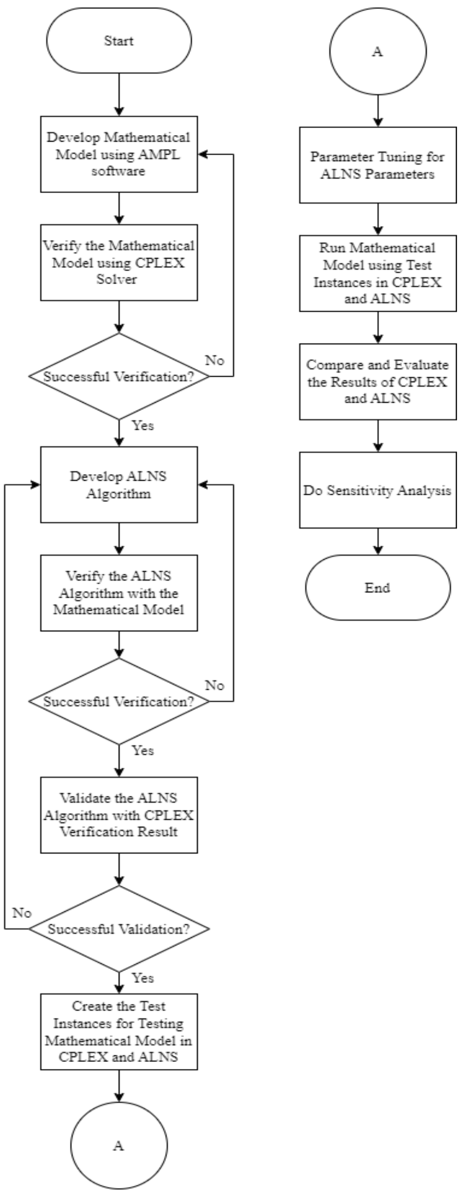

Figure 4 Research Framework

This research begins with developing a new mathematical model considering the usage of parcel lockers. The mathematical model is created using AMPL software using CPLEX solver. To verify the model, very small data instances are used to ensure that it meets the desired constraints and objectives. Once the model is verified, it confirms that the model is correct, and the research can proceed with creating the ALNS algorithm. ALNS algorithm needs to be verified with the mathematical model since the algorithm needs to fulfill the constraints of the model. Then, the ALNS is tested using the same small data instances as the CPLEX solver to validate the ALNS results against the CPLEX results. Subsequently, test instances are created and tested using both the CPLEX solver and the ALNS (after parameter tuning). The results from both methods are compared and evaluated. Finally, a sensitivity analysis is conducted to gain further insights into the model.

3.2 Problem Description

The problem of 2E-LRPSPD-PL is a development of two-echelon location routing problem with simultaneous pickup and delivery (2E-LRPSPD) by Demircan-Yildiz et al. (2016). It was the first research which explained about 2E-LRPSPD. In this research, the location decisions are done on satellites and parcel lockers. The routes describe two-echelon supply chain networks, in which the first echelon describes the routes from depot to intermediate facilities (opened satellites and opened parcel lockers). In the second echelon, the network outlines the routes from the opened satellites to home service customers and describes the parcel lockers that are opened to serve customers within their coverage area.

Based on Enthoven et al. (2020), parcel lockers only serve customers within its covering range. The customer's distance within covering range can be assumed as the acceptable distance for customers to go to parcel locker. Therefore, this model ensures that the capacity of the parcel lockers is sufficient to meet the demands of customers within their coverage area. In 2E-LRPSPD-PL, it is assumed that each vehicle has the same capacity and each customer has fixed delivery and pickup demand. Each customer is only served by single second echelon vehicle and each intermediate facilities is served only by single first echelon vehicle. Other than that, customer's request toward pickup and delivery of homogeneous product also happened at the same time. The goal of this paper is to minimize the total traveling cost, fixed cost for opening satellites and parcel lockers, cost of using vehicles, and compensation cost of customer's travel to a parcel locker.

2E-LRPSPD-PL is defined as a directed graph $G = (V, A)$, where V is set of vertices or nodes and A is set of arcs which connect all vertices in V, $A = \{(i,j) | i,j \in V, i \neq j\}$. Vertices V are made up of the following: $V = \{0\} \cup N \cup C$, where $\{0\}$ is a single depot, N is a collection of possible intermediate facilities, and C is a collection of customers. Set N is divided into a set of possible satellites No and a set of possible parcel lockers Np $(N = No \cup Np)$. Every possible satellite $k \in No$ has a fixed cost FD_k and a capacity CD_k. Concurrently, every possible parcel locker $k \in Np$ has a fixed cost Fl_k and a capacity CDL_k. Set C includes a set of home delivery customers C_h and a set of parcel locker customers C_l $(C = C_h \cup C_l)$. Every home service customer $i \in C_h$ has delivery demand e_i and pickup demand p_i. Parcel locker customer $i \in C_l$ also has delivery demand dl_i and pickup demand pl_i.

In the first echelon of 2E-LRPSPD-PL V_1, depot and a set of intermediate facilities are two main considered components, $V1 = \{0\} \cup N$. d_{ij}, $i,j \in V_1$, $i \neq j$ symbolizes the distance of arcs (i,j) in the first echelon. The route in the first echelon is started from depot to opened satellites and parcel lockers, then goes back to depot. Every first echelon vehicle has a fixed cost FV_1 and a capacity CV_1. For the second echelon, it is arranged by vertices $V_2 = V_2^h \cup V_2^l$. The second echelon distance of arcs (i,j) is symbolized by c_{ij}, $i,j \in V_2$, $i \neq j$. Each home service customer is served by a satellite using route $(i,j) \in V_2^h | V_2^h = No \cup C_h$. While each parcel locker customer is assigned to certain parcel lockers $V_2^l = Np \cup C_l$. The assignment of parcel locker customers to parcel locker is based on covering range r_k, where $k \in Np$. It shows the furthest distance at which the allocated customers can be serviced. The vehicle in the second echelon leaves an opened satellites to provide service for home service customers and goes back to its original opened satellite. Each vehicle has a fixed cost FV_2 and a capacity CV_2.

3.3 Mathematical Formulation

The decision variables and the mathematical model can be seen in the following table and formula.

Decision Variables:

U_2_{ij}	Remaining delivery demands after leaving node i if a vehicle travels from node i to node j in echelon 2, $\forall i,j \in V_2^h, i \neq j$
T_2_{ij}	Cumulated pickup demands up to node i if a vehicle travels from node i to node j in echelon 2, $\forall i,j \in V_2^h, i \neq j$
x_{ij}	If a vehicle travels from node i to node j in echelon 2 (home delivery), x_{ij} = 1; otherwise x_{ij} = 0, $\forall i,j \in V_2^h, i \neq j$
y_k	If a satellite k is opened or if a parcel locker k is opened, y_k = 1; otherwise y_k = 0, $\forall k \in N$
s_{ik}	If customer i is assigned to satellite k, s_{ik} = 1; otherwise s_{ik} = 0, $\forall i \in C_h, k \in N_o$
l_{ik}	If customer i is assigned to parcel locker k, l_{ik} = 1; otherwise l_{ik} = 0, $\forall i \in C_l, k \in N_p$
Ul_k	Number of delivery demand associated with parcel locker k $\forall k \in N_p$
Vl_k	Number of pickup demand associated with parcel locker k $\forall k \in N_p$
U_1_{ij}	Remaining delivery demands after leaving node i if a vehicle travels from node i to node j in echelon 1, $\forall i,j \in V_1, i \neq j$
T_1_{ij}	Cumulated pickup demands up to node i if a vehicle travels from node i to node j in echelon 1, $\forall i,j \in V_1, i \neq j$
a_{ij}	If a vehicle travels from node i to node j in echelon 1, a_{ij} = 1; otherwise a_{ij} = 0, $\forall i,j \in V_1, i \neq j$
Us_i	Number of delivery demands associated in satellite i, $\forall i \in N_o$
Ps_i	Number of pickup demands associated in satellite i, $\forall i \in N_o$

The mathematical model for 2E-LRPSPD-PL can be seen as follows:

$$Min \quad Z = Z_{trav} + Z_{vehicle} + Z_{ps} + \alpha \sum_{i \in Cl} \sum_{k \in Np} c_{ik} l_{ik} \tag{3.1}$$

$$Z_{trav} = \sum_{i \in V_2^h} \sum_{j \in V_2^h} c_{ij} x_{ij} + \sum_{i \in V1} \sum_{j \in V1} d_{ij} a_{ij} \tag{3.2}$$

$$Z_{vehicle} = \sum_{i \in N} FV_1 a_{0i} + \sum_{k \in No} \sum_{i \in C_h} FV_2 x_{ki} \tag{3.3}$$

$$Z_{ps} = \sum_{k \in No} FD_k y_k + \sum_{k \in Np} Fl_k y_k \tag{3.4}$$

Subject to:

$$\sum_{j \in V_2^h} x_{ij} = 1, \ \forall i \in C_h \tag{3.5}$$

$$\sum_{j \in V_2^h} x_{ji} = \sum_{j \in V_2^h} x_{ij}, \ \forall i \in V_2^h \tag{3.6}$$

$$\sum_{j \in V_2^h} U\_2_{ji} - \sum_{j \in V_2^h} U\_2_{ij} = e_i, \ \forall i \in C_h \tag{3.7}$$

$$\sum_{j \in V_2^h} T\_2_{ij} - \sum_{j \in V_2^h} T\_2_{ji} = p_i, \ \forall i \in C_h \tag{3.8}$$

$$U\_2_{ij} + T\_2_{ij} \leq CV_2 x_{ij}, \ \forall i,j \in V_2^h, \ i \neq j \tag{3.9}$$

$$\sum_{j \in C_h} U\_2_{kj} = \sum_{j \in C_h} s_{jk} e_j, \ \forall k \in No \tag{3.10}$$

$$\sum_{j \in C_h} U\_2_{jk} = 0, \ \forall k \in No \tag{3.11}$$

$$\sum_{j \in C_h} T\_2_{jk} = \sum_{j \in C_h} s_{jk} p_j, \ \forall k \in No \tag{3.12}$$

$$\sum_{j \in C_h} T\_2_{kj} = 0, \ \forall k \in No \tag{3.13}$$

$$U\_2_{ij} \leq (CV_2\text{-}e_i)x_{ij},\ \forall i \in C_h, j \in V_2^h \quad (3.14)$$

$$T\_2_{ij} \leq (CV_2\text{-}p_i)x_{ij},\ \forall i \in V_2^h, j \in C_h \quad (3.15)$$

$$U\_2_{ij} \geq e_j x_{ij},\ \forall i \in V_2^h, j \in C_h \quad (3.16)$$

$$T\_2_{ij} \geq p_j x_{ij},\ \forall i \in C_h, j \in V_2^h \quad (3.17)$$

$$\sum_{k \in No} s_{ik} = 1,\ \forall i \in C_h \quad (3.18)$$

$$\sum_{i \in C_h} e_i s_{ik} \leq CD_k y_k,\ \forall k \in No \quad (3.19)$$

$$\sum_{i \in C_h} p_i s_{ik} \leq CD_k y_k,\ \forall k \in No \quad (3.20)$$

$$x_{ik} \leq s_{ik},\ \forall i \in C_h, k \in No \quad (3.21)$$

$$x_{ki} \leq s_{ik},\ \forall i \in C_h, k \in No \quad (3.22)$$

$$x_{ij} + s_{ik} + \sum_{m \in No,\ m \neq k} s_{jm} \leq 2,\ \forall i,j \in C_h,\ i \neq j,\ \forall k \in No \quad (3.23)$$

$$Ul_k = \sum_{j \in C_l} l_{jk}\, dl_j,\ \forall k \in Np \quad (3.24)$$

$$Vl_k = \sum_{j \in C_l} l_{jk}\, pl_j,\ \forall k \in Np \quad (3.25)$$

$$\sum_{j \in C_l} dl_j l_{jk} \leq CDL_k y_k,\ \forall k \in Np \quad (3.26)$$

$$\sum_{j \in C_l} pl_j l_{jk} \leq CDL_k y_k,\ \forall k \in Np \quad (3.27)$$

$$\sum_{k \in Np} l_{ik} = 1,\ \forall i \in C_l \quad (3.28)$$

$$c_{ik} l_{ik} \leq r_k y_k,\ \forall k \in Np, i \in C_l \quad (3.29)$$

$$\sum_{j \in V_1} a_{ij} = y_i,\ \forall i \in N \quad (3.30)$$

$$\sum_{j \in V_1} a_{ji} = \sum_{j \in V_1} a_{ij},\ \forall i \in V_1 \quad (3.31)$$

$$\sum_{j \in V_1} U\_1_{ji} - \sum_{j \in V_1} U\_1_{ij} = Us_i,\ \forall i \in No \quad (3.32)$$

$$\sum_{j \in V_1} T\_1_{ij} - \sum_{j \in V_1} T\_1_{ji} = Ps_i,\ \forall i \in No \tag{3.33}$$

$$\sum_{j \in V_1} U\_1_{ji} - \sum_{j \in V_1} U\_1_{ij} = Ul_i,\ \forall i \in Np \tag{3.34}$$

$$\sum_{j \in V_1} T\_1_{ij} - \sum_{j \in V_1} T\_1_{ji} = Vl_i,\ \forall i \in Np \tag{3.35}$$

$$U\_1_{ij} + V\_1_{ij} \leq CV_1 a_{ij}, \forall i, j \in V_1,\ i \neq j \tag{3.36}$$

$$\sum_{j \in N} U\_1_{j0} = 0 \tag{3.37}$$

$$\sum_{j \in N} T\_1_{0j} = 0 \tag{3.38}$$

$$Us_t = \sum_{m \in C_h} e_m s_{mt},\ \forall t \in No \tag{3.39}$$

$$Ps_t = \sum_{m \in C_h} p_m s_{mt},\ \forall t \in No \tag{3.40}$$

$$x_{ij} \in \{0,1\},\ \forall i,j \in V_2^h,\ i \neq j \tag{3.41}$$

$$y_k \in \{0,1\},\ \forall k \in N \tag{3.42}$$

$$s_{ik} \in \{0,1\},\ \forall i \in C_h,\ k \in No \tag{3.43}$$

$$l_{ik} \in \{0,1\},\ \forall i \in C_l,\ k \in Np \tag{3.44}$$

$$a_{ij} \in \{0,1\},\ \forall i,j \in V_1,\ i \neq j \tag{3.45}$$

$$U\_2_{ij},\ T\_2_{ij} \geq 0,\ \forall i,j \in V_2^h,\ i \neq j \tag{3.46}$$

$$U\_1_{ij},\ T\_1_{ij} \geq 0,\ \forall i,j \in V_1,\ i \neq j \tag{3.47}$$

$$Ul_k,\ Vl_k \geq 0, \forall k \in Np \tag{3.48}$$

$$Us_k, Ps_k \geq 0, \forall\ k \in No \tag{3.49}$$

The objective function is the total traveling cost, fixed cost for opening satellites and parcel lockers, cost of using vehicles, and compensation cost of customer's travel to a parcel locker. The compensation cost is described by the distance-dependent cost factor (α) . Constraint (3.5) demonstrates that every customer is only ever visited once. Constraint (3.6) means that a vehicle in echelon

2 will exit node i upon entering. Constraint (3.7) and (3.8) eliminate subtour and make sure that delivery demand and pickup demand from customers are fulfilled. Constraint (3.9) indicates that the whole delivery and pickup demand which are inserted in vehicle echelon 2 do not go beyond the capacity in vehicle echelon 2. Constraint (3.10) guarantees that the overall load of the satellite's supply is equal to the total delivery demand of the customers assigned to a particular opened satellite. Constraint (3.11) shows that total delivery's load is zero when vehicle goes back to satellite. It is because all delivery demands have been delivered. Constraint (3.12) guarantees that the load of all opened satellite pickups meets the entire pickup demand of customers assigned to those opened satellites. Constraint (3.13) shows that the entire load of the pickup is zero when the vehicle begins from the satellite. It is because all pickup demands have not been delivered. Constraint (3.14) - (3.17) are bounding constraint, meaning that the constraint limits model's decision variables. Constraint (3.18) means that each home service customer is assigned to exactly one satellite. Constraint (3.19) makes sure that the entire amount of customer delivery demands allotted to satellites doesn't surpass the satellite's capacity. Constraint (3.20) ensures that the overall amount of customer pickup demands allotted to the satellite does not surpass the satellite's capability. Constraint (3.21) and (3.22) guarantee that every node with a direct link distance to the satellite must first be assigned to it. Constraint (3.23) ensures the requirement that two customers who are intricately connected in the same route be assigned to the same satellite. Constraint (3.24) shows that overall delivery demands of all clients assigned to a parcel locker equals the total delivery demands saved in the parcel locker. Constraint (3.25) shows that overall delivery demands of all clients assigned to a parcel locker equals the total pickup demands saved in the parcel locker. Constraint (3.26) makes sure that the total amount of delivery requests from customers that are allotted to parcel lockers don't surpass the locker's capacity. Constraint (3.27) makes sure that the total amount of pickup requests from customers that are allotted to parcel lockers don't surpass the locker's capacity. Constraint (3.28) means that each customer for a parcel locker is only assigned to one parcel locker. Constraint (3.29) indicates that a parcel locker can only serve specific customers who are inside the coverage range. Constraint (3.30) shows that

each satellite and each parcel locker are visited once and only once if the satellite or parcel locker is opened. Constraint (3.31) is a flow conservation constraint in echelon 1, which means that a vehicle will exit node i upon entering. Constraint (3.32) and (3.33) ensures that the delivery and pickup demand of satellite is fulfilled (fulfilling or accommodating delivery and pickup demand of from customers in echelon 2 which are assigned to the satellite). Constraint (3.34) and (3.35) ensures that the delivery and pickup demand of parcel locker is fulfilled (fulfilling or accommodating all delivery and pickup demand from customers in echelon 2 allocated to the parcel locker). Constraint (3.36) demonstrates that the overall demand for deliveries and pickups that are loaded into vehicle echelon 1 does not go beyond that vehicle's capacity. Constraint (3.37) shows that total delivery’s load is zero when vehicle goes back to depot. Constraint (3.38) shows that total pickup’s load is zero when vehicle leaves depot. Constraint (3.39) demonstrates that the overall delivery needs of all customers assigned to a satellite equals the total delivery demands saved in the satellite. Constraint (3.40) demonstrates that the overall pickup demands of all clients assigned to a satellite equals the total pickup demands saved in the satellite. Constraint (3.41) – (3.45) are binary constraints. Constraint (3.46) – (3.49) are positive integer constraints.

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CHAPTER IV
SOLUTION METHODOLOGY

In this section, Adaptive Large Neighborhood Search (ALNS) is explained as the method to solve 2E-LRPSPD-PL. ALNS implementation is started by creating initial solution for the second echelon network and the first echelon network. The initial solution is overhauled and repaired by some operators in the next step. The selection of operators is based on the performance of operators to find better solution in the previous iteration. Operators which result better solution will have higher probability to be chosen again in the next iterations.

4.1 Solution Representation

The solution of ALNS for 2E-LRPSPD-PL is represented by the vehicle routes and the allocation of customers to parcel lockers. The number of routes created in the first and second echelons represent the number of vehicles considered in the solution. If *p* routes are created, *p* number of vehicles are used. Therefore, one of the objective functions of 2E-LRPSPD-PL is to minimize the number of vehicles by considering the fixed cost of each vehicle and the number of routes generated. The number of routes is represented by the number of decisions to start a route from the depot and from opened satellites. By minimizing the number of vehicles, it also minimizes the number of routes generated. Routes in this problem are divided into those that occur in the second echelon and those in the first echelon.

In the second echelon, each route starts and ends at a specific opened satellite, represented by a number ranging from 1 to the total number of potential satellites. For example, if there are five potential satellites, they are symbolized by the numbers 1 through 5 (i.e., 1, 2, 3, 4, 5). In the second echelon routes, each route starts from a specific opened satellite, visits home service customers, and returns to the same satellite. Each route uses one second echelon vehicle to serve the customers, limiting the number of customers per route to the vehicle's capacity. Because this research includes simultaneous pickup and delivery, vehicle capacity constraint is applied to every visited customer. This means the vehicle's capacity cannot be exceeded when it meets the delivery demands and takes in the pickup demands of each customer.

In the second echelon routes, not all potential satellites are chosen. The decision to open satellites is based on their fixed cost (FD_k) and proximity to home service customers. The proximity of a satellite is defined as the total distance to all home service customers. A weighted sum calculation is used to balance these two factors, with fixed cost given a weight of 0.9 and distance proximity given a weight of 0.1. These weights were determined through trial and error. The formula of weighted sum calculation can be seen in formulation (4.1).

$$Total\ weight_k = 0.9\ (FD_k) + 0.1\ \left(total\ distance\ of\ satellite_k\right),\ \forall k \in N_o \qquad (4.1)$$

The initial solution indicates which satellites are opened and how many. The solution representation of how satellites are opened can be seen in Figure 7. A satellite serves as the starting and ending node for routes in the second echelon that cater to home service customers. Initially, routes are generated at the satellite with the lowest total weight. If the satellite's capacity is exceeded and there are remaining home service customers, the satellite with the second lowest total weight is chosen. This process is repeated until all home service customers are allocated. By using this method, ALNS can determine which satellites to open and how many to use. The solution representation of second echelon routes can be seen in Figure 5.

3	10	11	14	9	12	23	26	21	22	24	13	3

3	20	17	19	18	15	16	27	28	25	3

Figure 5 The Solution Representation of Second Echelon Routes

In the first echelon, each route starts and ends at depot which is represented by zero (0). Between zero as starting depot and zero as ending depot, several opened satellites and parcel lockers are visited. Same as second echelon route, each route in the first echelon uses one first echelon vehicle to serve the opened satellites and parcel lockers, limiting the number of nodes visited per route to the vehicle’s capacity. The vehicle capacity in the first echelon is also applied to every node. This means the combined total of pickups and remaining delivery demand at any node cannot exceed the vehicle's capacity. The solution representation of first echelon route(s) can be seen in Figure 6.

0	6	7	3	0

Figure 6 The Solution Representation of First Echelon Routes

In the example of solution representation of the first echelon route in Figure 5, there are numbers which are more than 5, namely 6 and 7. They reflect the opened parcel lockers. In this research, parcel lockers are represented by numbers that start from one after the total number of potential satellites and go up to the sum of the total potential satellites and the total potential parcel lockers. For example, if there are five potential satellites and three potential parcel lockers, parcel lockers are symbolized with numbers 6 through 8 (i.e., 6, 7, 8). Opened parcel lockers and their associated customers are one of the solution representatives in the second echelon of 2E-LRPSPD-PL. The solution representation of how parcel lockers are opened can be seen in Figure 7. Parcel locker customer allocation was done by mapping customers to the nearest opened parcel locker as long as the customers are inside the covering range of the parcel locker. If it was not the nearest, at least the customers could still go to parcel lockers in their covering range. In this problem, parcel lockers were opened as few as possible since the objective function is to minimize the cost.

The decision to open a parcel locker is based on the distance between the parcel locker and the customer. Customer allocations to parcel locker are prioritized based on the shortest distance, which directly affects the score to rank potential allocations. The fixed cost of opening a parcel locker also contributes to the allocation score. The allocation score is calculated by multiplying the distance between customer and to parcel locker by a distance weight of 0.95, and the fixed cost of the parcel locker by a cost weight of 0.05. This score is used to rank parcel lockers for each customer to support the customers in determining potential allocation. The process begins by sorting customers based on the number of potential parcel locker options, starting with those having the fewest options. Customers with fewer potential locker options have a higher urgency for allocation, meaning that if a specific parcel locker is not opened, certain customers cannot be accommodated. Other parcel lockers are taken into consideration for opening if there are customers who are not able to be assigned to the currently opened parcel lockers because of coverage range restrictions. The solution representation of parcel locker customer allocation can be seen in Figure 8.

```
y [*] :=
1 0
2 0
3 1
4 0
5 0
6 1
7 1
8 0
```

Figure 7 Solution Representation of Decision on Opening Satellites and Parcel Lockers

	6	7	8
29	0	1	0
30	0	1	0
31	1	0	0
32	0	1	0
33	0	1	0

Figure 8 Solution Representation of Parcel Lockers Customers Allocation

4.2 Initial Solution Generation

Here are the steps to generate initial solution for the vehicle routes in the second echelon:

Step 1: Create second echelon route vector to save the routes created in it.

Step 2: Make all potential satellites in open condition. Calculate the total weight of every potential satellite using formula in previous sub-chapter.

Step 3: Sort the potential satellites from the lowest total weight to the highest total weight.

Step 4: Insert the home service customers to potential satellites starting from the satellite with the lowest total weight. The insertion of home service customers uses nearest neighbor concept in which the nearest node from the latest inserted node in a route is added as a node which will be visited next.

Step 5: Terminate the route at the same satellite it started from if there is a vehicle capacity violation. The vehicle capacity constraint was explained in the previous sub-chapter. Save the routes in second echelon route vector.

Step 6: If the vehicle capacity constraint is violated, form a new route using the same satellite (still the one with the lowest total weight). Save the routes in second echelon route vector.

Step 7: If the satellite's capacity is exceeded, continue creating routes at the next satellite based on weight rank (the second lowest weight). Save the routes in second echelon route vector.

Step 8: If all home service customers have been inserted, close the remaining satellites that do not have any routes created in them.

Here are the steps to generate initial solution for the allocation of parcel locker customers to parcel locker:

Step 1: Collect all possible customer allocations to parcel lockers that respect the covering range constraint, noting the distance of each customer to each parcel locker and fixed cost of parcel locker.

Step 2: Calculate the score of parcel lockers toward customer in order to know the rank of parcel lockers in each customer from the lowest score until the highest score to determine the fixed allocation of customer to which parcel locker.

Step 3: Sort the customer having the fewest pairings to parcel lockers, progressing to the customer with the most pairings. Customer with the fewest pairings can be customer with allocation only to one parcel locker. While customers with the most pairings can be customers with allocation to all possible parcel lockers.

Step 4: Customer with the fewest allocation options should be prioritized for specific parcel locker, as they have limited or only one option. This means the parcel locker connected to such a customer should be opened first.

Step 5: The opened parcel locker is filled with customers who have possible allocations to it. If a customer cannot be allocated to the opened parcel locker due to the covering range, open a new parcel locker with the lowest score to the customer based on the customer's possible allocations. Allocate the customer to the newly opened parcel locker.

Step 6: For other unallocated customers, repeat step 4 until all customers are allocated.

Here are the steps to generate initial solution for the vehicle routes in the first echelon:

Step 1: Create an empty vector to capture the routes created in the first echelon.

Step 2: Create a route starting from depot 0. Insert opened satellites and opened parcel lockers into the route. The concept of nearest neighbor is also applied in this insertion.

Step 3: Terminate the route with depot 0 if there is a vehicle capacity violation. The vehicle capacity constraint was explained in the previous sub-chapter. Save the routes in the empty vector.

Step 4: If the vehicle capacity constraint is violated, form a new route and insert opened satellites or opened parcel lockers which have not been inserted yet.

4.3 Implementation of Adaptive Large Neighborhood Search

The common structure to implement ALNS procedure can be seen in Algorithm 1.

Algorithm 1. ALNS Pseudocode of 2E-LRPSPDP-PL

```
Input: list of destroy N, list of repair R, weight $w_{ij}, i \in N \cup R$, probability $p_i$,
maximum iteration MaxIter, degree of destruction D
Generate an initial solution S
Calculate the fitness values of initial solution f (S)
Sbest ← Sc ← S
f (Sbest) ← f (Sc) ← f (S)
Initialize: iteration (t) = 1
while t < MaxIter do
   Select a destroy operator m from R based on its weight
   Remove E nodes in Sc using DestroyList = N (S, E)
   Select a repair operator k from R based on its weight
   Repair nodes into Sc = R (Sc, DestroyList)
   Sc ← LocalSearch 2-opt (Repair (Sc, $p_k$))
   if f (Sc) < f (S) then
         S ← Sc
         f (S) ← f (Sc)
         if f (S) < f (Sbest) then
               Sbest ← S
               f (Sbest) = f (S)
   if modulo (t, Nsegment) = 0 then
         Update weight $w_{ij}$, probability $p_i$
   t = t + 1
End while
```

The pseudocode begins by initiating some ALNS parameters, including list of destroy and repair operators. Initial solution is then generated by implementing the steps which have been explained in section 4.2. In ALNS, there are three types of solutions which are considered, namely current solution *S*, transitional solution *Sc*, and best solution *Sbest*. The initial solution serves as both the initial current and best solution. The process of finding better solution is done afterwards by selecting and executing destroy and repair methods and performing local search. This process is repeated until the maximum number of iterations is reached, at which point the best solution is found.

During the iterations, destroy operator is selected based on the weight . *E* number of nodes are selected to be removed using a specific selected destroy operator. The number of nodes to be removed (*E*) is determined by multiplying the degree of destruction *D* by the number of nodes in each route of the first or second echelons, excluding the depot and satellite nodes. The number of nodes to be removed in the first echelon can be symbolized as *E_1* and in the second echelon as *E_2*. Degree of destruction is a value between 0 – 1 which is described in formulation (4.2).

$$D = \frac{D_1 + D_0}{t} + D_0 \tag{4.2}$$

D1 and D0 are two parameters which will be tuned later on. The process of destroy is started in the first echelon by removing *E_1* number of nodes. If the removed node is a satellite, then all customers who are allocated to the removed satellite are also removed. If the removed node is a parcel locker, home service customers in the second echelon are still removed with *E_2* number of nodes. Even if *E_1* = 0, then home service customers in the second echelon are still removed with *E_2* number of nodes.

After removing *E* nodes, re-insertion process is started by selecting a repair operator based on weight. The process of re-inserting nodes begins in the second echelon then continues to the first echelon. *E_2* or a greater number of home service customers nodes are inserted into the second echelon routes in order to accumulate the pickup and delivery demands in every route of second echelon to specific satellite from which routes are generated. This accumulation of pickup and delivery demands at the satellite facilitates the re-insertion process in the first echelon. Moreover, the calculation of pickup and delivery demands in the first echelon will also be easier if re-insertion process is started in the second echelon. The repair operator is used to result in a better solution in ALNS. Furthermore, this research also uses local search to provide more improvement toward the solution. Acceptance criteria are defined to filter better solution that can be possibly obtained in every iteration. If the transitional solution results in a lower cost than the best solution, then the best solution and current solution will be changed into the transitional solution. However, if the transitional solution cannot result in a lower cost than the best solution but results in a lower cost than current solution, the previous best solution will still remain. The best solution will also remain if the transitional solution cannot result in a lower cost than the current solution.

During initial iterations, each destroy and repair operator carries the same weight w_{ij} and same probability p_i. As the adaptive mechanism progresses through multiple iterations, these weights and probabilities undergo adjustment. Every *Nsegment* of iterations, the weight and probability of every destroy and repair operator will be updated based on their performance to result solution. Even if a specific operator fails to improve the solution, it still receives a weight update, albeit smaller compared to operators that contribute to improvements. The rationale behind giving larger weight updates to operators that improve solutions is to increase their probability of selection in subsequent iterations. This increased selection probability enhances the likelihood of obtaining better solutions in each iteration.

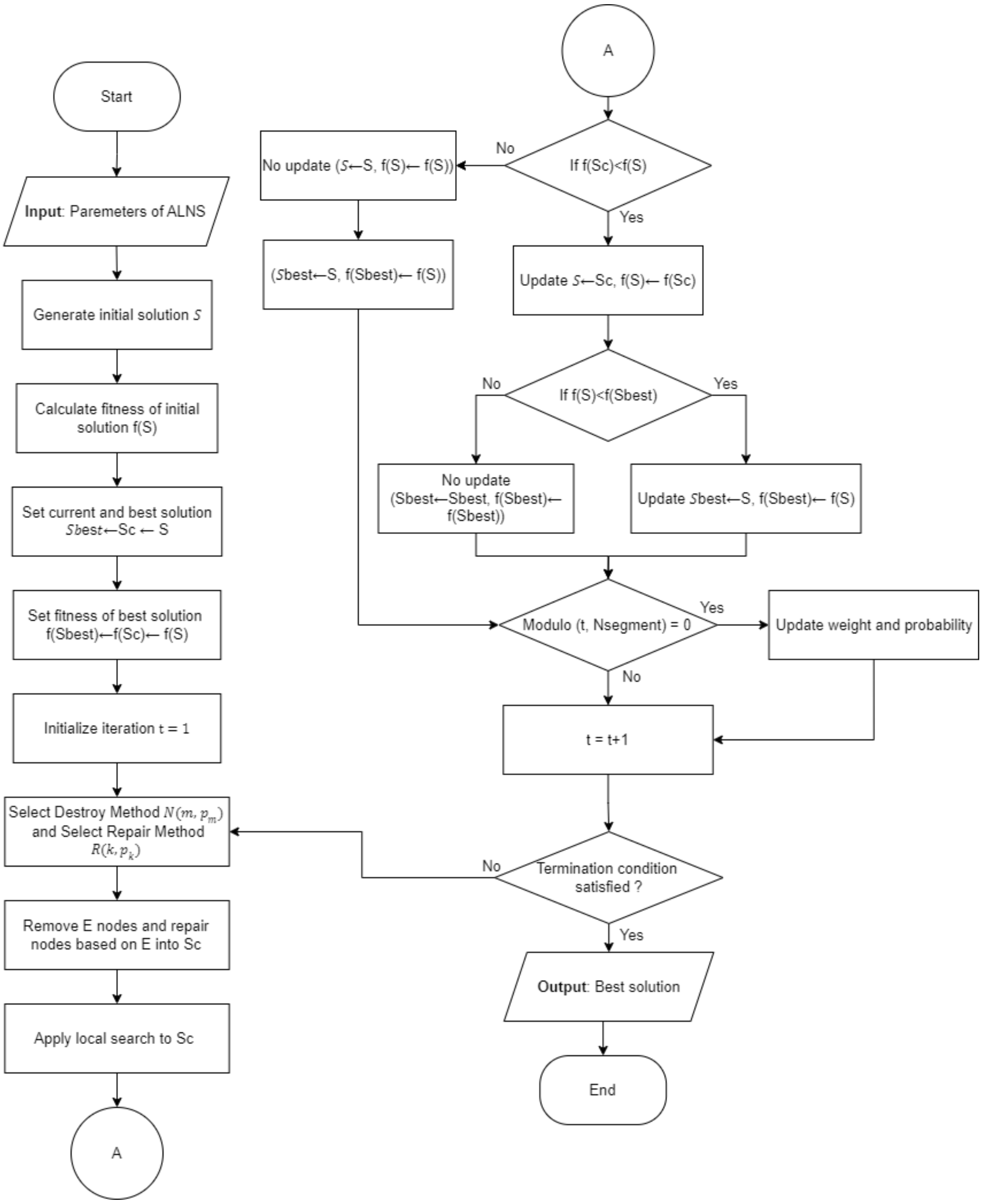

Figure 9 Flowchart of ALNS

4.4 Destroy Operator

This research proposes three destroy operators in ALNS. The first operator is random removal which removes *E* number of nodes from the routes randomly. The next operator is worst removal that removes nodes based on their removal cost, starting with the highest and proceeding to the lowest. The last destroy operator is cluster-based removal that removes nodes in clusters based on the geographical proximity of the nodes to the center of cluster according to K-means clustering approach. The removed nodes in the first echelon are added to the first echelon unvisited nodes set, UV_1. While the removed nodes in the second echelon are added to the home customers destroy set, UV_2. Here are more detailed explanations.

4.4.1 Random Removal

Random Removal algorithm is quite straightforward in which it selects *E* nodes randomly and erase them from the current solutions(Ropke & Pisinger, 2006). In this research, random removal is started by determining the number of nodes that can be removed in the first echelon (*E_1*) and the second echelon (*E_2*). In the first echelon, the algorithm identifies whether the route size (excluding depot) of the first echelon route is less than or equal to *E_1* or more. If the route size is less than or equal to *E_1*, then the algorithm will remove all of the satellites and parcel locker nodes in the first echelon. Otherwise, the algorithm will remove the nodes randomly according to the *E_1*. If *E_1* equals to zero, removal in the first echelon is disabled.

When a satellite is removed during first echelon removal, all home service customers in the second echelon who are allocated to the removed satellite are also removed. If a satellite is not selected to be removed in the first echelon or *E_1* equals to zero, home service customers in the second echelon will still be removed randomly based on *E_2*. According to the explanation about the removal in the second echelon, it can be concluded that the random removal in the second echelon is affected by the first echelon removal.

4.4.2 Worst Removal

Worst removal is an algorithm to remove costly nodes and re-insert them in another position that can result in a better solution (Ropke & Pisinger, 2006). In worst removal, the indicator of costly nodes can be seen through the removal cost calculation. In this research, removal cost is defined as the difference distance between visiting customer *i* in a route and not servicing customer *i* in a route. This algorithm calculates the removal cost for all nodes in the first echelon and all home service customers in the second echelon. In each echelon, the removal cost of each node is arranged from the highest to the lowest. Then, the removing procedure for each echelon is based on that arrangement. Node removal starts from the node with the highest removal cost until the lowest removal cost. The number of the removed nodes is determined by *E_1* and *E_2*.

4.4.3 Cluster-Based Removal

Cluster-based removal is an algorithm which selectively removes nodes from clusters to disrupt and improve the current solutions. Cluster-based removal is characterized by grouping nodes into clusters based on certain criteria. In this research, cluster is made based on geographical proximity by applying K-means clustering. K-means clustering is an algorithm which is used to split nodes into K clusters. In this research, only one cluster is formed in each echelon. In the cluster, a centroid is introduced as central position which represents the average position of all nodes in that cluster. The distance between each node and the centroid is calculated using Euclidean formula. Then the node removal process is based on distance proximity between node and the centroid. Node removal starts from the node with the closest distance to centroid until the farthest. The number of the removed nodes is determined by *E_1* and *E_2*.

4.5 Repair Operator

After undergoing destroy mechanism, the removed nodes are re-inserted by using selected repair operator. This research considers four repair operators, namely greedy insertion, greedy insertion with noise, greedy-based demand insertion, and hybrid insertion. The selected operator will re-insert nodes back into the current solutions by considering the valid criteria. Here are the valid criteria:

- Since this research considers simultaneous pickup and delivery, the accumulation of cumulative pickup and remaining delivery demands in every node of each route (new current solution) has to be lower than vehicle capacity of first echelon or second echelon.

- Total delivery demand on all routes and total pickup demand on all routes originating from a specific satellite cannot exceed the capacity of the satellite. This criterion is applied in the second echelon.

Based on the above valid criteria, every node that is attempted to be reinserted is checked against these criteria. The total cost of the new solutions in each iteration are also calculated to compare it with the cost of the previous iteration's solutions. All nodes are inserted until unvisited nodes set, *UV1* in the first echelon and home customers destroy set, *UV2* in second echelon are empty.

4.5.1 Greedy Insertion

Greedy insertion is a simple construction heuristic which inserts each node in destroy list into the selected route and position based on a specific criterion (Ropke & Pisinger, 2006). The criterion which is considered in this research is the distance increase if a node is placed in a specific position in a route. To calculate this distance increase, a node is iteratively placed in every position of every available route. Let n represent the position in a route and k be the selected route. The distance increase is evaluated by considering the difference the distance before and after node insertion. This involves calculating the distance between the node at n−1 and n, and then the distance from n−1 to the new inserted node, and from the new inserted node to n+1. A node is inserted into the position in route k (best route) that results in the minimum distance increase.

After inserting a node in a position of the best route, the route is evaluated toward the valid criteria which have been explained previously. If the route does not meet these criteria, different approaches are implemented to handle this in the first and second echelons. In the second echelon, if it is not valid, the node will be removed from the route. Then, the node will be attempted to be inserted in every position, excluding the one already tried in the best route, to ensure the possibility of compatibility with the valid criteria. If this mechanism also cannot fulfil the valid criteria, this operator will input the node into a list of uninserted customers or nodes. All above greedy insertion steps are applied toward all home customers destroy set, *UV2* in second echelon until the set is empty. For several nodes which become part of uninserted nodes list, this operator is assigned to create a new route for them by considering the valid criteria. In the first echelon, if it is not valid, the node will be removed from the route. This operator will look for a route with the fewest number of nodes. Then, the node will be inserted in the position that result in the lowest distance increase by considering the first point of valid criteria. All above greedy insertion steps are applied toward all unvisited nodes set, *UV1* in the first echelon until the set is empty.

4.5.2 Greedy Insertion with Noise

Greedy insertion with noise is a development of the basic greedy insertion. The overall steps in this operator are the same as the basic greedy insertion. The differentiation point is the noise which is multiplied by the distance increase. The consideration of noise enables the operator to not only consider the best position during insertion, but also consider the second-best position. It is important to consider other than best position because noise introduces randomness that can help the algorithm to avoid getting stuck in local optimal by exploring other alternatives. This approach balances the exploration and exploitation processes. The noise and the adjusted distance increase formulations can be seen in formulation (4.3) and (4.4).

$$\text{Adjusted distance increase} = \text{distance increase x noise} \qquad (4.3)$$

$$\text{noise} = 1 + \text{noise factor} \qquad (4.4)$$

The noise factor is a random value that follows normal distribution with mean 0 and a specific standard deviation. The reason the mean is expressed as 0 is to guarantee that, on average, the noise does not consistently skew the results in any way. With the addition of variability, this method preserves the initial features of the distance increase. The distances would continually rise or decrease if the mean were not zero, which might skew the optimization process. For standard deviation, the value will be tuned later. The noise factor is added by 1 to create a noise value that can ensure the distance increase is proportionally adjusted around its original value. If the noise factor is zero, the distance will remain. If the noise factor is positive, the distance will increase and if it is negative, the distance decreases.

4.5.3 Greedy-Based Demand Insertion

Greedy-based demand insertion has the same insertion flow as the basic greedy insertion. The differentiation point is in the way that customer from the destroy list is selected to be inserted in the second echelon. In the basic greedy insertion and greedy insertion with noise, customer is selected from the destroy list based on the shortest distance to each customer already included in the existing routes. While in greedy-based demand insertion, customer is selected from the destroy list based on the highest delivery or pickup demand among the customers in the list. The customer with the highest delivery or pickup demand is selected first. A demand-focused greedy insertion is created because this algorithm aims to prioritize visiting customers with larger loads first. This ensures that there is enough capacity in the vehicle to accommodate significant loads. For the first echelon, each node in the destroy list for all greedy insertions is selected randomly.

4.5.4 Hybrid Insertion

Hybrid insertion is combination of basic greedy insertion and random insertion. This hybrid insertion is implemented only in the second echelon since the nodes in the unvisited nodes set, *UV1* are just a few, considering only greedy insertion is enough. The combination of greedy and random insertions means that some of customers in the home customers destroy set, *UV2,* are reinserted using a greedy procedure, while others are reinserted randomly into the routes. The procedure to split customers into a group for which the greedy insertion will apply and a group for which the random insertion will apply is done adaptively. It means that most customers are categorized as a random insertion group in early iterations and are categorized as greedy insertion at the end of iterations. The purpose of doing this procedure adaptively is to maximize the exploration in the early iterations and exploitation at the end of iterations. The greedy insertion flow of procedure is the same as the basic greedy insertion, while random insertion is done randomly as long as it complies with the valid criteria.

4.6 Local search

ALNS in this research utilizes 2-opt local search for the first and second echelons. The procedure of 2-opt involves reversing nodes in a route or swapping nodes between routes. Swapping nodes means two nodes between two routes are swapped in order to result in a better solution. While reversing means to reverse the order of elements in a given subsequence of the solution. An example of reversing is ff the current solution is [0, 1, 2, 3, 4, 0], reversing the sub-sequence from the 2nd to the 4th element results in [0, 1, 4, 3, 2, 0]. The procedure of 2-opt local search is performed while ensuring the valid criteria are met.

4.7 Adaptive Mechanism

In ALNS, multiple destroy and repair operators can be selected to result in the best solution to a problem. As stated in the literature review of ALNS in chapter 2, the selection of operators is based on their past performance in the previous iterations. The performance of each ALNS operator is associated with a certain weight, which is updated during iterations and in turn influences the likelihood of the operator being chosen in the next iterations. A higher weight for an operator indicates that its performance is good and that it tends to produce better solutions during iterations. The idea of updating the weight is implemented in every segment of iterations. For example, if the total number of iterations is 10000 and the weight is updated every 100 iterations.

The updated weight of each operator follows formulation (4.5) and (4.6).

$$W_{\bar{d},t+1} = \alpha\left(W_{\bar{d},t}\right) + (1-\alpha)\beta \tag{4.5}$$

$$\beta = \begin{cases} Z_1 & if\, f(newsolution) \leq f(currentsolution) \\ Z_2 & if\, f(newsolution) > f(currentsolution) \end{cases} \tag{4.6}$$

α is decay parameter which controls the weight changing. The higher the α, the slower the weight changes, showing the stability in the weight changing. The value of α ranges between 0 and 1. When it is close to 1, it means that the weight is more stable and changes in weight are minimal. Otherwise, when it is close to 0, the weight changes more quickly. For β, it is the score which is used to change the weight based on the operator's performance in previous iteration. There are two possible values of β, it can be Z_1 if the new solution's objective function is lower than the current solution. It can be Z_2, if the new solution's objective function is higher than the current solution. The value of Z_1 is always bigger than Z_2 since the algorithm wants to give a higher score for an operator that can result in a better solution.

After having the weight of operator, probability of the operator can be obtained by doing weight normalization with formulation (4.7) and (4.8)

$$P_{destroy,\, i} = \frac{W_{destroy,\, i}}{\sum_{j=1}^{n} W_{destroy,j}} \tag{4.7}$$

$$P_{repair,\, i} = \frac{W_{repair,\, i}}{\sum_{j=1}^{m} W_{repair,j}} \tag{4.8}$$

$W_{destroy,\, i}$ and $W_{repair,\, i}$ are the weight of the i-th destroy operator and the weight of the i-th repair operator, respectively. $P_{destroy,\, i}$ and $P_{repair,\, i}$ are the normalized probability of the i-th destroy operator and normalized probability of the i-th repair operator, respectively. n is the total number of destroy operators, while m is the number of repair operators. This probability determines what destroy and repair operators will be selected in the next iterations.

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CHAPTER V
COMPUTATIONAL RESULT

In this chapter, computational results using CPLEX solver and ALNS are explained in detail. This chapter explains about some test instances which are used, the parameter tuning for ALNS parameters, the 2E-LRPSPD-PL results, and the sensitivity analysis. The explanation of sensitivity analysis also provides insight into the managerial implications of this research.

5.1 Test Instances

In this research, the data instances are tested toward the 2E-LRPSPD-PL model using CPLEX solver in AMPL. The data instances are also run using the proposed ALNS method which is built in Microsoft Visual Studio C++. The C++ codes of ALNS are run on a computer with Intel(R) Core(TM) i7-10700 CPU @ 2.90GHz 2.90 GHz and 64 GB of RAM. The instances tested against the 2E-LRPSPD-PL model originated from the 2E-LRP data set proposed by Nguyen et al. (2010). There are three data sizes which are tested in this research, namely small, medium, and large data. Small and medium data sets consist of 5 satellites and 25 or 50 customers. The vehicle capacity in the first echelon is 750 units, while the vehicle capacity in the second echelon is 100 or 150 units. The large data sets have 5 or 10 satellites and 100 customers. The vehicle capacity in the first echelon is 750 or 850 units, while the vehicle capacity in the second echelon is 100 or 150 units.

In this research, there are two types of customers namely, home service customers and parcel locker customers. The customers from test instances are classified into one of the two customer types by splitting the customers using a certain percentage. The customers are split with percentages of 0%, 20%, 40%, 60%, 80%, and 100% (Akkerman et al., 2023). Every percentage value shows the ratio of parcel locker customers relative to the total number of customers, while the difference between 100% and this ratio represents the portion of home service customers. In terms of parcel lockers, the number of customers is divided by 10 and rounded to the nearest integer to get the number of parcel lockers required in each data instance. In terms of coordinates, the placements of parcel lockers are determined at random in a range between 25% above the smallest and 25% below the largest value of x and y coordinates of customers. By having the coordinates of all facilities and customers, the distance between all of them are calculated using Euclidean distance. In this research, there is also information about the distance-dependent cost factor (α) which is determined as 0.25 (Enthoven et al., 2020).

Every parcel locker in this research has its own covering range. Creating covering range is started by allocating all customers to the closest parcel locker based on distance. The next step is to find the maximum distance between the parcel locker and the customers allocated to it. The maximum distance value becomes the covering range of the parcel locker. If there is a parcel locker which does not have any allocated customers, then the covering range is defined as the shortest distance between the parcel locker and any customers. The covering range of each parcel locker represents the number of customers that can be serviced by that parcel locker. It means that the capacity of parcel locker can also be determined based on the number of customers within its covering range. The parcel locker capacity can be determined by comparing the accumulated delivery demand and pickup demand of customers allocated to the parcel locker, and identifying which one is greater.

In terms of demand, the reference instances data only provide one type of demand data of customers. Since this research considers simultaneous pickup and delivery, two types of demand namely, delivery and pickup demands have been determined. This research uses a demand separation approach by Salhi and Nagy (1999) to obtain delivery and pickup demands. This demand separation approach uses a ratio which is calculated for every customer i using formulation (5.1).

$$r_i = min\,({}^{x_i}/_{y_i}\,;{}^{y_i}/_{x_i}) \tag{5.1}$$

x_i and y_i represent the coordinates of customer i. By having that ratio, delivery (d) and pickup (p) demands can be found by using formulation (5.2) and (5.3).

$$d_i = r_i . q_i \tag{5.2}$$

$$p_i = q_i - d_i \tag{5.3}$$

q_i represents the demand of customer i from the 2E-LRP dataset.

For this research, there are 4 small data instances, 4 medium data instances, and 4 large data instances. Each data instance is tested using scenarios where parcel locker customers are partitioned at 20% intervals, as explained earlier. The description of the instances can be seen in Table 2.

Table 2 List of Data Used as Test Instances

Test instances	**Number of Customers**	**Number of Satellites**	**Number of Parcel Lockers**	**Type of data**
25-5MN (0% - 100%)	25	5	3	Small
25-5MNb (0% - 100%)	25	5	3	
25-5N (0% - 100%)	25	5	3	
25-5Nb (0% - 100%)	25	5	3	
50-5MN (0% - 100%)	50	5	5	Medium
50-5MNb (0% - 100%)	50	5	5	
50-5N (0% - 100%)	50	5	5	
50-5Nb (0% - 100%)	50	5	5	
100-5MNb (0% - 100%)	100	5	10	Large
100-5N (0% - 100%)	100	5	10	
100-10MNb (0% - 100%)	100	10	10	
100-10N (0% - 100%)	100	10	10	

5.2 Parameter Tuning

Parameter tuning is important to be implemented in order to have a good result in solving test instances using ALNS. The parameters to be tuned include those for the repair operators, destroy operators, and the parameters involved in the adaptive mechanism of ALNS. In the repair operators, noise factor in greedy insertion with noise and hybrid fraction in hybrid insertion need to be tuned. The noise factor is a parameter that disrupts the insertion process of nodes into the route. It allows nodes to be inserted not in the best position, but in the second or third best positions. The purpose of this is to help ALNS avoid local optima during the insertion process. The hybrid fraction in hybrid insertion divides the customer instances into two groups: one where greedy insertion is applied and another where random insertion is used. In the removal process, the number of nodes to be removed is determined by the degree of destruction formula which has been explained at sub-chapter 4.3. There are parameters of D0 and D1 which will be tuned to find the best possible degree of destruction which affects to the number of removed nodes. In terms of searching process, the maximum iterations must be tweaked considering the number of nodes in the first and second echelons. This is because the maximum iterations help the algorithm explore the solutions effectively and efficiently within the solution space. In this research, the algorithm uses a constant of b value to be multiplied by the total number of nodes in the first and second echelons to result the maximum iterations. In the adaptive mechanism of ALNS, there are α and Nsegment that need to be tuned. α is a decay parameter which controls the sensitivity of weight updating. The value, ranging between 0 and 1, should be carefully determined to reflect the algorithm's characteristic, whether it requires stable weight changes or rapid weight adjustments. Nsegment explains about every how many iterations, the weight of operators will be updated. It should be adjusted effectively, as if Nsegment is too small, the weights will be updated too frequently, leading to significant fluctuations in the weights of operators. If it is too big, then the algorithm will not be responsive on the performance changing of operators.

For parameter tuning, the process is begun by deciding three different level values for each parameter. Then, the parameter is tuned using one factor at time (OFAT) to find two levels that give the lowest cost as best solution for each parameter. The tuning is continued using 2^k factorial to find the best combination of parameters. For noise factor and hybrid fraction, the parameter tuning which is used is OFAT only, while the others will use OFAT and 2^k factorial. The tuning parameter for the noise factor or hybrid fraction is done by activating only greedy insertion with noise or hybrid insertion in the repair mechanism. This approach avoids bias in understanding the performance affected by the parameters. The comparison may not be entirely equitable due to the inherent variability in the search process. Here are the three levels for each of parameter.

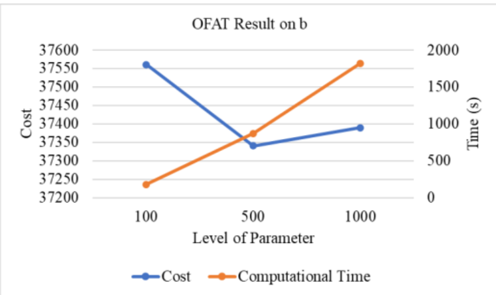
- *b:* 100, 500, 1000.
- D0, D1: (0.05 , 0.9); (0.1 , 0.9); (0.3 , 0.7).
- α: 0.1, 0.5, 0.99.
- Nsegment: 0.1%, 0.5%, 1.0%.
- Noise factor : 0.05, 0.2, 0.9.
- Hybrid fraction: (0.3 , 0.9); (0.1 , 0.7); (0.1 , 0.9).

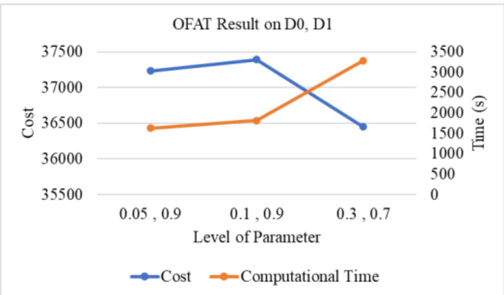
There are 4 data instances which are used as testing objects to do this parameter tuning. These data represent the small, medium, and large datasets. The presented results are the average of the objective functions from 4 data instances, each run using 5 replications. Table 3 shows the OFAT results.

Table 3 OFAT Results

Parameter	***b***	**D0, D1**	***α***	**Nsegment**	**Noise factor**	**Hybrid fraction**	**Average Solution**	**Avg. CPU (s)**
b	**100**	0.1, 0.9	0.5	0.1%	0.2	0.3, 0.9	37560.75	181.2768
	500	0.1, 0.9	0.5	0.1%	0.2	0.3, 0.9	37340.95	871.2785
	1000	0.1, 0.9	0.5	0.1%	0.2	0.3, 0.9	37389.55	1819.123
D0, D1	1000	**0.05, 0.9**	0.5	0.1%	0.2	0.3, 0.9	37233.65	1624.588

Parameter	*b*	D0, D1	*α*	Nsegment	Noise factor	Hybrid fraction	Average Solution	Avg. CPU (s)
	1000	**0.1, 0.9**	0.5	0.1%	0.2	0.3, 0.9	37389.55	1819.123
	1000	**0.3, 0.7**	0.5	0.1%	0.2	0.3, 0.9	36450.9	3287.008
α	1000	0.1, 0.9	**0.1**	0.1%	0.2	0.3, 0.9	37405.2	1850.701
	1000	0.1, 0.9	**0.5**	0.1%	0.2	0.3, 0.9	37389.55	1819.123
	1000	0.1, 0.9	**0.99**	0.1%	0.2	0.3, 0.9	37401.9	1802.47
Nsegment	1000	0.1, 0.9	0.5	**0.1%**	0.2	0.3, 0.9	37389.55	1819.123
	1000	0.1, 0.9	0.5	**0.5%**	0.2	0.3, 0.9	37298.05	1720.778
	1000	0.1, 0.9	0.5	**1.0%**	0.2	0.3, 0.9	37468.2	1846.863
Noise factor	1000	0.1, 0.9	0.5	0.1%	**0.05**	0.3, 0.9	37587.35	1849.937
	1000	0.1, 0.9	0.5	0.1%	**0.2**	0.3, 0.9	37277.55	1830.47
	1000	0.1, 0.9	0.5	0.1%	**0.9**	0.3, 0.9	37784.2	2804.202
Hybrid fraction	1000	0.1, 0.9	0.5	0.1%	0.2	**0.3, 0.9**	37587.1	2012.643
	1000	0.1, 0.9	0.5	0.1%	0.2	**0.1, 0.7**	37787.2	2186.969
	1000	0.1, 0.9	0.5	0.1%	0.2	**0.1, 0.9**	37723	1967.546





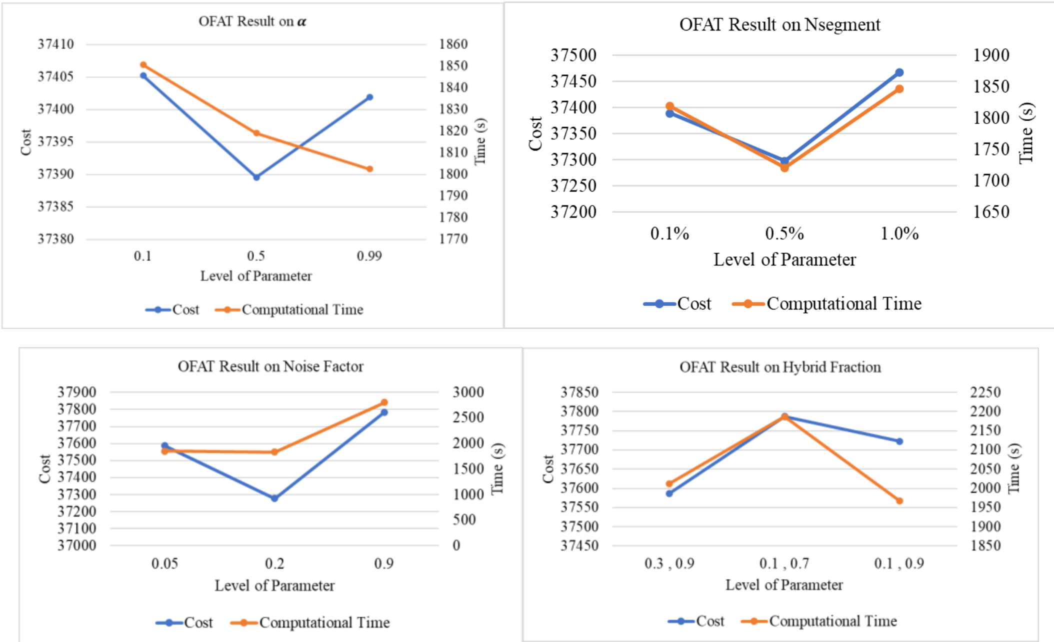


Figure 10 Comparison of Total Cost and Computation Time for Each Parameter in OFAT

Based on Figure 10, The two best values of b that represents the constant which affect maximum iterations are 500 and 1000. Normally, the bigger the b results in the lower cost, but in this case, b = 500 results in a lower cost than b = 1000 due to the variability that occured in the ALNS. The parameter D0, D1 are determined to have two best values namely, (0.05, 0.9) and (0.3, 0.7). α is set to be 0.5 and 0.99 and Nsegment is set to be 0.1% and 0.5% of maximum iterations. For noise factor and hybrid fraction, This research only looks for one value which can result in the lowest cost. These parameters are not continued to 2^k factorial since these parameters are less significant than the other parameters to affect the performance of the whole ALNS. These parameters are owned by repair operators which do not affect the selection of operators in the iterations. The noise factor is set to be 0.2 and hybrid fraction is set to be (0.3, 0.9).

The levels of each parameter which are used for 2^k factorial design can be seen in Table 4.

Table 4 Selected Levels of Each Parameter for 2K Factorial

Parameter	Low	High
b	1000	500
D0, D1	(0.05, 0.9)	(0.3, 0.7)
α	0.99	0.5
Nsegment	0.1%	0.5%

2^k factorial has purpose to understand the interaction between ALNS parameters. Since there are 4 parameters considered in 2^k factorial, there are 16 combinations of parameters which must be tested. The testing for 2^k factorial uses the same dataset as OFAT to capture the parameters' interactions in all types of data. The result can be seen in Table 5 and Figure 11.

Table 5 2K Factorial Results

b	**D0, D1**	***α***	**Nsegment**	**Average Solution**	**Avg. CPU (s)**
1000	0.05, 0.9	0.5	0.10%	37406.6	1413.7712
500	0.05, 0.9	0.5	0.10%	37535.8	878.136755
1000	0.3, 0.7	0.5	0.10%	36417.45	2965.85055
500	0.3, 0.7	0.5	0.10%	36527.45	1815.65834
1000	0.05, 0.9	0.99	0.10%	37486.2	1618.76195
500	0.05, 0.9	0.99	0.10%	37363.95	911.1998
1000	0.3, 0.7	0.99	0.10%	36477.75	3024.4392
500	0.3, 0.7	0.99	0.10%	36479.25	1833.140185
1000	0.05, 0.9	0.5	0.50%	37209.4	1556.87495
500	0.05, 0.9	0.5	0.50%	37455.9	924.013705
1000	0.3, 0.7	0.5	0.50%	36510.55	3122.3031

b	D0, D1	*α*	Nsegment	Average Solution	Avg. CPU (s)
500	**0.3, 0.7**	**0.5**	**0.50%**	**36430.05**	**1546.381535**
1000	0.05, 0.9	0.99	0.50%	37394.25	1602.0587
500	0.05, 0.9	0.99	0.50%	37455.85	925.71701
1000	0.3, 0.7	0.99	0.50%	36565.2	3590.70745
500	0.3, 0.7	0.99	0.50%	36632.3	1585.034165

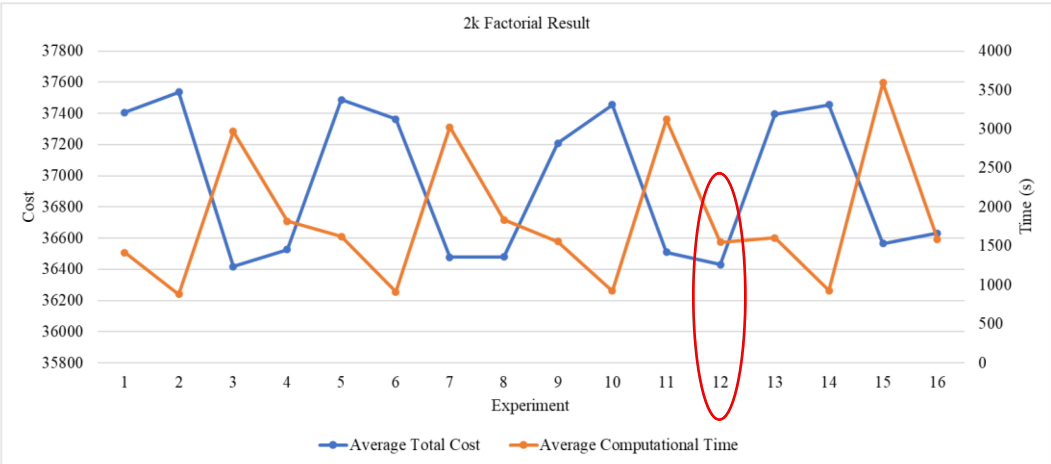


Figure 11 Comparison of Average Total Cost and Average Computational Time in 2K Factorial

Based on the above table and figure, the best combination of parameters that is used to run the test data of 2E-LRPSPDP-PL in ALNS is displayed in Table 6.

Table 6 Best Combination of Parameters to Test Data in ALNS

Parameter	Value in Experiment 12
b	500
D0, D1	(0.3, 0.7)
α	0.5
Nsegment	0.5%

Two experiments which result in the lowest total cost is experiment 3 and 12. But the parameters in experiment 12 are chosen to be used to test the data instances using ALNS since the computational time is lower than experiment 3.

5.3 Test Result of 2E-LRPSPD-PL

The test instances which have been modified previously are tested using CPLEX solver with a time limit of 18,000 and the ALNS model of 2E-LRPSPD_PL. Using CPLEX, the solution is considered as global optimal solution if the result is obtained under the time limit. Using the proposed ALNS, each data instance is tested in 5 replications. The test instance results using ALNS, in terms of best and average values, are compared to the CPLEX solver solutions. The comparison is concluded by the gap between the ALNS and CPLEX results.

The comparison of test results between ALNS and CPLEX solver can be seen in Table 7 and Appendix 1. In Appendix 1, the comparison between ALNS and CPLEX is displayed in form of graph. The graphs are used to display the significance between ALNS and CPLEX in terms of the results. The first and second columns represent the data instances and the percentage of parcel locker customers. The third and fourth columns show the CPLEX results and the computational time for the test instances. The fifth to seventh columns display the ALNS results (average objective and best objective) and their computational time. The gap between the ALNS and CPLEX results is presented in the eighth (gap for average objective) and ninth (gap for best objective) columns.

Table 7 Comparison of Test Results between ALNS and CPLEX Solver

Problem	% of Parcel Locker Customers	CPLEX		ALNS				
		Objective	CPU (s)	Average Objective	Best Objective	Avg. CPU (s)	Gap_a	Gap_b
25-5MN	0%	15007	29.093	15028.4	15007	88.76036	0.14%	0.00%
	20%	23314	5.469	23314	23314	80.35264	0.00%	0.00%
	40%	22878	1.25	22878	22878	72.6478	0.00%	0.00%
	60%	21121	0.609	21121	21121	42.503	0.00%	0.00%
	80%	20498	0.094	20498	20498	27.2062	0.00%	0.00%
	100%	15794	0.125	15794	15794	17.2234	0.00%	0.00%
25-5MNb	0%	14605	4.078	14605	14605	108.6265	0.00%	0.00%
	20%	19401	2.297	19401	19401	289.6065	0.00%	0.00%

Problem	% of Parcel Locker Customers	CPLEX		ALNS				
		Objective	CPU (s)	Average Objective	Best Objective	Avg. CPU (s)	Gap_a	Gap_b
	40%	27547	0.906	27547	27547	103.0906	0.00%	0.00%
	60%	26961	0.344	26961	26961	66.675	0.00%	0.00%
	80%	26952	0.109	26952	26952	49.335	0.00%	0.00%
	100%	20804	0.078	20804	20804	35.1156	0.00%	0.00%
25-5N	0%	16220	33.625	16282	16220	101.411	0.38%	0.00%
	20%	19757	32.296	19758.8	19757	105.668	0.01%	0.00%
	40%	18543	3.891	18543	18543	74.0792	0.00%	0.00%
	60%	21433	0.484	21433	21433	58.5548	0.00%	0.00%
	80%	20156	0.125	20156	20156	40.5336	0.00%	0.00%
	100%	13780	0.11	13780	13780	28.167	0.00%	0.00%
25-5Nb	0%	14187	10.328	14194.6	14187	102.9957	0.05%	0.00%
	20%	26074.8	3.656	26103.4	26074	122.1413	0.11%	0.00%
	40%	24311.5	0.579	24311	24311	100.9842	0.00%	0.00%
	60%	24494.2	0.266	24494	24494	68.0936	0.00%	0.00%
	80%	23919.5	0.094	23919	23919	43.8376	0.00%	0.00%
	100%	17692.2	0.078	17692	17692	25.9674	0.00%	0.00%
50-5MN	0%	25266	18088.5	26238.2	26093	554.2794	3.85%	3.17%
	20%	22295.5	18036.5	22349	22030	352.5066	0.24%	-1.21%
	40%	26537.5	184.64	26856	26837	206.384	1.20%	1.12%
	60%	24335	1.031	24335	24335	132.842	0.00%	0.00%
	80%	22637	0.281	22637	22637	73.172	0.00%	0.00%
	100%	17839	0.047	17839	17839	26.604	0.00%	0.00%
50-5MNb	0%	20208	18067.7	20668.8	20573	693.4716	2.28%	1.77%
	20%	21777	427.516	21908.2	21777	512.9844	0.60%	0.00%
	40%	26217	13.625	26217	26217	325.288	0.00%	0.00%
	60%	25829.8	4.172	25885	25885	234.798	0.21%	0.21%
	80%	24269	0.282	24269	24269	79.354	0.00%	0.00%
	100%	19255	0.078	19255	19255	31.014	0.00%	0.00%
50-5N	0%	23675	18066.6	24979.8	24821	667.443	5.51%	4.62%
	20%	33844	18151	33998.6	33880	325.4422	0.46%	0.11%
	40%	33263.5	5205.09	33387.6	33263	238.615	0.37%	0.00%
	60%	32576	7.172	32576	32576	134.596	0.00%	0.00%
	80%	30817.5	0.704	30817	30817	76.878	0.00%	0.00%
	100%	23752.8	0.062	23752	23752	34.77	0.00%	0.00%
50-5Nb	0%	22347	18138.3	22936	22840	730.3584	2.64%	2.16%
	20%	28042.8	5449.27	28184	28087	433.481	0.50%	0.16%
	40%	32806	103.578	32824.6	32812	343.56	0.06%	0.02%
	60%	32565	7.141	32604.2	32565	190.332	0.12%	0.00%
	80%	30810	0.203	30810	30810	88.11	0.00%	0.00%
	100%	23915	0.062	23915	23915	36.994	0.00%	0.00%

Problem	% of Parcel Locker Customers	CPLEX		ALNS				
		Objective	CPU (s)	Average Objective	Best Objective	Avg. CPU (s)	Gap_a	Gap_b
100-5MNb	0%	34533	18005.2	33408.8	33190	5277.628	-3.26%	-4.05%
	20%	34578.2	18077.5	33496.6	33016	3116.74	-3.13%	-4.73%
	40%	33202	18032.6	33743.6	33652	1536.804	1.63%	1.34%
	60%	35576	18007.6	35566.6	35508	1089.136	-0.03%	-0.19%
	80%	39195	8.641	39195	39195	347.356	0.00%	0.00%
	100%	31655	0.406	31655	31655	78.286	0.00%	0.00%
100-5N	0%	42127	18011.7	41426.6	40864	4598.132	-1.66%	-3.09%
	20%	54581	18005.2	54611	54472	2598.024	0.05%	-0.20%
	40%	51449.2	18079.8	51607	51409	1725.49	0.31%	-0.08%
	60%	43858.8	1094.38	43945.4	43873	889.402	0.20%	0.03%
	80%	41805	7.562	41805	41805	318.8818	0.00%	0.00%
	100%	32433	0.094	32433	32433	89.6538	0.00%	0.00%
100-10MNb	0%	40673	18014.1	31396.6	30593	3898.692	-22.81%	-32.95%
	20%	34514	18002	34427.6	34256	2168.54	-0.25%	-0.75%
	40%	41511.5	18018.4	42342.2	41688	1420.3	2.00%	0.42%
	60%	45981.2	18060.7	45981	45981	1360.122	0.00%	0.00%
	80%	45420.8	12.219	45420	45420	335.336	0.00%	0.00%
	100%	38866.2	0.125	38866	38866	86.942	0.00%	0.00%
100-10N	0%	51649	18000.9	49707	49526	3831.474	-3.76%	-4.29%
	20%	55562	18000.6	54938.8	53718	2320.818	-1.12%	-3.43%
	40%	63123.2	18062	64153.2	63308	1491.68	1.63%	0.29%
	60%	58504.2	18062.7	58936.6	58552	786.066	0.74%	0.08%
	80%	51994	30.812	51994	51994	302.294	0.00%	0.00%
	100%	41645.2	0.172	41648	41648	101.514	0.01%	0.01%

Based on Table 7, generally, ALNS algorithm for 2E-LRPSPD-PL can result in the same performance as CPLEX solver in the small data instances. The ALNS algorithm can find an optimal solution, as the CPLEX solver also produces optimal solutions for small data instances across all scenarios. CPLEX solver can be said to result in optimal solution if the objective is obtained below the time limit 18000 seconds. For medium-sized data instances, the ALNS algorithm can perform comparably to the CPLEX solver in certain scenarios. Generally, scenarios at 80% and 100% achieve optimal solutions across all datasets using the ALNS algorithm. However, in specific datasets, scenarios at 40% and 60% can also yield optimal solutions. For the dataset 50-5MNb, even a scenario at 20% can produce an optimal solution. In the dataset 50-5MN, the 20% scenario can find a better solution than the CPLEX solver. On the other hand, the scenario at 0% using the ALNS algorithm results in a gap compared to the CPLEX solver for any dataset. For large data instances, the ALNS algorithm generally performs comparably to the CPLEX solver in scenarios of 80% and 100%. However, in the dataset 100-10N, there remains a gap of less than 0.1% between the ALNS result and the CPLEX result. In the 60% scenario, the ALNS algorithm results in a gap of less than 1% compared to the CPLEX result across all large datasets. For the 40% scenario, the gap ranges between 0.29% and 2%, though in one instance, the ALNS algorithm finds a better solution than CPLEX in the dataset 100-5N. In the 0% and 20% scenarios, the ALNS algorithm generally produces better solutions than the CPLEX results. Notably, in the 100-10MNb dataset, the 0% scenario shows a significant improvement due to the ALNS algorithm's ability to open lower-cost facilities.

Based on overall performance, ALNS can be concluded to outperform the CPLEX solver, as shown in Figure 12. ALNS improves the results of the CPLEX solver by 0.68%. In terms of computational time, ALNS can, on average, produce solutions in a shorter time period than CPLEX, especially for cases where CPLEX cannot find an optimal solution within the time limit. Based on the detailed comparison between the CPLEX solver and the ALNS algorithm, ALNS can find optimal solutions for small data instances. For medium and large data instances, optimal or better solutions can be found in several scenarios. However, gaps are observed in some scenarios of medium and large data instances. These gaps in ALNS results may be due to the use of fewer destroy and repair operators, limiting the search process within the solution space. Another possible cause is the ineffective code and logic in C++, resulting in less effective solutions for ALNS in several datasets and scenarios.

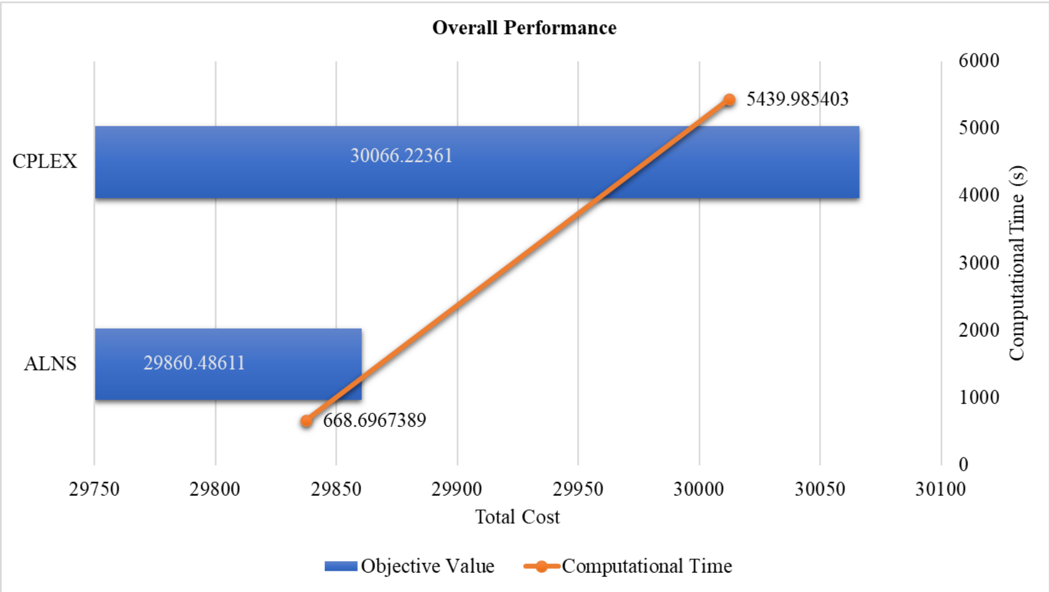


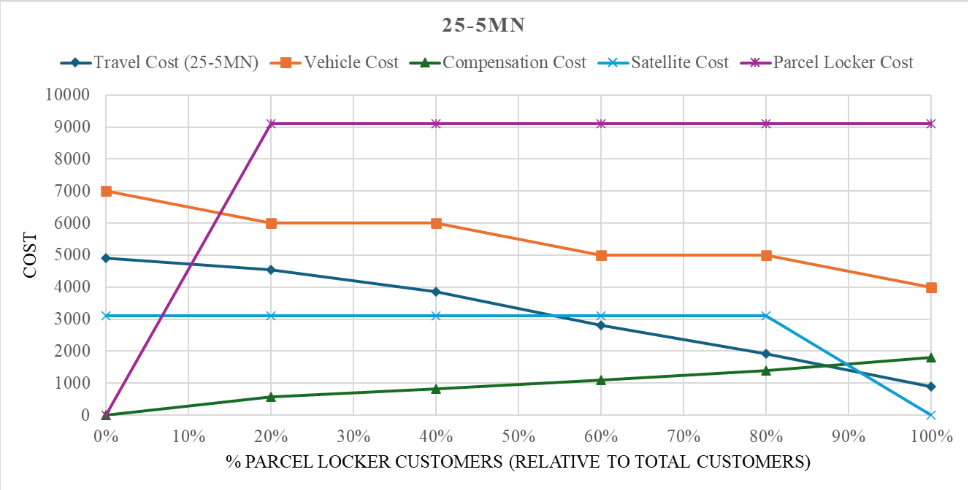
Figure 12 Comparison on Overall Performance between CPLEX and ALNS Algorithm

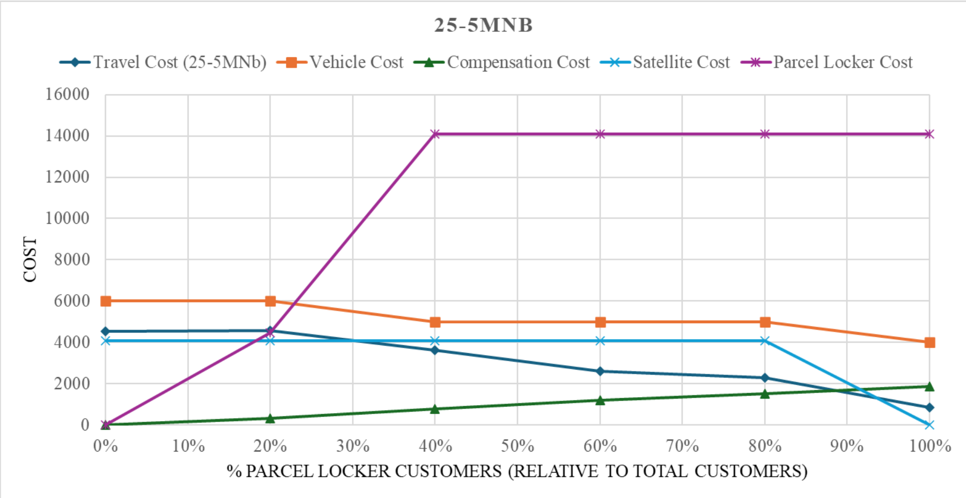
5.4 Sensitivity Analysis

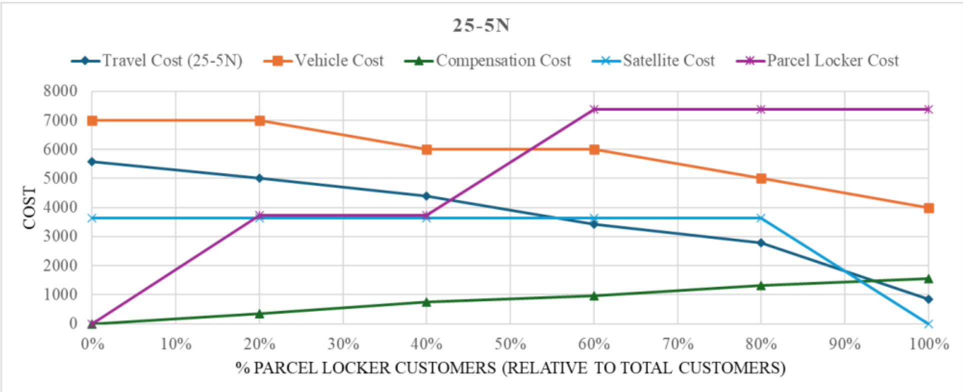
This section explains the impact of the ratio of parcel locker customers on the model's objective functions and the changes in factors that affect the effectiveness of parcel locker usage.

5.4.1 Impact of the Ratio of Parcel Locker Customers on the Model's Objective Functions

The changes in the model's objective functions in response to variations in the ratio of parcel locker customers are presented using scatter plots with straight lines. In this sensitivity analysis, the research uses data from all 25 customers as samples to capture the pattern of changes in each objective function. The sensitivity results can be seen in Figure 13.


25-5MN
Travel Cost (25-5MN)
Vehicle Cost
Compensation Cost
Satellite Cost
Parcel Locker Cost
COST
% PARCEL LOCKER CUSTOMERS (RELATIVE TO TOTAL CUSTOMERS)


25-5MNB
Travel Cost (25-5MNb)
Vehicle Cost
Compensation Cost
Satellite Cost
Parcel Locker Cost
COST
% PARCEL LOCKER CUSTOMERS (RELATIVE TO TOTAL CUSTOMERS)


25-5N
Travel Cost (25-5N)
Vehicle Cost
Compensation Cost
Satellite Cost
Parcel Locker Cost
COST
% PARCEL LOCKER CUSTOMERS (RELATIVE TO TOTAL CUSTOMERS)

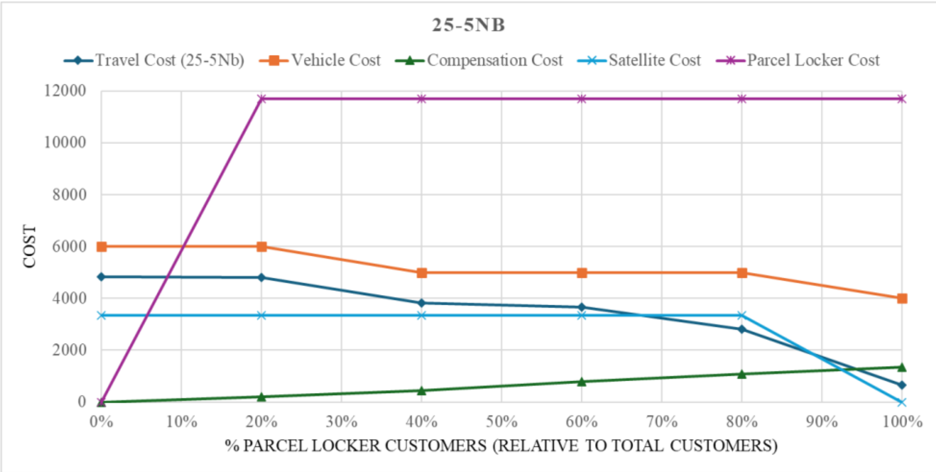
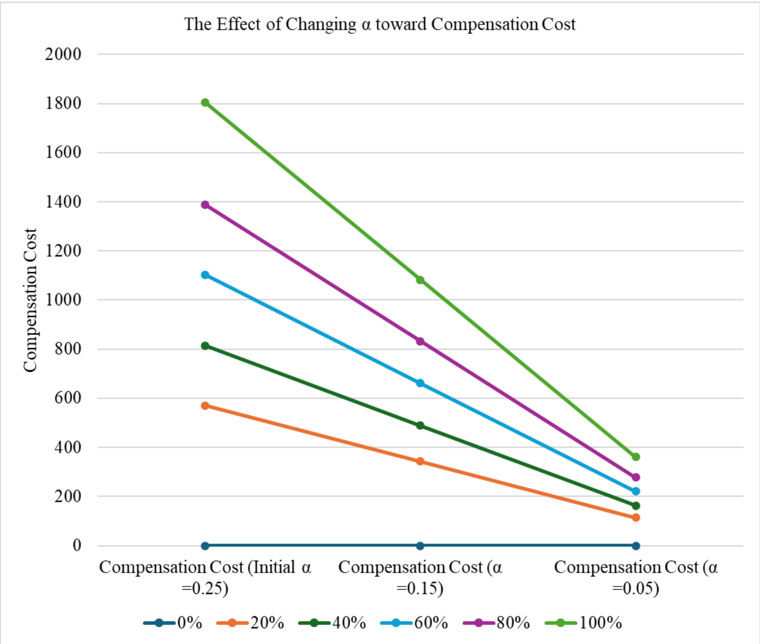


Figure 13 Cost Components of data 25 Customers

Based on four data types from 25 customers, each objective function shows similar patterns of change across the different data types. The travel cost has a declining trend along with the changes in ratio. When the ratio changes from 0% to 100%, the number of home service customers changing to parcel locker customers reduces the number of nodes to be visited in the second echelon, thereby decreasing the travel cost. For vehicle cost, overall results a declining trend along with the changes in ratio. The conversion of home service customers to parcel locker customers reduces the number of trips to visit home service customers. When the number of trips is reduced, the usage of vehicles is also reduced. However, if the number of trips remains static, the usage of vehicles will stay the same and the vehicle cost will be flat. Compensation cost shows an upward trend along with the changes in ratio. The compensation cost, associated with the distance traveled from parcel locker customers' locations to the parcel lockers, will always increase as the number of parcel locker customers increases. Satellite cost presents a declining-flat trend along with the changes in ratio. As the ratio of parcel locker customers increases, the number of opened satellites remains the same or decreases. If one satellite is sufficient at a 0% ratio, then the number of satellites will remain at one as the ratio increases to 80%. At a 100% ratio, no satellites are needed. The parcel locker cost shows an upward trend along with the ratio changes. If the ratio increases, it means the number of parcel locker customers is also increasing, causing the increased need for parcel lockers. The parcel locker cost may not change because the number of parcel lockers is considered sufficient to meet the demand at various ratios.

5.4.2 The Changes in Factors that Affect the Effectiveness of Parcel Locker Usage to Reduce Cost

In the test results of 2E-LRPSPD-PL, it can be seen that the use of parcel lockers in last-mile delivery does not always result in a lower total cost, even though the travel cost decreases effectively. In this section, the covering range of parcel locker and distance-dependent cost factor (α) will be varied to understand how parcel lockers effectively result in a lower total cost in last-mile delivery. In terms of individual cost components in the objective functions, α will directly affect the compensation cost given to parcel locker customers, while the covering range will impact both the cost of opening parcel lockers and the compensation cost. To understand the effect of covering range or α variations on the total cost or individual cost components mentioned above, data from 25-5MN is used as an example for the experiment. The description of 0%, 20%, 40%, 60%, 80%, and 100% in the graph represent the ratio of parcel locker customers relative to total number of customers. The impact of varying α toward costs can be seen in Figure 14.



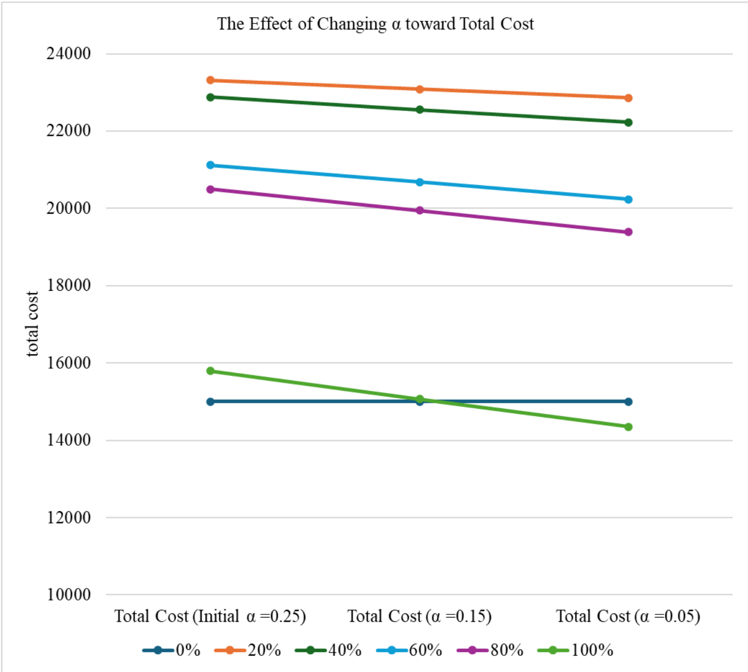
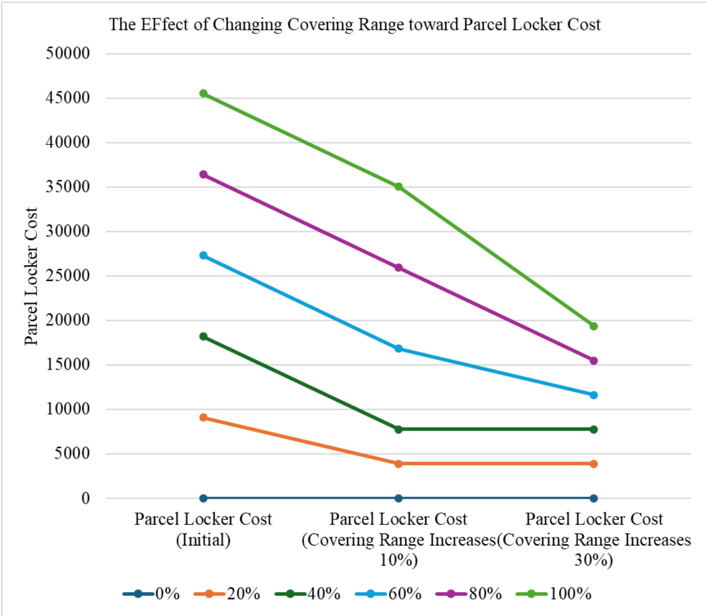


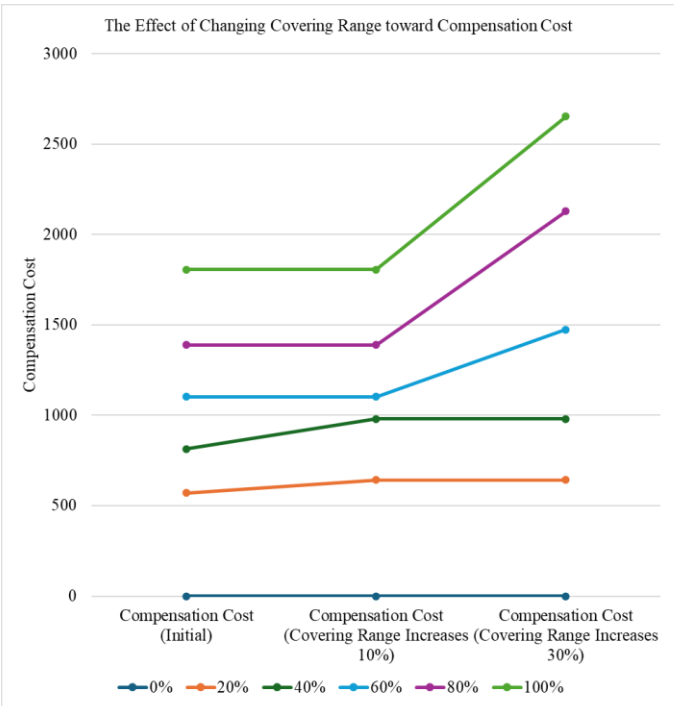
Figure 14 The impact of varying α on Compensation Cost and Total Cost

Based on Figure 14, lower α will result in a lower compensation cost and a lower overall total cost for each scenario of the parcel locker customer ratio. It means a lower α will result in more cost savings in terms of compensation cost and total cost. It can create an assumption that the usage of a parcel locker is effective if a company can set an efficient α or give reasonable compensation to parcel locker customers. If a company considers adopting parcel lockers as distribution strategy, it will be more efficient if the company fully adopts parcel lockers in the process of fulfilling customer demands. In the context of this research, which involves a two-echelon network, the company can use parcel lockers exclusively in the second echelon without relying on traditional last-mile delivery methods. Based on Figure 14, when a company fully adopts parcel lockers (100%) and encourages its customers to use them, the declining trend of total costs can result in lower total costs compared to the implementation of traditional last-mile delivery only (0% ratio) or other ratios. This result is suitable with the research of 2E-VRP-CO which explains that lower compensation cost results in a higher utilization rate of parcel lockers (Enthoven et al., 2020). A higher utilization rate means that using more parcel lockers provides more advantages under this condition. The ratio of 0% has no compensation cost and is stagnant in total cost across variations of α due to the absence of parcel locker customers.

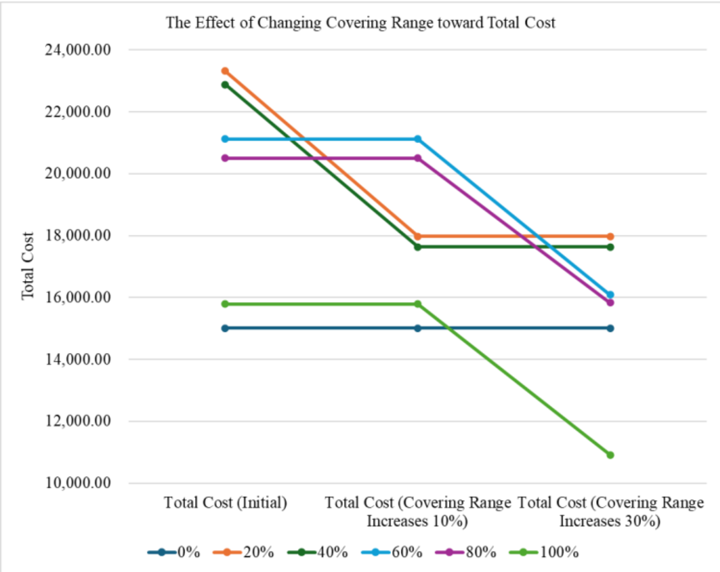
Other than α, variation of the covering range also impacts to the effectiveness of parcel locker in reducing costs as displayed in Figure 15.



(a)



(b)



(c)

Figure 15 (a) The Effect of Changing Covering Range on Parcel Locker Cost, (b) The Effect of Changing Covering Range on Compensation Cost, (c) The Effect of Changing Covering Range on Total Cost

Figure 15a shows that increasing the covering range results in lower parcel locker costs at each ratio of parcel locker customers. When the covering range is increased, each parcel locker can serve a larger number of customers. This reduces the overall need for parcel lockers. For example, if two parcel lockers are required under the initial conditions, fewer parcel lockers will be needed as the covering range is expanded. Therefore, the parcel locker cost becomes low. In Figure 15b, increasing the covering range results in higher compensation cost at each ratio of parcel locker customers. This condition is the opposite of parcel locker cost. If the covering range is increased, fewer parcel lockers are needed, leading to some parcel locker customers may undergoing longer distances which causes more expensive compensation cost. For example, when there are two parcel lockers, customers have the option to choose the one closer to their location. However, if the number of parcel lockers is reduced to one, some customers will lose the option to choose and will have to use the single available parcel locker, even if it's not the closest. So, determining the covering range should consider the trade-off between parcel locker cost and compensation cost. In Figure 15c, it can be concluded that the overall total cost will decrease (or remain stagnant at first and then decrease, or vice versa) if the covering range is increased. Despite the trade-off between parcel locker cost and compensation cost, the reduction in parcel locker cost appears to be more significant than the increase in compensation cost in terms of its effect on the total cost.

Similar managerial insights can be gained by varying the covering range, just as with varying α. If a company considers using parcel lockers, it will be more efficient if the company fully adopts parcel lockers (100%) in the process of fulfilling customer demands. Increasing covering range will ensure that the total cost will be more efficient alongside adopting 100% parcel lockers on servicing customers (in the second echelon). If a company still wants to use traditional last-mile delivery (visiting customers' houses by vehicles), efficiency can be achieved by encouraging more customers to use parcel lockers instead of home delivery or pickup. This is evident in the 60% and 80% ratios, which show a declining cost trend as the covering range increases. In these ratios, the total cost may decrease further if the covering range continues to expand. This analysis is supported by the research on the 2E-VRP-CO, which explains that a larger covering range results in a higher utilization rate of parcel lockers (Enthoven et al., 2020).

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CHAPTER VI
CONCLUSION AND FUTURE RESEARCH

In this section, the conclusion and future research ideas are explained in detail.

6.1 Conclusion

In this research, a two-echelon last-mile delivery system is updated by incorporating parcel lockers as intermediate facilities. Parcel lockers are used as a strategy to address the challenges of last-mile delivery. They are expected to reduce the supply chain cost of last-mile delivery, increase flexibility, and improve customer service quality. The mathematical model of the delivery system that considers parcel lockers is named 2E-LRPSPDP-PL. The inclusion of parcel lockers is the key difference between this model and the 2E-LRPSPD model developed in previous research. Since parcel lockers are used in this model, the concept of covering range is also introduced. Parcel lockers can only serve customers within their covering range, which helps manage the capacity of the lockers effectively and prevents customers from having to use a parcel locker that is far from their location.

The 2E-LRPSPD-PL model is presented as a two-indexed Mixed Integer Linear Programming (MILP) formulation. To test the model, data instances were created and evaluated using the CPLEX solver and the ALNS algorithm. The datasets include three sizes: small (25 customers), medium (50 customers), and large (100 customers). Various scenarios were considered to capture changes in the proportion of parcel locker customers versus home service customers. Each scenario represents the percentage of parcel locker customers (0%, 20%, 40%, 60%, 80%, 100%), with the remaining percentage representing home service customers. The objective of this research is to minimize total costs, which include traveling costs, vehicle costs, costs for opening facilities (satellites and parcel lockers), and compensation costs. The compensation cost serves as a price discount for customers who need to travel to the parcel locker.

The data instances are solved using the ALNS algorithm and compared to the results obtained from the CPLEX solver, which has been utilized with a time limit of 18000 seconds. The result from CPLEX is considered optimal if obtained within 18000 seconds. Based on overall performance, ALNS can outperform CPLEX, showing 0.33% - 0.68% better results. In detail, the ALNS algorithm can find an optimal solution comparable to the CPLEX result for small datasets. However, for medium and large datasets, the ALNS algorithm can mostly find optimal solutions in scenarios with 80% and 100% parcel locker customers. In other scenarios, the ALNS algorithm sometimes matches the CPLEX solution, sometimes performs better, and sometimes there is a gap with CPLEX. The most important aspect is that the ALNS algorithm can find solutions in a shorter time than CPLEX, particularly for cases where CPLEX cannot find an optimal solution within the time limit.

Based on the calculation results, the use of parcel lockers sometimes results in a lower total cost and sometimes in a higher total cost compared to not using parcel lockers. However, parcel lockers effectively reduce travel costs. Two important parameters that a company can control to achieve an effective total cost with parcel lockers are the covering range of the parcel locker and the distance-dependent cost factor, which affects the compensation cost. A lower distance-dependent cost factor and a higher covering range generally reduce the total cost when using parcel lockers. Alongside having a lower distance-dependent cost factor and a higher covering range, if the company wants to implement parcel lockers in the two-echelon networks, it will be more efficient for the company to fully adopt parcel lockers for fulfilling customer demands rather than mixing traditional last-mile delivery and parcel lockers, or solely using traditional last-mile delivery.

6.2 Future Research

Several future research ideas can be adapted as a development in this research. The most basic one is improving the ALNS algorithm to increase the effectiveness of outperforming the CPLEX result. The usage of more variation destroy and repair operators can be the key of improvement. Other than that, the development of a three-indexed MILP formulation for this model can be considered. It will help develop the model to consider more realistic cases such as split delivery. The idea of using time windows and multi-depot also makes the model more representative of the real world. Lastly, the consideration of some demand distributions can also be implemented in the next research.

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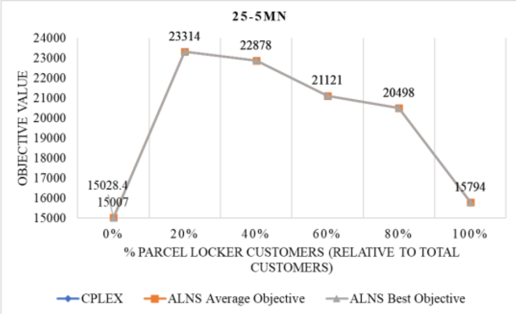
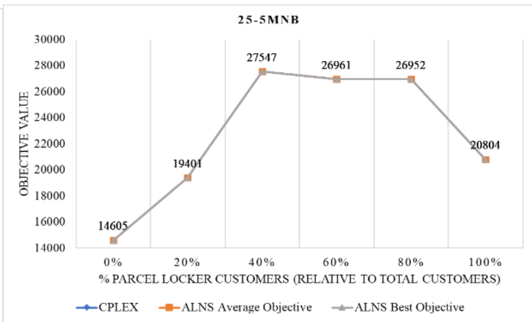
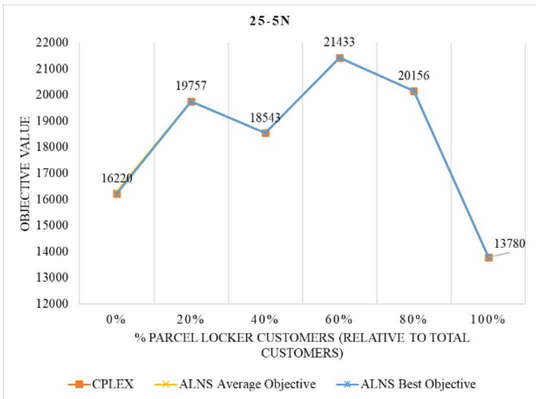
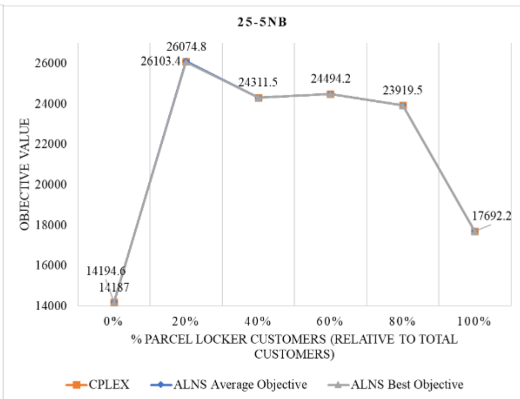
APPENDIX

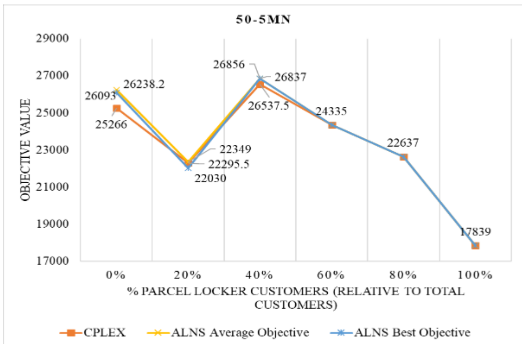
Appendix 1. The comparison of test results between ALNS and CPLEX solver in form of graph.

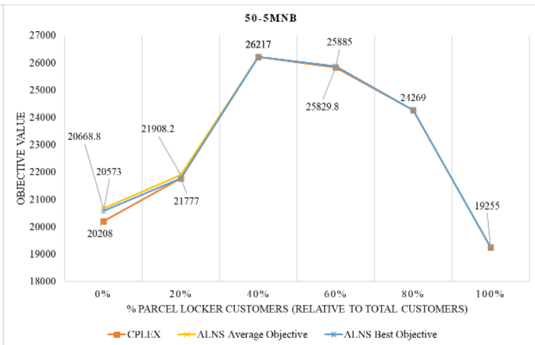


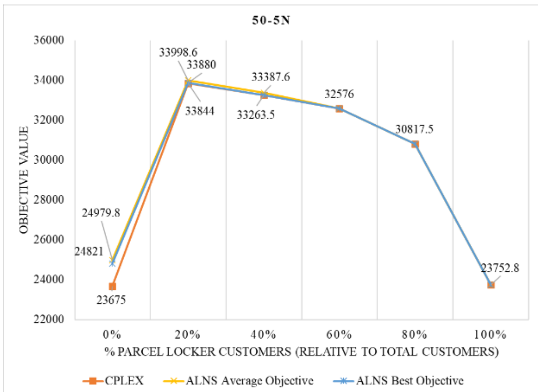


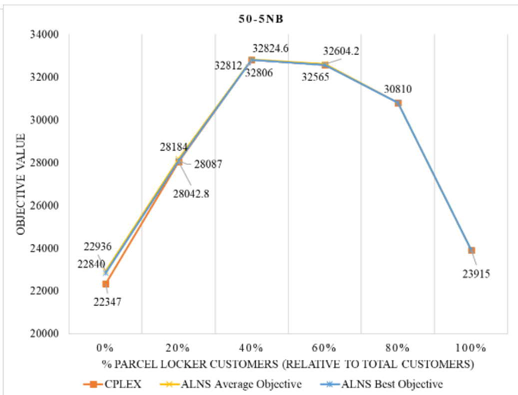


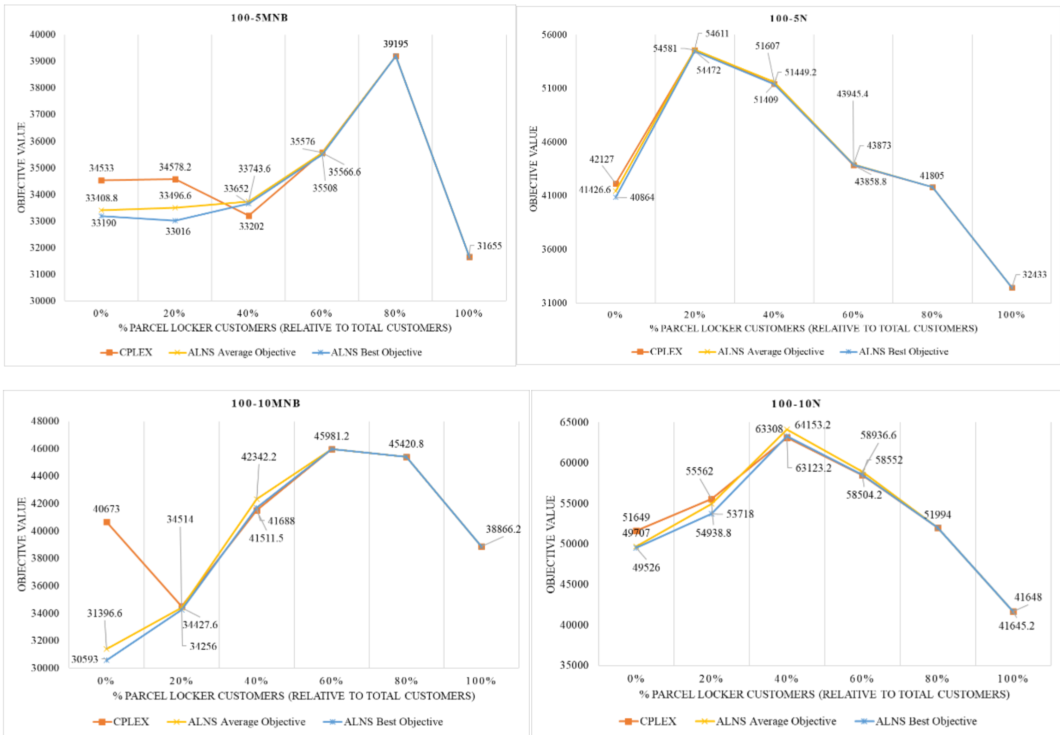












100-5MNB
OBJECTIVE VALUE
% PARCEL LOCKER CUSTOMERS (RELATIVE TO TOTAL CUSTOMERS)
0% 20% 40% 60% 80% 100%
34533 34578.2 33408.8 33496.6 33190 33016 33743.6 33652 33202 35576 35566.6 35508 39195 31655
CPLEX
ALNS Average Objective
ALNS Best Objective
100-5N
OBJECTIVE VALUE
% PARCEL LOCKER CUSTOMERS (RELATIVE TO TOTAL CUSTOMERS)
0% 20% 40% 60% 80% 100%
42127 41426.6 40864 54581 54611 54472 51607 51449.2 51409 43945.4 43873 43858.8 41805 32433
CPLEX
ALNS Average Objective
ALNS Best Objective
100-10MNB
OBJECTIVE VALUE
% PARCEL LOCKER CUSTOMERS (RELATIVE TO TOTAL CUSTOMERS)
0% 20% 40% 60% 80% 100%
40673 31396.6 30593 34514 34427.6 34256 42342.2 41688 41511.5 45981.2 45420.8 38866.2
CPLEX
ALNS Average Objective
ALNS Best Objective
100-10N
OBJECTIVE VALUE
% PARCEL LOCKER CUSTOMERS (RELATIVE TO TOTAL CUSTOMERS)
0% 20% 40% 60% 80% 100%
51649 49707 49526 55562 53718 54938.8 63308 64153.2 63123.2 58936.6 58552 58504.2 51994 41648 41645.2
CPLEX
ALNS Average Objective
ALNS Best Objective

Author Biography

Rafli Muhammad Rangga Kusuma was born in Surabaya, on June 28th, 2000. The author earned a bachelor’s degree in industrial and systems engineering from Institut Teknologi Sepuluh Nopember in 2022. The author then continued to a master's program in Industrial and Systems Engineering at the same institution from 2022 to 2024. In 2023, the author joined a double degree program at the National Taiwan University of Science and Technology (NTUST), majoring in Industrial Management. The author conducted and completed this research at NTUST under the supervision of Professor Vincent F. Yu.

During the master's studies, the author focused on logistics and supply chain management. The author was part of the teaching assistant team for Logistics and Supply Chain Management at ITS (LSCM ITS), where the author assisted lecturers in conducting practicums, teaching logistics software, and other related activities. At NTUST, the author was also a member of the Global Logistics and Supply Chain Management group. As a lab member at NTUST, the author gained experience in writing research papers, discussing research ideas with professors and peers, and participating in international conferences. Recently, the author has published a proceeding paper in IEEEXplore.

The author has a strong passion for transportation management, logistics, supply chain, production planning, and procurement. For any questions or further discussions related to this research, the author can be contacted via email at raflimuhammadranggakusuma@gmail.com or through LinkedIn at https://www.linkedin.com/in/raflirangga/.